Estimating Changes in Coho Salmon and Steelhead Abundance from Watershed Restoration: How Much Restoration Is Needed to Measurably Increase Smolt Production?

Article *in* North American Journal of Fisheries Management · December 2010

DOI: 10.1577/M09-162.1

Phil Roni
Cramer Fish Sciences

G. R. Pess
National Oceanic and Atmospheric Administration

Timothy Beechie
National Oceanic and Atmospheric Administration

Sarah A. Morley
National Oceanic and Atmospheric Administration

North American Journal of Fisheries Management 30:1469–1484, 2010
American Fisheries Society 2010
DOI: 10.1577/M09-162.1

[Article]

Estimating Changes in Coho Salmon and Steelhead Abundance from Watershed Restoration: How Much Restoration Is Needed to Measurably Increase Smolt Production?

PHILIP RONI,* GEORGE PESS, TIM BEECHIE, AND SARAH MORLEY
National Oceanic and Atmospheric Administration, Northwest Fisheries Science Center, Watershed Program, 2725 Montlake Boulevard East, Seattle, Washington 98112, USA

Abstract.—Using existing data from evaluations of habitat restoration, we estimated the average change in coho salmon *Oncorhynchus kisutch* and steelhead *O. mykiss* parr and smolt densities for common in-channel (culvert removal, large wood placement, boulder placement, and constructed logjams) and floodplain restoration techniques (constructed side channels and reconnected floodplain habitats). We then used these numbers and a Monte Carlo simulation to predict changes in fish numbers in a model watershed for two restoration scenarios: (1) restoration of all accessible habitat within the watershed and (2) restoration of the average amount historically implemented in Puget Sound watersheds (8% of total restorable areas). Mean increases in coho salmon parr or smolt density after restoration ranged from 0.19 to 2.32 parr/m for in-channel techniques and from 0.34 to 1.70 parr/m^2 for floodplain techniques. Increases in steelhead parr or smolt density ranged from −0.06 to 0.71 fish/m and from 0.03 to 0.06 fish/m^2 for in-channel and floodplain techniques, respectively. Under restoration scenario 1, the predicted mean increase in numbers was 1,459,254 (117%) and 285,302 (140%) for coho salmon parr and smolts and 93,965 (65%) and 28,001 (125%) for steelhead parr and smolts. Under scenario 2, the predicted mean increase in parr and smolts was 59,591 (5%) and 15,022 (7%) for coho salmon and 1,733 (1%) and 1,195 (5%) for steelhead. The percentage of floodplain and in-channel habitat that would have to be restored in the modeled watershed to detect a 25% increase in coho salmon and steelhead smolt production (the minimum level detectable by most monitoring programs) was 20%. However, given the large variability in fish response (changes in density or abundance) to restoration, 100% of the habitat would need to be restored to be 95% certain of achieving a 25% increase in smolt production for either species. Our study demonstrates that considerable restoration is needed to produce measurable changes in fish abundance at a watershed scale.

The listing of many Pacific salmon *Oncorhynchus* spp. populations as threatened or endangered under the U.S. Endangered Species Act has led to extensive recovery efforts for these populations. Several factors have been implicated in their decline including hatcheries, harvest, hydropower, and habitat degradation (Nehlsen et al. 1991). Much of the recovery effort for salmon and other endangered fishes has focused on minimizing the impacts of the first three factors, combined with implementing habitat improvement and restoration efforts (Williams et al. 1999; Collares-Pereira and Cowx 2004). An estimated one billion dollars has been spent annually on watershed restoration in the USA since 1990 (Bernhardt et al. 2005). More than 60% of projects completed during this period were for salmon and trout habitat restoration efforts in the Pacific Northwest and California (Bernhardt et al. 2005; Katz et al. 2007). Common techniques used to improve salmon habitat and restore watersheds include riparian planting, grazing reduction, road improvements to reduce runoff and fine sediment, removal of culverts and other barriers to fish migration, rehabilitation of floodplain habitats, conservation easements and acquisitions, nutrient enrichment, gravel augmentation, and placement of instream structures such as logs, boulders, and logjams (Roni et al. 2002, 2008; Bernhardt et al. 2005). Despite these large well-funded efforts, debate continues over the effectiveness of various habitat restoration techniques and the cumulative impact of multiple, poorly coordinated restoration actions at a watershed or regional scale (Reeves et al. 1991; Chapman 1996; Roni et al. 2002; Kondolf et al. 2008).

Biologists and restoration practitioners have been primarily concerned with the physical and biological effects of restoration projects. In contrast, resource managers and those funding and developing recovery plans for endangered species are typically more concerned with questions such as

1. How many more fish are produced by various restoration techniques?
2. How much habitat needs to be restored to significantly increase fish abundance? and

---

* Corresponding author: phil.roni@noaa.gov

Received October 5, 2009; accepted September 30, 2010

3. How much habitat needs to be restored to achieve "recovery" of a threatened, endangered, or depressed fish population?

Scientists and restoration practitioners alike have typically responded that it is not possible to address these questions because (1) we cannot estimate the effectiveness of certain restoration techniques and (2) it is not known which habitats or other factors actually "limit" fish abundance and the size of most salmon populations (Tear et al. 2005; Beechie et al. 2008). This is true for techniques that take several decades to effect a habitat change, such as road removal or riparian planting (Beechie et al. 2005; Pollock et al. 2005). Nevertheless, several studies have demonstrated the physical and biological effectiveness of individual techniques including instream structures (Slaney et al. 1994; Cederholm et al. 1997; Solazzi et al. 2000; Roni and Quinn 2001a), construction and reconnection of floodplain habitats (Giannico and Hinch 2003; Morley et al. 2005; Roni et al. 2006a), and replacement of road crossings that impair fish movement (Pess et al. 1998; Glen 2002). The amount and quality of different types of habitat are thought to be reasonable predictors of juvenile salmonid abundance and production. Also, habitat specific densities can be coupled with total habitat area to predict fish abundance (Reeves et al. 1989; Beechie et al. 1994; Sharma and Hilborn 2001). Thus, recent studies on changes in fish abundance from restoration contain data and findings that could be coupled with existing estimates of amount of habitat restored to estimate the potential increase in fish production from a suite of different instream and floodplain habitat restoration activities. The challenge is finding compatible data sets, because evaluations of restoration techniques often use different monitoring designs, use different metrics to quantify changes in fish abundance, occur in different geographic regions, or report findings for only a few sites or watersheds.

Regional and watershed level monitoring programs are being developed by state agencies and other groups to measure increases in Pacific salmon and steelhead *O. mykiss* (anadromous rainbow trout) production at a watershed scale (Bilby et al. 2005; NOAA 2007). Unfortunately, these programs will not be able to evaluate restoration success for many years because of the high interannual variation in fish abundance among both years and sites (Bisson et al. 1997; Liermann and Roni 2008; Dauwalter et al. 2009). Most restoration monitoring and evaluation programs are generally not designed to detect changes in fish abundance of less than 25% or 30% because of the high cost of monitoring many sites for many years (Paulsen and Fisher 2003; Liermann and Roni 2008). Moreover, few studies have estimated fish response to various restoration techniques at a watershed scale and those that have examined one or two techniques and produced highly variable results. For example, of three different watershed-scale evaluations of restoration in Oregon (Reeves et al. 1997; Solazzi et al. 2000; Johnson et al. 2005), only one showed a large increase (>200%) in coho salmon *O. kisutch* and steelhead smolt production (Solazzi et al. 2000), and all three studies focused on similar restoration techniques (large woody debris [LWD] placement or creation of pool or pond habitat). Thus, estimating watershed-scale increases in fish due to a suite of restoration techniques and estimating the amount of restoration needed to measurably increase fish production continue to be pressing research needs.

The question of whether restoration efforts should be spread widely across a basin or region or concentrated in key reaches or subbasins is an important question from a management, economic, and recovery planning standpoint. Restoration project databases such as those developed for the Pacific Northwest by Katz et al. (2007) and the entire USA by Bernhardt et al. (2005) demonstrate that restoration actions are rarely concentrated within a few key watersheds, but rather are spread out across the landscape. Nowhere is this more evident than the Pacific Northwest, where nearly 100 million dollars are spent every year on restoring watersheds to recover endangered Pacific salmon (NOAA 2007). Even within a single watershed, recent modeling efforts suggest that concentrating restoration efforts in specific subwatersheds will produce larger increases in salmon than spreading restoration actions equally across subwatersheds (Fullerton et al. 2010). It is therefore important to consider where the restoration is located across the landscape when estimating increases in fish production.

Addressing the questions and needs outlined above requires compatible data sets on the effectiveness of different techniques, an idea of how much habitat exists and how much can be restored, and some idea of the desired amount of change. In this paper we develop comparable estimates of the increase in numbers of coho salmon and steelhead parr and smolts for common habitat restoration techniques. We demonstrate how these data can be used to predict the range of coho salmon and steelhead parr and smolt abundance using two different watershed restoration scenarios. We then examine how much restoration would theoretically have to be completed to detect a measurable change in coho salmon and steelhead numbers under a typical monitoring program. Lastly, we discuss the implications of these estimates on planning and locating restoration projects.

TABLE 1.—Mean increase and SE of change in the number of coho salmon and steelhead parr and smolts or presmolts for six types of habitat restoration examined. For in-channel techniques the values shown are fish/m and for floodplain techniques they are fish/m^2. Study designs are as follows: PT = posttreatment, BA = before–after, BACI = before–after control–impact.

				Summer (parr)				Winter (smolts)			
				Coho salmon		Steelhead		Coho salmon		Steelhead	
Restoration type (reference)	Study design	Applicable sites or habitats	No. of sites	Mean	SE	Mean	SE	Mean	SE	Mean	SE
In-channel techniques											
Culvert replacement (barrier removal; Pess et al. 1998)	BACI	Small streams	6	0.36	0.17	0.05	0.01				
LWD in small streams (Roni and Quinn 2001)	PT	Small streams	28/22[a]	0.59	0.18	–0.06	0.10	0.21	0.07	0.04	0.02
Boulder weirs (Roni et al. 2006a)	PT	Medium streams	13	0.66	0.18	0.02	0.01				
Constructed logjams (Pess et al., in press)	BA	Large streams	16/6[b]	2.32	0.55	0.71	0.47	0.19	0.10	0.09	0.06
Floodplain techniques											
Restored floodplain habitats (Roni et al. 2006b)	BA	Floodplain reconnection	30					0.37	0.07		
Constructed groundwater channels (Morley et al. 2005)	PT	Floodplain habitats	22	1.70	0.31	0.06	0.03	0.34	0.09	0.03	0.01

[a] 28 sites contained coho salmon, 22 contained steelhead.

[b] Paired treatment and control sites in the Elwha River (16 during summer and 6 during winter).

Methods

Mean fish response to different techniques.—We used data from our previously published studies in western Washington and Oregon to produce compatible estimates of changes in mean parr and smolt densities to various restoration techniques (Pess et al. 1998; Roni and Quinn 2001a; Morley et al. 2005; Roni et al. 2006a, 2006b; Pess et al., in press). We did this because the numerous studies that have examined numeric fish response to common habitat restoration techniques such as LWD (single and multiple log placement and structures) and boulder weir placement, construction of groundwater-fed side channels, and reconnection of floodplain habitats (e.g., sloughs, oxbows) are from many different regions, rarely compatible, and not readily available (see Roni et al. 2008 for a thorough review). Fortunately, data from Pess et al. (1998), Roni and Quinn (2001a), Morley et al. (2005), Roni et al. (2006a, 2006b), and Pess et al. (in press) incorporate data on more than 85 different projects and were collected using similar methods and study designs (Tables A.1, A.2 in the appendix). Furthermore, these studies demonstrated significant changes in fish densities in response to restoration. We use the term "response" to refer to changes (increase or decrease) in fish densities due to restoration.

While data from each of these six studies used similar methodologies, there were some minor differences in fish identification and enumeration techniques. Because steelhead become smolts after one or more years in freshwater (Quinn 2005) and we were interested in parr and smolts rather than fry, we used only data for age-1 or older steelhead or trout (generally $\geq$60 mm in summer and $\geq$80 mm during winter at most of our sites, Roni and Quinn 2001). Snorkel surveys used to enumerate fish during monitoring of boulder weirs and constructed groundwater (CGW) channels could not consistently distinguish between cutthroat trout *O. clarkii* and steelhead. As steelhead are the dominant trout species in these streams (Roni et al. 2006b), we classified all trout as steelhead for the purposes of our analyses.

Designs for the six studies included posttreatment (comparisons of treatments to controls or references), before–after, and before–after control–impact designs (Table 1). We used the differences between the treatments and controls when possible to estimate fish response. Morley et al. (2005) and Roni et al. (2006a) did posttreatment comparisons of constructed sites or reconnected sites to nearby natural floodplain reference sites rather than paired control sites. Thus, the reference sites represented the desired postrestoration conditions as opposed to "control" sites, which would represent the original degraded conditions. Moreover, Roni et al. (2006a) and Morley et al. (2005) found that constructed or reconnected habitats produced similar fish numbers to nearby natural reference sites. Therefore, we included the data from the reference sites and the constructed and reconnected sites to calculate means and SE values for both reconnected floodplain habitats and CGW channels. We used posttreatment numbers of coho salmon and steelhead for floodplain habitat and culvert removal because coho salmon and steelhead numbers were zero prior to restoration.

We did not have winter data for boulder weir projects or for culvert reconnection projects. However, Roni and Quinn (2001a) sampled over 30 small streams throughout western Washington and Oregon that encompassed the range of stream sizes and gradient sampled by Pess et al. (1998). Therefore, winter data from Roni and Quinn (2001a) were used to

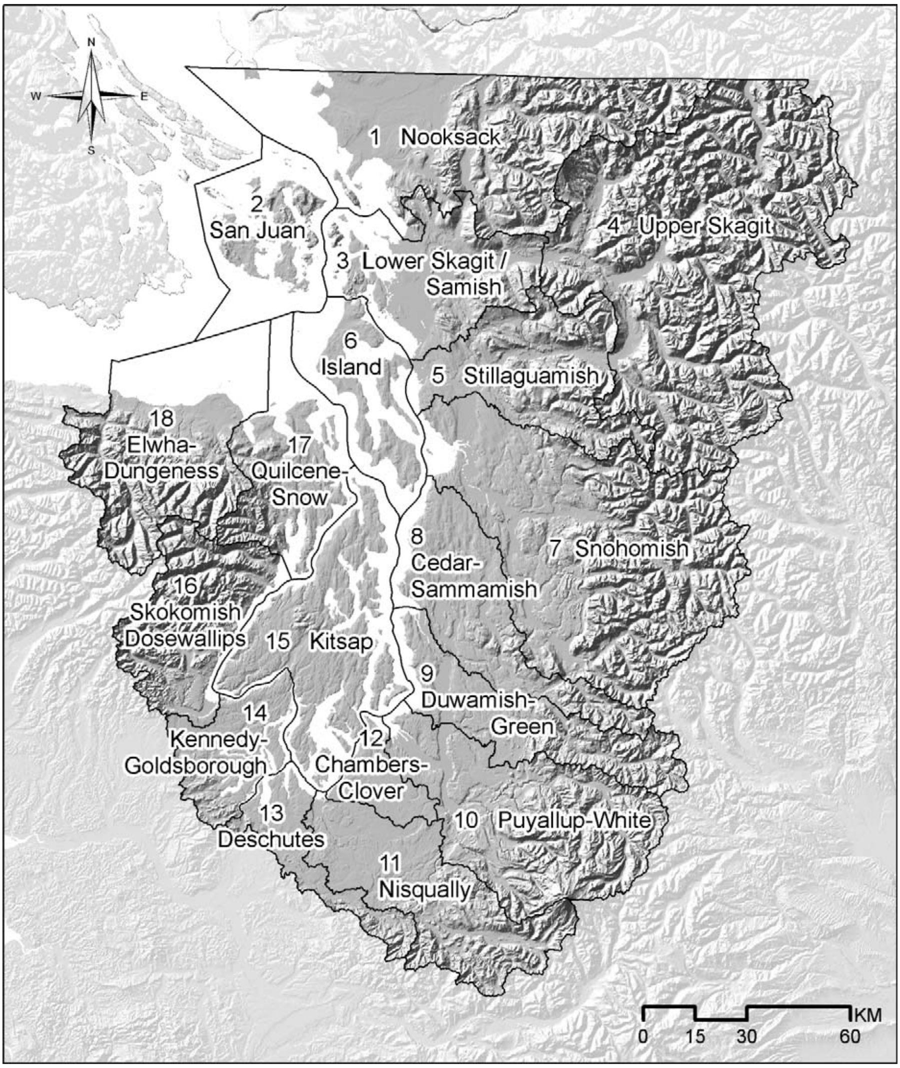

FIGURE 1.—Northwestern Washington State, the Puget Sound basin, and associated watersheds or watershed resource inventory areas as defined by the Washington Department of Fish and Wildlife. Some watersheds contain multiple basins or watersheds.

estimate increases in smolt numbers for culvert projects. Because boulder weirs were placed in streams midway in size between those examined for LWD and constructed logjam (CLJ) projects, we used the average response and pooled SD of CLJ and LWD projects to estimate smolt production from boulder weir placement. Similarly, we did not have summer coho salmon parr data for floodplain habitat reconnection, though Morley et al. (2005) sampled some of the same sites during summer and reconnected floodplain habitats included side channels as well as sloughs and ponds. Thus, summer data from CGW channels were used as an estimate of summer coho salmon parr numbers for floodplain habitat reconnection. We estimated increases in only coho salmon abundance for floodplain reconnection because few steelhead smolts are produced from floodplain ponds and sloughs (Roni et al. 2006a).

We used fish/m^2 as our response metric for reconnected floodplain habitats and CGW channel projects, and fish/m for LWD placement, boulder weir placement, and culvert removal projects. We did so because regional and nationwide restoration project databases report data on amount of habitat restored in

TABLE 2.—Types and amounts of habitat in a typical Puget Sound watershed, habitat restoration actions typically used in those habitats, and estimated cost of that restoration. Average costs for restoration techniques are from Shared Strategy for Puget Sound (2003) and are in 2003 U.S. dollars. Inaccessible streams are approximately 10% of accessible small streams.

Habitat	Typical Puget Sound watershed	Potential restoration treatment	Restoration cost	Total cost
Stream habitat				
Small streams, accessible (m)	126,012	Large woody debris	\$56/m	\$7,056,662
Small streams, inaccessible (m)	12,601	Culvert removal	\$75/m	\$945,089
Medium streams (m)	58,253	Boulders	\$300/m	\$17,475,938
Large streams (m)	117,751	Logjams	\$210/m	\$24,727,755
Floodplain habitat				
Existing side channels (m^2)	213,049	None		
Side channels lost (m^2)	306,766	Constructed groundwater channels	\$150/m^2	\$46,016,400
Existing sloughs and ponds (m^2)	77,240	None		
Inaccessible or lost sloughs and ponds (m^2)	319,755	Floodplain reconnection	\$85/m^2	\$27,179,175
Total cost to restore all above habitats				\$123,401,019

linear meters for streams and area in square meters for floodplain habitats and wetlands (Bernhardt et al. 2005; Katz et al. 2007; NOAA 2007).

Model watershed and restoration scenarios.—We first estimated the average habitat area found in major watersheds in the Puget Sound basin (PSB) to demonstrate how the differences in fish response to the restoration actions combined with different restoration strategies would lead to different increases in fish production in a single watershed (Figure 1; Table 2). We used the water resource inventory areas defined by the Washington Department of Fish and Wildlife to determine watershed boundaries (Figure 1). We selected the PSB as an area to develop our model watershed because (1) much of the fish data we used in our analysis was collected in western Washington and the PSB, (2) we have been involved in many restoration-planning efforts in the basin, and (3) data on habitat conditions across the basin were readily available. We used existing National Oceanic and Atmospheric Administration (NOAA) stream network and bankfull width (BFW) data for watersheds throughout the PSB to estimate the mean watershed area for major drainage basins and the average amount of small (5–15 m BFW), medium (15–25 m BFW), and large (>25 m BFW) stream channels suitable for salmon and steelhead (<12% gradient and below natural or manmade barriers). We did not have an estimate of all inaccessible habitat for each watershed, but assumed that 10% of total small stream length was inaccessible based on estimates from Beechie et al. (1994). Existing and isolated floodplain habitat was determined by estimates available for the Stillaguamish River basin, which is similar in size to the average PSB (~180,000 ha).

We developed two restoration scenarios to demonstrate how increases in coho salmon and steelhead numbers would vary under ideal (restore all) or historical restoration strategies. Scenario 1 included the ideal strategy of complete restoration of all accessible and isolated stream and floodplain habitat in the model watershed. This assumes that all in-channel and floodplain habitat is in need of some restoration. In contrast, scenario 2 included restoring the average amount of in-channel and floodplain habitat restored in the PSB under the Pacific Coastal Salmon Recovery Fund (PCSRF) from 2000 to 2009. For scenario 2, we queried the NOAA PCSRF database for all projects that reported the amount (length or area) of habitat restored and the technique (Table 3) for the entire PSB to estimate the average amount restored per watershed (watershed resource inventory area; Figure 1). The PCSRF database relies on project proponents to report total length and area of restoration so it is probably a conservative estimate of restoration activities under that program. It also does not include other restoration efforts in the region so it is not an estimate of total restoration in the region. While several different types of restoration projects have been implemented under the PCSRF (Table 3), we conducted our analysis only on those for which we had estimates of change in fish abundance. These projects included instream treatments (LWD, boulder weirs, and constructed logjams), wetlands treatments (floodplain and constructed groundwater channels), and culvert and barrier removal. Our estimates assume that all actions were implemented simultaneously. Restoration under scenario 2 is equivalent to restoring about 8% of the restoration under scenario 1.

We then ran a Monte Carlo simulation to estimate the range and probability of possible increases in smolt production from the two restoration scenarios (Manly 2006). We used the mean and SD of coho salmon and steelhead increases for each restoration technique to

TABLE 3.—Number of projects and length or area treated in the Puget Sound basin for various restoration activities funded by the Pacific Coastal Salmon Recovery Fund and completed between 2000 and 2009 (NOAA, unpublished data). Note that not all projects reported length and area treated, so the estimates should be viewed as conservative. The first three metrics or activities (bold italics) were examined in this paper.

Metric or restoration activity	Number of projects	Length or area km/ha	Length or area m/m^2	Average length or area per watershed
Instream length treated	***59***	***56 km***	***56,186 m***	***3,121 m***
Wetland area treated or created	***30***	***53 ha***	***526,448 m^2***	***29,247 m^2***
Stream length made accessible through culvert or barrier removal	***104***	***305 km***	***305,388 m***	***16,966 m***
Area acquired for protection–conservation	86	2,589 ha	25,889,079 m^2	1,438,282 m^2
Upland area treated	17	37 ha	372,710 m^2	20,706 m^2
Riparian area treated	41	380 ha	3,798,407 m^2	211,023 m^2
Riparian length treated	49	166 km	166,499 m	9,250 m
Estuarine area treated or created	36	201 ha	2,006,930 m^2	111,496 m^2
Upland road length treated	17	367 km	367,045 m	20,391 m^2
Stream bank length protected	85	117 km	116,878 m	6,493 m

create a distribution of project effectiveness values as inputs to the model. We then ran a Monte Carlo simulation with 10,000 model runs to estimate the distribution of possible outcomes for each restoration technique. The results for each technique were then multiplied by the area to be restored under each restoration scenario and the results for each habitat restoration type were combined to calculate the range of possible increases in coho salmon or steelhead numbers. Lastly, we calculated the mean and the 95% prediction interval of the Monte Carlo distributions.

For each restoration scenario we used the following treatments (restoration techniques): LWD placement in small channels (5–15 m BFW), boulder weir placement in small or medium-sized (15–25 m BFW) channels, CLJs in large channels (>25 m BFW), CGW channels, and floodplain habitat reconnection in large channels in floodplain habitats.

Calculation of restoration amount needed to detect fish response.—Finally, we estimated the amount of habitat restoration that would have to be completed to increase fish production by 25% in our model watershed. Previous studies by Bisson et al. (1997), Ham and Pearsons (2000), Roni and Quinn (2001a), Paulsen and Fisher (2003), Liermann and Roni (2008), and others have indicated that, in general, rigorous monitoring programs (e.g., 10 or more years or sites) typically cannot detect salmonid responses of less than 25–30%. Thus, we used a 25% increase in parr or smolt production as the minimum response size that could be detected. This, however, required that we have some estimate of prerestoration parr and smolt production. Using both prerestoration data for in-channel projects and postrestoration data for reconnected floodplain habitats (Tables A.1, A.2), we calculated mean densities for different habitat types outlined in Table 2 and multiplied those data by area or length estimated in Table 2 to determine the total parr and smolt production for the entire watershed. We then multiplied this number by 25% to provide a benchmark for increase in smolts needed (Table 4). Lastly, we used cost estimates taken from restoration efforts in western Washington prepared by the Shared Strategy for Puget Sound (SSPS 2003), to calculate the total costs in 2003 U.S. dollars of the various restoration scenarios (Table 2).

TABLE 4.—Estimated parr and smolt production in the modeled watershed before restoration. Twenty-five percent of mean production is used as a benchmark to estimate the amount by which smolt numbers would have to increase in order to be detected by most monitoring programs.

Habitat or restoration type	Habitat area or length	Parr: Coho salmon	Parr: Steelhead	Smolts: Coho salmon	Smolts: Steelhead
Stream habitat (m)					
Small streams	126,012	86,915	39,400	8,280	12,067
Medium streams	58,253	93,922	1,031	2,534	3,888
Large streams	117,751	53,488	99,238	2,509	4,444
Floodplain habitat (m^2)					
Side channels	213,049	882,355	4,730	190,662	1,986
Sloughs and ponds	77,240	131,421	0	26,516	0
Total		1,248,101	144,400	230,501	22,386
25% of mean production		312,025	36,100	57,625	5,596

Table 5.—Results of Monte Carlo simulation, including mean increase in number and 95% prediction interval for coho salmon and steelhead parr and smolts under two different restoration scenarios. Scenario 1 consists of restoring all accessible and isolated stream and floodplain habitat in the modeled watershed. Scenario 2 consists of restoring the same amount of stream and floodplain habitat restored in a typical watershed under the Pacific Coastal Salmon Recovery Fund in the Puget Sound basin from 2000 to 2009. The total amount of habitat restored is given in Tables 2 and 3.

	Scenario 1		Scenario 2	
Species and life stage	Mean	95% prediction interval	Mean	95% prediction interval
Coho salmon parr	1,459,254	54,724 to 2,874,566	59,591	−3,254 to +121,790
Coho salmon smolts	285,302	−73,447 to +657,087	15,022	5,143 to 35,249
Steelhead parr	93,965	−360,566 to +548,229	1,733	−2,307 to +5,957
Steelhead smolts	28,001	−13,259 to +68,817	1,195	171 to 2,209

Results

Mean increases in coho salmon parr or smolt density ranged from 0.19 to 2.32 fish/m for in-channel techniques and from 0.34 to 1.70 fish/m^2 for floodplain techniques (Table 1). Increases in steelhead parr or smolt densities ranged from −0.06 (a decrease) to +0.71 fish/m and from 0.03 to 0.06 fish/m^2 for in-channel and floodplain techniques, respectively. The largest increase for both coho salmon parr and steelhead parr and smolts was in response to CLJs, though this technique also had the largest SE (Table 1).

Average prerestoration estimates of fish production from our model watershed were 1,248,101 and 230,501 coho salmon parr and smolts, respectively, and 144,400 and 22,386 steelhead parr and smolts (Table 4). When increases in parr and smolt production from Table 1 were applied to restoration scenario 1 (restore all), the Monte Carlo simulation predicted a mean increase of 1,459,254 (117% increase) and 285,302 (140%) for coho salmon parr and smolts and 93,965 (65%) and 28,001 (125%) for steelhead parr and smolts, respectively (Table 5). When we applied scenario 2, the mean increase was 59,591 (5% increase) and 15,022 (7%) for coho salmon parr and smolts and 1,733 (1%) and 1,195 (5%) for steelhead parr and smolts, respectively. However, the 95% prediction intervals from the Monte Carlo simulation ranged from thousands to millions and included negative numbers in some instances (Table 5; Figure 2). For example, the 95% prediction interval under restoration scenario 1 was 54,724–2,874,566 for coho salmon smolts.

The contribution of different restoration techniques to the mean increase in parr and smolts varied by species and restoration scenario (Figure 3). For example, under scenario 1, the mean increase in coho salmon smolts was 285,302, of which 78% was from floodplain habitat restoration (41%) and CGW channels (37%), while for steelhead smolts 68% of the mean increase (28,001) was from CLJs (40%) and CGW channels (28%) (Figure 3). The differences between these two scenarios reflect differences in the proportion of restoration types under each scenario.

We next determined how much restoration in our model watershed would be necessary to increase mean smolt numbers by at least 25%, assuming an equal percentage of each habitat type was restored using the techniques discussed (Table 2). A total of 20% of each habitat type would have to be restored to produce a 25% increase in coho salmon or steelhead smolt production from prerestoration numbers. However, given the large variability in restoration response (Table 5), 100% of the habitat would need to be restored to be 95% certain of achieving a 25% increase in smolt production for either species. The total cost of restoring all in channel and floodplain habitat in the model watershed was approximately US\$123 million (2003 U.S. dollars; Table 2), while restoring 20% of the habitat (the amount needed to produce a mean increase of 25%) would cost approximately \$25 million.

Discussion

Coho Salmon and Steelhead Response by Restoration Technique

Our results provide a method for estimating juvenile coho salmon and steelhead response to common habitat restoration techniques, and the Monte Carlo simulations predict that large amounts of habitat would have to be restored within a watershed to have a measurable effect at a population or watershed scale. Our estimates of increase in parr and smolt numbers are within the range reported from other studies on restoration (e.g., Cederholm et al. 1997; Koning and Keeley 1997). Koning and Keeley (1997) reported an average increase in coho salmon smolt production from constructed ponds and side channels of 0.67 fish/m^2 and increases of 0.38 and 0.06 fish/m^2 for instream habitat restoration for coho salmon and rainbow trout parr, respectively. Our methods and estimates are also consistent with studies that have estimated coho salmon and steelhead parr and smolt production in

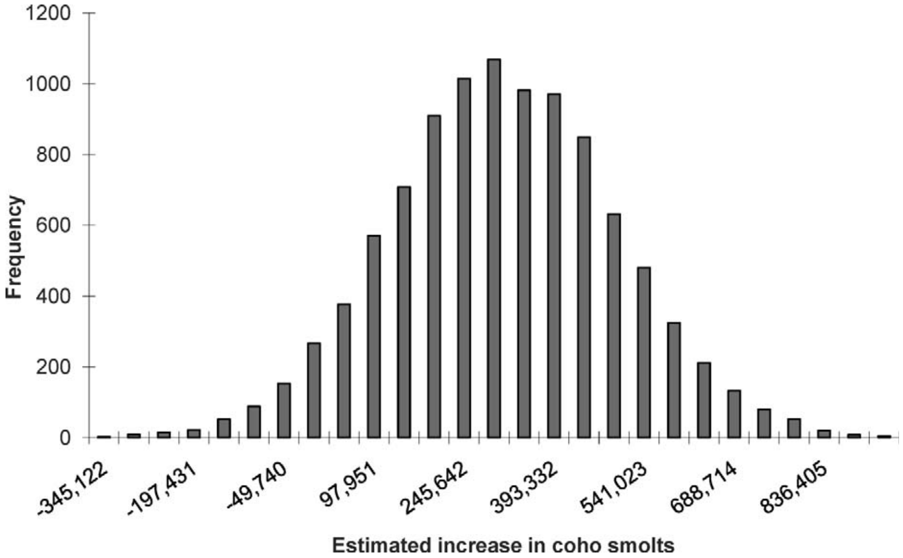

FIGURE 2.—Example of the frequency of Monte Carlo predictions of coho salmon smolt response to restoration scenario 1 in the modeled watershed. The simulation was run 10,000 times. The mean increase in coho salmon smolt production was 285,302.

different watersheds (Beechie et al. 1994; Pess et al. 2002) or in different habitat types (Bustard and Narver 1975a, 1975b; Reeves et al. 1989; Roni 2002). For example, Beechie et al. (1994) reported that coho salmon smolt production in pond-like channels and sloughs in the Skagit River basin, Washington, ranged from 0.07 to 1.31 smolts/m^2 with a mean of 0.52 smolts/m^2, which is similar to the range that we reported. In addition, the differing response of coho salmon and steelhead to the different restoration techniques are consistent with previous studies and reflects obvious differences in habitat preferences of the two species: coho salmon prefer pools and slow water areas, while steelhead are found in riffles, pools,

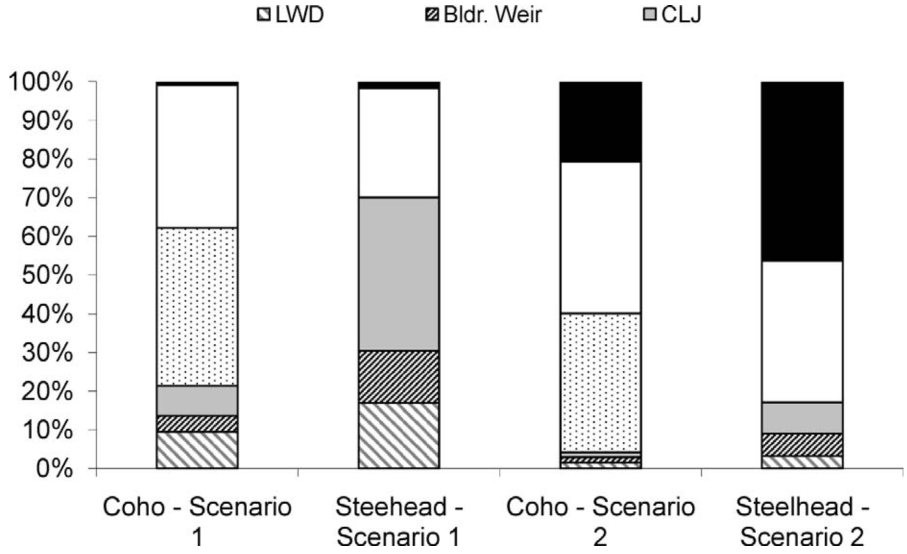

FIGURE 3.—Proportions of the mean increase in coho salmon and steelhead smolts provided by different restoration techniques under restoration scenarios 1 and 2. Abbreviations are as follows: LWD = large woody debris, Bldr. Weir = boulder weir, CLJ = constructed logjams, and CGW = constructed groundwater channel.

and side channels and rarely in ponds (Bustard and Narver 1975a, 1975b; Bisson et al. 1982; Roni 2002).

Percentage of Contribution and Limiting Factors

The large differences in fish response between the two restoration scenarios we simulated reflect the differences in the type and quantity of habitats restored as well as the fish response to those techniques. This is demonstrated by the fact that culvert removal produced 21% of the total increase in coho salmon smolt production under scenario 2 but only 1% under scenario 1, which is primarily because of the much higher proportion of the restoration that focused on culvert removal in scenario 2. Our approach also assumes that summer and winter rearing habitat are limiting for coho salmon and steelhead, which is typical for many streams in the coastal Pacific Northwest (Nickelson et al. 1992; Solazzi et al. 2000). Different limiting factors across watersheds would require different approaches. Beechie et al. (1994, 2001) and Pess et al. (2002) recommended two different approaches for coho salmon in two large but different watersheds located in the PSB. Beechie et al. (1994) found that coho salmon smolt production in the Skagit River basin was limited mainly by loss of side-channel sloughs, while for the Stillaguamish River basin Pess et al. (2002) found the loss of beaver pond habitat was the major reason for the decline in coho salmon smolt production. This indicates that both restoration type and basin characteristics will also influence fish response to restoration efforts. Should other factors such as spawning habitat or spawner abundance limit production, estimates using numbers in Table 1 would probably either overestimate or underestimate parr and smolt production from individual sites. This emphasizes the need to focus on different types of habitat if one is interested in different species or to balance the habitats restored if one is interested in recovering multiple species (Beechie and Bolton 1999; Greene and Beechie 2004; Steel et al. 2008).

Our aggregation of increases in fish numbers due to restoration also assumes that the response to each restoration action is independent and not influenced by other restoration actions. This may be a reasonable assumption in larger watersheds where restoration actions are often located long distances from each other. There is evidence that little movement of juvenile coho salmon and trout occurs between adjacent restoration projects or unrestored stream reaches (Kahler et al. 2001; Roni and Quinn 2001b). In contrast, other studies have reported broad-scale movements of juvenile coho salmon among different habitat types within a basin (Peterson 1982; Ebersole et al. 2006). Evidence from the estuarine environment suggests that the size and proximity of restoration actions can affect the physical and presumably biological response—with larger or adjacent sites creating disproportionally more habitat than do smaller disconnected sites (Hood 2009). Modeling efforts for floodplain habitat restoration also suggest differential effects on salmon survival based on project sequencing, proximity, size, and movement of predators among projects (Kondolf et al. 2008). Therefore, it is possible that fish habitat restoration actions may not be independent and by simply adding up all treated stream kilometers, our simulation may have overlooked any synergistic or competing effects of projects and, thus, under- or overestimated changes in fish abundance.

Reducing Variability

Our Monte Carlo simulations indicate just how large the variability in response to whole watershed restoration can be for a given restoration program. However, this is a product of the large variability in response to individual restoration techniques we examined. The variability in fish response to these techniques is partly related to natural variation in fish numbers, but often this considerable variation can be explained by the differences in projects themselves. Roni and Quinn (2001a) demonstrated that 25–50% of the variation in coho salmon and steelhead parr response to LWD placement in their study was explained by the different levels of change in pool area and LWD among projects. The large variability we see in response to restoration can be reduced through better estimates of fish response to techniques, but also through better-designed projects. Restoration projects that show little fish response are partly related to whether the site, reach, or watershed was in need of restoration, whether the proper technique was applied at that location, or, as is often the case, whether other upstream watershed processes were addressed (Roni et al. 2008). This suggests that improvements in restoration monitoring, planning, and implementation should help reduce the variability in restoration success rates we currently see across the landscape.

Regardless of the variability, the question remains as to whether these increases in fish production are large enough to be detected by a typical parr or smolt monitoring program. The results from our model watershed suggest that 20% of habitat would need to be restored to increase average smolt production by 25%. However, given the large 95% prediction intervals around the estimated increases in fish production and percentage of restoration potentially necessary, considerably more habitat may need to be restored to be assured of a detectable response.

Restoration Scale, Intensity, and Costs

The majority of well-funded restoration programs distribute money and projects across a region or much larger basins than we examined (for regional maps of restoration actions, see also NOAA 2007 or www.nwr.noaa.gov/Salmon-Recovery-Planning/PCSRF/Index.cfm). Clearly, these regional efforts collectively restored thousands of hectares and kilometers of habitat spread across a vast region and probably resulted in increased fish production. The amount of restoration is typically not equal across basins, though the actual amount of restoration occurring in any one basin is typically relatively small. Thus, in the absence of a plan to concentrate and complete restoration efforts in a few key basins or dramatically increase the total amount of restoration, it is unlikely that even the most rigorous basin-scale monitoring program will be able to detect a change in coho salmon or steelhead abundance at a watershed or population scale. This also suggests that if the desire is to recover whole watersheds or fish populations, basins and populations should be prioritized for restoration potential and restoration efforts concentrated in those areas rather than spread across the region. By contrast, restoration at the regional scale will require restoration across large areas, but monitoring programs are unlikely to detect changes without a substantial increase in restoration. Moreover, some Pacific salmon restoration programs have a goal to double fish production (e.g., Henderson and Healey 1993; McEwan and Jackson 1996). Doubling smolt production in the model watershed would require increasing coho salmon and steelhead smolt production by 230,501 and 22,386, respectively (Table 4). Assuming an equal percentage of each of the habitat types in our model watershed is restored, on average approximately 80% of the habitat would need to be restored to double production (230,501/285,302 × 100 = 81%). This suggests that it is likely that a large proportion of habitats within a watershed would need to be restored to double production. However, it is possible that focusing on a particular habitat limiting coho salmon or steelhead production rather than all habitat types may be more efficient (Beechie et al. 1994; Pess et al. 2002).

The cost of restoration is another factor that limits the amount and location of restoration in a region. The total cost of restoring all in-channel and floodplain habitat in the 180,000-ha model watershed was nearly $123 million (in 2003 dollars; Table 2). We use mean costs and there is typically a considerable range in costs of projects. Culvert removal costs, for example, will depend upon stream size and culvert size, the amount of fill to be removed, location, the number of culverts removed, and their proximity to other planned projects. We also assumed that all habitat needed to be restored, which could lead to overestimation of costs if considerable amount of habitat is already in good condition and does not need to be restored. We did not include costs of restoring riparian areas, roads, uplands, and other areas, which would require additional funds. Our cost analysis, though approximate, demonstrates the costs associated with restoring a whole watershed or implementing enough restoration to produce measurable changes. A cost–benefit analysis of different types of restoration would also be useful, but would require accurate costs for the projects from which we collected fish abundance data. We unfortunately did not have cost information and future research and analysis of this component is needed.

Other Considerations

We assumed in our analysis that restoration actions had an additive effect; our results may have differed if we had assumed that the fish response was multiplicative and multiplied prerestoration fish numbers by a ratio of treatment to control. The multiplicative approach requires that one has preproject estimates of fish densities and it cannot provide estimates for habitats where numbers are initially zero (i.e., reconnecting or creating habitat). As noted previously, it is also possible that restoration actions may have synergistic or competing effects or, as the amount of limiting habitat decreases through restoration, the fish response to restoration may decrease. Some restoration actions may lead to improvements for one life stage, but negatively affect another. This appears to be the case for LWD placement, which can lead to decreases in steelhead summer parr numbers through conversion of riffles to pools, but improves winter habitat, which is often the limiting factor (Roni and Quinn 2001a). Additional research and monitoring is needed to examine these potential confounding factors.

Estimates of fish response to other types of restoration, such as riparian restoration and road removal or repair, were not available (Table 3), and calculating whole-watershed restoration benefits for these types of actions was not possible. Moreover, these types of activities may take decades to produce changes in habitat that would result in a measurable change in fish production (Roni et al. 2002). Recovery efforts are also underway for species with different life histories such as Chinook salmon *O. tshawytscha* and Atlantic salmon *Salmo salar*. Our results demonstrate how one might estimate response for these species and other species, but additional research is needed to produce accurate estimates for different restoration techniques and species.

In summary, we provide a method for estimating juvenile coho salmon and steelhead response to habitat restoration that indicates that habitat restoration similar to the types we examined can produce substantial increases in fish production. Our results also indicate that considerable restoration is needed to produce and detect even small changes in fish abundance at a watershed or population scale.

Acknowledgments

We thank Jeremy Davies for providing and summarizing data on habitat and stream lengths for Puget Sound watersheds, Brendan Sylvander for providing summaries from the NOAA Pacific Coastal Salmon Recovery Fund database, and Hiroo Imaki for creating the map of the Puget Sound basin. We also thank Martin Liermann, Ashley Steel, Tracy Collier, John Stein, Josh Latterell, and three anonymous reviewers for helpful comments on earlier versions of this manuscript.

References

Beechie, T., E. Beamer, and L. Wasserman. 1994. Estimating coho salmon rearing habitat and smolt production losses in a large river basin, and implications for habitat restoration. North American Journal of Fisheries Management 14:797–811.

Beechie, T., and S. Bolton. 1999. An approach to restoring salmonid habitat-forming processes in Pacific Northwest watersheds. Fisheries 24(4):6–15.

Beechie, T. J., B. D. Collins, and G. R. Pess. 2001. Holocene and recent geomorphic processes, land use, and salmonid habitat in two north Puget Sound river basins. Water Science and Application 4:37–54.

Beechie, T., G. Pess, P. Roni, and G. Giannico. 2008. Setting river restoration priorities: a review of approaches and a three step process for identifying and prioritizing actions. North American Journal of Fisheries Management 28:891–905.

Beechie, T. J., C. N. Veldhuisen, D. E. Schuett-Hames, P. DeVries, R. H. Conrad, and E. M. Beamer. 2005. Monitoring treatments to reduce sediment and hydrologic effects from roads. Pages 35–66 *in* P. Roni, editor. Monitoring stream and watershed restoration. American Fisheries Society, Bethesda, Maryland.

Bernhardt, E. S., M. A. Palmer, J. D. Allan, G. Alexander, K. Barnas, S. Brooks, J. Carr, S. Clayton, C. Dahm, J. Follstad-Shah, D. Galat, S. Gloss, P. Goodwin, D. Hart, B. Hassett, R. Jenkinson, S. Katz, G. M. Kondolf, P. S. Lake, R. Lave, J. L. Meyer, T. K. O'Donnell, L. Pagano, B. Powell, and E. Sudduth. 2005. Synthesizing U.S. river restoration efforts. Science (Washington, D.C.) 308:636–637.

Bilby, R., W. Ehinger, T. Quinn, G. Volkhardt, K. Krueger, D. Seiler, G. Pess, C. Jordan, M. McHenry, and D. Poon. 2005. Study evaluates fish response to management actions. Western Forester 50:14–15.

Bisson, P. A., J. L. Nielsen, R. A. Palmason, and L. E. Grove. 1982. A system of naming habitat types in small streams, with examples of habitat utilization by salmonids during low stream flows. Pages 62–73 *in* N. B. Armantrout, editor. Acquisition and utilization of aquatic habitat inventory information. American Fisheries Society, Bethesda, Maryland.

Bisson, P. A., G. H. Reeves, R. E. Bilby, and R. Naiman. 1997. Watershed management and Pacific salmon: desired future conditions. Pages 447–474 *in* D. J. Stouder, P. A. Bisson, and R. J. Naiman, editors. Pacific salmon and their ecosystems: status and future options. Chapman and Hall, New York.

Bustard, D. R., and D. W. Narver. 1975a. Aspects of the winter ecology of juvenile coho salmon (*Oncorhynchus kisutch*) and steelhead trout (*Salmo gairdneri*). Journal of Fisheries Research Board of Canada 32:667–680.

Bustard, D. R., and D. W. Narver. 1975b. Preferences of juvenile coho salmon (*Oncorhynchus kisutch*) and cutthroat trout (*Salmo clarki*) relative to simulated alteration of winter habitat. Journal of Fisheries Research Board of Canada 32:681–687.

Cederholm, C. J., R. E. Bilby, P. A. Bisson, T. W. Bumstead, B. R. Fransen, W. J. Scarlett, and J. W. Ward. 1997. Response of juvenile coho salmon and steelhead to placement of large woody debris in a coastal Washington stream. North American Journal of Fisheries Management 17:947–963.

Chapman, D. W. 1996. Efficacy of structural manipulations of instream habitat in the Columbia River basin. Northwest Science 5:279–293.

Collares-Pereira, M. J., and I. G. Cowx. 2004. The role of catchment scale environmental management in freshwater fish conservation. Fisheries Management and Ecology 11:3–4.

Dauwalter, D. C., F. J. Rahel, and K. G. Gerow. 2009. Temporal variation in trout populations: implications for monitoring and trend detection. Transactions of the American Fisheries Society 138:38–51.

Ebersole, J. L., P. J. Wigington Jr., J. P. Baker, M. A. Cairns, and M. R. Church. 2006. Juvenile coho salmon growth and survival across stream network seasonal habitats. Transactions of the American Fisheries Society 135:1681–1697.

Fullerton, A. H., E. A. Steel, Y. Caras, and I. Lange. 2010. Effects of spatial pattern and economic uncertainties on freshwater habitat restoration planning: a simulation exercise. Restoration Ecology 18:1–16.

Giannico, G. R., and S. G. Hinch. 2003. The effect of wood and temperature on juvenile coho salmon winter movement, growth, density and survival in side-channels. River Research and Applications 19:219–231.

Glen, D. 2002. Recovery of salmon and trout following habitat enhancement works: review of case studies 1995–2002. Pages 93–112 *in* M. O'Grady, editor. Proceedings of the 13th international salmonid habitat enhancement workshop. Central Fisheries Board, Dublin.

Greene, C. M., and T. J. Beechie. 2004. Consequences of potential density-dependent mechanisms on recovery of ocean-type Chinook salmon (*Oncorhynchus tshawyt-*

scha). Canadian Journal of Fisheries and Aquatic Sciences 61:590–602.

Ham, K. D., and T. N. Pearsons. 2000. Can reduced salmonid population abundance be detected in time to limit management impacts? Canadian Journal of Fisheries and Aquatic Sciences 57:17–24.

Henderson, M. A., and M. C. Healey. 1993. Doubling sockeye salmon production in the Fraser River: is this sustainable development? Environmental Management (New York) 17:719–728.

Hood, W. G. 2009. Scaling tidal channel geometry with marsh island area: a tool for habitat restoration, linked to channel formation process. Water Resources Research 43:W03409.

Johnson, S. L., J. D. Rodgers, M. F. Solazzi, and T. E. Nickelson. 2005. Effects of an increase in large wood on abundance and survival of juvenile salmonids (*Oncorhynchus spp.)* in an Oregon coastal stream. Canadian Journal of Fisheries and Aquatic Sciences 62:412–424.

Kahler, T. H., P. Roni, and T. P. Quinn. 2001. Summer movement and growth of juvenile anadromous salmonids in small western Washington streams. Canadian Journal of Fisheries and Aquatic Sciences 58:1947–1956.

Katz, S. L., K. Barnas, R. Hicks, J. Cowen, and R. Jenkinson. 2007. Freshwater habitat restoration actions in the Pacific Northwest: a decade's investment in habitat improvement. Restoration Ecology 15:494–505.

Kondolf, G. M., P. L. Angermeier, K. Cummins, T. Dunne, M. Healey, W. Kimmerer, P. B. Moyle, D. Murphy, D. Patten, S. Railsback, D. J. Reed, R. Spies, and R. Twiss. 2008. Projecting cumulative benefits of multiple river restoration projects: an example from the Sacramento-San Joaquin river system in California. Environmental Management (New York) 42:933–945.

Koning, C. W., and E. R. Keeley. 1997. Salmonid biostandards for estimating production benefits of fish habitat rehabilitation techniques. Pages 1–21 *in* P. A. Slaney and D. Zaldokas, editors. Fish habitat rehabilitation procedures. British Columbia Ministry of Environments, Lands and Parks, and British Columbia Ministry of Forests, Watershed Restoration Technical Circular 9, Victoria.

Liermann, M., and P. Roni. 2008. More sites or more years? Optimal study design for monitoring fish response to watershed restoration. North American Journal of Fisheries Management 28:935–943.

Manly, B. F. J. 2006. Randomization, bootstrapping, and Monte Carlo methods in biology. Taylor and Francis, London.

McEwan, D., and T. A. Jackson. 1996. Steelhead restoration and management plan for California. California Department of Fish and Game, Sacramento.

Morley, S. A., P. S. Garcia, T. Bennett, and P. Roni. 2005. Juvenile salmonid use of constructed and natural side channels in Pacific Northwest rivers. Canadian Journal of Aquatic and Fishery Sciences 62:2811–2822.

Nehlsen, W., J. E. Williams, and J. A. Lichatowich. 1991. Pacific salmon at the crossroads: stocks at risk from California, Oregon, Idaho, and Washington. Fisheries 16(2):4–21.

Nickelson, T. E., J. D. Rodgers, S. L. Johnson, and M. F. Solazzi. 1992. Seasonal changes in habitat use by juvenile coho salmon (*Oncorhynchus kisutch*) in Oregon coastal streams. Canadian Journal of Fisheries and Aquatic Sciences 49:783–789.

NOAA (National Oceanic and Atmospheric Administration). 2007. Pacific Coastal Salmon Recovery Fund: FY2000–2006. NOAA National Marine Fisheries Service, 2007 Report to Congress, Seattle. Available: nwr.noaa.gov/Salmon-Recovery-Planning/PCSRF/Index.cfm. (November 2009).

Paulsen, C. M., and T. R. Fisher. 2003. Detecting juvenile survival effects of habitat actions: power analysis applied to endangered Snake River spring-summer Chinook (*Oncorhynchus tshawytscha*). Canadian Journal of Aquatic Science 60:1122–1132.

Pess, G. R., M. C. Liermann, M. L. McHenry, R. J. Peters, and T. R. Bennett. In press. Juvenile salmon response to the placement of engineered log jams (ELJs) in the Elwha River, Washington State, U.S.A. River Research and Applications.

Pess, G. R., M. McHugh, D. Fagen, P. Stevenson, and J. Drotts. 1998. Stillaguamish salmonid barrier evaluation and elimination project (phase III). Tulalip Tribe, Fiscal Year 1997, Progress Report Number 98–2, Marysville, Washington.

Pess, G. R., D. R. Montgomery, T. J. Beechie, and L. Holsinger. 2002. Anthropogenic alterations to the biogeography of salmon in Puget Sound. Pages 129–154 *in* D. R. Montgomery, S. Bolton, and D. B. Booth, editors. Restoration of Puget Sound rivers. University of Washington Press, Seattle.

Peterson, N. P. 1982. Immigration of juvenile coho salmon (*Oncorhynchus kisutch*) into riverine ponds. Canadian Journal of Fisheries and Aquatic Sciences 39:1308–1310.

Pollock, M. M., T. J. Beechie, S. S. Chan, and R. Bigley. 2005. Monitoring of restoration of riparian forests. Pages 67–96 *in* P. Roni, editor. Monitoring stream and watershed restoration. American Fisheries Society, Bethesda, Maryland.

Quinn, T. P. 2005. The behavior and ecology of Pacific salmon and trout. American Fisheries Society, Bethesda, Maryland.

Reeves, G. H., F. H. Everest, and T. E. Nickelson. 1989. Identification of physical habitats limiting the production of coho salmon in western Oregon and Washington. USDA Forest Service, Pacific Northwest Research Station, Technical Report PNW-GTR-245, Portland, Oregon.

Reeves, G. H., J. D. Hall, T. D. Roelofs, T. L. Hickman, and C. O. Baker. 1991. Rehabilitating and modifying stream habitats. Pages 519–557 *in* W. R. Meehan, editor. Influences of forest and rangeland management on salmonid fishes and their habitats. American Fisheries Society, Special Publication 19, Bethesda, Maryland.

Reeves, G. H., D. B. Hohler, B. E. Hansen, F. H. Everest, J. R. Sedell, T. L. Hickman, and D. Shively. 1997. Fish habitat restoration in the Pacific Northwest: Fish Creek of Oregon. Pages 335–359 *in* J. E. Williams, C. A. Wood, and M. P. Dombeck, editors. Watershed restoration: principles and practices. American Fisheries Society, Bethesda, Maryland.

Roni, P. 2002. Habitat use by fishes and pacific giant salamanders in small western Oregon and Washington streams. Transactions of the American Fisheries Society 131:743–761.

Roni, P., T. J. Beechie, R. E. Bilby, F. E. Leonetti, M. M. Pollock, and G. R. Pess. 2002. A review of stream restoration techniques and a hierarchical strategy for prioritizing restoration in Pacific Northwest watersheds. North American Journal of Fisheries Management 22:1–20.

Roni, P., C. Dietrich, D. King, S. Morley, and P. Garcia. 2006a. Coho smolt production from constructed and natural floodplain habitats. Transactions of the American Fisheries Society 135:1398–1408.

Roni, P., K. Hanson, and T. Beechie. 2008. Global review of the physical and biological effectiveness of stream habitat rehabilitation techniques. North American Journal of Fisheries Management 28:856–890.

Roni, P., G. Pess, T. Bennett, S. Morley, and K. Hanson. 2006b. Rehabilitation of stream channels scoured to bedrock: the effects of boulder weir placement on aquatic habitat and biota in southwest Oregon, USA. River Research and Applications 22:962–980.

Roni, P., and T. P. Quinn. 2001a. Density and size of juvenile salmonids in response to placement of large woody debris in western Oregon and Washington streams. Canadian Journal of Fisheries and Aquatic Sciences 58:282–292.

Roni, P., and T. P. Quinn. 2001b. Effects of wood placement on movements of trout and juvenile coho salmon in natural and artificial stream channels. Transactions of the American Fisheries Society 130:675–685.

Sharma, R., and R. Hilborn. 2001. Empirical relationships between watershed characteristics and coho salmon (*Oncorhynchus kisutch*) smolt abundance in 14 western Washington streams. Canadian Journal of Fisheries and Aquatic Sciences 58:1453–1463.

Slaney, P. A., B. O. Rublee, C. J. Perrin, and H. Goldberg. 1994. Debris structure placements and whole-river fertilization for salmonids in a large regulated stream in British Columbia. Bulletin of Marine Science 55:1160–1180.

Solazzi, M. F., T. E. Nickelson, S. L. Johnson, and J. D. Rodgers. 2000. Effects of increasing winter rearing habitat on abundance of salmonids in two coastal Oregon streams. Canadian Journal of Fisheries and Aquatic Sciences 57:906–914.

SSPS (Shared Strategy for Puget Sound). 2003. A primer on habitat project costs. Available: sharedsalmonstrategy.org/files/PrimeronHabitatProjectCosts.pdf. (August 2007).

Steel, E. A., A. Fullerton, Y. Caras, M. B. Sheer, P. Olson, D. Jensen, J. Burke, M. Maher, and P. McElhany. 2008. A spatially explicit decision support system for watershed-scale management of salmon. Ecology and Society 13:50.

Tear, T. H., P. Kareiva, P. Angermeir, P. Comer, B. Czech, R. Kautz, L. Landon, D. Mehlman, K. Murphy, M. Ruckelshaus, J. Scott, and G. Wilhere. 2005. How much is enough? The recurrent problem of setting measurable objectives in conservation. BioScience 55:835–849.

Williams, N. W., P. A. Bisson, D. L. Bottom, L. D. Calvin, C. C. Coutant, M. W. Erho Jr., C. A. Frissell, J. A. Lichatowich, W. J. Liss, W. E. McConnaha, P. R. Mundy, J. A. Stanford, and R. R. Whitney. 1999. Return to the river: scientific issues in the restoration of salmonid fishes in the Columbia River. Fisheries 24(3):10–19.

Appendix: Additional Information Used to Calculate Responses to Restoration

TABLE A.1.—Data used to calculate fish response for each stream restoration technique, including restoration type, study site (stream), length and area sampled, and number of coho salmon or steelhead present. Abbreviations are as follows: LWD = large woody debris, BW = boulder weir, CLJ = constructed log jam, Cont. = control, Treat. = treatment, and WFSR = West Fork Smith River; blank cells indicate that the species were not present. Data are from Roni and Quinn (2001a), Roni et al. (2006b), and Pess et al. (in press). Elwha River CLJ site names include the site number followed by the year sampled.

Restoration type	Stream	Life stage	Length (m)		Area (m^2)		Number of coho salmon		Number of steelhead	
			Cont.	Treat.	Cont.	Treat.	Cont.	Treat.	Cont.	Treat.
LWD	Bear	Parr	100	100	469	639	101	309	297	96
	Bergsvick	Parr	100	100	464	340	9	45	4	8
	Bewley	Parr	100	100	390	487	19	13	6	6
	Buster	Parr	100	100	327	521	47	77	1	0
	Deer	Parr	75	75	158	161	33	64		
	Elliott	Parr	100	100	319	452	1	1	26	31
	Farmer	Parr	100	100	468	567	2	8	36	54
	Kenusky	Parr	100	100	306	353	35	66	0	1
	Killam	Parr	100	100	409	453	13	27	32	57
	Klootchie	Parr	100	100	462	573	17	48	12	11
	Lobster	Parr	100	100	464	588	176	419	33	36
	Lousignont	Parr	100	100	483	669	122	227	11	13
	South Fork Little Nestucca River	Parr	110	111	719	680	63	168	34	23
	Rock	Parr	100	100	474	604	198	323	76	87
	Tobe	Parr	100	100	322	308	28	49	45	41
	Beaver	Parr	80	80	174	184	218	230		
	Benson	Parr	100	100	299	334	23	25	11	13
	Burn	Parr	100	86	328	340	140	460	28	17

TABLE A.1.—Continued.

Restoration type	Stream	Life stage	Length (m)		Area (m^2)		Number of coho salmon		Number of steelhead	
			Cont.	Treat.	Cont.	Treat.	Cont.	Treat.	Cont.	Treat.
	French	Parr	120	120	948	963	69	49	42	37
	Hoppers	Parr	75	75	272	227	54	48		
	Hyas	Parr	100	100	803	674	12	133	86	109
	Laughing Jacobs	Parr	100	100	255	257	46	34		
	Midnight	Parr	100	100	214	318	13	196	3	7
	Newbury	Parr	100	100	380	450	23	38		
	Porter	Parr	93	93	432	624	109	46	37	59
	Punch	Parr	100	100	392	492	34	60		
	Shuwah	Parr	80	80	293	320	171	210		
	Soosette	Parr	100	100	362	313	107	75	0	5
	Townsend	Parr	84	80	352	295			79	53
	Bear	Smolt	100	100	1,166	916	4	26	23	36
	Bergsvick	Smolt	100	100	581	564	5	11	2	5
	Bewley	Smolt	100	100	553	698	0	16	4	13
	Buster	Smolt	100	100	707	738	17	26	0	1
	Deer	Smolt	75	75	284	263	6	10	0	0
	Elliott	Smolt	105	105	603	861	0	0	3	3
	Farmer	Smolt	100	100	667	718	0	1	9	17
	Kenusky	Smolt	100	100	506	513	3	21	8	7
	Killam	Smolt	100	100	647	824	1	5	12	22
	Klootchie	Smolt	100	100	624	753	4	16	5	13
	Lobster	Smolt	100	100	835	930	8	60	12	19
	Lousignont	Smolt	100	100	731	833	11	34	3	8
	South Fork Little Nestucca River	Smolt	110	110	912	949	7	103	1	10
	Rock	Smolt	100	100	1,099	1,162	8	134	17	29
	Tobe	Smolt	100	100	553	494	4	7	9	13
	Beaver	Smolt	80	80	305	305	5	26		
	Benson	Smolt	100	100	578	552	2	2	18	17
	Burn	Smolt	100	100	451	446	11	96	18	5
	French	Smolt	120	120	1,114	1,457	8	11	56	41
	Hoppers	Smolt	75	75	297	304	10	17		
	Hyas	Smolt	100	100	1,041	824	0	0	58	50
	Laughing Jacobs	Smolt	100	100	493	516	0	13		
	Midnight	Smolt	100	100	290	438	0	0	0	7
	Newbury	Smolt	100	100	444	536	0	5		
	Porter	Smolt	100	100	790	869	42	18	21	36
	Punch	Smolt	100	100	576	688	14	16		
	Shuwah	Smolt	80	80	358	438	14	35		
	Soosette	Smolt	100	100	431	460	5	7	0	8
	Townsend	Smolt	84	86.5	398	389			15	16
BW	Big	Parr	200	200	1,213	1,549	298	402	3	6
	Cherry	Parr	200	200	1,379	1,281	366	716	2	7
	Johnson	Parr	200	200	308	658	294	323	3	6
	Middle I	Parr	200	200	1,551	2,108	82	134	0	2
	Middle II	Parr	200	200	1,404	2,085	413	648	0	4
	Paradise I	Parr	200	200	980	1,294	140	372	6	16
	Paradise II	Parr	200	200	1,186	707	181	140	4	1
	South Fork Elk	Parr	200	200	1,162	1,000	217	380	4	7
	WFSR Beaver	Parr	200	200	1,606	2,665	265	285	8	19
	WFSR Crane	Parr	200	200	1,764	2,512	568	494	9	4
	WFSR Moore	Parr	200	200	1,549	1,923	329	501	2	1
	WFSR Skunk	Parr	200	200	1,227	1,600	560	791	3	10
	WFSR Upper	Parr	200	200	998	1,108	479	719	2	2
Culvert	Beaver pond	Parr	100	100	130	130	0	4	2	1
	Bjorndahl	Parr	200	200	260	260	0	20	4	6
	Lower Cherokee	Parr	110	110	143	143	0	115	8	7
	Upper Cherokee	Parr	100	100	130	130	0	28	8	7
	Duane's	Parr	100	100	140	140	0	65	8	7
	Katie	Parr	100	100	140	140	0	2	2	4
CLJ	Elwha River 6-2000	Parr	70	65	742	1,950	5	120	75	50
	Elwha River 6-2001	Parr	90	35	1,035	501	123	81	100	27
	Elwha River 6-2002	Parr	80	35	643	587	0	12	15	1
	Elwha River 6-2003	Parr	90.7	22.5	1,097	286	105	55	21	50
	Elwha River 7-2000	Parr	83	21	1,021	59	1	70	33	65
	Elwha River 7-2001	Parr	67	18	851	72	35	35	261	16
	Elwha River 7-2002	Parr	50	23	104	241	0	6	4	15
	Elwha River 7-2003	Parr	86.3	22.7	1,320	107	27	210	9	68

TABLE A.1.—Continued.

			Length (m)		Area (m^2)		Number of coho salmon		Number of steelhead	
Restoration type	Stream	Life stage	Cont.	Treat.	Cont.	Treat.	Cont.	Treat.	Cont.	Treat.
	Elwha River 9-2000	Parr	83	52	1,021	1,560	0	86	15	36
	Elwha River 9-2001	Parr	67	60	851	858	0	260	95	36
	Elwha River 9-2002	Parr	30	50	104	344	0	120	0	85
	Elwha River 9-2003	Parr	86.3	40.4	1,320	755	329	218	101	13
	Elwha River 28-2000	Parr	50	34.5	1,825	828	0	55	23	65
	Elwha River 28-2001	Parr	40	40	760	960	0	176	63	260
	Elwha River 28-2002	Parr	40	34	403	509	0	6	57	54
	Elwha River 28-2003	Parr	79.3	150.5	1,943	1,054	1	420	14	19
	Elwha River 6-2001	Smolt	62.8	58.7	710	839	1	45	4	13
	Elwha River 6-2003	Smolt	75	13	555	135	0	4	0	0
	Elwha River 7-2000	Smolt	110	15.9	1,452	68	4	8	0	7
	Elwha River 7-2001	Smolt	20.3	29.8	124	185	0	0	0	0
	Elwha River 7-2002	Smolt	43.1	31	259	102	0	0	0	0
	Elwha River 7-2003	Smolt	83	30	726	93	0	0	16	4
	Elwha River 9-2001	Smolt	110	33.4	1,452	491	13	2	5	6
	Elwha River 9-2003	Smolt	43.1	41.5	259	403	0	3	0	3

TABLE A.2.—Data used to calculate fish response to floodplain restoration and constructed side channels, including study site (stream), area sampled, and number of coho salmon or steelhead present. Abbreviations are as follows: CGW = constructed groundwater channel; NA = not applicable. Data are from Morley et al. (2005) and Roni et al. (2006a).

Restoration type	Site	Life stage	Meters sampled	Area (m^2)	Coho salmon	Steelhead
Floodplain	Calawah Springs	Smolt	NA	900	1,199	NA
	Tall Timber	Smolt	NA	1,980	348	NA
	Dismal Pond	Smolt	NA	4,858	1,094	NA
	Hoh Springs	Smolt	NA	3,000	874	NA
	Lewis Channel	Smolt	NA	2,000	581	NA
	Mosley Springs	Smolt	NA	2,250	954	NA
	Peterson Pond	Smolt	NA	2,150	136	NA
	Young Slough	Smolt	NA	3,000	1,013	NA
	Barnaby Slough	Smolt	NA	72,828	7,100	NA
	Boundary	Smolt	NA	3,138	641	NA
	Cascade Mill	Smolt	NA	7,050	361	NA
	Constant	Smolt	NA	3,699	509	NA
	Countyline	Smolt	NA	22,250	7,266	NA
	Etach	Smolt	NA	62,657	7,128	NA
	False All	Smolt	NA	5,214	2,128	NA
	Finney	Smolt	NA	1,198	143	NA
	Harrison Pond	Smolt	NA	140,000	3,916	NA
	Little Park	Smolt	NA	18,800	6,267	NA
	Mannser	Smolt	NA	27,492	12,283	NA
	Marsh Pond	Smolt	NA	17,398	156	NA
	Oakes	Smolt	NA	1,926	350	NA
	Park Slough I	Smolt	NA	2,295	2,337	NA
	Park Slough II	Smolt	NA	1,644	1,594	NA
	Seed	Smolt	NA	7,305	1,201	NA
	Suiattle Slough	Smolt	NA	3,116	3,571	NA
	Swamp	Smolt	NA	8,622	1,515	NA
	Zander	Smolt	NA	1,483	274	NA
	Gold Basin	Smolt	NA	5,000	1,365	NA
	Hazel Pond	Smolt	NA	9,584	4,165	NA
	Rowen Pond	Smolt	NA	4,000	4,272	NA
CGW	Barnaby I	Parr	100	634	802	6
	Barnaby II	Parr	100	407	1,462	34
	Cascade Seep	Parr	100	312	332	24
	Clear Creek	Parr	50	168	69	0
	Constant	Parr	100	452	2,001	39
	Illabot I	Parr	100	718	809	29
	Illabot II	Parr	100	829	1,983	16
	Lewis I	Parr	80	280	152	0
	Lewis II	Parr	80	373	1,298	2
	Marblemount Slough	Parr	100	675	227	374

TABLE A.2.—Continued.

Restoration type	Site	Lifestage	Meters sampled	Area (m^2)	Coho salmon	Steelhead
	Mosley I	Parr	50	87	25	5
	Mosley II	Parr	100	290	311	0
	Nolan I	Parr	50	160	106	1
	Nolan II	Parr	100	552	248	1
	Park Slough I	Parr	120	597	2,017	170
	Park Slough II	Parr	100	645	2,945	50
	Poppe side channel	Parr	50	87	73	0
	Rayonier	Parr	50	289	69	3
	Sauk side channel	Parr	240	1,830	2,078	18
	Taylor Con	Parr	100	1,557	3,617	38
	Taylor Nat	Parr	100	792	2,962	0
	Youngs Slough	Parr	100	690	86	0
	Barnaby I	Smolt	100	79	123	22
	Barnaby II	Smolt	100	749	226	11
	Cascade	Smolt	50	319	233	19
	Clear Creek	Smolt	120	345	15	20
	Constant	Smolt	50	573	317	4
	Illabot I	Smolt	100	868	146	1
	Illabot II	Smolt	50	971	1,606	4
	Lewis I	Smolt	240	345	16	11
	Lewis II	Smolt	100	410	84	7
	Marblemount Slough	Smolt	100	730	99	0
	Mosley I	Smolt	100	122	10	10
	Mosley II	Smolt	100	388	91	15
	Nolan I	Smolt	100	216	23	7
	Nolan II	Smolt	100	546	92	7
	Park Slough I	Smolt	50	663	315	10
	Park Slough II	Smolt	100	647	348	4
	Poppe side channel	Smolt	100	231	10	5
	Rayonier	Smolt	100	284	42	2
	Sauk side channel	Smolt	50	2,551	320	35
	Taylor I	Smolt	80	1,447	1,979	131
	Taylor II	Smolt	80	904	165	11
	Young	Smolt	100	821	71	10