Estimates of Gene Flow for Select Puget Sound Early Winter Steelhead Hatchery Programs

Annette Hoffmann, Ph.D.

Washington Department of Fish and Wildlife
Region 6, Fish Program
48 Devonshire Rd
Montesano, WA 98563
Annette.Hoffmann@dfw.wa.gov

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ACRONYMS

EWS	Early Winter Steelhead
ESS	Early Summer Steelhead
SSMP	Statewide Steelhead Management Plan
PEHC	Proportion Effective Hatchery Contribution
DGF	Demographic Gene Flow
H	Hatchery
N	Natural

DGF INPUT PARAMETERS

O_N	Proportion of natural fish that may spawn with hatchery strays
O_H	Proportion of hatchery strays that may spawn with natural fish
k_1	Fitness of an HxN mating relative to an NxN mating
k_2	Fitness of an HxH mating relative to an NxN mating
q	Proportion of natural spawners that are of hatchery origin

This report is submitted to National Marine Fisheries Service, Sustainable Fisheries Division to fulfill Terms and Conditions associated with Endangered Species Act Biological Opinions for early winter steelhead hatchery programs in Puget Sound.

Consultation #WCR-2015-2024
Dungeness, Nooksack and Stillaguamish early winter steelhead
Term and Condition 2f:

> "Within 16 months of the decision date for this opinion, conduct and submit a report to NMFS on sensitivity analysis of the Scott-Gill gene flow estimation method, based on as much empirical Puget Sound specific evidence as possible of point estimates and variability in escapements of hatchery-origin and natural-origin fish, proportion of hatchery returnees remaining in the river to spawn, temporal and spatial overlap of hatchery-origin and natural-origin spawners, incident of residuals, precocity rates, and contribution of non-anadromous O. mykiss to spawning."

Consultation #WCR-2015-3441
Snohomish early winter steelhead
Term and Condition 2f:

> "Within 16 months of the decision date for this opinion, conduct and submit a report to NMFS on sensitivity analysis of the Scott-Gill gene flow estimation method, based on as much empirical Puget Sound specific evidence as possible of point estimates and variability in escapements of hatchery-origin and natural-origin fish, proportion of hatchery returnees remaining in the river to spawn, temporal and spatial overlap of hatchery-origin and natural-origin spawners, incident of residuals, precocity rates, and contribution of non-anadromous O. mykiss to spawning."

The deadline for these Terms and Conditions was extended to December 31, 2017 by Tim Tynan, dated August 29, 2017.

1. Introduction

Hatchery programs can provide substantial economic, cultural, and conservation benefits, but potentially they can also pose risks to natural populations of salmon and steelhead. The Washington Department of Fish and Wildlife (Department or WDFW) operates segregated early winter steelhead hatchery programs in six Puget Sound watersheds for the purpose of providing recreational and tribal fishing opportunities. When Puget Sound steelhead were listed under the Endangered Species Act, the federal register notice (71 FR15666) concluded that "Potentially harmful hatchery practices may pose ecological and genetic risks to natural populations and may represent a factor limiting the viability of the Puget Sound steelhead DPS into the foreseeable future." The federal register notice also concluded that "the continued destruction and modification of steelhead habitat is the principal factor limiting the viability of the Puget Sound steelhead DPS into the foreseeable future."

The Statewide Steelhead Management Plan (SSMP, WDFW 2008) directs the Department to operate harvest augmentation programs in a manner that is consistent with meeting the watershed-specific goals for the diversity, spatial structure, productivity, and abundance of natural origin stocks. The SSMP further states that the long-term goal for segregated harvest augmentation programs affecting natural origin stocks of importance for conservation and recovery is an average gene flow of less than 2% from the hatchery to the natural origin stock.

The Department and Puget Sound treaty tribes used several analyses to evaluate the potential genetic effects of the early winter steelhead programs on natural origin steelhead. The analyses are complementary in that they use multiple sources of information and address multiple questions.

1) <u>Genetic Introgression</u>. Genetic based introgression results (proportion of hatchery-natural hybrids) from hybridization between hatchery and natural origin individuals (Warheit, 2014), and introgression estimates were used to address the question "How have past early winter hatchery program practices affected the genetic characteristics of natural origin steelhead?" The analysis relied on tissue samples from collections of natural-origin steelhead, and provided a direct measure of the cumulative effects of past early winter hatchery program practices, which could include recent management changes such as the elimination of off-station plants, elimination of recycling returning adults, and reductions in number of fish released.

2) <u>Proportion Effective Hatchery Contribution</u>. The proportion effective hatchery contribution (PEHC) is the proportion of natural spawners that are genetically derived from the early winter hatchery program and includes hatchery-natural origin hybrids, pure natural-natural origin fish and hatchery-hatchery lineage fish. The PEHC is also calculated from an analysis of tissue samples collected from natural-origin steelhead (Warheit 2014). Since the PEHC estimate includes pure hatchery-lineage fish that have the potential to generate hybrid offspring, it addresses a broader question than would genetic introgression alone: "How may early winter hatchery program practices affect the potential for genetic introgression?"

3) <u>Demographic Gene Flow (DGF)</u>. Whereas genetic introgression is a cumulative state, gene flow is the process that leads to genetic introgression. Gene flow may vary each year in response to hatchery program characteristics such as the number and location of fish released and the number of natural-origin spawners. To address the questions "What was the historical gene flow that led to the current introgression results and what is the anticipated gene flow with the new proposed

program?", a potential range of gene flows from the early winter hatchery program into the natural origin populations was calculated based on various assumptions of hatchery steelhead fitness, the overlap in spawn timing between hatchery and natural origin steelhead, and hatchery stray rates.

This report describes the methods for the DGF as developed by Busack (2014) to provide estimates and the potential range of gene flow. Warheit (2014) and its revision (Warheit 2017, in prep) provide estimates of genetic introgression and PEHC.

2. *Demographic Gene Flow Equation (DGF)*

The DGF method uses a gene flow formula developed by WDFW geneticists and described in the WDFW Statewide Steelhead Management Plan (WDFW, 2008) and later updated by Busack (2014). The gene flow formula utilizes the relative abundance of hatchery and natural origin spawners on the spawning ground, their temporal and spatial overlap, and the relative reproductive success of the three types of matings (hatchery x hatchery [HxH], hatchery x natural [HxN], and natural x natural [NxN]). Figure 1 (reproduced from WDFW 2008) depicts the three different mating scenarios. In Region A, only hatchery-origin fish are present, and only HxH matings take place. In Region C, only natural fish are present, and all matings are NxN. In Region B, both types of spawners are present so all three types of matings can occur.

The level of gene flow described in the SSMP and updated by Busack (2014) is calculated as:

$$Gene\ Flow = \frac{a+b}{a+2b+c} \qquad \text{Equation 1}$$

where

$$a = k_1\left[q(1-o_H) + \frac{q^2{o_H}^2}{X}\right]$$
$$b = k_2\left[\frac{q(1-q)o_N o_H}{X}\right]$$
$$c = \left[(1-q)(1-o_N) + \frac{(1-q)^2{o_N}^2}{X}\right]$$

and where

$$X = (1-q)O_N + qO_H.$$

In this equation, O_H and O_N are the proportion of the hatchery and natural origin spawners, respectively, in Region B , k_1 and k_2 are the fitness of HxH and HxN matings relative to NxN, respectively, and q is the proportion of hatchery fish among all natural spawners.

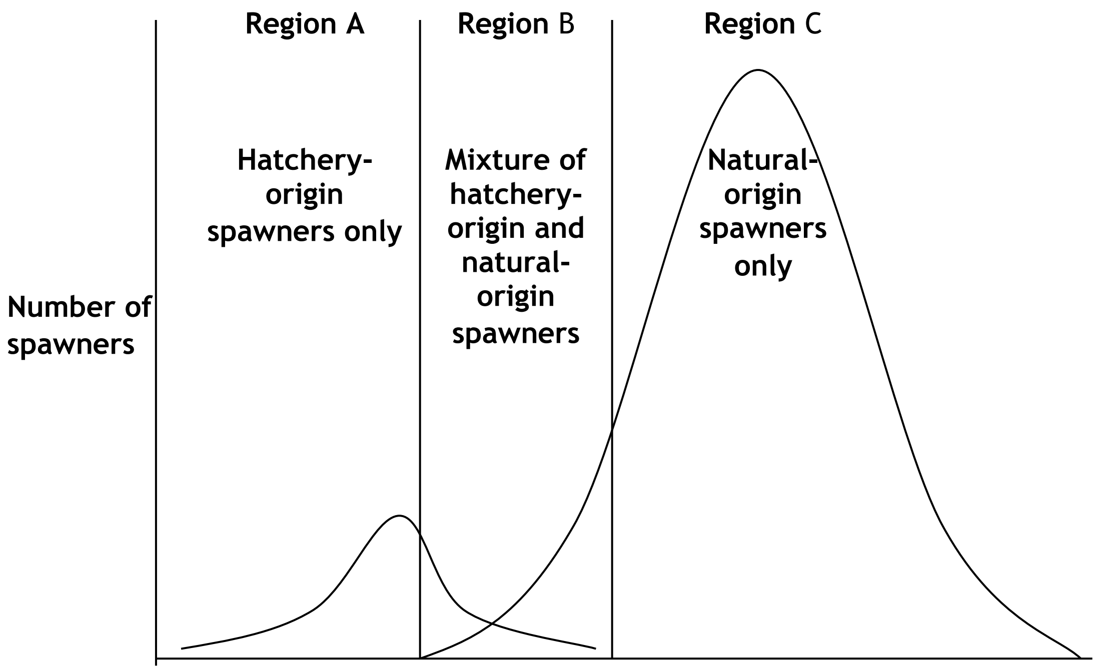


Figure 1. Schematic of temporal spawning overlap between early-run hatchery-origin winter steelhead and natural-origin winter steelhead. The shape, sizes, and placement of curves does not represent any particular real situation (reproduced from WDFW 2008).

3. *Input Parameters and Estimates for DGF*

To calculate the DGF, the five basic input parameters (O_N, O_H, k_1, k_2, q) were calculated in different ways to span the range of possibilities.

a. **Hatchery and Natural Surrogate Populations**

i. Hatchery surrogate populations

Tokul Creek Hatchery (for Early Winter Steelhead - EWS) and Reiter Ponds (for Early Summer Steelhead -ESS) have consistently had the highest survival rates and the most reliable returns. For many years, they were used as broodstock sources for most out of basin programs. Thus Tokul and Reiter provided logical surrogates for any straying hatchery fish both within and out of basin systems. The exception was Soos Creek Hatchery which provided broodstock for its own ESS program.

i. Natural surrogate populations

For natural origin winter steelhead, Scott and Gill (2008) reviewed Washington state data for the spawn timing and identified Snow Creek, a small stream that is a tributary to Discovery Bay and the Strait of Juan de Fuca, as having one of the strongest complete data sets to represent spawn timing of natural winter steelhead populations. Prior to initiation of research at Snow Creek, no hatchery-origin smolts had been released into Snow Creek, and, in the return years 1977-1978 and 1979-1980, any hatchery-origin strays from other watersheds were identified as they were passed upstream at the rack (Johnson et al.

1978; Johnson et al. 1980). Based on analysis of scale patterns, only one hatchery-origin steelhead is known to have been passed upstream during these two years. Redd surveys were conducted at approximately one week intervals with redds first observed on February 4, 1980 and the last new redds constructed were observed on May 24, 1978.

Scott and Gill (2008) also presented information on the spawn timing of winter steelhead for the Clearwater River, a tributary to the Queets River on the north Washington coast. Redd surveys were conducted in the mainstem of the Queets River and in tributaries on an irregular schedule in the years 1973 through 1980 (Cederholm 1984). Cederholm reported survey data for every year from 1973 through 1980, but 1978 was the only year with at least one survey in each of the months of January, February, and March. As in Snow Creek, no releases of hatchery-origin steelhead had occurred in the watershed in the years prior to the surveys. However, unlike Snow Creek, the incidence of hatchery-origin steelhead that may have strayed from other watersheds is not known. Cederholm found that redd construction appeared to occur earlier in the tributary streams than in the mainstem Clearwater River. Spawning was observed from January through June in both the tributaries and in the mainstem Clearwater River.

b. Proportion of Natural-Origin Spawners in Spawn Timing Overlap (O_N).

O_N is the proportion of all natural origin steelhead spawners spawning in Region B (Figure 1). For simplification and because it was conservative, the estimates of O_N were calculated as the proportion of natural spawning prior to Region C (including both Regions A and B).

i. Method 1–Surrogate populations with normal distribution assumptions

The boundary of Region C was defined as the date beyond which hatchery fish were unlikely to spawn. Under a normal curve, the probability of an observation beyond the mean plus three standard deviations is unlikely (0.13%). For this method, O_N is depicted by the shaded areas in Figure 2 and is the probability that a natural origin fish would spawn prior to the Region C boundary (Table 1). O_N was calculated for both the Snow Creek and Clearwater River curves relative to each of the hatchery programs (Figure 3, Table 2).

Table 1. Mean spawn dates and associated standard deviations for two natural winter populations and three early hatchery programs.

Facility/Population	Population	Mean Spawning Date	Mean Spawning Day Number[1] (day)	Standard Deviation (day)	Natural/Hatchery Cutoff Date[2]
Snow Creek	Natural Winter	March 28	118	18.1	February 2
Clearwater River	Natural Winter	April 21	142	20.4	February 19
Reiter Pond	ESS	January 27	58	12.2	March 4
Soos Creek	ESS	January 13	44	13.5	February 23
Tokul Creek	EWS	January 13	44	14.6	February 26

[1] December 1 is Day Number 1.
[2] The Cutoff Date is the date corresponding to the mean Day Number minus three standard deviations for natural populations (Region C boundary) and the mean Day Number plus three standard deviations for the hatchery programs (Region A boundary).

Table 2. O_N values for two Snow Creek and Clearwater River natural populations.

Surrogate natural population	Reiter Pond early summers	Soos Creek early summers	Tokul Creek early winters
Snow Creek O_N	9.38%	3.29%	4.72%
Clearwater River O_N	0.95%	0.25%	0.39%

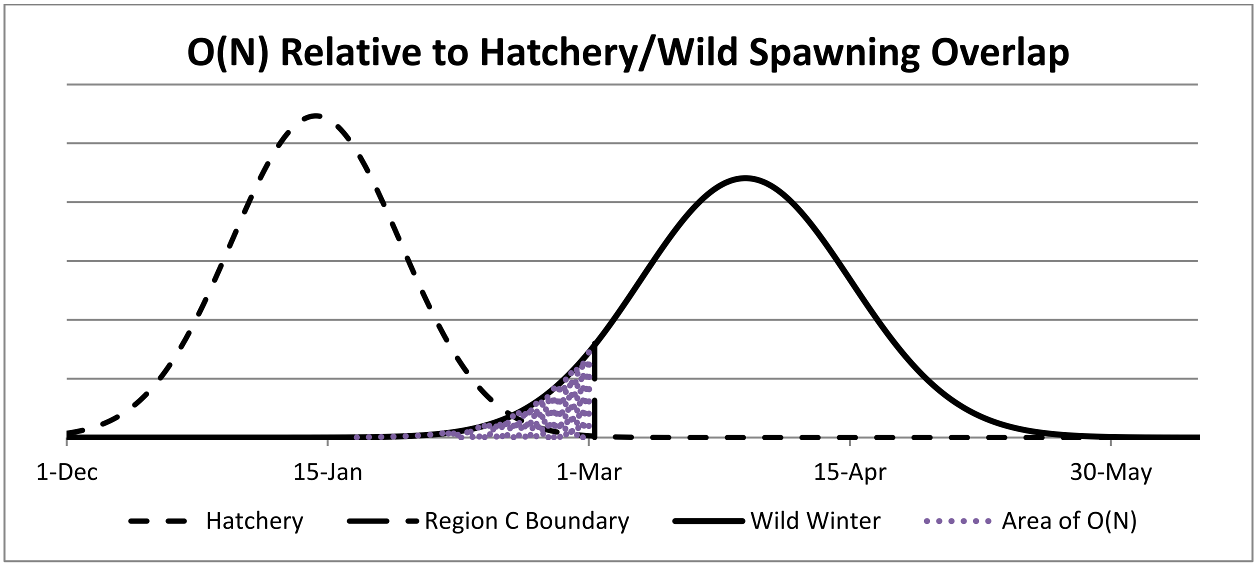


Figure 2. Example of hatchery and natural origin winter steelhead spawn timing curves with Region C boundary date calculated as the mean of the hatchery curve plus three standard deviations. O_N is the shaded area under the natural origin curve to the left of the Region C boundary line.

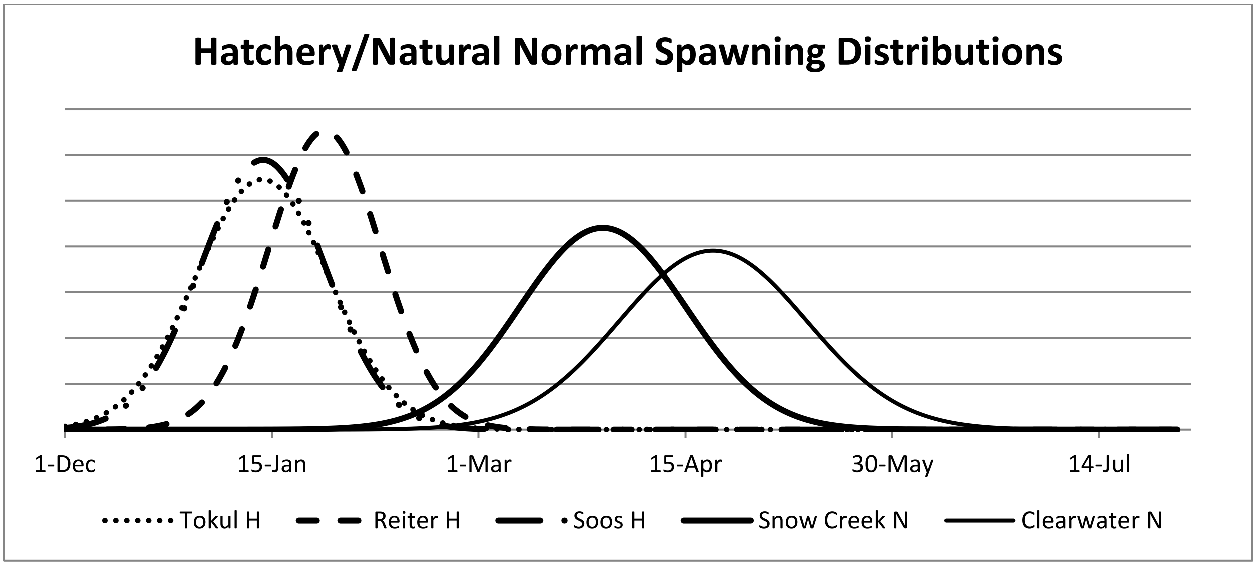


Figure 3. Normal curves constructed for two early summer hatchery steelhead programs (Reiter, Soos), one early winter hatchery steelhead program (Tokul), and two natural origin winter populations (Snow Creek, Clearwater River).

c. Sensitivity to the Normal Distribution Assumption

Sensitivity to the normal distribution assumption was evaluated by comparing a Normal to a Gamma distribution curve (Table **3**). The parameters (α and β) of an asymmetrical Gamma distribution function were calculated from the Normal μ and σ parameters: $\alpha = (\mu/\sigma)^2$ and $\beta = \sigma^2/\mu$ for the natural origin populations in Snow Creek and the Clearwater River. O_N was calculated using both Snow Creek and Clearwater natural origin parameterizations relative to the Tokul Creek early winter hatchery cutoff. Given the results below and the sensitivity levels of DGF to O_N (Figure 11), the Normal distribution was deemed sufficient.

Table 3. Sensitivity in O_N when using two different spawning timing distributions.

	Normal			Gamma		
Watershed	**Mean**	**StDev**	**O_N P(<Feb 26)[/1]**	**Alpha**	**Beta**	**O_N P(<Feb 26)[/1]**
Snow Creek	March 28	18.1	4.7%	42.50	2.78	3.68%
Clearwater River	April 21	20.4	0.4%	48.45	2.93	1.36%

[/1] February 26th was the date by which 99.9% of spawning would have occurred by hatchery origin EWS under the normal assumption. Tokul Creek EWS had a mean spawning date of January 13th with a standard deviation of 14.6 days.

ii. Method 2- Empirical data with Gamma distribution assumptions (Cases 3 and 6)

In this method, O_N was based on local river-specific observed redd data. Complete spawning information is challenging to obtain for most natural steelhead populations. Similarly sized redds may be made by hatchery-origin steelhead or by other species during the early portion of natural-origin spawn timing. The intermixing of similar redd construction among species is further complicated by the fact that steelhead are iteroparous, so it was rare to find either live steelhead defending redds or steelhead carcasses to inform identification of redd to species and/or origin (WDFW District Biologists, pers. Comm). Consequently, surveys generally begin mid-March to ensure that observed redds were constructed by natural-origin steelhead spawners, and as such March 15th was chosen as the cutoff for the Region C boundary. The Gamma distribution, which allows for asymmetrical spawn timing, was fit to observed redd data post March 15 by minimizing the sum of the squared errors between the observed proportion of redds and a statistically fitted proportion of redds. The Gamma distribution parameters in the resultant model were then used to estimate the proportion of natural origin redds created prior to March 15 (O_N) (Table 4, Figure 4-9). Typically, a Gamma distribution begins at a defined 0, and curves out to the right to infinity. In this case, a mirror image of the Gamma was used, with a zero point (July 30) clearly beyond the end of the spawning season and curving out to the left.

Table 4. Estimates of O_N from river-specific redd data.

Natural Winter Population	O_N
Nooksack River Winter	6.64%
Stillaguamish River Winter	1.25%
Pilchuck River Winter	1.06%
Snohomish/Skykomish River Winter	0.81%
Snoqualmie River Winter	1.83%
Green River Winter	2.41%

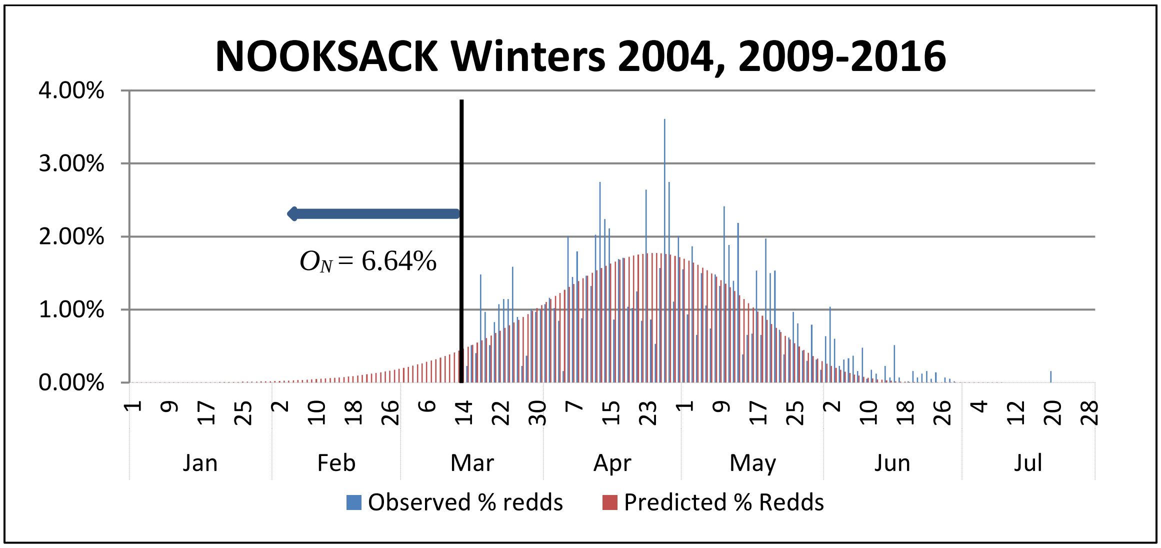


Figure 4. Nooksack River winter steelhead observed and predicted redd distribution. O_N was estimated as 6.64% of the area under the predicted curve to the left of March 15.

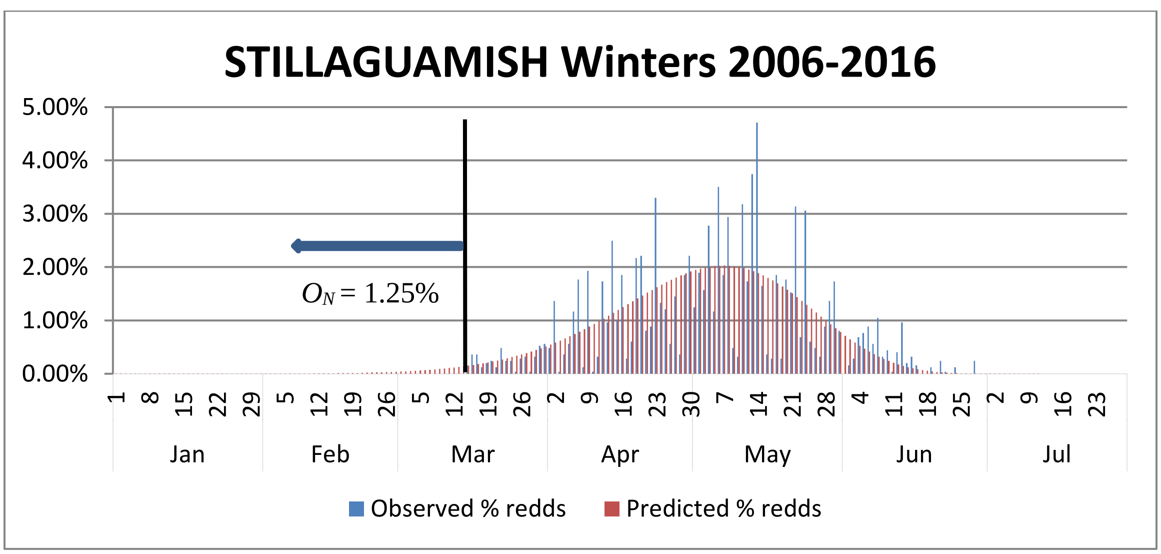


Figure 5. Stillaguamish River winter steelhead observed and predicted redd distribution. O_N was estimated as 1.25% of the area under the predicted curve to the left of March 15.

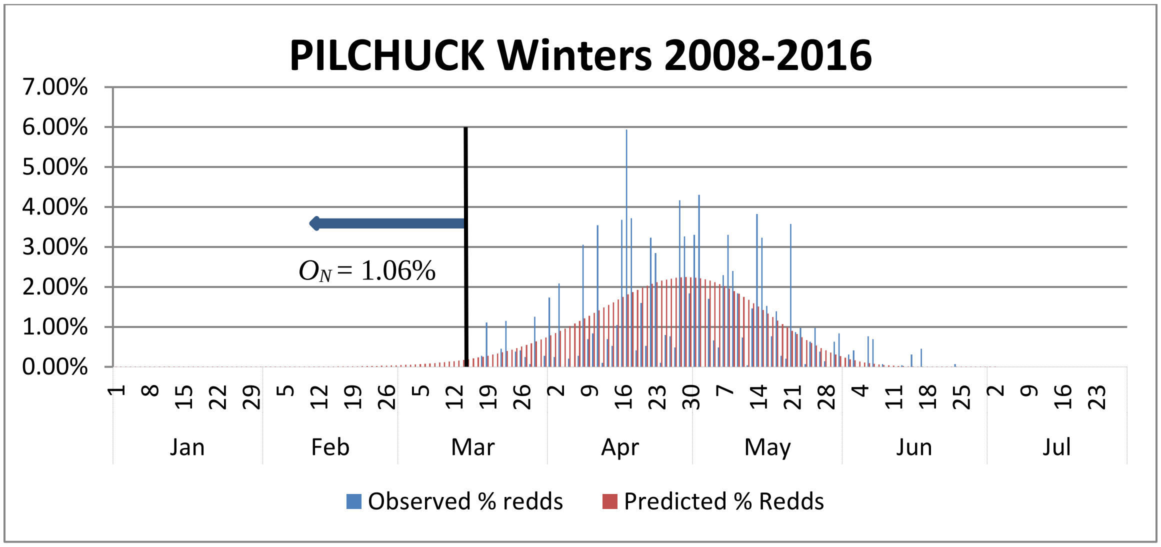


Figure 6. Pilchuck River winter steelhead observed and predicted redd distribution. O_N was estimated as 1.06% of the area under the predicted curve to the left of March 15.

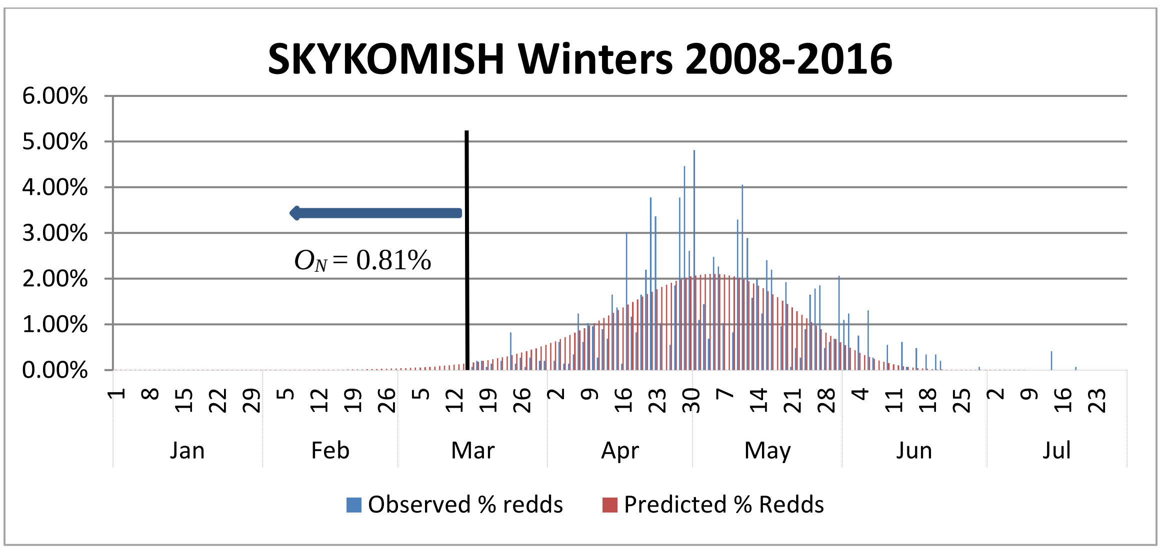


Figure 7. Snohomish/Skykomish River winter steelhead observed and predicted redd distribution. O_N was estimated as 0.81% of the area under the predicted curve to the left of March 15.

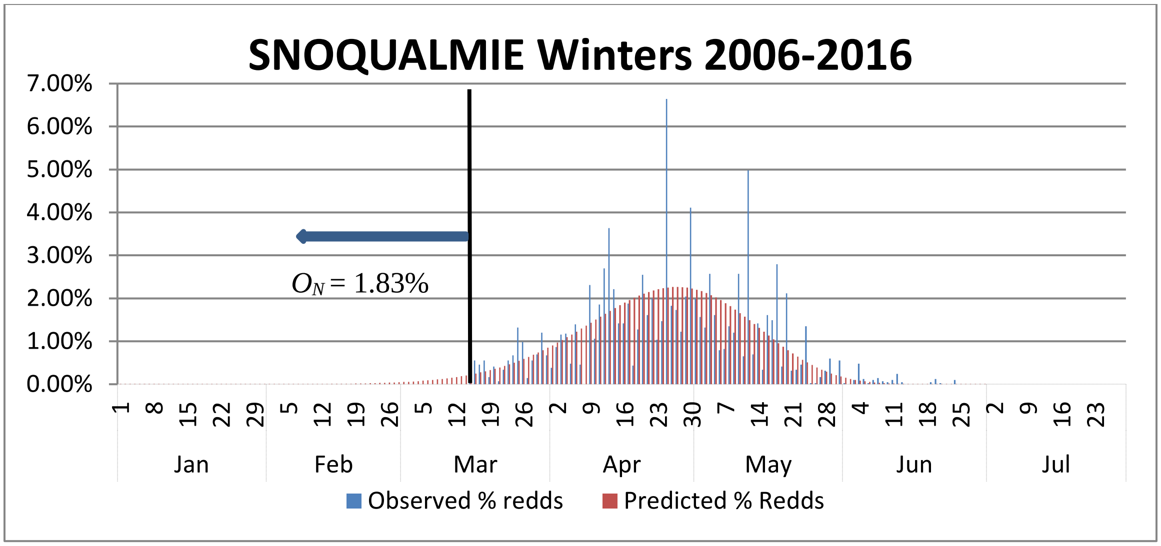


Figure 8. Snoqualmie River winter steelhead observed and predicted redd distribution. O_N was estimated as 1.83% of the area under the predicted curve to the left of March 15.

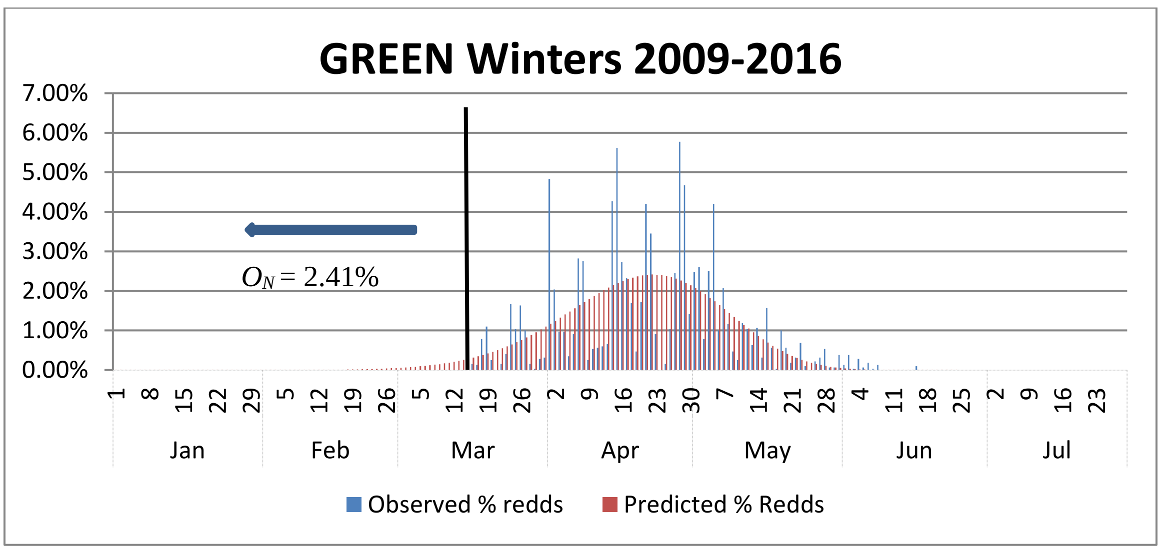


Figure 9. Green River winter steelhead observed and predicted redd distribution. O_N was estimated as 2.41% of the area under the predicted curve to the left of March 15.

d. Proportion of Hatchery-Origin Spawners in Spawn Timing Overlap (O_H)

O_H is the proportion of hatchery origin steelhead spawning naturally in Region B (Figure 1). Conceptually, and similarly to O_N, O_H was calculated conservatively to be the proportion of hatchery origin spawners to the right of Region A (including both Regions B and C).

iii. Method 1– Surrogate programs with normal distribution assumptions

The boundary of Region A was defined as the date before which natural-origin fish were unlikely to spawn. Under a normal curve, the probability of an observation prior to the mean minus three standard deviations is unlikely (0.13%). For this method, O_H is depicted by the shaded area in Figure 10 and is the probability that a hatchery origin fish would spawn after the Region A boundary defined as the natural origin mean minus three standard deviations (Table 1). With this method, O_H was calculated for all three hatchery programs relative to both Snow Creek and Clearwater River natural populations (Table 5).

Table 5. O_H values for three early hatchery programs.

Hatchery Origin Population	Snow Creek	Clearwater River
Tokul Creek Early Winters	8.79%	0.58%
Reiter Pond Early Summers	30.67%	2.82%
Soos Creek Early Summers	7.37%	0.33%

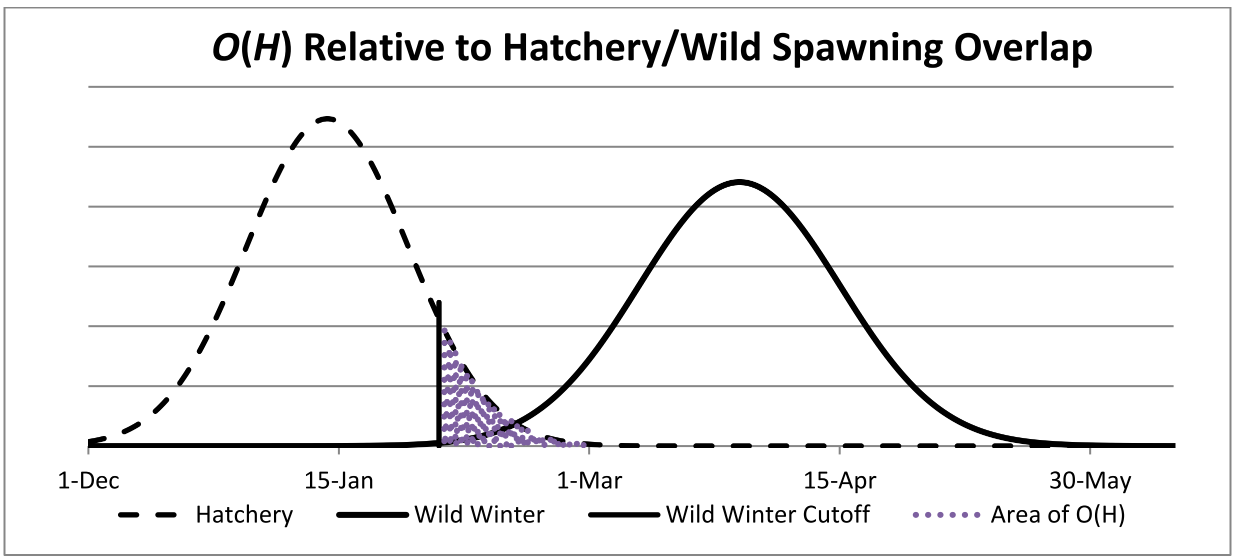


Figure 10. Hypothetical example of hatchery and natural origin winter steelhead spawn timing curves with a natural origin cutoff date calculated as the mean of the natural origin curve plus three standard deviations. For Method 1, the O_H parameter is calculated as the area under the hatchery curve to the left of the natural origin cutoff line**.**

i. Method 2– Empirical data proportions

In this method, O_H was based on data from river specific hatchery programs under the assumption that those fish returning to the hatchery rack or straying to natural spawning grounds have similar maturation schedules. January 31 was chosen as the Region A boundary as natural origin spawning is expected to be rare before then. Since 2009, Puget Sound hatcheries have operated traps well into March to minimize the number of hatchery-origin fish straying to natural spawning areas. This practice provided adequate data to estimate O_H as the percent of early winter hatchery fish not spawned before January 31st. Allowing one week for early winter hatchery fish returning to the rack to ripen for spawning, the best estimate of O_H was the simple percent of returns to the rack after January 26 (Table 6).

For the early summer programs, the number of spawning events at hatcheries did not provide enough contrast to calculate meaningful proportions. Instead, a normal distribution assumption was used with the mean spawning date and standard deviations to estimate the proportion of hatchery strays that would spawn past Region A (Table 1, Table 6).

Table 6. Estimates of O_H from early winter hatchery programs for Cases 3 and 6.

Early Winter Hatchery Program	O_H
Kendall Creek	12.34%
Whitehorse	14.80%
Reiter-Wallace	35.55%
Tokul Creek	13.51%

e. Relative Fitness of Hatchery x Hatchery Crosses (k_1).

The parameter, k_1, is the fitness of a hatchery by hatchery mating relative to a natural by natural mating where the fitness of a natural by natural cross is 1.0. Because the early winter hatchery programs have been operated with a segregated, nonlocal broodstock for more than 60 years, it is anticipated that the relative fitness will be low for fish produced from the domestication inherent in this type of program. The range of k_1 values (0.02 to 0.13) used drawn from the empirical studies for steelhead programs that use nonlocal broodstock (Araki et al. 2008). For early summer hatchery steelhead, the HSRG recommended a value of 0.18.

f. Relative Fitness of Hatchery x Natural Crosses (k_2).

The parameter, k_2, is the fitness of a hatchery by natural mating relative to a natural by natural mating, where the fitness of a natural by natural cross is 1.0. The value for k_2 was estimated by assuming that a hatchery by natural cross would be twice as fit as a hatchery by hatchery cross, relative to a natural by natural cross. With that in mind, the early winter k_2, 0.54 was estimated as halfway between the average values used for k_1 and 1.0:

$$\frac{1-\frac{0.02+0.13}{2}}{2}+\frac{0.02+0.13}{2}=0.54$$

and the early summer k_2, 0.59 was likewise estimated as halfway between the value used for k_1 and 1.0:

$$\frac{1-0.18}{2}+0.18=0.59.$$

g. Proportion of Total Natural Spawners of Hatchery-Origin (q)

The proportion of total natural spawners that are of hatchery origin (q) was estimated from run reconstructions for each population of natural winter steelhead. The run reconstructions relied on WDFW redd survey data that were expanded by the proportion of spawning that occurred prior to the initiation of spawner surveys. The expanded redd survey data provided an estimate of total spawners, including both natural and hatchery origin steelhead.

The hatchery-origin spawners in natural spawning areas (HOS) were estimated from the return of hatchery-origin fish to the hatchery expanded by assumed stray rates. The Hatchery Scientific Review Group has generally used stray rates of 10% or 20% for hatchery programs where juveniles are released on-station and the hatchery has adult collection facilities. To be conservative a stray rate of 20% or 30% was assumed for on-station releases. Given hatchery returns and an assumed stray rate, estimates of HOS were calculated for on-station releases. The return rates from on-station releases were applied to off-station releases to estimate the number of adults returning from the off-station releases. A stray rate of 100% was assumed for off-station releases so that all those fish returning were assumed to contribute to HOS.

4. Gene Flow Estimates

Gene flow was estimated under six different scenarios, or Cases, as seen in Table 7.

Table 7. Description of input sources for DGF estimates under six alternative Cases.

	CASE 1	CASE 2	CASE 3	CASE 4	CASE 5	CASE 6
Stray Rate Assumption	20%	20%	20%	30%	30%	30%
Hatchery EWS	Tokul	Tokul	Local program	Tokul	Tokul	Local program
Hatchery ESS	Reiter/Soos[/1]	Reiter/Soos[/1]	Reiter/Soos[/1]	Reiter/Soos[/1]	Reiter/Soos[/1]	Reiter/Soos[/1]
Natural Winter Population	Snow Creek	Clearwater River	Local population	Snow Creek	Clearwater River	Local population

[/1]Soos was used for the Green River only.

Estimates of the potential range of gene flow from early winter and early summer hatchery steelhead programs into natural winter steelhead populations in the Nooksack, Stillaguamish, Snoqualmie, Pilchuck, Snohomish/Skykomish and Green are provided in Table 8 - 16. For each year, gene flow was calculated using the annual natural origin run size and hatchery return data. Since there are no longer off-station releases, the last row in each table is the predicted gene flow based on the current on-station release size permitted in the 2016 Biological Opinions (NMFS 2016a, 2016b).

Table 8. Estimated gene flow from the early winter hatchery program for the Nooksack River Winter steelhead population under six alternative cases.

Spawn Year	**Case 1** Natural: Snow Creek Hatchery: Tokul Creek Stray Rate = 0.20		**Case 2** Natural: Clearwater R. Hatchery: Tokul Creek Stray Rate = 0.20		**Case 3** Natural: Nooksack Hatchery: Kendall Stray Rate = 0.20		**Case 4** Natural: Snow Creek Hatchery: Tokul Creek Stray Rate = 0.30		**Case 5** Natural: Clearwater R. Hatchery: Tokul Creek Stray Rate = 0.30		**Case 6** Natural: Nooksack Hatchery: Kendall Stray Rate = 0.30	
	K_1= 0.02	K_1= 0.13	K_1= 0.02	K_1= 0.13	K_1= 0.02	K_1= 0.13	K_1= 0.02	K_1= 0.13	K_1= 0.02	K_1= 0.13	K_1= 0.02	K_1= 0.13
2001-2002	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2002-2003	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2003-2004	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2004-2005	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2005-2006	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2006-2007	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2007-2008	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2008-2009	0.05%	0.14%	0.02%	0.14%	0.09%	0.18%	0.09%	0.24%	0.04%	0.24%	0.14%	0.31%
2009-2010	0.06%	0.16%	0.03%	0.16%	0.10%	0.21%	0.11%	0.27%	0.05%	0.28%	0.17%	0.36%
2010-2011	0.09%	0.24%	0.04%	0.24%	0.15%	0.32%	0.16%	0.41%	0.07%	0.41%	0.25%	0.54%
2011-2012	0.11%	0.28%	0.05%	0.28%	0.17%	0.37%	0.18%	0.48%	0.08%	0.49%	0.29%	0.63%
2012-2013	0.04%	0.10%	0.02%	0.10%	0.06%	0.13%	0.06%	0.16%	0.03%	0.17%	0.10%	0.22%
2013-2014	0.14%	0.35%	0.06%	0.35%	0.21%	0.46%	0.23%	0.59%	0.10%	0.60%	0.35%	0.78%
2014-2015	0.25%	0.66%	0.12%	0.67%	0.39%	0.87%	0.42%	1.12%	0.20%	1.15%	0.64%	1.46%
2015-2016	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Average All Years	0.11%	0.27%	0.05%	0.28%	0.17%	0.36%	0.18%	0.47%	0.08%	0.48%	0.28%	0.62%
Average of years with no off-station plants	0.11%	0.27%	0.05%	0.28%	0.17%	0.36%	0.18%	0.47%	0.08%	0.48%	0.28%	0.62%
DGF with Permitted Release 150,000	0.16%	0.42%	0.07%	0.43%	0.26%	0.56%	0.28%	0.72%	0.13%	0.74%	0.42%	0.95%

Table 9. Estimated gene flow from the early winter hatchery program for the Stillaguamish River Winter steelhead population under six alternative cases.

Spawn Year	**Case 1** Natural: Snow Creek Hatchery: Tokul Creek Stray Rate = 0.20		**Case 2** Natural: Clearwater R. Hatchery: Tokul Creek Stray Rate = 0.20		**Case 3** Natural: Stillaguamish Hatchery: Whitehorse Stray Rate = 0.20		**Case 4** Natural: Snow Creek Hatchery: Tokul Creek Stray Rate = 0.30		**Case 5** Natural: Clearwater R. Hatchery: Tokul Creek Stray Rate = 0.30		**Case 6** Natural: Stillaguamish Hatchery: Whitehorse Stray Rate = 0.30	
	K_1= 0.02	K_1= 0.13	K_1= 0.02	K_1= 0.13	K_1= 0.02	K_1= 0.13	K_1= 0.02	K_1= 0.13	K_1= 0.02	K_1= 0.13	K_1= 0.02	K_1= 0.13
2001-2002	0.67%	1.83%	0.33%	1.91%	0.71%	2.24%	0.90%	2.54%	0.46%	2.66%	0.88%	3.04%
2002-2003	0.04%	0.11%	0.02%	0.11%	0.08%	0.16%	0.07%	0.17%	0.03%	0.17%	0.12%	0.25%
2003-2004	0.14%	0.37%	0.06%	0.37%	0.22%	0.50%	0.20%	0.53%	0.09%	0.54%	0.30%	0.71%
2004-2005	0.44%	1.18%	0.21%	1.22%	0.53%	1.50%	0.59%	1.61%	0.29%	1.67%	0.66%	1.99%
2005-2006	0.22%	0.57%	0.10%	0.58%	0.32%	0.77%	0.34%	0.89%	0.16%	0.91%	0.44%	1.15%
2006-2007	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2007-2008	0.18%	0.46%	0.08%	0.46%	0.27%	0.62%	0.27%	0.71%	0.13%	0.72%	0.37%	0.93%
2008-2009	0.22%	0.58%	0.10%	0.59%	0.32%	0.77%	0.34%	0.90%	0.16%	0.92%	0.44%	1.16%
2009-2010	0.18%	0.46%	0.08%	0.47%	0.27%	0.62%	0.27%	0.71%	0.13%	0.73%	0.37%	0.94%
2010-2011	0.20%	0.51%	0.09%	0.52%	0.29%	0.68%	0.30%	0.77%	0.14%	0.79%	0.40%	1.01%
2011-2012	0.20%	0.51%	0.09%	0.52%	0.29%	0.69%	0.33%	0.87%	0.15%	0.89%	0.43%	1.12%
2012-2013	0.10%	0.26%	0.05%	0.26%	0.17%	0.36%	0.17%	0.44%	0.08%	0.45%	0.26%	0.60%
2013-2014	0.14%	0.36%	0.06%	0.37%	0.22%	0.50%	0.24%	0.61%	0.11%	0.63%	0.33%	0.82%
2014-2015	0.09%	0.24%	0.04%	0.24%	0.15%	0.33%	0.16%	0.40%	0.07%	0.41%	0.24%	0.55%
2015-2016	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Average All Years	0.22%	0.57%	0.10%	0.59%	0.30%	0.75%	0.32%	0.86%	0.15%	0.88%	0.40%	1.10%
Average of years with no off-station plants	0.13%	0.34%	0.06%	0.35%	0.21%	0.47%	0.22%	0.58%	0.10%	0.59%	0.32%	0.77%
DGF with Permitted Release 130,000	0.15%	0.38%	0.07%	0.38%	0.23%	0.52%	0.25%	0.64%	0.11%	0.65%	0.34%	0.85%

Table 10. Estimated gene flow from the early summer hatchery program for the Stillaguamish River Winter steelhead population under six alternative cases.

Spawn Year	**Case 1** Natural: Snow Creek Hatchery: Reiter Stray Rate = 0.20		**Case 2** Natural: Clearwater R. Hatchery: Reiter Stray Rate = 0.20		**Case 3** Natural: Stillaguamish Hatchery: Reiter Stray Rate = 0.20		**Case 4** Natural: Snow Creek Hatchery: Reiter Stray Rate = 0.30		**Case 5** Natural: Clearwater R. Hatchery: Reiter Stray Rate = 0.30		**Case 6** Natural: Stillaguamish Hatchery: Reiter Stray Rate = 0.30	
	K_1= 0.09	K_1= 0.18	K_1= 0.09	K_1= 0.18	K_1= 0.09	K_1= 0.18	K_1= 0.09	K_1= 0.18	K_1= 0.09	K_1= 0.18	K_1= 0.09	K_1= 0.18
2001-2002	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2002-2003	0.17%	0.21%	0.09%	0.17%	0.20%	0.26%	0.23%	0.29%	0.13%	0.23%	0.27%	0.35%
2003-2004	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2004-2005	0.81%	1.04%	0.46%	0.85%	0.76%	1.10%	1.00%	1.28%	0.57%	1.05%	0.89%	1.33%
2005-2006	0.07%	0.09%	0.04%	0.07%	0.09%	0.12%	0.12%	0.15%	0.06%	0.12%	0.15%	0.19%
2006-2007	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2007-2008	0.08%	0.10%	0.04%	0.08%	0.10%	0.13%	0.14%	0.18%	0.08%	0.14%	0.17%	0.22%
2008-2009	0.61%	0.78%	0.34%	0.63%	0.60%	0.86%	0.81%	1.04%	0.46%	0.84%	0.75%	1.10%
2009-2010	0.27%	0.35%	0.15%	0.27%	0.31%	0.41%	0.38%	0.48%	0.21%	0.38%	0.41%	0.55%
2010-2011	0.35%	0.44%	0.19%	0.35%	0.38%	0.51%	0.48%	0.61%	0.26%	0.49%	0.49%	0.68%
2011-2012	0.80%	1.03%	0.45%	0.84%	0.75%	1.09%	1.09%	1.40%	0.62%	1.15%	0.96%	1.44%
2012-2013	0.52%	0.66%	0.29%	0.53%	0.53%	0.74%	0.87%	1.12%	0.49%	0.91%	0.80%	1.17%
2013-2014	0.51%	0.65%	0.28%	0.52%	0.52%	0.72%	0.85%	1.08%	0.48%	0.88%	0.78%	1.14%
2014-2015	0.18%	0.23%	0.10%	0.18%	0.22%	0.28%	0.31%	0.39%	0.17%	0.31%	0.34%	0.46%
2015-2016	0.16%	0.17%	0.07%	0.13%	0.16%	0.21%	0.27%	0.29%	0.12%	0.23%	0.26%	0.35%
Average All Years	0.38%	0.48%	0.21%	0.39%	0.39%	0.54%	0.54%	0.69%	0.30%	0.56%	0.52%	0.75%
Average of years with no off-station plants	0.34%	0.43%	0.19%	0.34%	0.36%	0.49%	0.57%	0.72%	0.32%	0.58%	0.55%	0.78%
DGF with Permitted Release 70,000	0.28%	0.36%	0.15%	0.28%	0.32%	0.42%	0.48%	0.60%	0.26%	0.48%	0.49%	0.68%

Table 11. Estimated gene flow from the early winter hatchery program for the Snoqualmie River Winter steelhead population under six alternative cases.

Spawn Year		Case 1 Natural: Snow Creek Hatchery: Tokul Creek Stray Rate = 0.20		Case 2 Natural: Clearwater R. Hatchery: Tokul Creek Stray Rate = 0.20		Case 3 Natural: Snoqualmie Hatchery: Tokul Creek Stray Rate = 0.20		Case 4 Natural: Snow Creek Hatchery: Tokul Creek Stray Rate = 0.30		Case 5 Natural: Clearwater R. Hatchery: Tokul Creek Stray Rate = 0.30		Case 6 Natural: Snoqualmie Hatchery: Tokul Creek Stray Rate = 0.30	
		K_1= 0.02	K_1= 0.13	K_1= 0.02	K_1= 0.13	K_1= 0.02	K_1= 0.13	K_1= 0.02	K_1= 0.13	K_1= 0.02	K_1= 0.13	K_1= 0.02	K_1= 0.13
2001-2002		2.39%	7.92%	1.54%	8.74%	2.25%	9.38%	3.06%	10.68%	2.15%	11.94%	2.88%	12.62%
2002-2003		0.71%	1.97%	0.35%	2.05%	0.84%	2.45%	0.97%	2.76%	0.50%	2.91%	1.06%	3.38%
2003-2004		1.40%	4.19%	0.78%	4.49%	1.41%	5.04%	1.86%	5.83%	1.11%	6.35%	1.79%	6.94%
2004-2005		1.10%	3.17%	0.58%	3.36%	1.16%	3.85%	1.46%	4.41%	0.82%	4.73%	1.46%	5.29%
2005-2006		0.94%	2.67%	0.49%	2.81%	1.03%	3.27%	1.28%	3.77%	0.70%	4.02%	1.31%	4.55%
2006-2007		1.15%	3.33%	0.61%	3.54%	1.20%	4.04%	1.62%	4.95%	0.93%	5.34%	1.58%	5.91%
2007-2008		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2008-2009		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2009-2010		1.32%	3.90%	0.72%	4.16%	1.34%	4.69%	1.68%	5.19%	0.98%	5.61%	1.64%	6.20%
2010-2011		1.10%	3.18%	0.58%	3.36%	1.16%	3.86%	1.68%	5.20%	0.98%	5.62%	1.64%	6.20%
2011-2012		1.08%	3.12%	0.57%	3.30%	1.15%	3.79%	1.66%	5.10%	0.96%	5.52%	1.62%	6.09%
2012-2013		1.14%	3.30%	0.61%	3.50%	1.20%	4.01%	1.74%	5.39%	1.02%	5.85%	1.69%	6.43%
2013-2014		0.58%	1.56%	0.28%	1.62%	0.71%	1.98%	0.92%	2.61%	0.47%	2.74%	1.02%	3.20%
2014-2015		0.66%	1.79%	0.32%	1.86%	0.78%	2.25%	1.04%	2.98%	0.54%	3.15%	1.11%	3.63%
2015-2016		0.24%	0.62%	0.11%	0.64%	0.35%	0.84%	0.40%	1.06%	0.19%	1.09%	0.53%	1.37%
Average All Years		1.06%	3.13%	0.58%	3.34%	1.12%	3.80%	1.49%	4.61%	0.87%	4.99%	1.49%	5.52%
Average of years with no off-station plants		0.80%	2.26%	0.41%	2.38%	0.89%	2.79%	1.24%	3.72%	0.69%	3.99%	1.27%	4.49%
DGF with Permitted Release	74,000	0.49%	1.31%	0.23%	1.35%	0.63%	1.67%	0.79%	2.19%	0.40%	2.28%	0.90%	2.71%

Table 12. Estimated gene flow from the early summer hatchery program for the Snoqualmie River Winter steelhead population under six alternative cases.

Spawn Year	**Case 1** Natural: Snow Creek Hatchery: Reiter Stray Rate = 0.20		**Case 2** Natural: Clearwater R. Hatchery: Reiter Stray Rate = 0.20		**Case 3** Natural: Snoqualmie Hatchery: Reiter Stray Rate = 0.20		**Case 4** Natural: Snow Creek Hatchery: Reiter Stray Rate = 0.30		**Case 5** Natural: Clearwater R. Hatchery: Reiter Stray Rate = 0.30		**Case 6** Natural: Snoqualmie Hatchery: Reiter Stray Rate = 0.30	
	K_1= 0.09	K_1= 0.18	K_1= 0.09	K_1= 0.18	K_1= 0.09	K_1= 0.18	K_1= 0.09	K_1= 0.18	K_1= 0.09	K_1= 0.18	K_1= 0.09	K_1= 0.18
2001-2002	3.40%	4.66%	2.26%	4.20%	2.83%	4.70%	3.77%	5.22%	2.56%	4.76%	3.14%	5.26%
2002-2003	2.52%	3.38%	1.59%	2.95%	2.14%	3.42%	2.81%	3.80%	1.80%	3.35%	2.36%	3.83%
2003-2004	2.52%	3.37%	1.58%	2.94%	2.13%	3.41%	2.81%	3.79%	1.80%	3.34%	2.36%	3.82%
2004-2005	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2005-2006	2.29%	3.05%	1.42%	2.64%	1.96%	3.10%	2.56%	3.43%	1.61%	3.00%	2.16%	3.47%
2006-2007	3.15%	4.29%	2.06%	3.83%	2.63%	4.32%	3.50%	4.81%	0.00%	4.34%	2.91%	4.84%
2007-2008	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2008-2009	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2009-2010	8.09%	12.11%	6.71%	12.28%	7.29%	12.82%	8.88%	13.42%	7.57%	13.77%	8.15%	14.31%
2010-2011	6.05%	8.78%	4.62%	8.55%	5.21%	9.08%	6.66%	9.77%	5.23%	9.64%	5.81%	10.17%
2011-2012	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2012-2013	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2013-2014	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2014-2015	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2015-2016	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Average All Years	2.16%	3.05%	1.56%	2.88%	1.86%	3.14%	2.38%	3.40%	1.58%	3.25%	2.07%	3.52%
Average of years with no off-station plants	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
DGF with Permitted Release -	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 13. Estimated gene flow from the early winter hatchery program for the Pilchuck River Winter steelhead population under six alternative cases.

Spawn Year		**Case 1** Natural: Snow Creek Hatchery: Tokul Creek Stray Rate = 0.20		**Case 2** Natural: Clearwater R. Hatchery: Tokul Creek Stray Rate = 0.20		**Case 3** Natural: Pilchuck Hatchery: Reiter-Wallace Stray Rate = 0.20		**Case 4** Natural: Snow Creek Hatchery: Tokul Creek Stray Rate = 0.30		**Case 5** Natural: Clearwater R. Hatchery: Tokul Creek Stray Rate = 0.30		**Case 6** Natural: Pilchuck Hatchery: Reiter-Wallace Stray Rate = 0.30	
		K_1= 0.02	K_1= 0.13	K_1= 0.02	K_1= 0.13	K_1= 0.02	K_1= 0.13	K_1= 0.02	K_1= 0.13	K_1= 0.02	K_1= 0.13	K_1= 0.02	K_1= 0.13
2001-2002		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2002-2003		0.26%	0.69%	0.12%	0.71%	0.47%	1.05%	0.30%	0.79%	0.14%	0.81%	0.50%	1.10%
2003-2004		0.13%	0.33%	0.06%	0.34%	0.31%	0.55%	0.15%	0.38%	0.07%	0.38%	0.34%	0.60%
2004-2005		0.24%	0.62%	0.11%	0.63%	0.44%	0.95%	0.27%	0.71%	0.13%	0.72%	0.47%	1.01%
2005-2006		0.18%	0.47%	0.08%	0.48%	0.38%	0.75%	0.21%	0.54%	0.10%	0.55%	0.41%	0.81%
2006-2007		0.04%	0.11%	0.02%	0.11%	0.14%	0.20%	0.05%	0.12%	0.00%	0.13%	0.16%	0.23%
2007-2008		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2008-2009		0.57%	1.53%	0.27%	1.58%	0.69%	2.08%	0.64%	1.74%	0.31%	1.81%	0.74%	2.18%
2009-2010		0.41%	1.09%	0.19%	1.12%	0.59%	1.55%	0.46%	1.24%	0.22%	1.27%	0.62%	1.62%
2010-2011		0.33%	0.87%	0.15%	0.89%	0.52%	1.27%	0.37%	0.99%	0.18%	1.01%	0.56%	1.33%
2011-2012		0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2012-2013		0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2013-2014		0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2014-2015		0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2015-2016		0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Average All Years		0.17%	0.44%	0.08%	0.45%	0.27%	0.65%	0.19%	0.50%	0.09%	0.51%	0.29%	0.68%
Average of years with no off-station plants		0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
DGF with Permitted Release	-	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 14. Estimated gene flow from the early winter hatchery program for the Snohomish/Skykomish River Winter steelhead population under six alternative cases.

Spawn Year		**Case 1** Natural: Snow Creek Hatchery: Tokul Creek Stray Rate = 0.20		**Case 2** Natural: Clearwater R. Hatchery: Tokul Creek Stray Rate = 0.20		**Case 3** Natural: Skykomish Hatchery: Reiter-Wallace Stray Rate = 0.20		**Case 4** Natural: Snow Creek Hatchery: Tokul Creek Stray Rate = 0.30		**Case 5** Natural: Clearwater R. Hatchery: Tokul Creek Stray Rate = 0.30		**Case 6** Natural: Skykomish Hatchery: Reiter-Wallace Stray Rate = 0.30	
		K_1= 0.02	K_1= 0.13	K_1= 0.02	K_1= 0.13	K_1= 0.02	K_1= 0.13	K_1= 0.02	K_1= 0.13	K_1= 0.02	K_1= 0.13	K_1= 0.02	K_1= 0.13
2001-2002		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2002-2003		0.26%	0.69%	0.12%	0.70%	0.41%	0.94%	0.34%	0.90%	0.16%	0.92%	0.46%	1.18%
2003-2004		0.17%	0.43%	0.08%	0.44%	0.32%	0.64%	0.23%	0.59%	0.10%	0.60%	0.38%	0.83%
2004-2005		0.15%	0.40%	0.07%	0.40%	0.31%	0.60%	0.21%	0.55%	0.10%	0.56%	0.37%	0.79%
2005-2006		0.09%	0.23%	0.04%	0.24%	0.22%	0.39%	0.13%	0.34%	0.06%	0.34%	0.28%	0.52%
2006-2007		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2007-2008		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2008-2009		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2009-2010		0.39%	1.03%	0.18%	1.06%	0.50%	1.33%	0.55%	1.50%	0.27%	1.55%	0.60%	1.84%
2010-2011		0.25%	0.66%	0.12%	0.67%	0.40%	0.91%	0.38%	1.00%	0.18%	1.03%	0.49%	1.30%
2011-2012		0.81%	2.25%	0.41%	2.36%	0.75%	2.68%	1.27%	3.72%	0.69%	3.97%	1.03%	4.33%
2012-2013		0.68%	1.88%	0.34%	1.96%	0.68%	2.27%	1.08%	3.12%	0.57%	3.30%	0.92%	3.65%
2013-2014		0.39%	1.02%	0.18%	1.05%	0.49%	1.32%	0.63%	1.72%	0.31%	1.79%	0.64%	2.09%
2014-2015		1.00%	2.86%	0.52%	3.02%	0.87%	3.35%	1.55%	4.70%	0.88%	5.06%	1.22%	5.43%
2015-2016		0.76%	1.71%	0.31%	1.78%	0.64%	2.08%	1.00%	2.85%	0.52%	3.00%	0.86%	3.34%
Average All Years		0.45%	1.20%	0.22%	1.24%	0.51%	1.50%	0.67%	1.91%	0.35%	2.01%	0.66%	2.30%
Average of years with no off-station plants		0.73%	1.95%	0.35%	2.03%	0.69%	2.34%	1.10%	3.22%	0.59%	3.42%	0.93%	3.77%
DGF with Permitted Release	167,600	0.60%	1.63%	0.29%	1.70%	0.63%	1.99%	0.96%	2.72%	0.50%	2.87%	0.84%	3.20%

Table 15. Estimated gene flow from the early summer hatchery program for the Snohomish/Skykomish River Winter steelhead population under six alternative cases.

Spawn Year	**Case 1** Natural: Snow Creek Hatchery: Reiter Stray Rate = 0.20		**Case 2** Natural: Clearwater R. Hatchery: Reiter Stray Rate = 0.20		**Case 3** Natural: Skykomish Hatchery: Reiter Stray Rate = 0.20		**Case 4** Natural: Snow Creek Hatchery: Reiter Stray Rate = 0.30		**Case 5** Natural: Clearwater R. Hatchery: Reiter Stray Rate = 0.30		**Case 6** Natural: Skykomish Hatchery: Reiter Stray Rate = 0.30	
	K_1= 0.09	K_1= 0.18	K_1= 0.09	K_1= 0.18	K_1= 0.09	K_1= 0.18	K_1= 0.09	K_1= 0.18	K_1= 0.09	K_1= 0.18	K_1= 0.09	K_1= 0.18
2001-2002	3.49%	4.80%	2.33%	4.34%	2.53%	4.54%	4.54%	6.39%	3.21%	5.98%	3.40%	6.17%
2002-2003	2.20%	2.92%	1.35%	2.51%	1.58%	2.72%	2.91%	3.93%	1.87%	3.48%	2.08%	3.68%
2003-2004	2.00%	2.64%	1.22%	2.26%	1.45%	2.47%	2.53%	3.39%	1.59%	2.96%	1.81%	3.17%
2004-2005	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2005-2006	2.21%	2.94%	1.36%	2.53%	1.59%	2.74%	2.78%	3.75%	1.78%	3.30%	1.99%	3.50%
2006-2007	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2007-2008	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2008-2009	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2009-2010	10.28%	15.73%	9.12%	16.41%	9.28%	16.65%	12.67%	19.64%	11.86%	20.91%	12.03%	21.18%
2010-2011	4.20%	5.87%	2.92%	5.43%	3.11%	5.62%	5.54%	7.96%	4.13%	7.65%	4.29%	7.84%
2011-2012	3.99%	5.54%	2.74%	5.09%	2.93%	5.29%	5.24%	7.48%	3.85%	7.14%	4.02%	7.33%
2012-2013	2.57%	3.45%	1.62%	3.02%	1.84%	3.22%	3.95%	5.48%	2.70%	5.03%	2.89%	5.23%
2013-2014	2.01%	2.66%	1.22%	2.27%	1.45%	2.48%	3.13%	4.27%	2.05%	3.81%	2.25%	4.01%
2014-2015	3.32%	4.54%	2.19%	4.08%	2.40%	4.28%	5.01%	7.12%	3.64%	6.75%	3.81%	6.94%
2015-2016	4.63%	5.67%	2.81%	5.23%	3.00%	5.42%	6.86%	8.81%	4.64%	8.58%	4.80%	8.77%
Average All Years	3.72%	5.16%	2.63%	4.83%	2.83%	5.04%	5.01%	7.11%	3.76%	6.87%	3.94%	7.08%
Average of years with no off-station plants	3.13%	4.08%	1.96%	3.65%	2.17%	3.85%	4.74%	6.42%	3.26%	6.04%	3.44%	6.24%
DGF with Permitted Release 116,000	1.95%	2.57%	1.18%	2.20%	1.41%	2.40%	3.05%	4.14%	1.98%	3.68%	2.19%	3.88%

Table 16. Estimated gene flow from the early summer hatchery program for the Green River Winter steelhead population under six alternative cases.

Spawn Year	**Case 1** Natural: Snow Creek Hatchery: Soos Creek Stray Rate = 0.20		**Case 2** Natural: Clearwater R. Hatchery: Soos Creek Stray Rate = 0.20		**Case 3** Natural: Green Hatchery: Soos Creek Stray Rate = 0.20		**Case 4** Natural: Snow Creek Hatchery: Soos Creek Stray Rate = 0.30		**Case 5** Natural: Clearwater R. Hatchery: Soos Creek Stray Rate = 0.30		**Case 6** Natural: Green Hatchery: Soos Creek Stray Rate = 0.30	
	K_1= 0.09	K_1= 0.18	K_1= 0.09	K_1= 0.18	K_1= 0.09	K_1= 0.18	K_1= 0.09	K_1= 0.18	K_1= 0.09	K_1= 0.18	K_1= 0.09	K_1= 0.18
2001-2002	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2002-2003	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2003-2004	0.13%	0.22%	0.12%	0.24%	0.17%	0.29%	0.23%	0.38%	0.21%	0.41%	0.30%	0.49%
2004-2005	5.04%	8.74%	5.31%	10.04%	6.09%	10.71%	6.22%	10.81%	6.68%	12.46%	7.51%	13.18%
2005-2006	0.32%	0.53%	0.29%	0.58%	0.41%	0.68%	0.51%	0.85%	0.47%	0.93%	0.65%	1.09%
2006-2007	1.37%	2.32%	1.32%	2.59%	1.72%	2.92%	1.71%	2.91%	1.67%	3.26%	2.13%	3.65%
2007-2008	1.06%	1.78%	1.01%	1.98%	1.34%	2.26%	1.42%	2.40%	1.37%	2.67%	1.77%	3.02%
2008-2009	3.42%	5.90%	3.50%	6.71%	4.17%	7.29%	5.01%	8.68%	5.28%	9.97%	6.05%	10.64%
2009-2010	2.76%	4.73%	2.77%	5.36%	3.38%	5.88%	3.50%	6.04%	3.59%	6.88%	4.26%	7.46%
2010-2011	1.14%	1.91%	1.08%	2.12%	1.43%	2.42%	1.45%	2.46%	1.40%	2.74%	1.81%	3.09%
2011-2012	0.64%	1.07%	0.60%	1.18%	0.82%	1.37%	1.07%	1.81%	1.02%	2.01%	1.35%	2.29%
2012-2013	1.15%	1.94%	1.10%	2.16%	1.45%	2.45%	1.63%	2.76%	1.58%	3.08%	2.02%	3.46%
2013-2014	0.54%	0.90%	0.50%	0.99%	0.69%	1.15%	0.91%	1.53%	0.86%	1.69%	1.15%	1.93%
2014-2015	0.22%	0.37%	0.20%	0.40%	0.29%	0.47%	0.38%	0.62%	0.35%	0.68%	0.48%	0.80%
2015-2016	0.09%	0.14%	0.08%	0.16%	0.11%	0.19%	0.15%	0.25%	0.14%	0.27%	0.19%	0.32%
Average All Years	1.38%	2.35%	1.38%	2.65%	1.70%	2.93%	1.86%	3.19%	1.89%	3.62%	2.28%	3.95%
Average of years with no off-station plants	0.37%	0.62%	0.35%	0.68%	0.48%	0.79%	0.63%	1.05%	0.59%	1.16%	0.80%	1.34%
DGF with Permitted Release 100,000	0.49%	0.81%	0.45%	0.89%	0.63%	1.04%	0.82%	1.38%	0.77%	1.52%	1.04%	1.75%

5. *Sensitivity to Input Assumptions*

The gene flow equation demonstrates different levels of sensitivity to the different input parameters. To explore the generic sensitivity, a baseline gene flow (Table 17) was calculated using the average input value over all the watersheds and all the cases considered. Variation in gene flow from that baseline was calculated by varying each parameter in isolation, keeping all others the same (Figure 11). The parameters were systematically each reduced by 50% and increased by 50%.

Table 17. Input parameter values used in sensitivity analysis.

Input parameter	Average value over all watersheds and cases	Parameter value at a 50% increase	Parameter value at a 50% decrease
O(n)	2.89%	4.33%	1.44%
O(h)	13.82%	20.72%	6.91%
K1	0.10	0.15	0.05
K2	0.57	0.85	0.28
On-station pHOS	5.98%	8.97%	2.99%

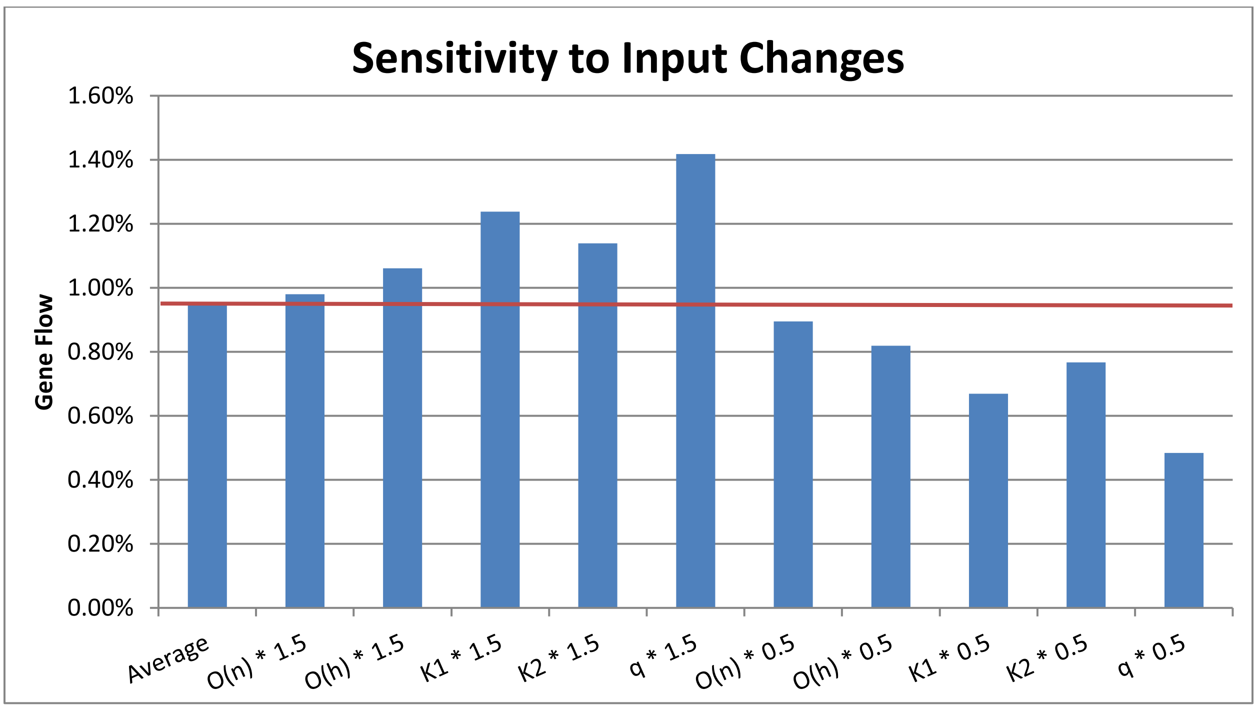


Figure 11. Gene flow values when varying each parameter in isolation by a 50% increase and a 50% decrease over the input value averaged over all watersheds and all cases. The average line demonstrates the comparison.

Varying two parameters at a time provides the gene flow values in Table 18.

Table 18. Gene flow values resulting from varying two parameters at a time. The top diagonal portion of the table reflects gene flows for the two parameters at a 50% reduced value. The bottom diagonal portion of the table reflects gene flows for the two parameters at a 50% increased value.

	O(n)	O(h)	K1	K2	pHOS
O(n)		0.80%	0.60%	0.74%	0.46%
O(h)	1.11%		0.52%	0.71%	0.40%
K1	1.26%	1.33%		0.48%	0.35%
K2	1.18%	1.31%	1.42%		0.38%
pHOS	1.47%	1.54%	1.86%	1.67%	

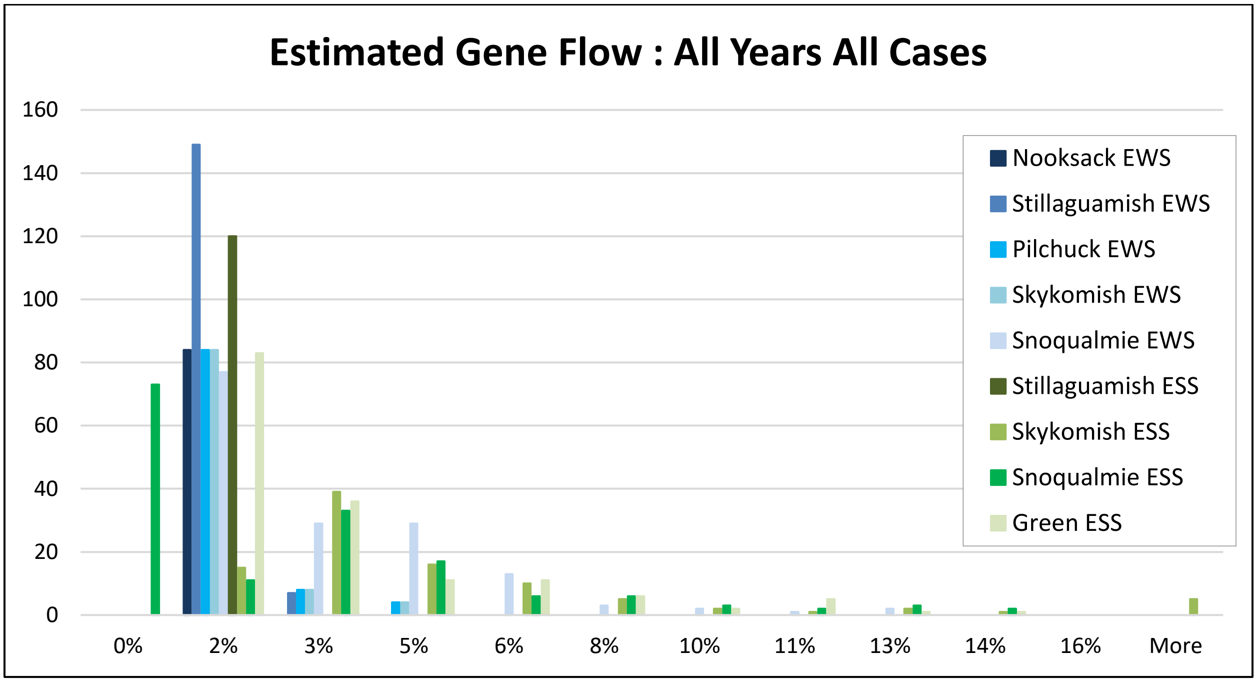
Top diagonal 50% reduced

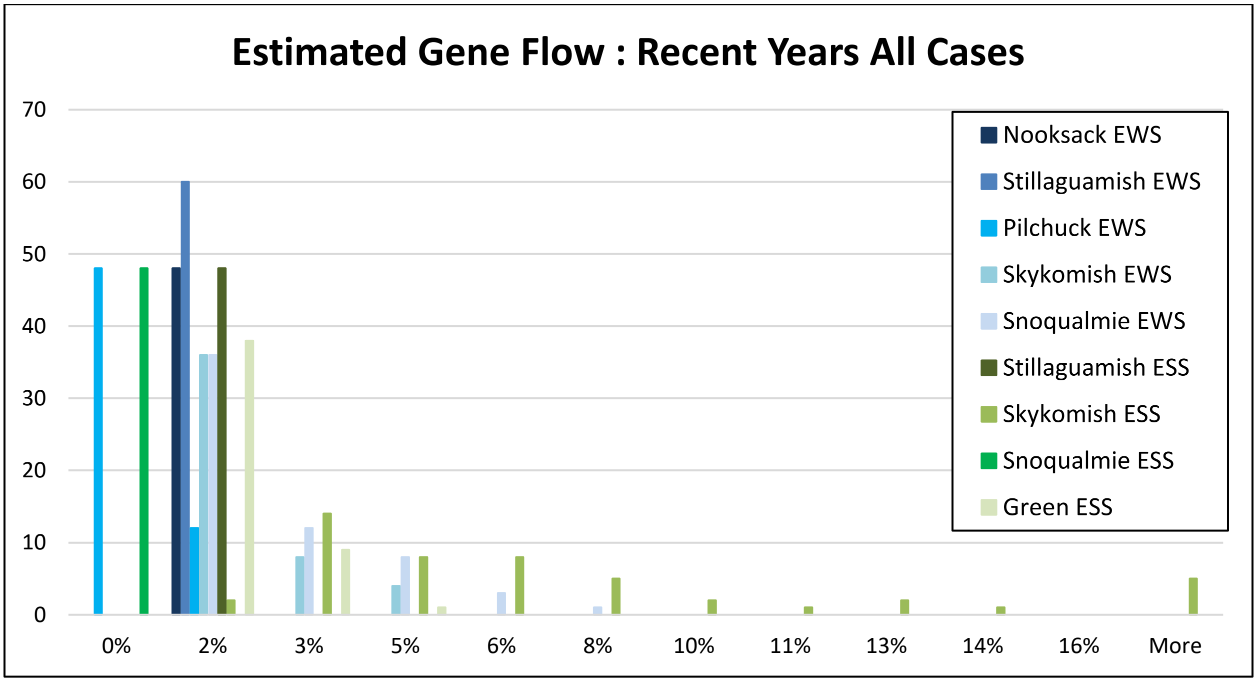
Bottom diagonal 50% increased

To further demonstrate the sensitivity of the DGF and also a sense of the range of DGF's calculated, histograms were created for DGF's averaged over all years for each natural population and hatchery program combination for all six Cases (

Figure **12**).

Figure 12. Histograms of the calculated DGF's overall population/program combinations. The values shown are divided into the two stray rate assumptions (20%, 30%) and whether the calculation was averaged over all years 2001/02-2015/16 or whether the calculation represented the proposed release numbers.





Gene flow may also occur through precocious male hatchery steelhead or resident O. mykiss. However, these pathways were not considered here.

References

Araki, H., B.A. Berejikian, M. J. Ford, and M.S. Blouin. 2008. Fitness of hatchery-reared salmonids in the wild. Evol. Appl. 1(2):342-355.

Busack, C. 2008. Derivation of gene flow equation. Pages 69-71 *IN*: Scott, J.B., Jr. and W.T. Gill, (editors). 2008. *Oncorhynchus mykiss*: Assessment of Washington State's anadromous populations and programs. Science Division, Washington Department of Fish and Wildlife. Olympia, Washington. Available from: http://wdfw.wa.gov/publications/00150/.

Busack, C. 2014. Error in Scott-Gill Equation for Gene Flow. Memo from NOAA Fisheries, 11/3/2014.

Cederholm, C.J. 1984. Clearwater River wild steelhead spawning. In Walton, J.M., and D.B. Houston, editors. Proceedings of the Olympic Wild Fish Conference, March 23-25, 1983. Fisheries Technology Program, Peninsula College, Port Angeles, Washington.

Johnson, T., J. Tagart, S. Elle, and H. Michael. 1978. Snow Creek research station. *In* Progress Report: June 30, 1978 for Cooperative Agreement #14-16-0001-6345 IFC between the U.S. Fish and Wildlife Service and the Washington State Game Department. Washington State Game Department. Olympia, Washington.

Johnson, T.H., J.H. Michael, and F.S. Elle. 1980. Migration and timing of adult steelhead and cutthroat trout in Snow Creek and Salmon Creek during the 1979-80 spawning season. *In* Progress report: June 30, 1980 for Cooperative Agreements #14-16-0001-5776 FS and #14-16-0001-6345 IFC between the U.S. Fish and Wildlife Service and the Washington State Game Department. Washington State Game Department. Olympia, Washington.

Warheit, K. I. 2014. Measuring reproductive interaction between hatchery-origin and wild steelhead (*Oncorhynchus mykiss*) from northern Puget Sound populations potentially affected by segregated hatchery programs. Washington Department of Fish and Wildlife. Olympia, Washington. October 10, 2014.

WDFW 2008. Washington Department of Fish and Wildlife Statewide Steelhead Management Plan: Statewide Policies, Strategies and Actions. Washington Department of Fish and Wildlife. Olympia, Washington. February 29, 2008.

Appendix. Raw Steelhead Data - hatchery release numbers and spawning ground surveys of natural spawners

Appendix Table 1. Raw steelhead data for the Nooksack River system (WDFW databases).

	Kendall Hatchery Releases		Adult Returns	
Spawn Year (SY)	On-station EWS (SY-2)[/1]	Off-station EWS (SY-2)[/1]	Nooksack Winter Natural Spawners (SY)[/2]	Kendall EWS Hatchery Returns (SY)
2001-2002	35,000	-		193
2002-2003	30,500	-		7
2003-2004	34,800	-		73
2004-2005	160,000	-		372
2005-2006	137,000	38,500		218
2006-2007	141,700	-		66
2007-2008	165,000	-		158
2008-2009	160,000	-	772	34
2009-2010	164,000	-	1,901	96
2010-2011	146,500	-	1,774	135
2011-2012	106,200	-	1,747	156
2012-2013	99,999	-	1,805	55
2013-2014	116,360	-	1,521	169
2014-2015	118,806	-	2,081	443
2015-2016	0	-	1,842	36

[/1] Release years were matched up with natural spawn years to properly account for contributors to natural spawning surveys.
[/2] The raw data from the spawning ground surveys are unadjusted, i.e. do not account for spawners before the surveys began.

Appendix Table 2. Raw steelhead data for the Stillaguamish River system (WDFW databases).

Spawn Year (SY)	Whitehorse Hatchery Releases				Adult Returns		
	On-station EWS (SY-2) [/1]	Off-station EWS (SY-2) [/1]	On-station ESS (SY-3) [/1]	Off-station ESS (SY-3) [/1]	Stillaguamish Winter Natural Spawners (SY) [/2]	Whitehorse EWS Hatchery Returns (SY)	Whitehorse ESS Hatchery Returns (SY)
2001-2002	88,640	20,136	-	17,637	1,436	410	
2002-2003	113,036	10,570	48,245	13,750	2,678	65	40
2003-2004	118,245	20,371	59,999	46,910	3,002	188	
2004-2005	133,966	37,991	51,749	48,868	1,874	300	61
2005-2006	144,801	10,224	44,901	732	2,743	373	39
2006-2007	142,427	10,000	77,776	-		140	56
2007-2008	138,756	10,004	73,633	-	1,241	133	22
2008-2009	143,919	10,018	76,254	29,321	487	67	23
2009-2010	144,654	10,080	76,928	20,072	1,509	164	39
2010-2011	115,220	10,045	76,428	20,430	1,469	166	48
2011-2012	76,605	-	75,250	20,236	1,379	226	108
2012-2013	128,066	-	75,055	-	2,085	172	243
2013-2014	152,599	-	69,945	-	1,469	169	166
2014-2015	86,725	-	76,225	-	2,296	172	91
2015-2016	0	-	65,079	-	2,775	7	80

[/1] Release years were matched up with natural spawn years to properly account for contributors to natural spawning surveys.
[/2] The raw data from the spawning ground surveys are unadjusted, i.e. do not account for spawners before the surveys began.

Appendix Table 3. Raw steelhead data for the Skykomish/Snohomish River system (WDFW databases).

Spawn Year (SY)	Reiter/Wallace Hatchery Releases					Adult Returns			
	On-station EWS (SY-2) [/1]	Off-station EWS into Skykomish (SY-2) [/1]	Off-station EWS into Pilchuck (SY-2) [/1]	On-station ESS (SY-3) [/1]	Off-station ESS into Skykomish (SY-3) [/1]	Skykomish Winter Natural Spawners (SY) [/2]	Pilchuck Winter Natural Spawners (SY) [/2]	Reiter/Wallace EWS Hatchery Returns (SY)	Reiter/Wallace ESS Hatchery Returns (SY)
2001-2002	115,289	76,129	24,033	176,320	40,453	1,166	279	[1/]	545
2002-2003	119,896	55,339	29,035	117,363	27,775	1,915	696	128	497
2003-2004	153,366	44,250	25,496	136,492	58,584	3,404	1,522	193	549
2004-2005	168,234	41,500	25,000	-	221,209	2,850	604	162	606
2005-2006	192,000	34,333	28,316	107,217	47,763	3,038	580	119	537
2006-2007	182,025	33,854	25,108	165,000	64,383		976	49	675
2007-2008	206,324	27,260	28,104	168,800	40,500		646	[2/]	754
2008-2009	202,536	15,073	35,025	149,440	33,728		344	201	1,073
2009-2010	172,445	25,014	25,314	160,135	56,082	732	294	142	1,181
2010-2011	168,194	15,675	31,200	178,361	30,562	1,150	552	167	790
2011-2012	171,900	-	-	151,652	27,936	876	848	665	543
2012-2013	165,955	-	-	190,604	-	1,008	1,036	632	691
2013-2014	160,000	-	-	182,500	-	1,188	676	396	606
2014-2015	167,308	-	-	187,500	-	940	1,008	920	885
2015-2016	174,561	-	-	205,693	-	1,312	822	745	1,607

[/1] Release years were matched up with natural spawn years to properly account for contributors to natural spawning surveys.
[/2] The raw data from the spawning ground surveys are unadjusted, i.e. do not account for spawners before the surveys began.

Appendix Table 4. Raw steelhead data for Snoqualmie River system (WDFW databases).

	Tokul Hatchery Releases		Reiter Hatchery Releases	Adult Returns	
Spawn Year (SY)	On-station EWS (SY-2) [/1]	Off-station EWS (SY-2) [/1]	Off-station ESS (SY-3) [/1]	Snoqualmie Winter Natural Spawners (SY) [/2]	Tokul EWS Hatchery Returns (SY)
2001-2002	145,340	31,308	49,531	789	1,148
2002-2003	170,372	32,974	31,225	988	330
2003-2004	165,458	30,048	49,984	1,506	1,169
2004-2005	161,661	31,813	51,523	1,060	584
2005-2006	156,333	26,810	44,091	1,856	908
2006-2007	173,456	15,117	42,671	992	797
2007-2008	160,442	20,073	52,470		581
2008-2009	177,712	20,186	50,838		386
2009-2010	166,585	49,968	56,560	662	362
2010-2011	165,185	-	62,763	664	727
2011-2012	167,638	-	-	792	850
2012-2013	152,000	-	-	614	701
2013-2014	163,400	-	-	822	425
2014-2015	153,000	-	-	966	576
2015-2016	26,045	-	-	986	198

[/1] Release years were matched up with natural spawn years to properly account for contributors to natural spawning surveys.
[/2] The raw data from the spawning ground surveys are unadjusted, i.e. do not account for spawners before the surveys began.

Appendix Table 5. Raw steelhead data for Green River system (WDFW databases).

	Soos Creek Hatchery Releases		Adult Returns	
Spawn Year (SY)	On-station ESS (SY-3) [/1]	Off-station ESS (SY-3) [/1]	Green Winters Natural Spawners (SY) [/2]	Soos ESS Hatchery Returns (SY)
2001-2002			1,068	
2002-2003			1,615	
2003-2004	65,860	-	2,359	130
2004-2005	61,137	40,000	1,298	777
2005-2006	57,435	2,448	1,955	215
2006-2007	43,660	30,945	1,452	194
2007-2008	124,343	40,120	833	147
2008-2009	89,013	7,828	304	348
2009-2010	64,264	32,300	423	156
2010-2011	53,380	28,700	855	115
2011-2012	109,600	-	392	107
2012-2013	55,609	10,000	656	174
2013-2014	74,408	-	997	228
2014-2015	79,984	-	1,622	149
2015-2016	30,482	-	2,145	77

[/1] Release years were matched up with natural spawn years to properly account for contributors to natural spawning surveys.
[/2] The raw data from the spawning ground surveys are unadjusted, i.e. do not account for spawners before the surveys began.