Development of escapement goals for Grays Harbor fall Chinook using spawner-recruit models

May 2014
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Abstract

Grays Harbor fall Chinook are currently managed for a system-total escapement goal of 14,600 naturally spawning adults (Chehalis: 12,364, Humptulips: 2,236), a goal established in 1979 based on estimates of total accessible spawning habitat and spawning habitat capacity for individual streams in the Grays Harbor Basin. Grays Harbor escapement goals have received additional attention since this capacity-based goal was developed, most recently by QDNR and WDFW in 2007 (a joint effort) and between 1999 and 2003 by the Chinook Technical Committee (CTC) of the Pacific Salmon Commission (PSC) and its Washington members. To develop an escapement goal for common use in the CTC's review of indicator stock performance and by the Grays Harbor co-managers (QDNR and WDFW) in management, QDNR and WDFW recently conducted stock-recruitment analyses for Grays Harbor fall Chinook using updated escapement, terminal run reconstruction, and ocean abundance datasets. Goals were developed separately for each main tributary (Chehalis, Humptulips) and summed to generate an aggregate goal for the CTC Grays Harbor fall Chinook escapement indicator stock. Of three spawner-recruit functions considered (Shepherd, Beverton-Holt, Ricker), the Ricker model was identified as being the most appropriate form for both the Chehalis and Humptulips datasets. Parameter estimates indicate that the adult spawning escapement needed to produce maximum sustained yield (mean S_{msy}) for the Grays Harbor fall Chinook indicator stock aggregate is 13,326 (age 3+ individuals); S_{msy} is 9,753 for the Chehalis River and 3,573 for the Humptulips River. Although there are uncertainties and limitations associated with these updated escapement goals (e.g., narrow range of parent-generation spawning escapement levels), they constitute the best estimates of sustainable management parameters available for Grays Harbor fall Chinook at this time.

Introduction

The abundance-based management regime for Chinook salmon established by the 2008 Pacific Salmon Commission (PSC) is intended to sustain production at levels associated with maximum sustained yield (MSY, measured in terms of adult equivalents) over the long term. For Grays Harbor fall Chinook, the present escapement goal of 14,600 (Chehalis: 12,364, Humptulips: 2,236) was established in 1979, based on spawning capacity estimates (adults / mile of spawning habitat) for individual streams in the Chehalis and Humptulips river basins and estimates of accessible spawning habitat in these basins (QDNR and WDFW, 2007). The escapement goals were most recently reviewed by QDNR and WDFW (a joint effort) in 2007 and Alexandersdottir in 2000 (personal communication).

The Chinook Technical Committee (CTC) is to review the biological basis for Chinook salmon management objectives under the Pacific Salmon Treaty (PSC, 2009), Chapter 3, Section 2. (b) (iv), The CTC shall "…evaluate and review existing escapement objectives that fishery management agencies have set for Chinook stocks subject to this Chapter for consistency with MSY or other agreed biologically-based escapement goals and, where needed, recommend goals for naturally spawning Chinook stocks that are consistent with the intent of this Chapter …".

The Grays Harbor fall Chinook stock is an aggregate of predominantly wild production with two major (Chehalis and Humptulips rivers, inclusive of tributaries) and multiple minor (Hoquiam and Wishkah rivers, South Bay tributaries) population segments. Grays Harbor Chinook spawn and rear in several tributaries in the basins draining the Black and Willapa hills, Olympic Mountains, Cascade foothills, and coastal Washington lowlands, the majority of which are characterized by a rain-dominated hydrology. The quality of Chinook spawning and rearing habitat varies widely across the Grays Harbor system. Many headwater reaches are affected by current and legacy logging impacts, whereas lowland river reaches are affected primarily by agricultural, residential, and industrial land uses. Although ongoing restoration activities aim to improve habitat conditions overall, there is great uncertainty about future conditions in the basin given the potential construction of new and major flood control projects in the upper Chehalis Basin (e.g., flood control dam, enhanced levee system, etc.).

The stock expresses a life history typical of Washington Coast fall Chinook, with adults returning to Grays Harbor from September through October and spawning from October to December. Juveniles typically emigrate as subyearling smolts the following spring and spend one to five years rearing off of the Alaska and British Columbia coasts. In addition to mixed-maturity ocean fishery exposure, Grays Harbor Chinook are subject to harvest in a combination of terminal estuarine and freshwater commercial (treaty and non-treaty), sport, and ceremonial and subsistence fisheries. In terms of stock size, the total natural-origin mature run (escapement + fishery landings) to the mouth of Grays Harbor has averaged *ca*. 25,000 fish during the period of record considered in this document (1986-2005 brood years).

This stock-recruitment analysis was performed using terminal run size estimates, expanded to pre-fishing recruits using results from the CTC's cohort reconstruction (i.e., '.OUT' files from the March 2012 CTC analysis) for the Washington Coastal fall Chinook coded-wire tag (CWT) indicator stock (Queets fall Chinook), for brood years 1986 to 2005[1]. Preterminal removals were estimated by multiplying Grays Harbor terminal run (inclusive of incidental mortality) by the ratio of Queets preterminal abundance (adult equivalent) / Queets terminal run. Terminal incidental mortality was also estimated using CWT data for the Queets indicator stock (i.e., ratios of total mortality to landed mortality for terminal fisheries) for corresponding brood years, ages, and fisheries. Although sizeable fall Chinook (*ca*. 200,000) CWT groups have been released from hatchery facilities within the Grays Harbor system in the past, release intermittency precludes the use of these data here. Where comparisons have been made, data indicate that the Queets indicator stock is a suitable surrogate for the present analysis (Appendix A). Spawning escapement estimates for the Grays Harbor system are based on a combination of extensive and intensive redd surveys and assume 2.5 fish (adults) / redd. Each of these data elements are described in detail below. Lastly, S_{msy} goals were estimated for the Humptulips and Chehalis rivers (Chehalis production includes all non-Humptulips production) separately, and S_{msy} for the indicator stock as a whole was taken as the sum of these estimates.

Methods

Data preparation

Terminal data

Grays Harbor production considered in this analysis is composed of Humptulips River and Chehalis River. Additional production from other Grays Harbor tributaries (South Bay: Elk and Johns, catch only[2]; Chehalis estuary: Hoquiam, and Wishkah rivers, catch and escapement) is included in Chehalis River production. Production is calculated as escapement + terminal catch (adjusted for incidental mortality) + pre-terminal catch (adjusted for incidental mortality and adult equivalence). Adult equivalence (AEQ) is the expected contribution to spawning escapement in the absence of fishing.

Hatchery escapement

The size of hatchery releases (Table 1) and hatchery rack returns (Tables 2) suggests that there is a high probability for stray hatchery contributions to natural escapement in portions of the Grays Harbor Basin. Off-station brood stock collection is common practice in the Chehalis Basin, particularly at Satsop Springs, which may also lead to straying. Table 1 shows releases

[1] The analysis was restricted to 1986+ to maintain consistency with the CWT time series associated with the Queets wild broodstock fall Chinook indicator stock program (Salmon River Fish Culture Center).

[2] Limited freshwater sport catch (<5 fish per stream per year) is occasionally reported on catch record cards for Elk, Johns, and misc. South Bay tributaries. Due to a general lack of production, Chinook escapement is not monitored in these streams.

in the Chehalis River from a variety of hatcheries and locations. As indicated in Table 1, the mark rate (% adipose clipped) of hatchery releases has increased to sufficiently high levels to allow for reliable identification of hatchery strays in natural spawning areas since return year 2010 in the Chehalis and 2011 in the Humptulips.

Table 2 shows Chehalis River returns to 4 hatcheries: Bingham Creek (weir and trap), Lake Aberdeen (Van Winkle Creek), Mayr Brothers (Wishkah River), and Satsop Springs. Some straying is expected for all of these facilities and particularly for Bingham Creek prior to 1993 when the height of its weir was raised (Jim Jorgensen, personal communication). Humptulips was the only hatchery releasing Chinook into the Humptulips River (Table 1). However this hatchery has high straying because, in the years covered in this analysis, the hatchery (and weir) were located on Stevens Creek but the hatchery (imprint) water source was the Humptulips River (HSRG, 2004).

Wild spawning escapement

Streams in the Grays Harbor basin are designated as index (weekly survey), extensive (annual survey), and un-surveyed. Index areas are surveyed for new redds weekly from approximately October 1st to December 30th. Extensive areas are sampled once per season as close to spawning peak as possible. Each index area is associated with one or more extensive areas.

Where i = survey wk. and n = total survey wks., the cumulative redds in index area j is

$$\sum_{i=1}^{n} new\ redds\ index\ area_{\ j}\ for\ week_{\ i}$$

and season total redd abundance for extensive area k associated with index area j is estimated by expansion.

Where p = week when spawning peak occurs in index area j and associated extensive area k, redd estimate for extensive area k =

$$\frac{\#\ redds\ in\ extensive\ area_{\ k}\ week_{\ p}}{\#\ redds\ in\ index\ area_{\ j}\ week_{\ p}} * season\ cumulative\ redds\ in\ index\ area_{\ j}$$

Un-surveyed areas are then estimated using redd densities (cumulative redds / river mile) from surveyed reaches with similar habitat-type. Additionally, given that high water events periodically interrupt weekly index area surveys, a variety of ad-hoc methods are occasionally used to estimate missing weeks in index area spawning. Although percentages vary from year to year (i.e., in response to weather, flows, staffing levels), index, extensive, and non-surveyed reaches comprise *ca*. 20%, 50%, and 30%, respectively, of the total stream length used by fall Chinook for spawning.

Final basin escapement is computed as the sum of cumulative redds in intensive, extensive, and un-surveyed reaches, multiplied by an assumed 2.5 fish (adults) / redd. The current survey design does not allow for the estimation of uncertainty associated with redd totals and/or the constant fish-per-redd multiplier. However, three years of mark-recapture studies conducted in the Little Hoquiam River (Chitwood 1987, 1988, 1989), a tributary of the Grays Harbor system, verify that this constant has local relevance is consistent across years (mean 2.50, CV(mean) = 7%).

WDFW estimated natural- and hatchery-origin components using two methods. When the majority of hatchery returns were from mass-marked (i.e., adipose fin-clipped) broods, the hatchery stray component of total escapement was estimated during carcass surveys. Resulting estimates of stray hatchery spawners were used in conjunction with hatchery rack observations to estimate an overall hatchery stray rate for each basin. Prior to complete mass marking, the stray hatchery component of natural spawning escapement was estimated by applying, retrospectively, the mean stray rate for recent mass-marked return years (2009+). See Appendix B for complete wild-origin estimation details.

Lastly, in all analyses, parent generation escapement (i.e., spawners) includes both natural- and hatchery-origin fish spawning naturally. No adjustments were made to account for the possibility of a reproductive fitness differential for hatchery- vs. natural-origin parents. On the recruitment side, only natural-origin escapement was included in production calculations.

Table 1. Releases of smolt stage fall Chinook into the Chehalis and Humptulips rivers (brood years 1986 – 2011) from 11/2013 RMIS query. AD = adipose clipped, UM = unclipped.

Brood	Chehalis[1]				Humptulips			
Year	AD (ALL)	UM	AD+CWT	% AD	AD (ALL)	UM	AD+CWT	% AD
1986	0	880,764	0	0%	201,993	81,327	201,468	71%
1987	72,710	2,310,675	71,919	3%	215,725	96,575	209,254	69%
1988	0	480,350	0	0%	208,403	283,747	206,735	42%
1989	44,998	299,970	44,667	13%	205,993	554,093	203,892	27%
1990	144,638	591,245	142,363	20%	212,156	1,952	207,589	99%
1991	169,022	490,348	164,363	26%	0	62,100	0	0%
1992	0	1,414,946	0	0%	0	402,700	0	0%
1993	0	752,763	0	0%	0	345,800	0	0%
1994	0	719,700	0	0%	0	467,800	0	0%
1995	0	562,342	0	0%	0	230,200	0	0%
1996	0	139,978	0	0%	0	237,435	0	0%
1997	0	269,932	0	0%	0	540,700	0	0%
1998	0	114,836	0	0%	0	437,000	0	0%
1999	0	409,000	0	0%	0	385,100	0	0%
2000	0	275,000	0	0%	0	259,425	0	0%
2001	0	103,300	0	0%	0	228,385	0	0%
2002	0	111,000	0	0%	0	535,750	0	0%
2003	211,302	274,726	136,663	43%	199,964	308,161	196,605	39%
2004	251,416	533,419	247,590	32%	185,982	297,538	180,029	38%
2005	144,365	36,835	143,995	80%	236,285	131,725	236,285	64%
2006	44,506	113,094	43,438	28%	198,689	324,411	198,689	38%
2007	238,950	4,430	0	98%	312,430	1,570	0	100%
2008	408,847	153	204,786	100%	270,710	3,790	0	99%
2009	116,749	526	0	100%	148,929	896	0	99%
2010	154,086	14	0	100%	567,997	4,217	0	99%
2011	621,978	12,656	0	98%	535,268	10,599	0	98%

[1]Includes releases into the mainstem Chehalis, Satsop, Hoquiam, Wishkah rivers, and Van Winkle Creek, as well as releases into the Wynoochee River for three broods (1992-94).

Table 2. Returns of fall Chinook to Chehalis River and Humptulips River hatcheries, return years 1989–2011 (source: WDFW Run Reconstruction, Dec. 2013).

Return Year	Satsop Springs/ Bingham	Lake Aberdeen	Mayr Bros (Wishkah)	Humptulips
1989	58	0	0	433
1990	30	0	0	169
1991	279	0	0	95
1992	431	0	0	190
1993	303	0	0	216
1994	292	0	0	236
1995	255	14	0	135
1996	343	86	0	150
1997	102	53	0	276
1998	100	67	0	298
1999	8	60	0	260
2000	3	55	0	169
2001	4	60	33	175
2002	0	291	80	405
2003	36	130	35	617
2004	314	84	0	474
2005	59	112	9	710
2006	73	342	41	1476
2007	132	74	7	363
2008	185	32	16	248
2009	94	91	13	467
2010	105	99	4	442
2011	330	130	51	852

Estimation of origin (hatchery or wild) and age in terminal fisheries

Sampling for CWTs and mark rates is done in Chehalis tribal net, Quinault Tribal net, and non-treaty fisheries by the Chehalis Tribe, the Quinault Indian Nation (QIN), and the Washington Department of Fish and Wildlife (WDFW), respectively. However, this sampling is considered unreliable for determination of hatchery / wild composition in most years (Jim Jorgenson, personal communication). Consequently, total hatchery return and wild spawning escapement are used to assign catch to production origin in terminal fisheries. The proportion wild Chehalis stock is estimated as Chehalis River wild-origin escapement / [total hatchery-origin escapement + Chehalis River wild-origin escapement]. The proportion wild Humptulips stock is estimated in a similar manner; for both rivers, hatchery-origin escapement includes hatchery fish homing to facilities as well as strays.

Scale samples obtained in the terminal fishery and in escapement sampling are used to determine age composition of returns. Scale samples are taken in treaty and non-treaty net fisheries and during Chehalis and Humptulips spawning ground surveys. No scale samples are taken in recreational sport fisheries. Scale samples from areas 2A, 2D, and the Chehalis River are used to estimate age proportions for Chehalis River stock (Figure 1). Scale samples from area 2C and the Humptulips River are used to proportion Humptulips River stock (Figure 1).

For return years during which raw data were available (2001-2011), the proportional abundance by age *a* (*a* = 3,4,..,6) in the terminal return was estimated for the Chehalis and Humptulips populations using a weighted average from samples collected in fisheries and escapements according to:

Notation	**Definition**
PR_a	Proportion age a
SC	Scale sample
CA	Catch
ESC	Escapement estimate
sp	Subscript for sample obtained in spawning survey
	Chehalis stock
2AD	Subscript for area 2A + area 2D
Cheh	Subscript for Chehalis River
tr	Subscript for treaty net fishery
nt	Subscript for non-treaty net fishery
	Humptulips stock
2C	Subscript for area 2C
Hump	Subscript for Humptulips River
tr	Subscript for treaty net fishery
nt	Subscript for non-treaty net fishery

For example, the weighed age 3 proportion for Chehalis stock is computed as

$$PR_3 = \frac{SC_{3,tr,2AD}}{\sum_{a=3}^{6} SC_{3,tr,2AD}} * CA_{tr,2AD} + \frac{SC_{3,nt,2AD}}{\sum_{a=3}^{6} SC_{3,nt,2AD}} * CA_{nt,2AD} + \frac{SC_{3,sp,Cheh}}{\sum_{a=3}^{6} SC_{3,sp,Cheh}} * ESC_{Cheh}$$

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and the weighed age 3 proportion for Humptulips stock is computed as

$$PR_3 = \frac{SC_{3,tr,2C}}{\sum_{a=3}^{6} SC_{3,tr,2C}} * CA_{tr,2C} + \frac{SC_{3,nt,2C}}{\sum_{a=3}^{6} SC_{3,nt,2C}} * CA_{nt,2C} + \frac{SC_{3,sp,Hump}}{\sum_{a=3}^{6} SC_{3,sp,Hump}} * ESC_{Hump}$$

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The relative abundance of returns for ages 4-6 is computed similarly. The weights used to estimate age composition for return years prior to 2001 are of undocumented origin.

Assignment of terminal marine catch to stock (Chehalis or Humptulips)

Net and sport catch in the Grays Harbor estuary (Marine Area 2.2, sub-areas 2A, 2B, 2C, and 2D; Figure 1) and its tributaries must be assigned to stock (Chehalis or Humptulips). Marine catch in Area 2.2 is composed of marine sport, non-Treaty net, and Quinault Treaty net (Table 3a). Freshwater catch includes freshwater sport, Quinault Treaty net, and Chehalis Tribal net (Table 3b). Stock assignment for freshwater net and sport fisheries is made on the basis of catch location, i.e., catches are assumed to be of 100% local origin stock. To assign catches in Grays Harbor's mixed-stock estuary areas (net fisheries in 2A-2D and sport fisheries in 2.2) rule- or CWT-based methods are used, and to account for spatial differences in treaty and non-treaty fisheries within catch areas (e.g., 2C) different methods are used to apportion their respective catches to the Chehalis and Humptulips population segments.

For treaty net fisheries, all catch occurring in areas 2A and 2D is assumed Chehalis stock and Area 2C treaty catch is assumed Humptulips stock. No treaty fisheries have occurred in Area 2B during the period covered in this analysis. Non-treaty net catch in Area 2A is apportioned in the same manner as treaty catch (i.e., 100% Chehalis), Areas 2B-2D non-treaty net and Area 2.2 non-treaty sport catches are apportioned to population segments based on historic CWT release–recovery data. Assignments are made based on the average probability of encountering fish from each stock in a particular catch area, given the run size of Chehalis wild- or hatchery-origin and Humptulips wild- or hatchery-origin fish in the return year of interest. Specifically, the catch (C_{SFY}) of stock *S* (Chehalis-wild, Chehalis-hatchery, Humptulips-wild, Humptulips-hatchery) in catch area *F* is computed for each return year (*Y*) as

$$P_{SFY} = \frac{P_{SFbase} * N_{SY}}{\sum_{S} P_{SFbase} * N_{SY}}$$

where,

C_{SFY} = catch of stock *S*, in fishery *F* (non-treaty net or sport), in return year *Y*,

C_{FY} = total catch in fishery *F* in return year *Y*,
P_{SFY} = is the catch probability of stock *S* in fishery *F* in return year *Y*,
P_{SFbase} = is the historic mean fraction of terminal CWT recoveries (i.e., of total CWT run entering, Grays Harbor) for stock *S* recovered in fishery *F* in base period years (1974 – 2010), and,
N_{SY} = the total terminal return of stock *S* in return year *Y,* and

$$C_{SFY} = P_{SFY} * C_{FY}.$$

Final non-treaty 2B-2D and 2.2 catch assignments must be determined through iteration, because P_{SFY} is a function of N_{SY}, which itself depends on C_{SFY}. This approach provides unbiased stock assignment if the distributions of Chehalis and Humptulips fish (within Grays Harbor) remain constant over time and if all stocks entering a particular area experience the same harvest rate.

Lastly, for both non-treaty and treaty fisheries, assignment of stock to production type (i.e., hatchery/wild) follows the method described above under '*Estimation of origin (hatchery or wild) and age in terminal fisheries*', and no discounts are made to estuarine catch to account for out-of-Grays-Harbor strays entering the system.

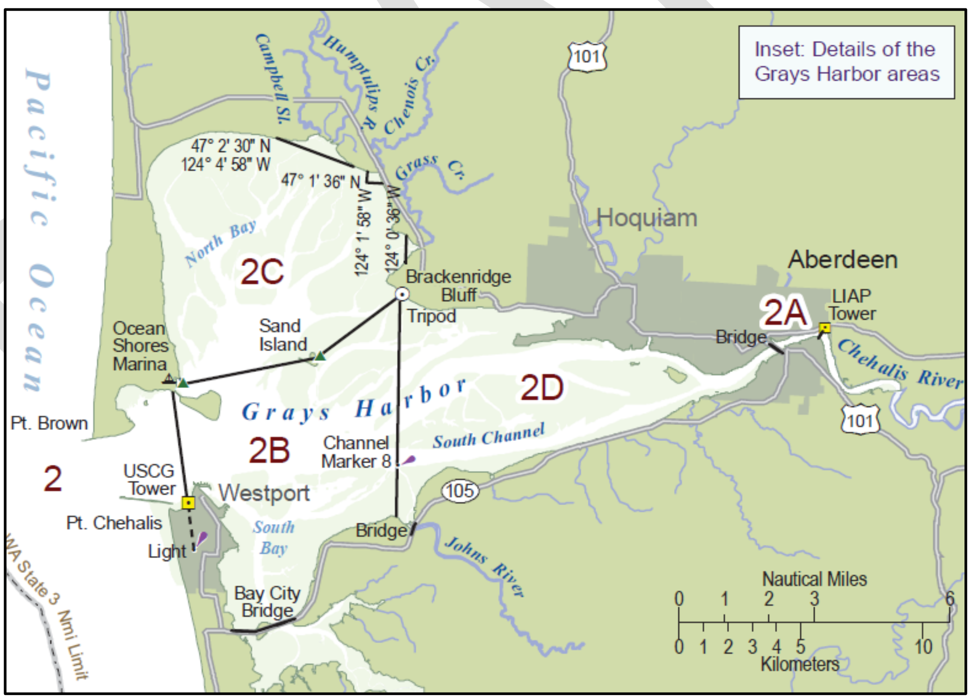

Figure 1. Grays Harbor Commercial Area Fishing Map.

Table 3a. Grays Harbor marine fisheries.

Grays Harbor	Subsets of 2.2	Fisheries		
Marine area 2.2	2A (subset of 2.2)	Marine sport	Quinault Indian Nation Treaty net	Non-Treaty net
	2B (subset of 2.2)	Marine sport		Non-Treaty net
	2C (subset of 2.2)	Marine sport	Quinault Indian Nation Treaty net	Non-Treaty net
	2D (subset of 2.2)	Marine sport	Quinault Indian Nation Treaty net	Non-Treaty net

Table 3b. Grays Harbor freshwater fisheries.

Grays Harbor Rivers	Tributaries	Fisheries		
Chehalis River	main stem	Freshwater sport	Chehalis Tribal Treaty net	Quinault Indian Nation Treaty net
	Van Winkle Creek	Freshwater sport		
	Wynoochee River	Freshwater sport		
	Satsop River	Freshwater sport		
	Cloquallum Creek	Freshwater sport		
	Black River	Freshwater sport		
	Skookumchuck River	Freshwater sport		
	Newaukum River	Freshwater sport		
Humptulips River	main stem	Freshwater sport		Quinault Indian Nation Treaty net
Elk River		Freshwater sport		
Johns River		Freshwater sport		
Hoquiam River		Freshwater sport		
Wishkah River		Freshwater sport		
Misc South Bay		Freshwater sport		

Queets River CWT Indicator Stock Data

Data for CTC exploitation rate analysis consist of CWT release, recovery, and catch sample data. The data are typically obtained from the Regional Mark Information System (RMIS) with supplementation (when necessary) from local management. Data are input into the Cohort Analysis System (CAS; Wostman and Associates) and stored in the CAS.mdb database. This analysis used Queets data in the CAS March 2012 database. The QIN commercial net, freshwater sport and escapement data in the CAS March 2012 database were removed and replaced with updated and corrected data from QDNR.

Commercial net fisheries in the Queets River are electronically sampled at ~25%. Freshwater sport is estimated using WDWF's catch record card (CRC) system. Queets spawning escapement is estimated using similar survey methods to those described above for the Grays Harbor system (i.e., redd counts). Returning CWT indicator stock adults do not return to the

Salmon River Fish Culture Center; thus, escapement recoveries occur on the spawning grounds. When spawning survey tag recoveries are available from all 3 tributaries (Queets River, Clearwater River, and Salmon River) the number of indicator CWTs in spawning escapement is estimated by tag expansion. When tag recoveries are insufficient for tag expansion, the total number of indicator stock CWTs in spawning escapement is derived using a ratio estimation approach based on a combination of data collected in terminal net fisheries and during spawning ground surveys, specifically the proportion indicator stock in commercial catch (indicator catch / total catch), age proportions (indicator $_{\text{age } i}$ / total indicator) of tags recovered in spawning surveys, and the total escapement to spawning beds in the Queets, Clearwater, and Salmon rivers:

Notation	Definition
$PRind^{net}$	Proportion CWT indicator in sampled commercial net fisheries
$PRind^{esc}{}_{a}$	Proportion CWT indicator age a, of total CWT indicator recovered in escapement surveys
ESC^{est}	Total estimated escapement to spawning beds in Salmon, Queets, and Clearwater rivers

Proportion indicator age *a*, in escapement =

$$PRind^{net} * PRind^{esc}{}_{a} * ESC^{est}$$

Queets River escapement estimates used in these calculations assume 2.5 fish / redd and all CWT calculations include fish of age 2 to 6.

After data are loaded into the CTC CAS database, the CAS maps the data to 85 fine-scale fisheries and generates one report (C-file) for each brood year. The C-files are inputs for the CTC's Coshak program. The Coshak program re-maps recoveries to 32 PSC fisheries (and escapement) and conducts a full cohort analysis, providing estimates of fishery-specific and total exploitation rates, maturation probabilities, release-to-age 2 survival rates, and adult equivalency (AEQ) factors (CTC 1988). The AEQ factors for each brood year and age are the proportion expected to return to spawn in the absence of a fishery (Table 4). The Coshak program calculates mortality estimates in terms of landed and incidental mortality due to undersized release in retention fisheries (shaker mortality), and incidental mortality in non-retention fisheries for legal- and sub-legal size encounters.

Table 4. Adult equivalent factors (AEQ; the proportion expected to return in the absence of fishery removal) is calculated by the COHSHK program.

Brood year	Age				
	2	3	4	5	6
1986	0.549	0.784	0.931	0.991	1.000
1987	0.546	0.779	0.911	0.987	1.000
1988	0.522	0.743	0.909	0.992	1.000
1989	0.514	0.733	0.909	0.982	1.000
1990	0.524	0.742	0.913	0.988	1.000
1991	0.515	0.732	0.910	0.985	1.000
1992	0.517	0.737	0.907	0.956	1.000
1993	0.531	0.758	0.922	0.982	1.000
1994	0.528	0.750	0.922	0.978	1.000
1995	0.524	0.746	0.914	0.996	1.000
1996	0.530	0.752	0.929	0.990	1.000
1997	0.534	0.762	0.923	0.984	1.000
1998	0.522	0.745	0.917	0.986	1.000
1999	0.516	0.737	0.904	0.968	1.000
2000	0.523	0.747	0.915	0.979	1.000
2001	0.549	0.784	0.953	0.995	1.000
2002	0.533	0.759	0.925	0.991	1.000
2003	0.523	0.746	0.921	0.990	1.000
2004	0.524	0.748	0.921	0.983	1.000
2005	0.530	0.757	0.927	0.993	1.000

Estimating Terminal Incidental Mortality and Pre-fishing Recruits from Queets CWT Data

Data for Grays Harbor fall Chinook are limited to estimates of landed catch in the terminal run and escapement. All pre-terminal mortality (landed + incidental) in Grays Harbor terminal fisheries was estimated using Queets River fall Chinook stock and methods devised by Morishima (personal communication [memo], 2011). Queets River was selected because of its proximity to Grays Harbor and because Queets River CWT indicator stock are used the CTC's annual exploitation rate analysis.

Incidental mortality

Estimates of Grays Harbor wild terminal catch (freshwater sport, terminal marine sport, and terminal net) were expanded to include incidental mortality using CTC estimates of incidental mortality for corresponding fisheries in the Queets River indicator stock CWT dataset.

Notation	**Definition**
GH_a	Grays Harbor stock age a
QTS_a	Queets stock age a
tn	Subscript for terminal net
tmfs	Subscript for terminal marine sport (inside Grays Harbor) + freshwater sport.
os	Subscript for ocean sport
landed	Superscript for landed mortality
total	Superscript for landed mortality + incidental mortality

Grays Harbor terminal net total mortality (landed catch + incidental mortality) for run year $_i$ =

$$\sum_{a=3}^{a=6} GH_{tn,a}^{landed} * \frac{Qts_{tn,a}^{total}}{Qts_{tn,a}^{landed}}$$

.

Grays Harbor terminal marine and freshwater sport total mortality (landed catch + incidental mortality) for run year $_i$ =

$$\sum_{a=3}^{a=6} GH_{tmfs,a}^{landed} * \frac{Qts_{tmfs,a}^{total}}{Qts_{tmfs,a}^{landed}}$$

.

Estimation of Pre-fishing AEQ Recruits

Estimating the total pre-fishing abundance (i.e., recruitment or production) additionally requires estimates of total (landed + incidental) ocean fishery mortality. These values were estimated using the gear-specific ratios (net and combined troll + sport) of preterminal mortality to terminal abundance estimated for the Queets River CWT indicator stock, adjusted for adult equivalency Pre-terminal fishery mortalities were converted to AEQ estimates because production is the expected spawning return in the absence of fishing (i.e., some portion of the catch would be reduced by natural mortality).

In this analysis preterminal-to-terminal ratios were applied to ages 2, 3, and 4 for all pre-terminal fisheries except ocean net. The ratios were applied to ocean net fisheries for ages 2, and 3 only. Grays Harbor pre-terminal fishery mortalities (ocean net, ocean troll, and ocean sport) were estimated for each brood year (1986 - 2005).

Total AEQ Grays Harbor (GH) ocean sport and ocean troll fishery mortality for brood year i and age a =

$$\sum_{a=3}^{a=6}(GH\ terminal\ catch_a + GH\ escapement_a) * \frac{Qts\ AEQ\ preterm\ troll\ \&\ sport\ total\ mortality_{\ a}}{Qts\ terminal\ mortality_a\ + Qts\ escapement_a}$$

,

and total AEQ Grays Harbor ocean net catch for brood year i and age a =

$$\sum_{a=3}^{a=6}(GH\ terminal\ catch_a + GH\ escapement_a) * \frac{Qts\ AEQ\ preterm\ net\ total\ mortality_{\ a}}{Qts\ terminal\ mortality_a\ + Qts\ escapement_a}$$

Given these estimates, Grays Harbor production for brood year *i* was computed as the sum of AEQ pre-terminal mortality (estimated above), terminal catch (with incidental mortality adjustment), and wild escapement (Table 5). Grays Harbor is composed of two separately managed stocks: Chehalis River and Humptulips River. Therefore the estimates of production described above were computed separately for each stock so that an independent spawner-recruit analysis could be conducted for each stock. All estimates of terminal incidental mortality and preterminal production were computed using programs and utilities developed by QDNR (R. Coshow) and executed using SAS (Copyright (c) 2002-2008 by SAS Institute Inc., Cary, NC, USA.).

Table 5. Brood year escapement and production for Grays fall Chinook Harbor. Preterminal production is adjusted for adult equivalent (AEQ) and incidental mortality. Terminal production includes incidental mortality. Brood escapement includes hatchery + natural spawners, production is natural only.

Sub-basin	Brood year	Brood year escapement	Pre-terminal production (AEQ)		Terminal production				
			Ocean troll & sport	Ocean net	Area 2.2 sport	Non-treaty net	Treaty net	Escape.	FW sport
Chehalis	1986	9,483	18,714	149	259	3,130	4,448	10,756	1,349
	1987	12,850	12,414	389	230	1,977	2,779	7,064	740
	1988	21,945	16,200	348	268	3,575	4,710	11,863	1,628
	1989	20,066	22,414	848	323	3,784	5,253	11,636	1,722
	1990	12,893	11,987	17	469	3,769	5,147	12,056	2,415
	1991	12,571	5,798	79	326	708	1,195	5,718	1,166
	1992	11,974	25,449	0	1,577	2,576	5,732	21,602	2,835
	1993	10,472	13,747	87	1,435	609	3,115	12,343	994
	1994	9,919	2,524	0	241	79	743	4,074	106
	1995	9,786	3,579	0	271	365	1,246	5,206	270
	1996	16,161	13,104	0	1,079	1,811	3,782	10,706	1,388
	1997	14,402	6,960	0	1,369	1,168	2,140	9,064	1,463
	1998	10,101	10,564	0	993	386	873	13,249	856
	1999	8,409	22,768	0	2,539	257	2,292	27,467	797
	2000	7,892	10,191	330	967	106	1,411	13,383	282
	2001	7,902	8,396	1	715	122	1,372	11,539	130
	2002	9,694	19,964	109	767	227	1,231	12,291	213
	2003	16,111	15,010	0	298	380	857	11,655	133
	2004	26,320	5,337	100	12	187	499	5,138	6
	2005	13,367	10,008	85	0	425	1,717	11,787	0
Humptulips	1986	4,325	10,879	63	29	2,453	3,302	2,591	1,150
	1987	6,163	4,616	177	21	1,290	1,332	1,921	577
	1988	6,213	7,717	133	30	2,287	1,882	3,901	1,423
	1989	5,611	9,019	339	28	1,429	2,190	4,069	1,692
	1990	4,102	4,597	11	40	1,052	2,461	3,494	2,206
	1991	1,821	2,694	38	33	442	1,114	1,722	1,062
	1992	4,618	6,178	0	93	914	2,360	4,703	1,998
	1993	2,877	4,757	40	95	403	1,683	3,471	975
	1994	4,401	1,240	0	20	51	683	1,644	112
	1995	2,941	573	0	11	17	273	877	40
	1996	4,066	1,749	0	38	64	412	2,007	127
	1997	3,766	1,155	0	43	24	277	1,573	49
	1998	2,428	2,010	0	32	18	261	2,393	334
	1999	1,954	4,714	0	98	38	615	5,316	1,193
	2000	1,493	5,132	120	80	69	736	5,300	692
	2001	1,590	3,110	0	53	62	920	3,920	259
	2002	2,147	7,380	33	54	171	1,348	3,179	431
	2003	3,760	4,196	0	17	261	963	2,340	206
	2004	5,453	2,769	67	3	282	575	1,478	220
	2005	6,328	6,296	44	0	882	1,560	5,115	1,229

Spawner–recruit modelling

Our spawner-recruit analysis largely follows the approach recommended by the CTC in the 1999 document 'Maximum Sustained Yield or Biologically Based Escapement Goals for Selected Chinook Salmon Stocks Used by the Pacific Salmon Commission's Chinook Technical Committee for Escapement Assessment' (CTC 1999) and reinforced in their recently published 'Bilateral Data Standards for Escapement Goals' (CTC 2013). The first step in the analysis was to determine the shape of the spawner-recruit function. The Shepherd model, written as,

$$\boldsymbol{R} = \frac{\boldsymbol{\alpha S}}{\boldsymbol{1+\beta S^{\gamma}}}, \qquad \text{Eq. 1}$$

can take the shape approximating a Ricker function when the parameter $\gamma > 1$, a Beverton-Holt function when $\gamma = 1$, or a strictly increasing function when $\gamma < 1$ (Figure 1). Thus, by first fitting the data to a Shepherd model, one can verify the underlying shape of spawner-recruit function empirically using a likelihood ratio test. Should test results reject that $\gamma \leq 1$, i.e., that the curve is more in the shape of a Ricker function, then that spawner-recruit model will be used, thereby reducing the number of estimated parameters.

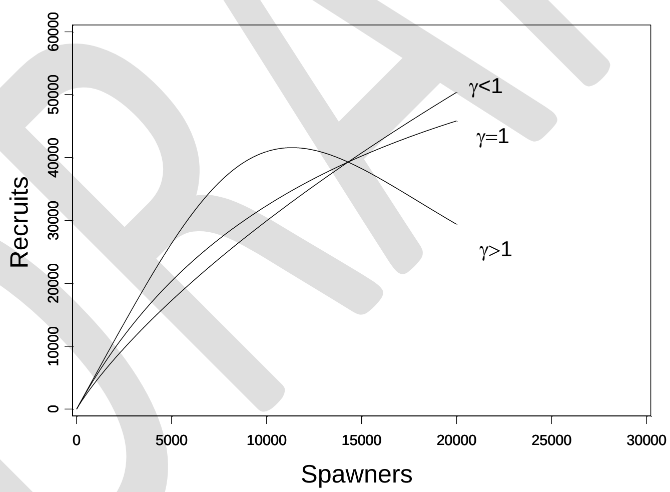

Figure 2. The functions of the Shepherd model for different values of the parameter.

In the case where the Shepherd model could not be fit to the data (non-convergence of the optimizer), we fit the spawner-recruit data were the Beverton-Holt and Ricker spawner-recruit models, which are, respectively

$$R = \frac{\propto S}{1+\beta S},$$

and

$$\boldsymbol{R} = \propto \boldsymbol{S}\boldsymbol{e}^{-\boldsymbol{\beta}\boldsymbol{S}}. \qquad \text{Eq. 2}$$

We used the non-linear least squares (nls) function in S-plus to fit the model Beverton-Holt model with additive errors,

$$\boldsymbol{R_i} = \frac{\propto \boldsymbol{S_i}}{\boldsymbol{1}+\boldsymbol{\beta}\boldsymbol{S_i}} + \boldsymbol{\varepsilon_i} \qquad \text{Eq. 3}$$

where ε_i, the error terms, are independent with mean 0 and constant variance, σ^2. A linear form of Eq. 3 that is can be fit to the data using least squares is,

$$\frac{\boldsymbol{S_i}}{\boldsymbol{R_i}} = \frac{\boldsymbol{1}}{\boldsymbol{\alpha}} + \frac{\boldsymbol{\beta}}{\boldsymbol{\alpha}}\boldsymbol{S_i} + \boldsymbol{\varepsilon_i}.$$

More often, spawner-recruit data has a multiplicative error structure, where the Beverton-Holt model is

$$\boldsymbol{R_i} = \frac{\boldsymbol{\alpha}\boldsymbol{S_i}}{\boldsymbol{1}+\boldsymbol{\beta}\boldsymbol{S_i}} * \boldsymbol{\varepsilon_i} \qquad \text{Eq. 4}$$

In this case, we fit the model using nonlinear least-squares (nls) as,

$$\boldsymbol{ln}\left(\frac{\boldsymbol{S_i}}{\boldsymbol{R_i}}\right) = \boldsymbol{ln}\left(\frac{\boldsymbol{1}}{\boldsymbol{\alpha}}\right) + \frac{\boldsymbol{\beta}}{\boldsymbol{\alpha}}\boldsymbol{S_i} + \boldsymbol{ln}(\boldsymbol{\varepsilon_i})$$

where $ln(\varepsilon_i)$ are independent with mean 0 and constant variance, σ^2. We verified the appropriate choice of error structure through residual analysis. Linearizing the Ricker function to

$$\boldsymbol{ln}\left(\frac{\boldsymbol{R_i}}{\boldsymbol{S_i}}\right) = \mathbf{ln}(\boldsymbol{\alpha}) - \boldsymbol{\beta}\boldsymbol{S_i} + \boldsymbol{ln}(\boldsymbol{\varepsilon_i}) \qquad \text{Eq. 5}$$

assumes a multiplicative error structure and is easily fit to the data using least squares methods.

Although the Shepherd model gives support to the underlying shape of the spawner-recruit function, we also assessed model fit by testing significance of estimates parameters. For both the Ricker and Beverton-Holt function, we tested the hypotheses H_o: $\alpha = 1$ and H_o: $\beta = 0$ against the one-tailed alternatives, H_a: $\alpha > 1$ and H_a: $\beta > 0$ at the α= 0.10 significance level using a t-distribution. When alpha and beta equal 1 and 0, respectively, the models reduce to R = S.

Further model refinement was done by checking the underlying assumptions of least squares regression, most notably the assumption of uncorrelated errors, by analyzing residual errors. The presence of serial correlation among the error terms was analyzed using autocorrelation function and partial autocorrelation plots and through a time series plot of residuals by brood year. Variances of model parameters will be underestimated if correlation between errors are not taken into account. In the presence of serial correlation between errors, we refit the model by differencing the predictor and dependent variables (Cochrane-Orcutt procedure; Neter et al. 1996, pg 509), spawners and recruits, respectively, as follows,

$$S_i' = S_i - rS_{i-t} \text{ ;}$$

$$R_i' = R_i - rR_{i-t}\text{; and}$$

$$S_i' = \ln(\alpha)' + \beta' R_i'$$

where r = the correlation between error terms;

t = the lag of the significant correlation;

$\ln(\alpha)'$= the adjusted intercept;

β' = the adjusted slope.

Adjusted model parameters and standard errors are,

$$\ln(\alpha) = \frac{\ln(\alpha)'}{1-r},;$$

$$SE(\ln(\alpha)) = \frac{SE(\ln(\alpha)')}{1-r} \text{ and;}$$

$$\beta = \beta'.$$

Calculations of escapement goals (S_{msy}) for the Beverton-Holt model were calculated as,

$$\hat{\boldsymbol{S}}_{\boldsymbol{msy}} = \frac{(\sqrt{\hat{\boldsymbol{\alpha}}}-\mathbf{1})}{\hat{\boldsymbol{\beta}}} \qquad \text{Eq. 6}$$

with variance approximated by the delta method,

$$\widehat{\boldsymbol{Var}}(\hat{\boldsymbol{S}}_{\boldsymbol{msy}}) = \widehat{\boldsymbol{Var}}(\hat{\boldsymbol{\alpha}})\left(\frac{-\mathbf{1}}{\mathbf{2}\sqrt{\hat{\boldsymbol{\alpha}}}\hat{\boldsymbol{\beta}}}\right)^{\mathbf{2}} + \widehat{\boldsymbol{Var}}(\hat{\boldsymbol{\beta}})\left(\frac{(\sqrt{\hat{\boldsymbol{\alpha}}}-\mathbf{1})}{\hat{\boldsymbol{\beta}}^{\mathbf{2}}}\right)^{\mathbf{2}} + \mathbf{2}\widehat{\boldsymbol{Cov}}(\hat{\boldsymbol{\alpha}},\hat{\boldsymbol{\beta}})\left(\frac{-\mathbf{1}}{\mathbf{2}\sqrt{\hat{\boldsymbol{\alpha}}}\hat{\boldsymbol{\beta}}}\cdot\frac{(\sqrt{\hat{\boldsymbol{\alpha}}}-\mathbf{1})}{\hat{\boldsymbol{\beta}}^{\mathbf{2}}}\right). \qquad \text{Eq. 7}$$

For the Ricker function, S_{msy} is calculated by the approximation of Hilborn and Walters (1992),

$$\hat{\boldsymbol{S}}_{\boldsymbol{smy}} = \left(\frac{\boldsymbol{ln}(\hat{\boldsymbol{a}})+\frac{\hat{\boldsymbol{\sigma}}^{\mathbf{2}}}{\mathbf{2}}}{\hat{\boldsymbol{\beta}}}\right)\left[\mathbf{0.5} - \mathbf{0.07}\left(\boldsymbol{ln}(\hat{\boldsymbol{a}}) + \frac{\hat{\boldsymbol{\sigma}}^{\mathbf{2}}}{\mathbf{2}}\right)\right], \qquad \text{Eq. 8}$$

The variance for Eq. 8 is approximated by the delta method as,

$$\widehat{\boldsymbol{Var}}(\hat{\boldsymbol{S}}_{\boldsymbol{smy}}) = \widehat{\boldsymbol{Var}}(\boldsymbol{ln}(\hat{\boldsymbol{a}}))\left[\frac{\mathbf{1}}{\hat{\boldsymbol{\beta}}}\left(\mathbf{0.5} - \mathbf{2} * (\mathbf{0.07}\left(\boldsymbol{ln}(\hat{\boldsymbol{a}}) + \frac{\hat{\boldsymbol{\sigma}}^{\mathbf{2}}}{\mathbf{2}}\right)\right)\right]^{\mathbf{2}} + \widehat{\boldsymbol{Var}}(\hat{\boldsymbol{\beta}})\left[\frac{-\boldsymbol{ln}(\hat{\boldsymbol{a}})+\frac{\hat{\boldsymbol{\sigma}}^{\mathbf{2}}}{\mathbf{2}}}{\hat{\boldsymbol{\beta}}^{\mathbf{2}}}\left[\mathbf{0.5} - \mathbf{0.07}\left(\boldsymbol{ln}(\hat{\boldsymbol{a}}) + \frac{\hat{\boldsymbol{\sigma}}^{\mathbf{2}}}{\mathbf{2}}\right)\right]\right]^{\mathbf{2}} + \mathbf{2}\widehat{\boldsymbol{Cov}}(\boldsymbol{ln}(\hat{\boldsymbol{a}}),\hat{\boldsymbol{\beta}})\left[\frac{\mathbf{1}}{\hat{\boldsymbol{\beta}}}\left(\mathbf{0.5} - \mathbf{2} * (\mathbf{0.07}\left(\boldsymbol{ln}(\hat{\boldsymbol{a}}) + \frac{\hat{\boldsymbol{\sigma}}^{\mathbf{2}}}{\mathbf{2}}\right)\right)\right]\cdot\left[\frac{-\boldsymbol{ln}(\hat{\boldsymbol{a}})+\frac{\hat{\boldsymbol{\sigma}}^{\mathbf{2}}}{\mathbf{2}}}{\hat{\boldsymbol{\beta}}^{\mathbf{2}}}\left[\mathbf{0.5} - \mathbf{0.07}\left(\boldsymbol{ln}(\hat{\boldsymbol{a}}) + \frac{\hat{\boldsymbol{\sigma}}^{\mathbf{2}}}{\mathbf{2}}\right)\right]\right] + \widehat{\boldsymbol{Var}}(\hat{\boldsymbol{\sigma}}^{\mathbf{2}})\left[\frac{\mathbf{1}}{\hat{\boldsymbol{\beta}}}\left(\frac{\mathbf{0.5}}{\mathbf{2}} - (\mathbf{0.07}\left(\boldsymbol{ln}(\hat{\boldsymbol{a}}) + \frac{\hat{\boldsymbol{\sigma}}^{\mathbf{2}}}{\mathbf{2}}\right)\right)\right]^{\mathbf{2}}. \qquad \text{Eq. 9}$$

Lastly, although not presented here, we evaluated the potential explanatory value of including marine survival covariates in spawner–recruit models during preliminary analysis stages. Specifically, we assessed correlations between residuals from Ricker models and estimates of early marine survival (release to age 2) for the Queets CWT indicator stock and found no association (Pearson correlation coefficient < 0.40). This finding combined with considerations of model parsimony led us to abandon further exploration of survival or environmental covariates.

Results

Grays Harbor Fall Chinook system-total Goal

Given that the PSC's Chinook Technical Committee recognizes only a single Grays Harbor fall Chinook escapement indicator stock, the separate estimates of S_{msy} for the Chehalis and Humptulips were combined to estimate an escapement goal for the Grays Harbor system as a whole. The system-total escapement goal, 13,326 adult spawners, is the sum of Ricker-based S_{msy} estimates for the Chehalis River (9,753; Hilborn and Walters [1992] approximation from Ricker model [Eq. 8] with a multiplicative error structure) and the Humptulips River (3,573 adults; Hilborn and Walters [1992] approximation from Ricker model [Eq. 8] with autocorrelated, multiplicative errors).

Chehalis Fall Chinook

We used the program R to fit the Shepherd model (Eq. 1) to the Chehalis fall Chinook spawner-recruit data. Results of the likelihood ratio test that $\gamma \leq 1$ were non-committal at a significance level of 0.10 (Table 6). Hence, both the Beverton-Holt and Ricker models were fit using these data.

Table 6. Stock, parameter estimates for the Shepard model.

Parameter	Value	Standard Error
$\hat{\alpha}$	2.431	0.315
$\hat{\beta}$	3.065×10^{-66}	3.72×10^{-64}
$\hat{\gamma}$	14.977	11.93
Likelihood Ratio Test	2.69	
$P(\gamma \leq 1)$	0.10	

Residual analysis of the Beverton-Holt function with additive errors (Eq. 3) showed this error structure to poorly represent these data, with a clear decreasing trend in residual plot where there should be none (Figure 3). A Beverton-Holt model fit with a multiplicative error structure (Eq. 4) eliminated this trend and better satisfied the error assumptions (i.e., mean 0, constant variance; Figure 4). Further, there was no evidence of serial correlation among the errors as verified by the ACF and PACF plots (Figure 5), and no clear temporal pattern in residuals (Figure 6). Estimates and associated variances for model parameters and the S_{msy}, and the mean squared error for the model are presented in Table 7.

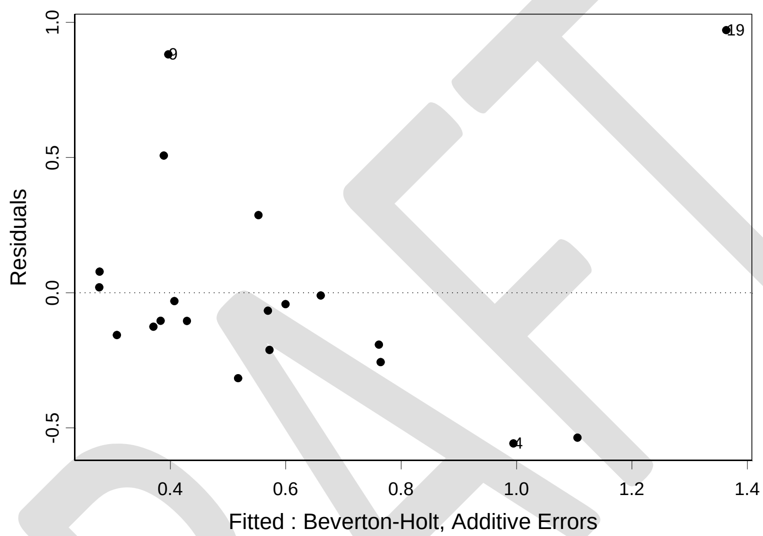

Figure 3. Residual plot from the fit of Beverton-Holt model with additive errors (Eq. 3) to the Chehalis fall Chinook data.

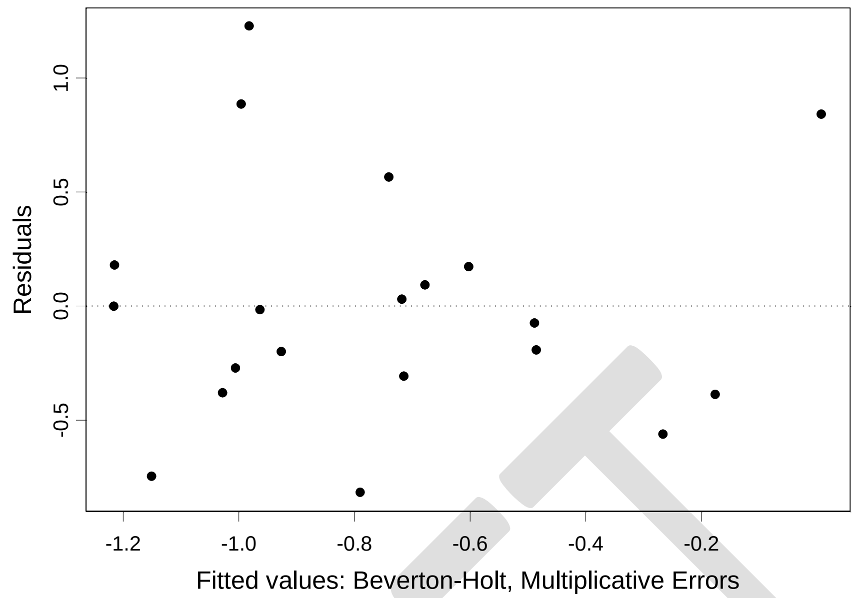

Figure 4. A plot of the residuals versus fitted values for the Beverton-Holt model with multiplicative errors (Eq. 4) for Chehalis Fall Chinook.

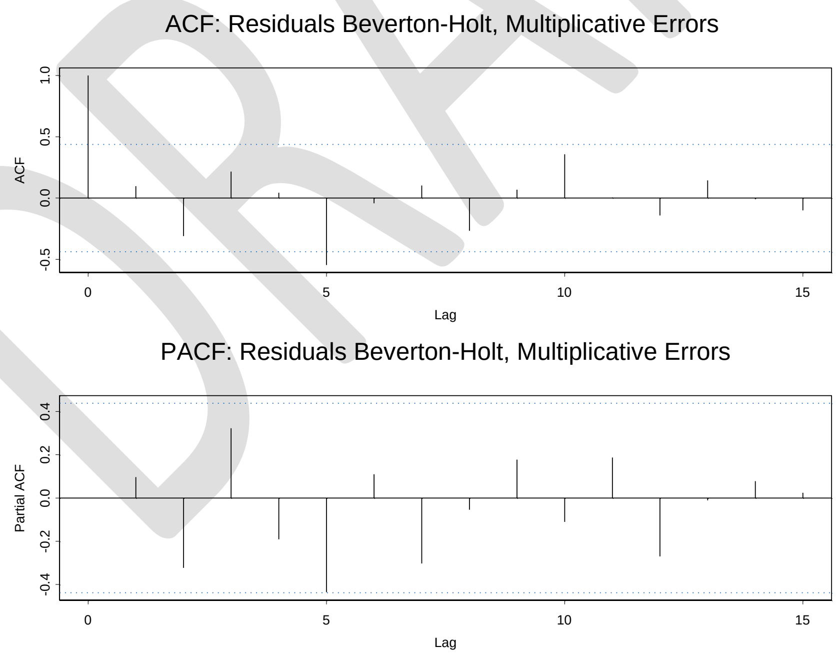

Figure 5. Autocorrelation and partial autocorrelation plots for the residuals from the Beverton-Holt model fit with multiplicative errors (Eq. 4) for the Chehalis fall Chinook data.

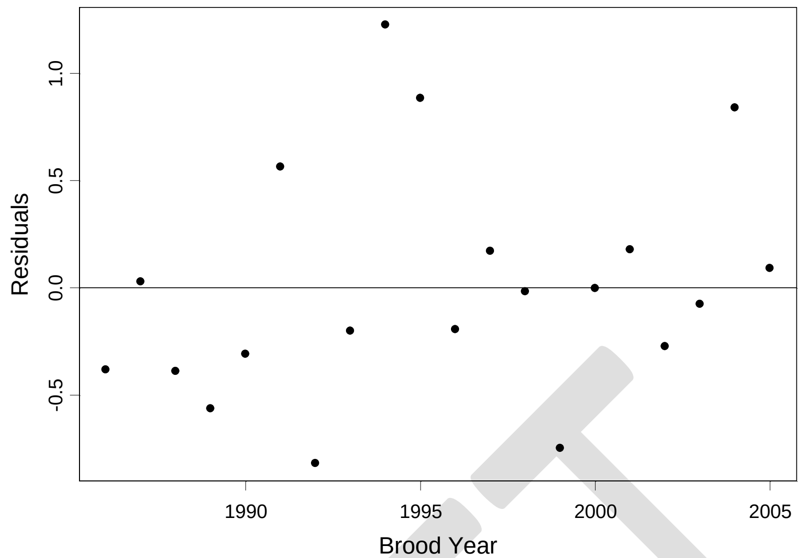

Figure 6. A time series plot of the residuals from the Beverton-Holt model fit with multiplicative errors for the Chehalis fall Chinook data.

Table 7. Estimates of the parameters for the Beverton-Holt spawner-recruit function for Chehalis Fall Chinook, assuming multiplicative errors (Eq. 4).

Parameter	Estimate	Standard Error	*t*-test results
α	315.55	18347.2	$P(\alpha \leq 1) = 0.493$
β	0.0012	0.680	$P(\beta \leq 0) = 0.493$
S_{msy}	1,443	122660.4	

The Ricker model with multiplicative errors was also fit to the Chehalis Chinook spawner-recruit data set (Eq. 5). A plot of residuals versus fitted values showed that multiplicative error was appropriate for these data (Figure 7). As with the Beverton-Holt model, there was no serial correlation among the error terms (Figures 8 and 9). These plots support the assumption that errors are independent with mean 0 and constant variance. Estimates of model parameters for the Ricker function in Eq. 2, their associated standard errors, and S_{msy} for the Chehalis fall Chinook data are in Table 8. The S_{msy} value for the Ricker model, estimated according to the Hilborn and Walters (1992) approximation (Eq. 8), is 9,357.

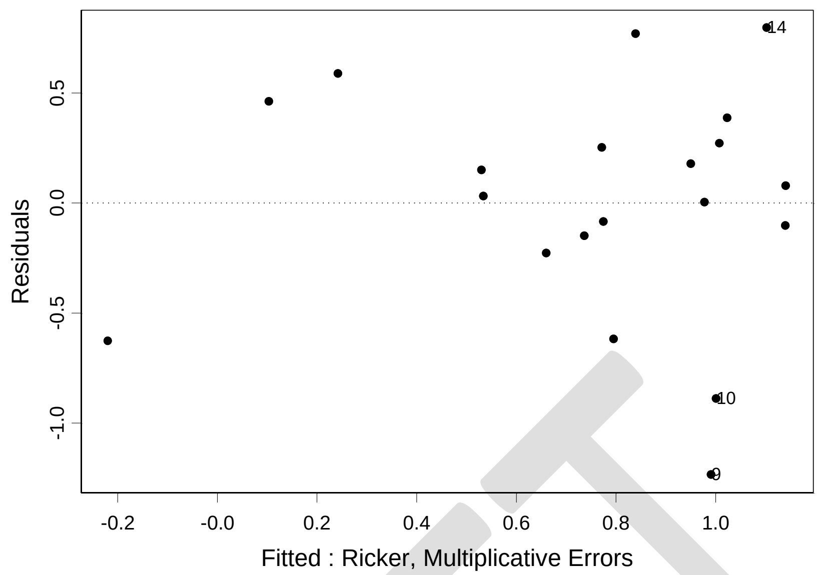

Figure 7. A plot of the residuals versus fitted values for the Ricker model with multiplicative errors (Eq. 5).

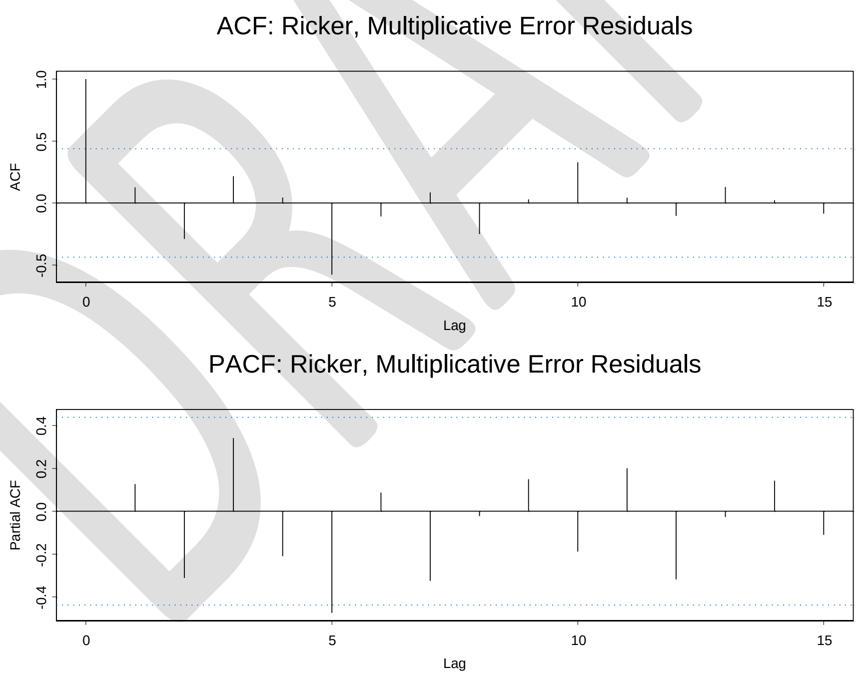

Figure 8. ACF and PACF for residuals from the fit of the Ricker model with multiplicative errors (Eq. 5) for the Chehalis fall Chinook data.

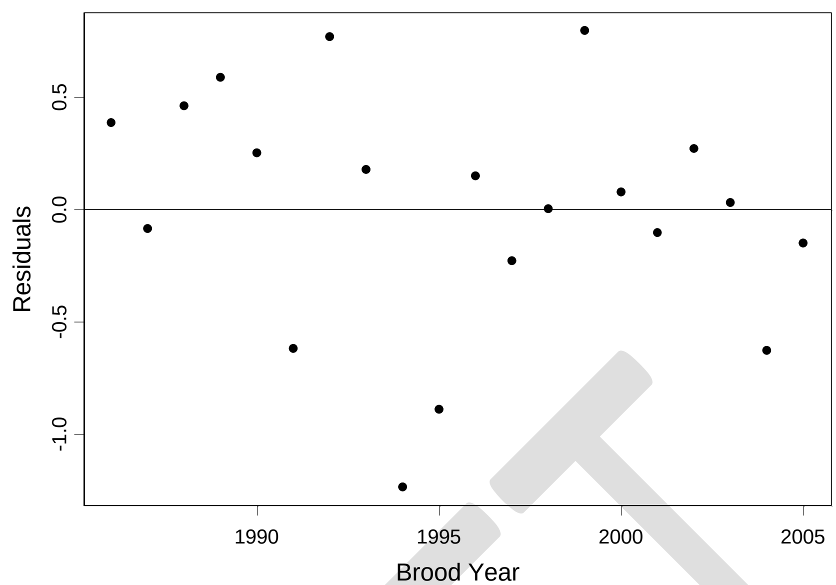

Figure 9. Time series plot of residuals from the fit of the Ricker model with multiplicative errors (Eq. 5) for the Chehalis fall Chinook data.

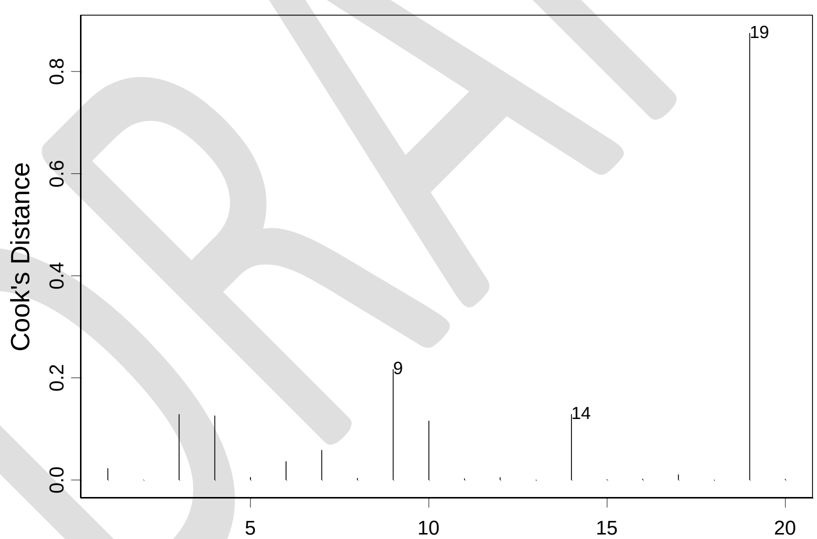

Figure 10. Plot of Cook's distances for the from the fit of the Ricker model with multiplicative errors (Eq. 5) for the Chehalis fall Chinook data showing that the 2004 had the highest influence on the model fit.

Table 8. Estimates and standard errors for parameters of the Ricker model (Eq. 2), and S_{msy}

Parameter	Estimate	Standard Error	*t*-test results
α	5.61	2.03	$P(\alpha \le 1) = 0.016$
β	0.000074	0.000025	$P(\beta \le 0) < 0.01$
S_{msy}	9,357	4329	

Of models considered, the information in the Chehalis spawner-recruit data supports the Ricker model (Figure 11). Evidence supporting the Beverton-Holt model is weak, or non-existent in these data. Parameter estimates do not differ significantly from zero (Table 7) and furthermore the S_{msy} value calculated from these estimates yields an escapement goal that falls well below the range of escapements seen in the observed data, i.e., S_{msy} = 1,443 vs. a series minimum of 7,892. In other words, S_{msy} computed from Beverton-Holt model parameters is based on an extrapolation of the curve beyond the range of the data. The Ricker model provided a better fit to the observed data and a Ricker-based S_{msy} is well within the range of historic escapements. Hence, S_{msy} for this stock should be based on the Ricker model.

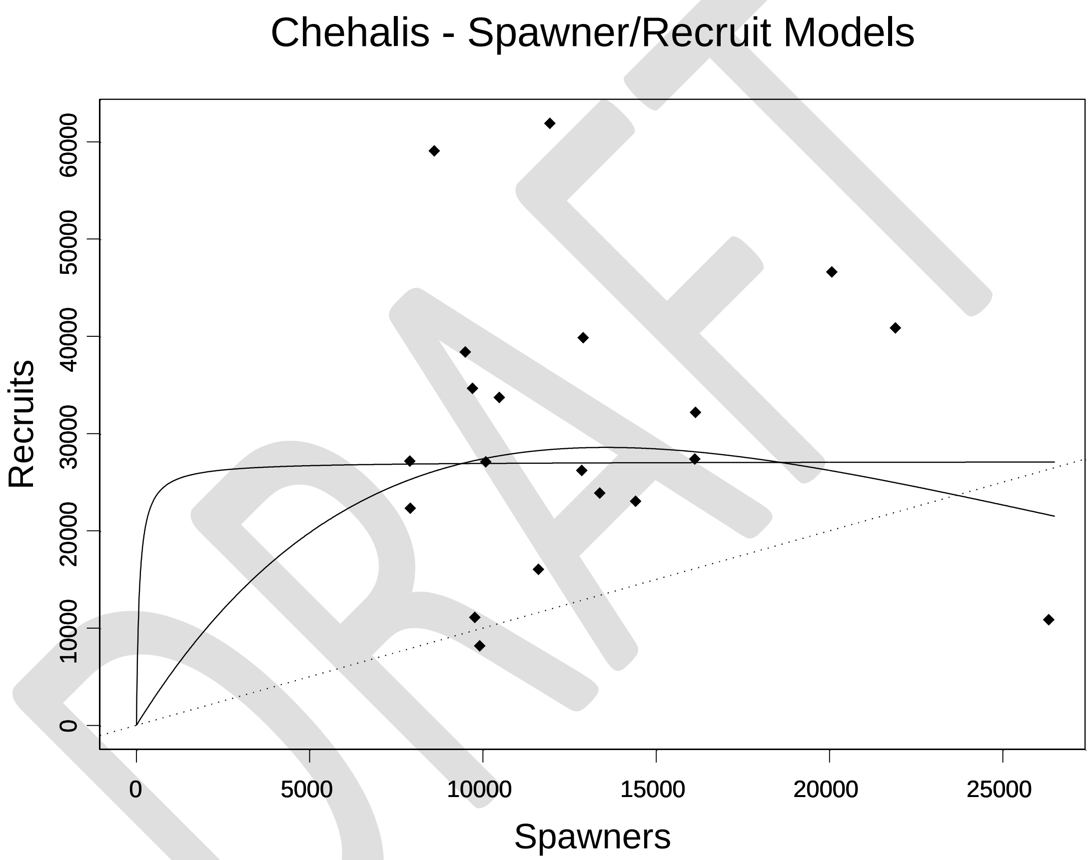

Figure 11. Beverton-Holt and Ricker spawner-recruit models fit to the Chehalis fall Chinook data. The dotted line in the line of equality between spawners and recruits.

We conducted additional analyses to assess the influence of a statistical outlier (2004 brood year; Figure 10) on Ricker α, β, and associated S_{msy} estimates. First, we fit the Ricker function of Eq. 5 using the bootstrap procedure of Efron and Tibshirani (1983). By resampling the data 1,000 times, with replacement, this procedure creates replicate data sets with varying degrees of outlier influence and allows for an assessment of bias in estimated S_{msy} relative to the unknown population parameter. Bootstrapped estimates of α and β differed slightly but not significantly (Table 9) from the point estimates summarized in Table 8, and produced a curve with higher fitted values than the original model did at high spawner levels (Figure 12). To further assess outlier influence, we computed point and bootstrapped estimates of α, β, and S_{msy} (Ricker) using a dataset that excluded the 2004 data point altogether (Table 9). In this case, point estimates from the fitted model were identical to their bootstrapped analogs, but Ricker parameters differed considerably from those based on the complete dataset. Excluding the 2004 point caused a decrease in estimates of Ricker productivity and capacity parameters and an increase in S_{msy} (9,357 to 14,007; Table 9). Despite this clear influence, available information suggests that the low level of recruitment associated with the 2004 brood is a biological reality and not an artifact of sampling. Thus, the bootstrapped S_{msy} value of 9,753 is recommended for adoption as the escapement goal for the Chehalis segment of the Grays Harbor fall Chinook indicator stock.

Table 9. Estimates and standard errors for parameters of the Ricker model (Eq. 2), and S_{msy} (Eq. 8), from an evaluation of the influence of the 2004 brood year (BY) data point.

Analysis	Parameter	Estimate	Standard Error	*t*-test results
Ricker (all BYs)	α	5.606	1.986	$P(\alpha \le 1) = 0.016$
	β	0.000074	0.000025	$P(\beta \le 0) < 0.010$
	S_{msy}	9,357	4296	
Bootstrap Ricker (all BYs)	α	5.29	2.10	$P(\alpha \le 1) < 0.028$
	β	0.000068	0.000029	$P(\beta \le 0) < 0.012$
	S_{msy}	9,753	2983	
Ricker (excl. 2004 BY)*	α	3.92	1.389	$P(\alpha \le 1) < 0.025$
	β	0.000042	0.000031	$P(\beta \le 0) < 0.096$
	S_{msy}	14,007	13,040	

* Bootstrapped estimates are equivalent and have SE = 0.0.

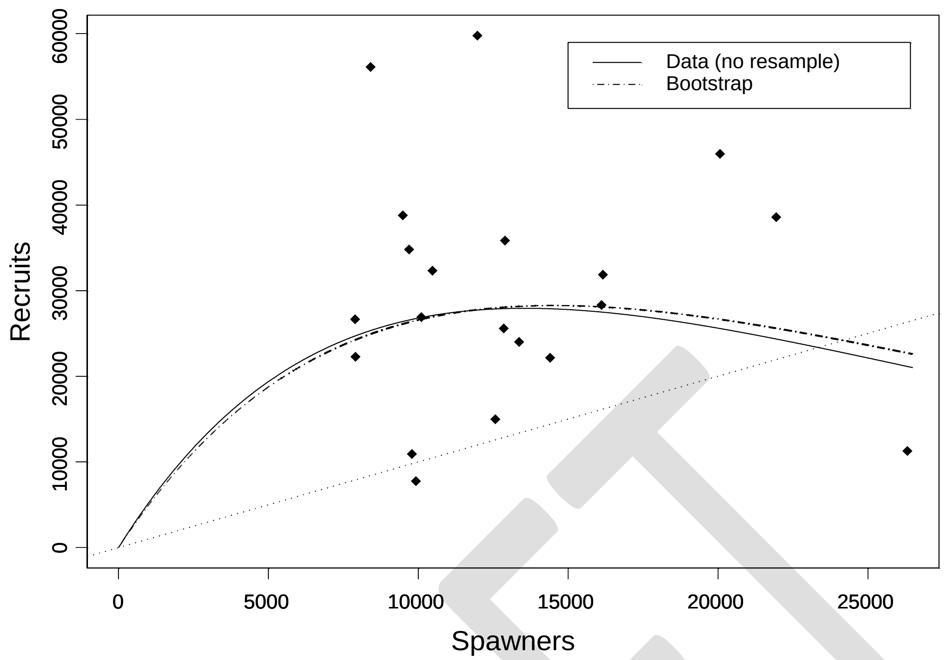

Figure 12. A comparison of the fit of the Ricker spawner-recruit model using the bootstrap procedure to the original fitted curve.

Humptulips Fall Chinook

Unlike the Chehalis analysis, we could not fit the Shepherd model to the Humptulips Chinook spawner-recruit data due to non-convergence of the nls function in both R and S-plus. This likely owes to the lack of definitive pattern in the spawner-recruit data when a three-parameter model is considered (Figure 13). Hence, we fit the two-parameter Beverton-Holt and Ricker models only to the Humptulips data set.

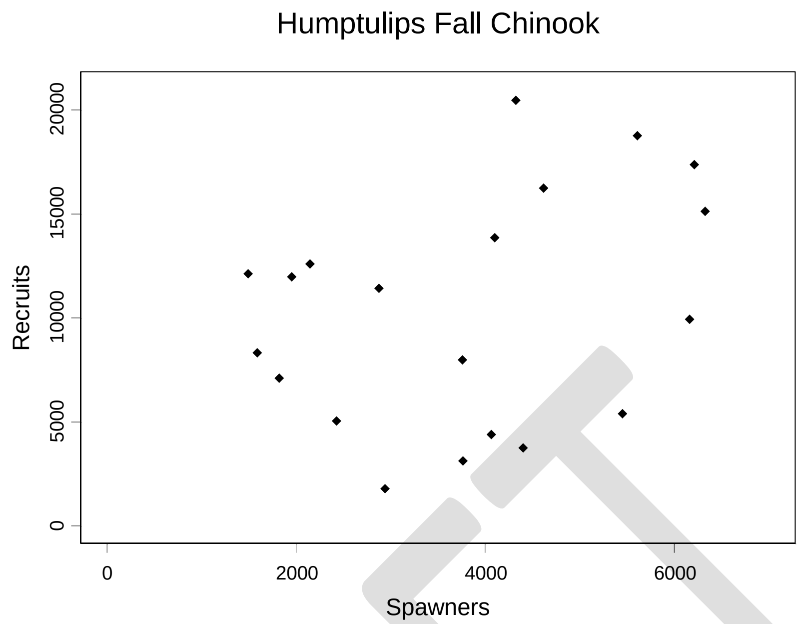

Figure 13. Scatter plot of the Humptulips fall Chinook spawner-recruit data.

We fit the Beverton-Holt model to the Humptulips spawner-recruit data first assuming additive (Eq. 3) then multiplicative (Eq. 4) errors. Although the residual plot for the model with additive error did not show any strong patterns (Figure 14), residuals for the model with multiplicative errors better approximate error assumptions (Figure 15). The assumption of uncorrelated errors, however, does not hold for this model, as both the ACF and PACF residual plots show a significant lag-1 correlation (Figure 16). Further, residuals show a discernable temporal trend, with estimated recruits being consistently underestimated in early and late years and overestimated in the middle of the series (Figure 17). Parameter estimates and unadjusted standard errors for this model are given in Table 10, as is the S_{msy}. To allow for comparisons to other models, the residual standard error in Table 10 is based on the difference between observed and predicted recruits on the original scale.

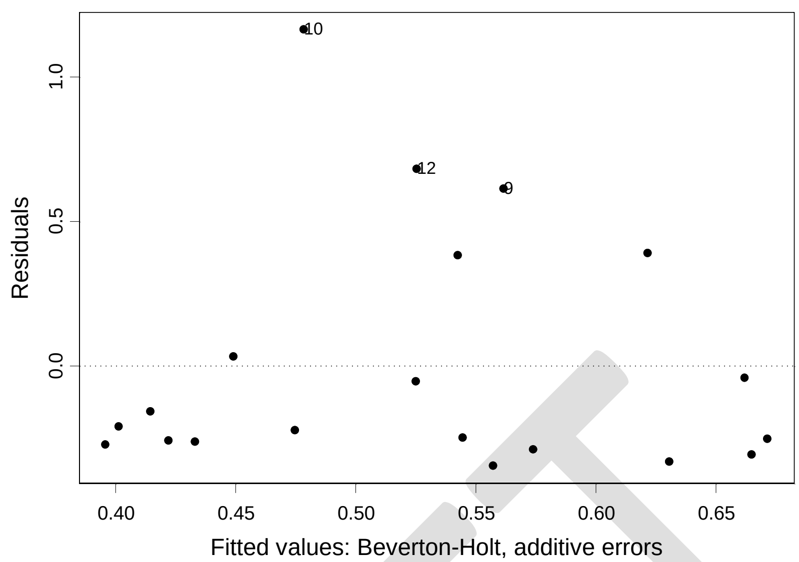

Figure 14. Residual plot from the fit of Beverton-Holt model with additive errors (Eq. 3) to the Humptulips fall Chinook data.

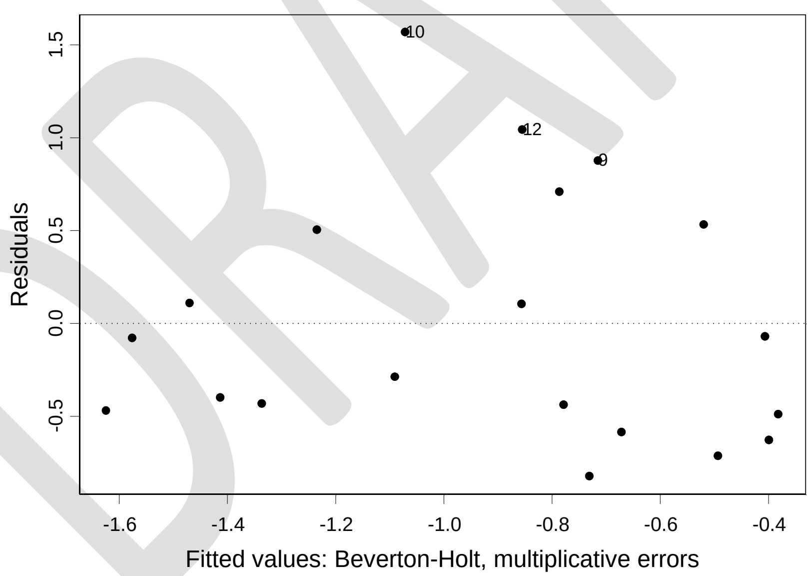

Figure 15. A plot of the residuals versus fitted values for the Beverton-Holt model with multiplicative errors (Eq. 4) for Humptulips Fall Chinook.

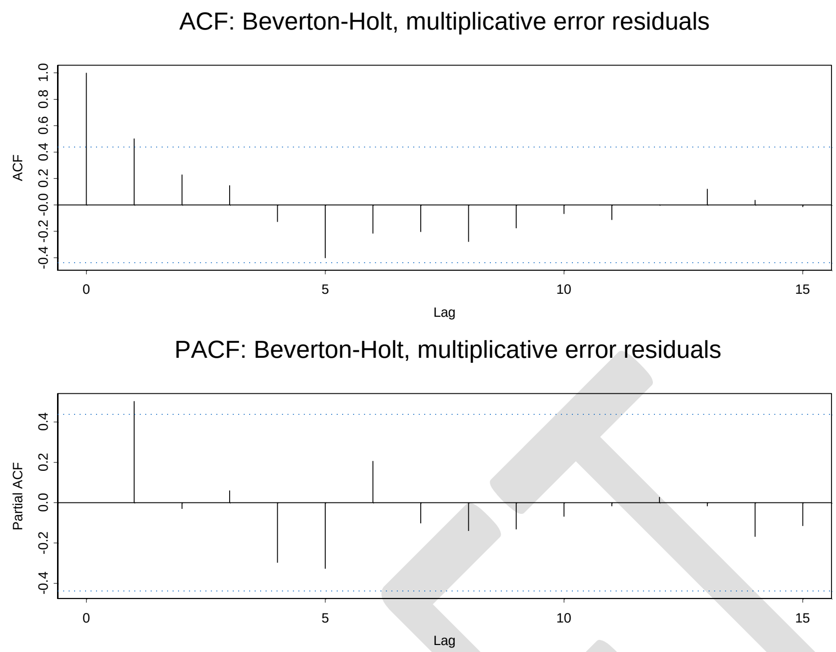

Figure 16. Autocorrelation and partial autocorrelation plots for the residuals from the Beverton-Holt model fit with multiplicative errors for the Humptulips fall Chinook data.

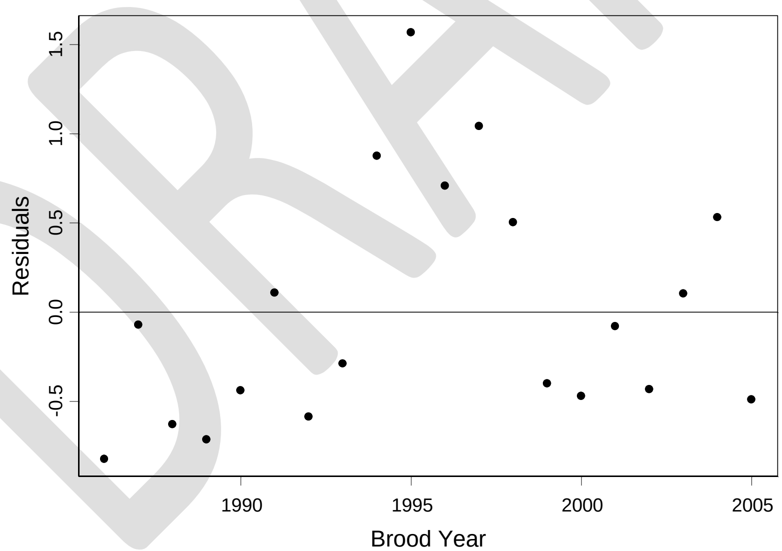

Figure 17. Time series plot of residuals from the fit of the Beverton-Holt model with multiplicative errors (Eq. 4) for the Humptulips fall Chinook data.

Table 10. Estimates of the Beverton-Holt for the spawner-recruit data for Humptulips Fall Chinook, assuming multiplicative (Eq. 5) errors.

Parameter	Estimate	Standard Error	*t*-test results
α	18.70	53.08	$P(\alpha \leq 1) = 0.63$
β	0.0018	0.0003	$P(\beta \leq 0) < 0.01$
S_{msy}	1,816	5417.4	

Similar to the Chehalis analysis, we fit the Ricker model with multiplicative errors (Eq. 5) to the Humptulips spawner-recruit data, as the Beverton-Holt analysis suggested this to be the most appropriate form and Ricker model residuals confirm (Figure 18). Ricker residuals also show a significant correlation among error variances at lag = 1 (Figure 19), indicating that an ARMA(1,1) error structure is needed to account for temporal dependence in the data. Residuals from the Ricker model also have a temporal trend, with periods of consistent over- or under estimation of recruits (Figure 20). In contrast to the Chehalis, there are no statistical outliers contained within the Humptulips data set (Figure 21). Estimates of model parameters, associated unadjusted standard errors, and S_{msy} for Ricker model are in Table 11. Note that the residual standard error in Table 11 is based on the difference between observed and predicted recruits on the original scale so that it could be compared to other models.

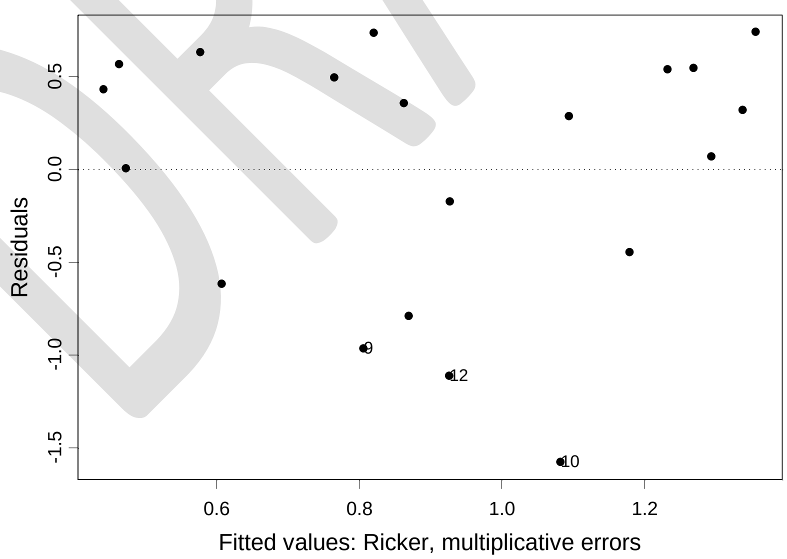

Figure 18. A plot of the residuals versus fitted values for the Ricker model with multiplicative errors for the Humptulips populations.

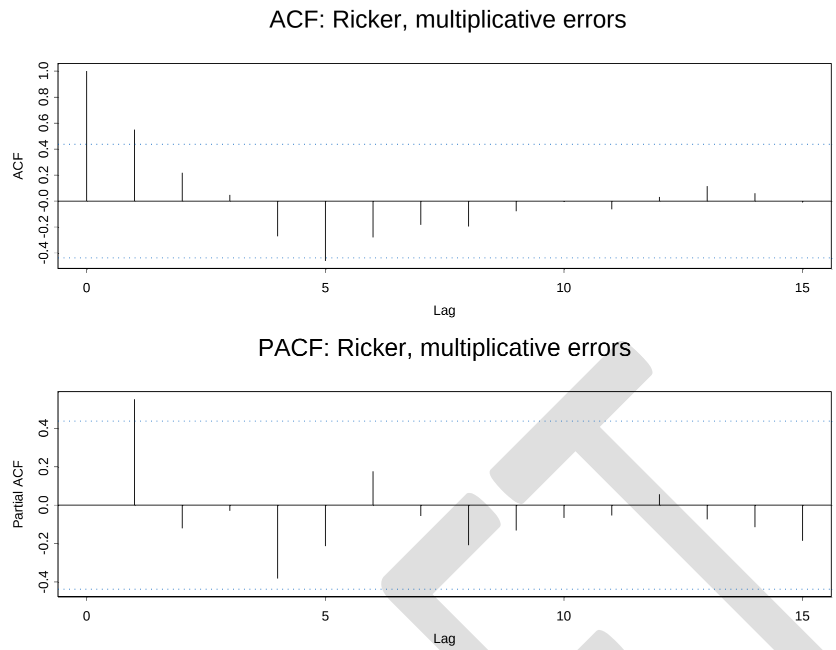

Figure 19. ACF and PACF for residuals from the fit of the Ricker model with multiplicative errors for the Humptulips fall Chinook data showing a significant correlation at lag 1 for both the ACF and PACF.

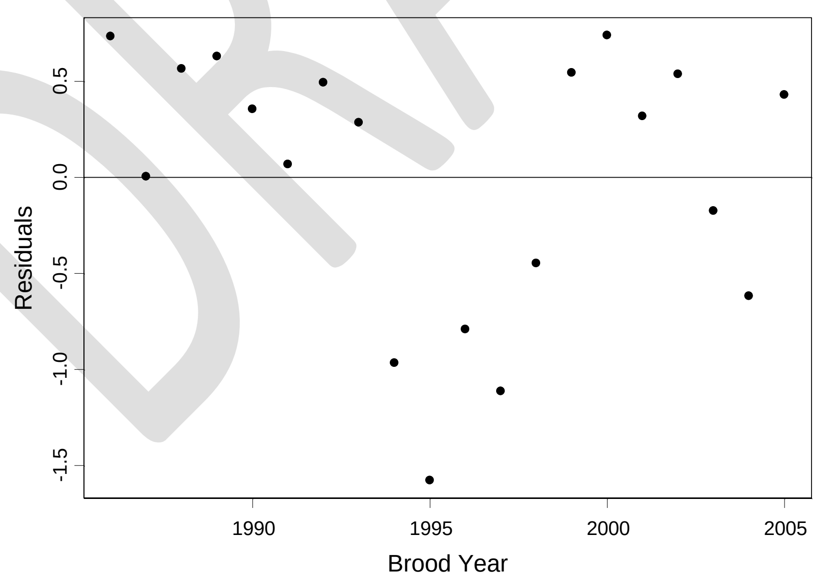

Figure 20. Time series plot of residuals from the fit of the Ricker model with multiplicative errors for the Humptulips fall Chinook data.

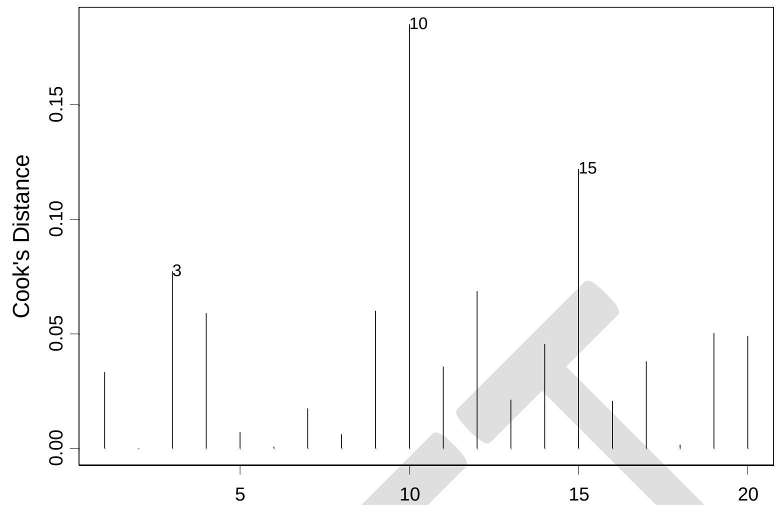

Figure 21. Plot of Cook's distances for the from the fit of the Ricker model with multiplicative errors for the Humptulips fall Chinook data showing that there was no data point having a clear influence on the model fit.

To address the lag-1 autocorrelation discussed above, we refit the Ricker model using the Cochrane-Orcutt procedure, which is equivalent to an ARMA(1,1) model. Changes in the estimate of α, its associated standard error, and the S_{msy} are in Table 11. Probabilities associated with the *t*-test for significance of the α parameter increase, as expected, but there was little change in estimates of β and S_{msy}. Analysis of the residuals from the adjusted model showed that the correlation between errors was eliminated (Figure 22). A comparison of the Ricker models between the original and adjusted model is shown graphically in Figure 23.

Table 11. Estimates and standard errors for parameters of the Ricker model, and S_{msy} for the Humptulips fall Chinook spawner-recruit data.

Model	Parameter	Estimate	Standard Error	*t*-test results
Original	α	5.14	2.16	$P(\alpha \leq 1) = 0.036$
	β	0.00019	0.0001	$P(\beta \leq 0) = 0.039$
	S_{msy}	3,676	2454	
Adjusted for autocorrelation	α	5.16	2.60	$P(\alpha \leq 1) = 0.064$
	β	0.0002	0.0001	$P(\beta \leq 0) = 0.031$
	S_{msy}	3,573	2177	

As was found in the Chehalis analysis, variation in Humptulips spawner-recruit data was better explained by the Ricker than the Beverton-Holt model (Table 10). Estimates of Beverton-Holt α and β did not differ from their null expectations (1 and 0, respectively) whereas Ricker estimates did (Table 11). Thus, the Ricker model, adjusted for autocorrelation, is considered to be the most appropriate for these data; S_{msy} for this model is 3,573.

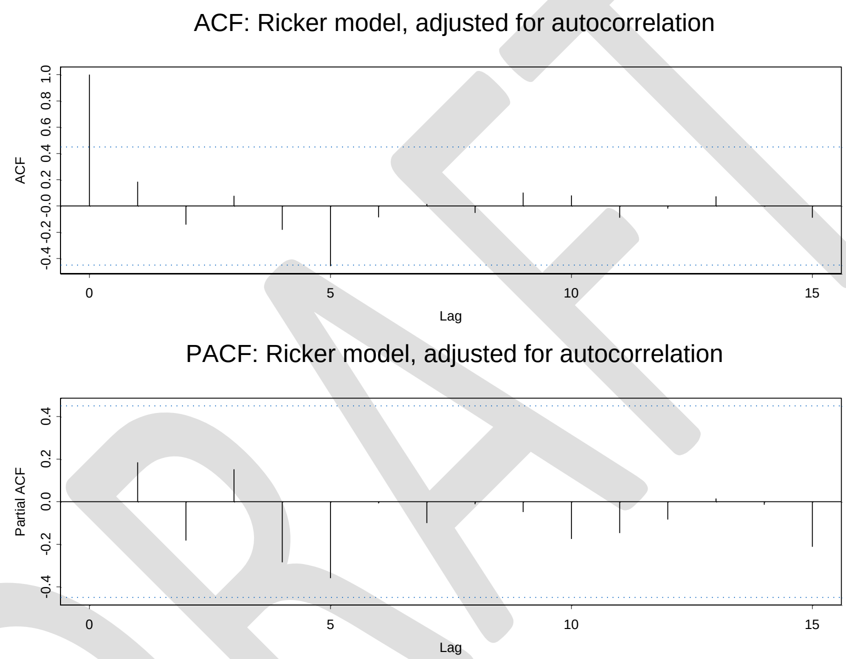

Figure 22. ACF and PACF plots of the residuals from the Ricker model after adjusting for autocorrelation.

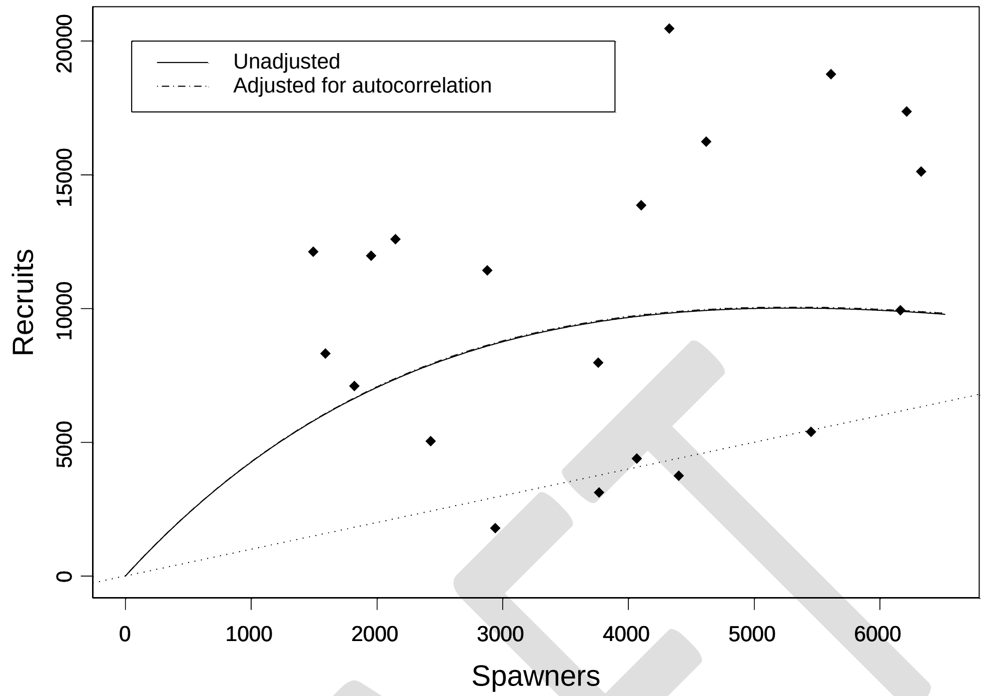

Figure 23. Comparison between the adjusted and unadjusted Ricker models for the Humptulips fall Chinook data.

Discussion

The lack of CTC-agreed escapement goals for several Washington escapement indicator stocks poses challenges to evaluations of the effectiveness of PSC management. This is particularly true for Puget Sound, but significant gaps also remain among coastal Washington indicator stocks. We propose to fill one major gap in coastal fall Chinook production, Grays Harbor, based on the spawner–recruit analysis reviewed here. Following a comprehensive review and compilation of escapement and production datasets for 20 brood years (1986-2005), the Grays Harbor co-managers (QDNR and WDFW) developed a biologically based escapement objective using methods consistent with those recommended by the CTC (CTC 1999; CTC 2013).

The improvements that the proposed goal offer to the management of Grays Harbor fall Chinook salmon are numerous. Most importantly, the S_{msy}-based goal provides a system-wide management objective that is firmly rooted in contemporary and basin-specific measures of stock productivity and capacity. In contrast, the current co-managers' management objective dates to the late 1970s, is largely undocumented, and is based on spawning habitat capacity assumptions of unknown origin. Secondly, the data review and documentation required for the analysis spurred several improvements to the base datasets (escapement and catch) underlying the analysis and used in ongoing terminal management (e.g., forecasting, fishery models). For example, an improved stray hatchery accounting method was developed and implemented, and several years of draft escapement estimates were also finalized. Additionally, as a joint QDNR-WDFW technical product, this effort fostered improved data exchange and collaboration among state–tribal parties. Lastly, by drawing upon CTC-created and -vetted datasets (i.e., the CTC's CWT cohort reconstruction for Queets), this effort syncs assumptions about Grays Harbor productivity and mortality with those embedded within the CTC models/algorithms, and emphasizes the utility of the coast-wide CWT indicator stock program. In sum, the data review and analysis required to estimate the escapement goal proposed here adds to the level of technical rigor with which Grays Harbor fall Chinook are managed.

The proposed goal is 13,326 adult spawners for the Grays Harbor aggregate, with system-specific S_{msy} values of 9,753 and 3,573 for the Chehalis and Humptulips sub-populations, respectively. Relative to the current Washington co-managers' capacity-based goal (14,600, basin total), this biologically based goal constitutes a *ca*. 10% decrease in escapement targets for the system as a whole. The new goal, however, is notably similar to estimates generated through prior (draft) spawner–recruit analyses conducted by the CTC and its Washington members, despite limited overlap in underlying datasets and differences in analytical approaches (Table 12). Using brood years 1976-1991 (vs. 1986-2005 here), for instance, the CTC estimated a system-total Grays Harbor goal of 13,024 (Table 12). Goodman (Table 12), whose estimate was based on separate Chehalis and Humptulips goals, arrived at 13,476 for a Grays Harbor goal and estimated sub-population goals comparable to ours. Among the three CTC-related efforts to estimate biologically based management objectives, Alexandersdottir's (Table 12) differed from ours—and the others—the most (12,444 vs. 13,326). However, much of this difference can be attributed to Alexandersdottir's use of a different analytical framework (i.e., inclusion of a marine survival covariate). Ultimately, the correspondence between our estimate of S_{msy} and those from past, somewhat independent efforts suggests that there is temporal stability in spawner–recruit parameters and strengthens the case for replacing the co-managers' current capacity-based goal with the proposed biologically based one.

Table 12. History of escapement goals in use or estimated through prior analysis efforts affiliated with the Chinook Technical Committee. CTC, Alexandersdottir, and Goodman are unpublished analyses reviewed in Clark (2003, unpublished memo) and years attached to names denote the year in which the analysis/review occurred.

Origin of goal	Broods included	Chehalis River	Humptulips River	Grays Harbor Total
WA Co-mgr goal (1979)	N/A	12,364	2,236	14,600
CTC (1999)	1976-1991	N/A	NA	13,024
Alexandersdottir (1999)	1976-1991	8,489	3,955	12,444
Goodman (2003)	1976-1991	10,084	3,392	13,476
Proposed goal (2014)	1986-2005	9,753	3,573	13,326

Although the goal proposed here improves the scientific basis for Grays Harbor fall Chinook salmon management, this advancement is not without weaknesses relative to the '*Bilateral Data Standards for MSY or Other Biologically-Based Escapement Goals*' that were adopted by the CTC in 2013 (CTC 2013). In particular, while our analysis conforms to CTC standards (CTC 1999, 2013) in most respects, it falls short in two key areas. First, our estimates of escapement lack a measure of uncertainty (Item 1 in CTC 2013 stock-recruit analysis data standards checklist). Second, the degree of contrast in spawning stock size (i.e., max escapement / min escapement, Item 7 of CTC 2013) is marginal for both the Chehalis (3.3) and Humptulips (4.0) population segments relative to the recommended minimum level of contrast (>4.0). Although we recognize these shortcomings, they are inherent features of the historic spawner–recruit data series. The first shortcoming illustrates a need for WDFW and QDNR to consider undertaking efforts to improve the escapement survey methods in use within the Grays Harbor basin, provided that any changes maintain consistency and compatibility with the proposed goal (e.g., calibrated to redd-based escapements). In contrast, the challenges introduced by narrow spread in parent escapements are an unavoidable reality in systems like Grays Harbor where escapement goal-based management has been in place for decades. In the absence of extreme overharvest (and/or stock collapse) or severely restricted fisheries (and/or record-high recruitment), escapements in such cases are effectively fated towards a narrow spread by management design. Taken together, both of these shortcomings demonstrate that periodic future comparisons of new—especially extreme—data points to fitted models will be necessary to maintain confidence in the proposed management objective. Similarly, future reviews should consider whether or not the stationarity assumptions inherent to spawner–recruit analysis remain valid, particularly if the flood control measures proposed for the Chehalis Basin move forward and impact the availability and/or productivity of spawning and rearing habitats.

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Appendix A
Validation of Queets CWT Indicator Stock As Surrogate For Grays Harbor

The development of an escapement goal for Grays Harbor fall Chinook requires the number of pre-fishing ocean recruits to be estimated using reliable methods. Working from the spawning grounds outwards, the ocean recruit estimates used in the spawner-recruit analysis were computed using a combination of (1) rule-based terminal run-reconstruction methods (i.e., to estimate the run entering Grays Harbor) and (2) CWT cohort analysis methods (i.e., to account for mortality in preterminal ocean fisheries). This appendix addresses the data choices associated with the latter estimation step and specifically validates the assumption that the Queets River fall Chinook CWT indicator stock is an appropriate surrogate for Grays Harbor fall Chinook.

Data Overview and Analysis
Although CWT'd Chinook have been released from various locations (Bingham Creek, Humptulips, Lake Aberdeen, and Satsop Springs hatcheries) in the Grays Harbor system for decades, the recovery data associated with these releases are considered inadequate for the type of cohort analysis required to estimate exploitation rates in preterminal fisheries. Firstly, CWT Chinook have only been released sporadically from Grays Harbor facilities over the period used for escapement goal development (1986-2005 brood years). Secondly, even for more recent years (2003 onward) when releases were more continuous, there are insufficient escapement recoveries to a complete cohort analysis. For these reasons it was necessary to estimate preterminal fishery mortality for Grays Harbor Chinook using the continuous time series of adult-equivalent (AEQ) exploitation rates (ERs) generated for the Queets River fall Chinook PSC-CTC indicator stock.

Given this surrogate data application, it is informative to determine whether or not Chinook salmon from a distant (i.e., ocean entry 50 miles up the coast) and somewhat different river (i.e., in terms of hydrologic and geomorphic setting) share a common ocean life history (i.e., in terms of survival, distribution, exploitation, propensity to mature at different ages, etc.) as is implicitly assumed in the current Grays Harbor escapement goal analysis. We evaluated the merits of this assumption by comparing patterns in pre-terminal ocean CWT recoveries, by age, for the three most recent completed broods (2003-2005) between Queets River and Humptulips Hatchery release groups (Table 1). Additionally, we assessed whether or not there might be other 'far-north migrating' CWT stocks that could be be equally appropriate for Grays Harbor ocean recruit estimation by considering similar data for Columbia Upriver Bright (URB, Priest Rapids and Ringold Springs hatcheries) and Willapa Bay (WPA, Forks Creek Hatchery) release groups. We did not consider other Washington Coast indicators (i.e., Sooes, Hoko) due to the lack of terminal harvest (necessary for terminal incidental mortality estimation) for these stocks. We conducted our analysis in two stages. Given the data deficiencies outlined above for Grays Harbor CWT groups, we first (Analysis 1) made comparisons between metrics computed from nominal fishery recoveries rather than for parameters estimated from a full cohort analysis. Thus, inferences regarding early marine survival (release-to-age 2) and maturation rates were made based on proxy values in our first set of analyses. To gain further confidence with the surrogate CWT indicator stock application—the magnitude of expansion for preterminal fishery impacts in particular (i.e., exploitation rates)—we conducted a second set of analyses (Analysis 2) involving only Queets vs. Grays Harbor comparisons for parameters estimated from a full cohort reconstruction. This required that gaps in freshwater terminal fishery and/or escapement

CWT recoveries be filled through ratio estimation methods (i.e., missing recoveries were 'imputed' based on expected recoveries per sampled fish, described below).

Analysis 1 Findings

Do Queets River and Grays Harbor Chinook have a similar ocean distribution?

There is clear evidence indicating that the Queets-as-surrogate application is reasonable from an ocean distribution perspective. Overall (all ages; $\chi^2 = 6.93$, df = 8, $P = 0.545$), age 4 ($\chi^2 = 1.55$, df = 7, $P = 0.981$), and age 5 ($\chi^2 = 1.55$, df = 7, $P = 0.981$) distributions were not significantly different. Ocean recovery distributions were centered primarily in Southeast Alaska troll, net, and sport fisheries (60-75% of all recoveries) with the bulk of remaining recoveries occurring in Northern BC troll and sport fisheries (Table 2; Figure 1, 2). Few recoveries were observed in Southern US (WA Coast sport and troll) and West Coast Vancouver Island fisheries for both stocks. Age 3 and age 6 recovery distributions appeared to differ to some extent, however, recovery distributions for these ages are based on few tags (Age 3, n = 14 and 8 for GHR and QUE, respectively; Age 6, n = 3 and 6, respectively). Taken together, these results combined with the heavy contribution of age 4 and 5 fish to the total Grays Harbor terminal run (85% of total on average) suggest that from a distribution perspective the Queets CWT data can serve as a suitable proxy in the absence of a continuous Grays Harbor-specific CWT time series. This, however, does not address the 'gorilla assumption' (i.e., that hatchery CWT groups are suitable indicators of natural fish), nor does it speak to the potential for subtle distributional differences (i.e., within spatiotemporal strata of CTC ERA fisheries).

Do Queets River and Grays Harbor Fall Chinook have a similar maturation schedule?

While estimated fishery recoveries alone cannot be used to estimate maturation probabilities, the adult equivalency factors applied to preterminal fishery mortalities are a function of maturation and natural mortality rates. Thus, whether or not both stocks have similar maturation schedules, in addition to the distributional assumptions discussed above, has implications for the suitability of Queets data for the Grays Harbor context. Although the comparison is somewhat circular due to the interdependency maturation and fishing mortality rates, maturation schedule differences can be inferred based on comparisons of the overall age composition of preterminal fishery recoveries. Specifically, if the two stocks experience similar preterminal fishing mortality rates, then the overall age composition of preterminal fishery recoveries should be comparable if both stocks have similar maturation schedules. Given the caveats outlined above, the average age composition of brood year 2003-2005 recoveries for Grays Harbor and Queets Chinook suggests these two stocks may behave slightly differently with respect to maturation (Table 3). The recovery distribution for Grays Harbor is skewed towards age 4s, whereas that for Queets is skewed towards age 5s. This suggests that Grays Harbor fish may have a higher propensity to mature at age 4 (i.e., fewer fish remaining in the ocean as age 5+ individuals) compared to Queets fish. A difference of this degree is likely inconsequential to the ocean recruit estimation context here, given that AEQ factors are relatively insensitive to modest changes in maturation probability.

Do Queets River and Grays Harbor fall Chinook experience similar early marine survival?

As with maturation, this question cannot be answered directly with the data in hand. However, if the assumptions described above for the maturation proxy comparison are made here, the estimated total number of recoveries per released Chinook may serve as a proxy of overall marine survival. Given that an overwhelming majority of natural mortality occurs prior to fish reaching age 2, this index will reflect early marine survival primarily. The mean estimated recoveries total per 1,000 fish released was virtually identical for the two stocks, at 2.6 (Grays Harbor) and 2.8 (Queets) (Table 1). Although this similarity provides further confidence in the Queets-as-surrogate application, equal early marine survival is not a necessary requirement to achieve unbiased estimates of Grays Harbor ocean recruits given that the analysis ultimately depends on rates computed from abundance after release-to-age 2 mortality has occurred.

Is there a better surrogate CWT indicator stock that could be used in place of Queets River? The answer to this question appears to be no for at least three reasons: (1) The only stocks that might be appropriate are those with northerly centered (i.e., SEAK- and NBC-oriented) ocean distributions, which beyond the Queets include stocks like Oregon Coast fall Chinook, Columbia River upriver bright fall and summer Chinook, and Willapa fall Chinook. However, a comparison of average recovery distributions for brood year 2003-2005 between Grays Harbor and a subset of these stocks (Queets, Columbia URB, and Willapa; Figure 3) illustrates that the Queets selection is the most similar option. Whereas Grays Harbor and Queets have similar recovery distributions, the Willapa distribution is centered more in northern BC (i.e., 40-50% greater fraction of preterminal recoveries in NBC, Figure 3) than Southeast Alaska. Although Columbia River upriver brights have a similar Alaska recovery component, they also have a greater presence in southern fisheries (WCVI and Washington Coast). Age 6 fish are also less common (though present) for URBs (<1% of fish making it to terminal area for a given brood) than for either Grays Harbor or Queets (5-10%). (2) Geomorphic and hydrologic differences notwithstanding, the spatial proximity and genetic relatedness of Grays vs. Queets basins suggests the Queets to be a more logical choice. Had the recovery distribution for Willapa Bay Chinook been similar to that for Grays Harbor, and had its data series been continuous, perhaps the same argument could have been made in its favor. (3) Relative to the other possible options, the Queets River fall Chinook CWT dataset has been thoroughly reviewed and modified as needed (by US CTC-AWG members) to ensure its accuracy, and it extends further (and more continuously) into the past.

Analysis 2 Findings
Whereas Analysis 1 suggests that the Queets River CWT indicator stock is a suitable surrogate for Grays Harbor Chinook from a distribution/ life history parameter standpoint, it did not address the surrogate application in terms of ocean exploitation rates, despite the fact that ocean ER ultimately defines the expansion from terminal run to pre-fishing ocean abundance. Given this, we used a modified version of the Humptulips Hatchery CWT dataset (BY 2003-2005) to complete a full cohort analysis so that ocean ERs could be estimated and compared to analogous Queets values. In brief, we filled freshwater CWT recovery gaps for the 2003-2005 brood Humptulips Hatchery CWT releases using simple estimation methods. For each tag group *i*, basin-level escapement recoveries ($\widehat{CWT_{Esc\,i}}$) in a given run year were estimated based on the recovery rate ($\frac{\widehat{cwt_{net\,i}}}{C_{net}}$) of tag *i* in the combined freshwater net (Humptulips River, catch area 72F) and North Bay net (2C) catch (C_{net}) and basin-total escapement, according to:

$$(1)\ \widehat{CWT_{Esc\,i}} = \frac{\widehat{cwt_{net\,i}}}{C_{net}}(\widehat{H_{Esc}} + \widehat{N_{Esc}})$$

where $\widehat{H_{Esc}}$ and $\widehat{N_{Esc}}$ are total Humptulips escapements of hatchery (to hatchery rack and strays to spawning grounds) and natural Chinook, respectively. Age-specific estimators were not needed given that the Grays Harbor Chinook run reconstruction assumes a similar age composition for net catches and escapements. This ratio estimation approach was also used to estimate expected CWT recoveries for the Humptulips freshwater sport fishery, with the quantity $\widehat{H_{Esc}} + \widehat{N_{Esc}}$ being replaced by Humptulips sport catch (from WDFW Catch Record Card) for that run year. This estimation approach is built on the following key assumptions:

(1) The 2C and 72F net fishery catches are perfectly known and have been sampled representatively for CWTs.
(2) Similar to (1), escapements have been accurately estimated.
(3) The 2C and 72F net fisheries exclusively catch fish that would otherwise contribute to Humptulips escapement had they not been caught (i.e., catches are 100% Humptulips-bound fish, regardless of whether they are homing correctly or strays from elsewhere).
(4) The age composition (age 3+) of fishery catches and spawning escapement are similar. In other words, all ages are similarly vulnerable to net and sport fisheries.

Although an improvement over using RMIS freshwater recovery data for Humptulips Hatchery Chinook CWT groups on an unmodified basis, this approach is not without its own shortcomings. For example, by assuming #2 above for catch area 2C, more tags become available for estimation. Yet, this condition is probably violated to some degree. Further, if a particular age class was not encountered (or sampled) in the net fishery, then by equation 1 it cannot be encountered in the escapement. This result is particularly nonsensical in cases where actual escapement CWT data illustrate that a particular tag group was present in a run year. In such cases, additional steps were taken to generate an estimate of total recoveries via alternative means. Issues such as these, combined with uncertainty regarding the validity of the assumptions outlined above, suggest that results from a cohort analysis built on these freshwater recoveries should not be over-interpreted or considered in high-precision quantitative terms. Rather, they are presented as an indicator regarding whether or not Grays Harbor ocean ERs are sufficiently similar to Queets ocean ERs to proceed with their use in escapement goal development.

Caveats notwithstanding, results from a full cohort analysis conducted using the modified CWT dataset described above, and other considerations, suggest that it is reasonable to proceed with Queets CWT data in the development of a Grays Harbor escapement goal. First, ocean ERs are similar for the two stocks, with the age class (age 4) most represented in ocean fisheries exhibiting an ER difference of only 5% (Grays > Queets) (Table 4, Figure 4). However, there is an overall tendency towards Grays Harbor having a higher exploitation rate, ~10-13% (relative difference) higher than Queets. Although sample sizes are low (n = 3 broods), none of these differences are statistically significant. Second, it is quite likely that further improvements in the accuracy of the modified freshwater Humptulips Hatchery CWT recovery dataset described here will translate into an increased terminal abundance of Humptulips CWTs and therefore reduced ocean ER, effectively reducing the gap in ERs for the two indicator stocks. For example, there are at least two years in the time series (2006, 2007) where the 2-2 sport fishery was open for Chinook retention but no Humptulips CWTs were recovered (due to sampling limitations). Given the mixed-stock status of that fishery, however, there was no attempt to estimate missing recoveries for this fishery in the modified CWT dataset described here.

Third, if the modest ER difference described here are an accurate reflection in stock differences, they will ultimately yield a slightly higher (i.e., more conservative) escapement goal. That is to say, expanding the Grays Harbor terminal run size to estimate pre-fishing ocean recruits using a lower Queets ocean ER will effectively make the stock appear less productive (e.g., lower Ricker α parameter) than it actually is. S_{msy} calculations made using a draft version of the S-R dataset suggest that consistent difference in ocean ERs on the order of 10-15% (relative difference, Grays > Queets) may yield a goal that is *ca*. 5% higher than it would be if Grays Harbor CWT data were available for the entire series. Lastly, other relevant exploitation rate analysis outputs, i.e., early marine survival rates (release to age 2, Table 5), maturation probabilities (Table 6), and AEQ factors (Table 6), illustrate that the life history parameters assessed using proxies in Analysis 1 are in fact similar for the two stocks. The only noteworthy difference is the tendency towards earlier maturation in Grays Harbor compared to Queets fish, as inferred above.

Table 1. Total releases, estimated preterminal (PT) fishery recoveries, and the ratio of recoveries:releases (Rec./Rel., 1,000s) for Grays Harbor (Humptulips Hatchery, codes: 632390, 633073, 633384) and Queets River (Salmon River Fish Culture Center, codes: 210545, 210593, 210679) brood years 2003-2005 release groups.

	Grays Harbor				Queets River			
Brood Year	Releases	Obs'd PT Rec's[1]	Est'd PT Rec's	Rec./ 1K Rel.	Releases	Obs'd PT Rec's[1]	Est'd PT Rec's	Rec./ 1K Rel.
2003	196,605	313	493	2.5	206,096	252	299	1.4
2004	180,029	161	255	1.4	170,652	100	552	3.2
2005	236,285	87	937	4.0	194,075	186	717	3.7
Mean	204,306	187	562	2.6	190,274	179	522	2.8
SD	28,908	115	346	1.3	18,025	76	211	1.2

[1]Approximated under the assumption that one estimated tags record equates to a single tag in hand.

Table 2. Average preterminal fishery CWT recovery distribution, by age, for Grays Harbor (Humptulips Hatchery) and Queets River (Salmon River Fish Culture Center) for brood year 2003-2005 releases.

		Est'd Recs	Southeast Alaska AABM			Northern BC AABM		WCVI AABM		Wash. Coast (ISBM)	
Origin	Age	(mean)	Troll	Net	Sport	Troll	Sport	Troll	Sport	Troll	Sport
Grays Hbr.	3	125	54.2	0.0	0.0	15.2	13.2	10.2	0.0	0.0	7.2
	4	975	52.9	1.0	3.5	24.4	13.0	0.6	4.0	0.0	0.6
	5	561	57.9	0.0	7.8	22.8	10.7	0.0	0.5	0.0	0.0
	6	23	73.4	0.0	0.0	0.0	26.6	0.0	0.0	0.0	0.0
	All	1685	54.9	0.6	4.6	22.9	12.5	1.1	2.5	0.1	0.9
Queets	3	87	34.8	0.0	1.2	16.4	11.2	11.4	8.0	17.0	0.0
	4	638	56.7	1.5	4.6	19.7	13.6	0.9	3.0	0.0	0.0
	5	789	58.3	1.4	10.9	17.1	10.9	0.0	0.8	0.0	0.2
	6	53	68.7	0.0	9.3	20.0	2.0	0.0	0.0	0.0	0.0
	All	1568	56.7	1.3	7.7	18.2	11.7	1.0	2.0	1.2	0.1

Table 3. Age composition of preterminal fishery recoveries for Grays Harbor (Humptulips Hatchery) and Queets River (Salmon River Fish Culture Center) brood year 2003-2005 CWT releases.

Age	Grays Harbor	Queets River
3	6%	6%
4	58%	43%

5	35%	48%
6	1%	3%

Table 4. Age-specific and overall ocean exploitation rates for Grays Harbor (Humptulips Hatchery, codes: 632390, 633073, 633384) and Queets River (Salmon River Fish Culture Center, codes: 210545, 210593, 210679) brood years 2003-2005 release groups.

		Ocean ER		
Age	Brood Year	Queets	Grays Harbor	Queets/ Grays
Age 3	2003	0.594	0.291	2.04
	2004	0.540	0.491	1.10
	2005	0.305	0.365	0.84
	mean	0.480	0.382	1.26
Age 4	2003	0.626	0.748	0.84
	2004	0.321	0.353	0.91
	2005	0.353	0.356	0.99
	mean	0.433	0.486	0.89
Age 5	2003	0.348	0.834	0.42
	2004	0.475	0.422	1.13
	2005	0.455	0.528	0.86
	mean	0.426	0.595	0.72
Age 6	2003	0.570	0.367	1.55
	2004	0.351	0.148	2.38
	2005	0.067	0.701	0.10
	mean	0.329	0.405	0.81
All ages	2003	0.504	0.651	0.77
	2004	0.429	0.397	1.08
	2005	0.340	0.424	0.80
	mean	0.424	0.491	0.87

Table 5. Release-to-age-2 survival for Grays Harbor (Humptulips Hatchery, codes: 632390, 633073, 633384) and Queets River (Salmon River Fish Culture Center, codes: 210545, 210593, 210679) brood years 2003-2005 release groups.

Brood Year	Queets	Grays Harbor
2003	1.0%	1.4%
2004	2.7%	1.4%
2005	4.2%	3.6%
mean	2.6%	2.1%
sd	1.6%	1.3%

Table 6. Maturation rates (Mat. Prob.) and adult equivalency factors (AEQ Factor) for Grays Harbor (Humptulips Hatchery, codes: 632390, 633073, 633384) and Queets River (Salmon River Fish Culture Center, codes: 210545, 210593, 210679) brood years 2003-2005 release groups.

		Queets River				Grays Harbor			
Metric	Age	2003	2004	2005	mean	2003	2004	2005	mean
Mat. Prob.	2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	3	0.03	0.03	0.04	0.03	0.16	0.03	0.08	0.09
	4	0.22	0.31	0.25	0.26	0.44	0.37	0.54	0.45
	5	0.94	0.84	0.47	0.75	0.66	0.87	0.91	0.82
	6	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
AEQ Factor	2	0.52	0.52	0.51	0.52	0.55	0.53	0.55	0.54
	3	0.74	0.75	0.72	0.74	0.78	0.75	0.78	0.77
	4	0.92	0.92	0.89	0.91	0.93	0.93	0.95	0.94
	5	0.99	0.98	0.95	0.98	0.97	0.99	0.99	0.98
	6	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

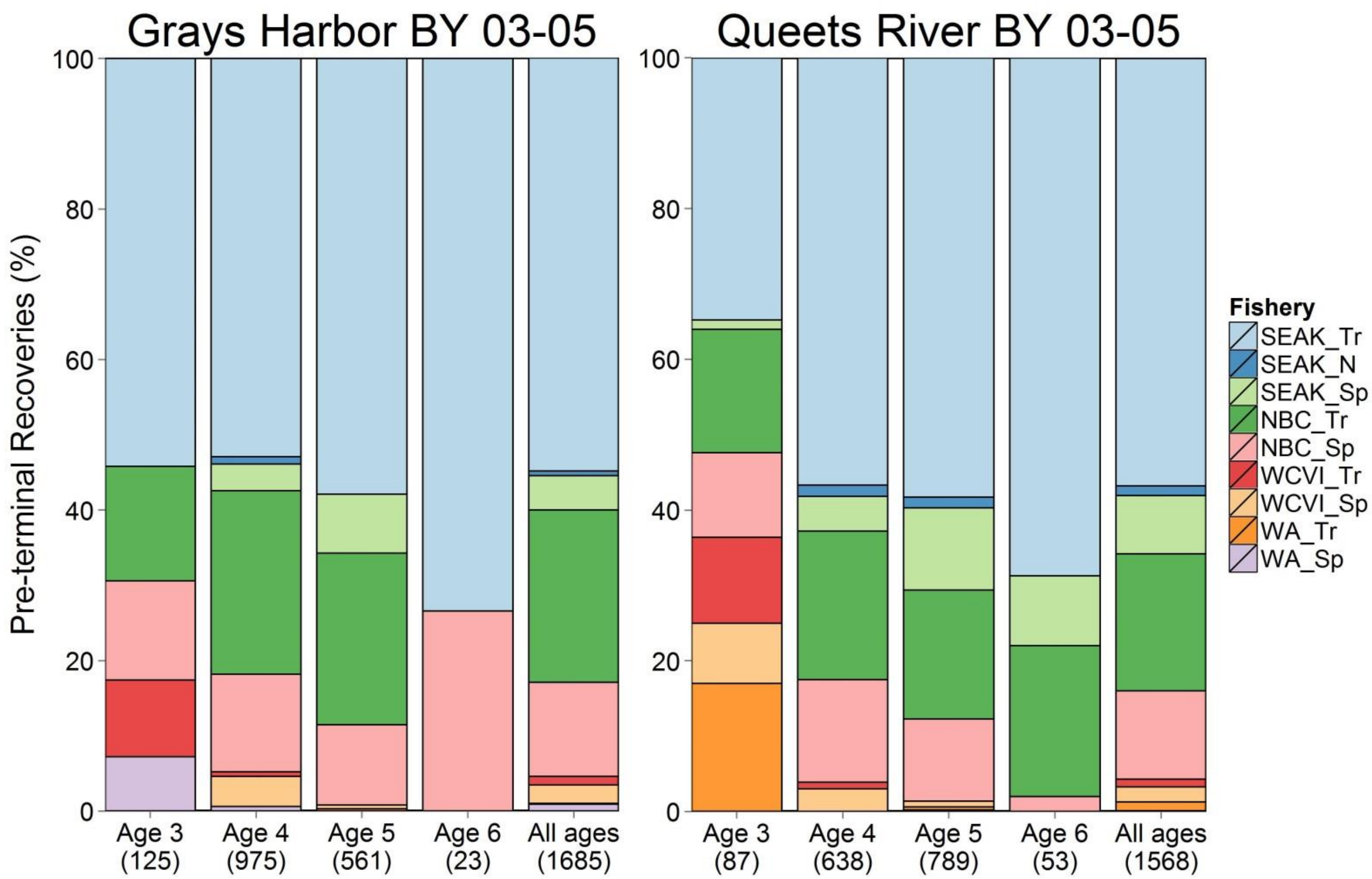

Figure 1. Age-specific preterminal fishery recovery distributions for Grays Harbor (Humptulips Hatchery) and Queets River (Salmon River Fish Culture Center) CWT release groups, brood years 2003-2005. Numbers below ages represent the average number of estimated recoveries per age class for the three brood years.

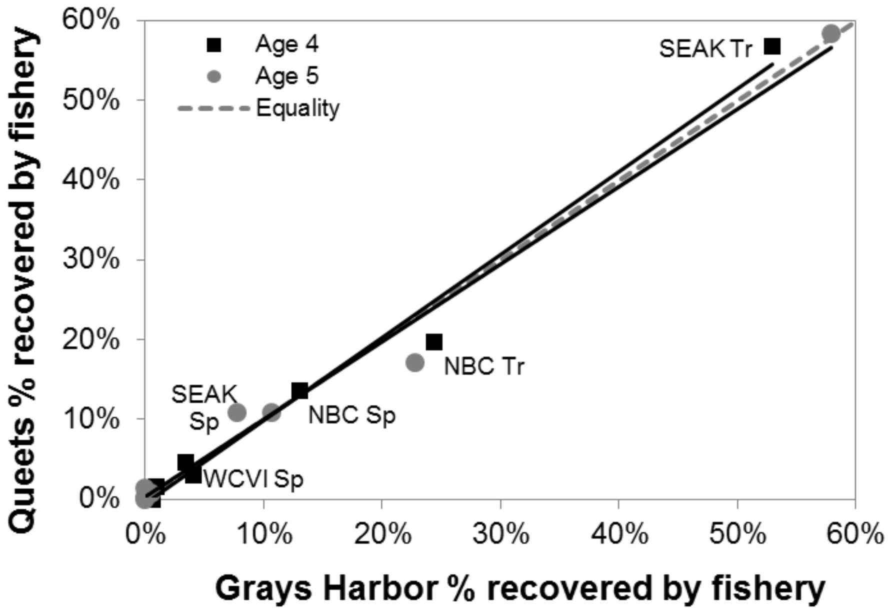

Figure 2. Comparison of preterminal fishery recovery distributions for age-4 and age-5 Chinook salmon from Grays Harbor (Humptulips Hatchery) and Queets River (Salmon River Fish Culture Center) across PSC AABM and Southern US/Canadian ISBM fisheries. The clustered points near the origin are for three fisheries comprising <1% each of the recovery distribution, SEAK Net, Washington Coast Sport, and Washington Coast Troll (See Table 3 for details). Solid lines are fitted regressions, by age.

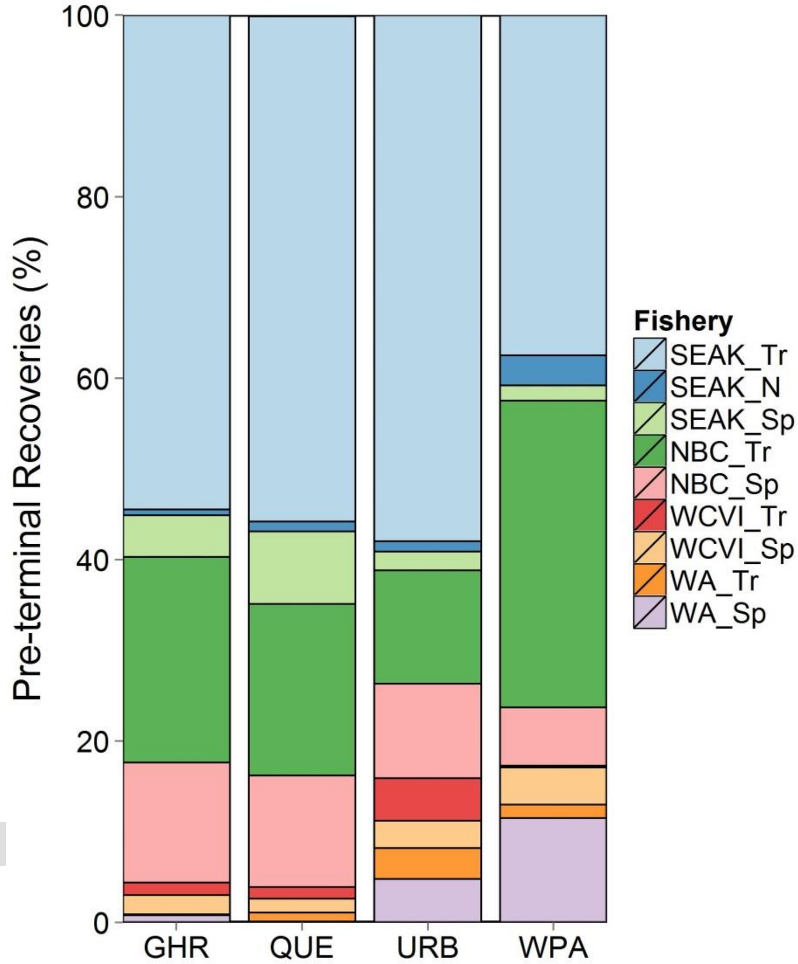

Figure 3. Distribution of pre-terminal fishery recoveries of coded wire tags for Grays Harbor (GHR, Humptulips Hatchery), Queets (QUE, Salmon River Fish Culture Center), Columbia Upriver Bright (URB, Priest Rapids and Ringold Springs hatcheries), and Willapa Bay (WPA, Forks Creek Hatchery) fall Chinook salmon, brood year 2003-2005 releases. Recoveries from terminal marine net and sport fisheries are excluded, consistent with the application of CWT data in the estimation of total ocean recruits.

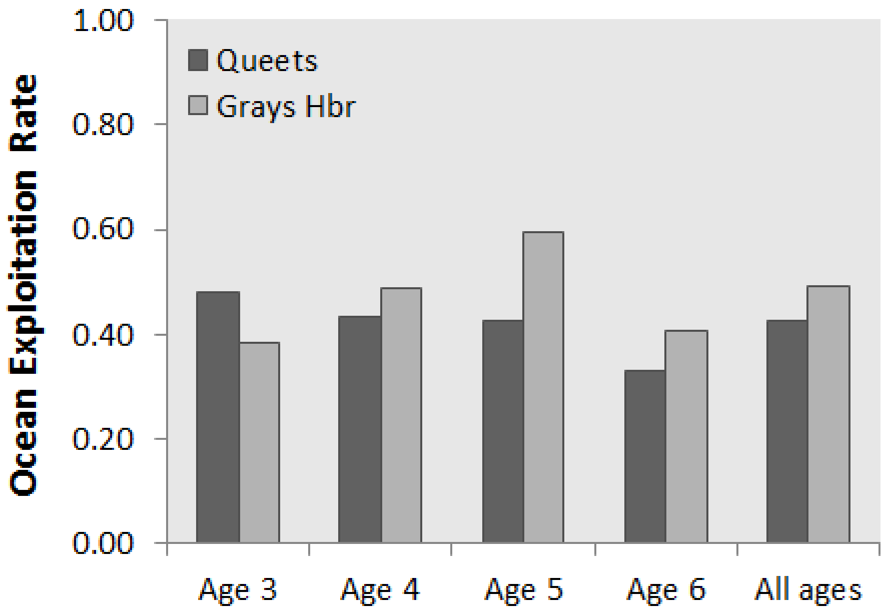

Figure 4. Age-specific and overall ocean exploitation rates for Grays Harbor (Humptulips Hatchery, codes: 632390, 633073, 633384) and Queets River (Salmon River Fish Culture Center, codes: 210545, 210593, 210679) brood years 2003-2005 release groups.

Appendix B
Estimating the Hatchery Component of Natural Escapement

Estimates of the hatchery- and natural-origin components of total escapement to the spawning grounds [i.e., $\widehat{S_{total}}$, hatchery- ($\widehat{S_{HOS}}$) plus natural-origin ($\widehat{S_{NOS}}$) fish spawning naturally] are needed to accurately account for brood year production by source. The accounting procedure is relatively straightforward for recent broods (2007+), due to the fact that ≥98% of all Grays Harbor hatchery Chinook releases have been adipose-fin clipped. For years prior to mass marking, however, alternative estimation procedures are needed. For each hatchery-affected river within the Grays Harbor system (i.e., Humptulips, Wishkah, Satsop, and Wynoochee), we retrospectively estimated $\widehat{S_{HOS}}$ as a function of the hatchery rack return (H_{rack}) in a given year and the recent (i.e., post-mass marking) average stray rate ($\bar{s}$) for that hatchery, and subsequently compute $\widehat{S_{NOS}}$ by subtraction.

Using this approach, $\widehat{S_{NOS}}$ was computed as

$$(1)\quad \widehat{S_{NOS}} = \widehat{S_{total}} - \widehat{S_{HOS}}$$

where $\widehat{S_{total}}$ is the redd-based estimate of total natural spawners for the tributary of interest and $\widehat{S_{HOS}}$ is the hatchery contribution to that total (i.e., strays). Accordingly, $\widehat{S_{HOS}}$ was estimated as

$$(2)\quad \widehat{S_{HOS}} = \widehat{H_{total}} - H_{rack}$$

where $\widehat{H_{total}}$ is the basin-level total escapement of hatchery-origin fish (i.e., strays, $\widehat{S_{HOS}}$, and fish returning to the facility, H_{rack}). Basin-level hatchery-origin escapement, $\widehat{H_{total}}$, was estimated by expanding the observed rack return (assumed to be perfectly known) to account for the fraction of fish expected to stray (stray rate, $\bar{s}$) on average,

$$(3)\quad \widehat{H_{total}} = \frac{H_{rack}}{1-\bar{s}}$$

Finally, the average stray rate was estimated as the mean of *i* yearly estimates ($\hat{s}_i$), which were computed as

$$(4)\quad \hat{s}_i = \frac{\widehat{S_{HOS}}_i}{H_{rack\,i} + \widehat{S_{HOS}}_i}$$

where $\widehat{S_{HOS}}_i$ was estimated directly from spawning ground survey data (i.e., the redd-based escapement estimate and carcass survey estimate of the hatchery fraction). Individual $\hat{s}_i$ were only computed for return years during which a sufficiently large number of carcasses were inspected for marks and hatchery returns were from adipose-clipped broods.

For run reconstruction purposes, we used the estimators described above to account for hatchery and natural-origin contributions to total natural spawning escapement for return years 1986 to 2010, thereafter we used year-specific estimates of strays ($\widehat{S_{HOS}}_i$). The mean stray rates that were applied retrospectively are presented in Table B.1 below. Although the reliability of this approach depends on the validity of a number of assumptions (described below), it has advantages over the approaches used in the past. Foremost, it ties the abundance of hatchery fish on the spawning grounds directly to a readily observable indicator of hatchery run strength (i.e., returns to the hatchery) and therefore decouples total hatchery- and natural-origin returns. Previous methods, in contrast, assumed that either a constant number of natural spawners were of hatchery origin (i.e., $\widehat{S_{HOS}} = \widehat{S_{total}} - k$, Chehalis basin) or that a constant fraction of total basin-level escapement was of hatchery origin [$\widehat{S_{HOS}} = k(\widehat{S_{total}} - H_{rack})$, Humptulips basin].

Table B.1. Estimates of stray rate used to retrospectively assign a fraction of total natural spawners to the hatchery origin category.

Population	Sub-basin	Hatcheries	Years	Mean	SD	CV
Chehalis	Satsop	Satsop/Bingham	2010-12	0.84	0.06	0.07
	Wynoochee	Lake Aberdeen	2009, 2011-12	0.62	0.09	0.15
Humptulips	All	Humptulips	2011-2012	0.44	0.01	0.03

The primary assumptions introduced into run reconstruction by using this estimation framework, and their plausibility, include the following:

(1) Stray rates are constant from year to year. The validity of this assumption depends on a number of factors, but is likely to be true on average in the absence of major changes to hatchery practices (rearing, release) or the configuration of hatchery facilities, or in the face of anomalous environmental conditions during the spawning migration.
(2) Escapement to the hatchery rack consists of hatchery origin fish only. If untrue, this natural production straying to the hatchery can be accounted for a manner similar to what has been outlined above for hatchery strays.
(3) Hatchery fish home accurately to their basin of origin (e.g., Humptulips River for Humptulips Hatchery) or to a known/assumed set of streams (e.g., Wynoochee River for Van Winkle/Lake Aberdeen releases).
(4) The number of fish spawning naturally has been estimated accurately. The validity of this assumption is unknown given the use of redd counts and a constant fish-per-redd multiplier (2.5). Further, the variance of $\widehat{S_{total}}$ (and associated quantities) cannot be estimated given the existing survey design.

Appendix C. Spawner–recruit time series used to estimate escapement goals for the Chehalis and Humptulips rivers, brood years 1986-2005.

Table C.1. Spawner and recruit data used in the analysis of biologically based escapement goals for the Grays Harbor Basin. Parent-generation spawners include age 3+ individuals of hatchery and natural origin. Recruits include natural origin (only) spawners, terminal catch and incidental mortalities, and adult equivalent ocean catch and incidental mortalities. See text for further details.

	Chehalis		Humptulips	
Brood	**Spawners**	**Recruits**	**Spawners**	**Recruits**
1986	9,483	38,805	4,325	20,467
1987	12,850	25,593	6,163	9,935
1988	21,945	38,592	6,213	17,372
1989	20,066	45,980	5,611	18,766
1990	12,893	35,859	4,102	13,861
1991	12,571	14,990	1,821	7,105
1992	11,974	59,771	4,618	16,246
1993	10,472	32,329	2,877	11,425
1994	9,919	7,767	4,401	3,749
1995	9,786	10,937	2,941	1,792
1996	16,161	31,869	4,066	4,398
1997	14,402	22,164	3,766	3,122
1998	10,101	26,921	2,428	5,046
1999	8,409	56,120	1,954	11,975
2000	7,892	26,671	1,493	12,128
2001	7,902	22,275	1,590	8,323
2002	9,694	34,801	2,147	12,596
2003	16,111	28,334	3,760	7,983
2004	26,320	11,281	5,453	5,394
2005	13,367	24,022	6,328	15,125