Determination of Gerrard Rainbow Trout Stock Productivity at Low Abundance

Final Report

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and

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and

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Executive Summary

Annual stock assessment of the juvenile Gerrard Rainbow Trout (*Oncorhynchus mykiss*) population in the Lardeau and Duncan rivers is considered a management priority within the Kootenay Region. Assessing and determining the Gerrard rainbow trout stock's productivity and capacity is essential for managing this highly exploited population. Understanding how population regulate themselves is a key parameter in assessing stock productivity which can only be obtained at low abundance. The unprecedented collapse of the lakes' Kokanee population in 2012 has provided an ideal opportunity to obtain information on the population dynamics at low stock abundance, a key data piece required for determining stock status and developing biological reference points. This report summarizes spring 2018 survey work conducted on the Lardeau and Duncan rivers to assess juvenile recruitment at low stock abundance and the development of reference points for conservation and management of this stock.

Spawner escapements at Gerrard using area under the curve (AUC) from daily counts have provided an index of abundance since 1961.Since 2006 juvenile monitoring of has occurred, with the exception of 2015, providing an information on recruitment. Combined, juvenile recruitment and spawning stock information provide the necessary data in developing a stock recruitment relationship for the Gerrard population.

In 2018 and 2019, age 1 abundance for the Lardeau and Duncan rivers was estimated to be 97,967 (95% CRI 67,939-142,639) and 28,296 (95% CRI 18,564-41,642), respectively. The large variation in recruitment from 2018 to 2019 is a result of large changes in total spawner returns and fluctuations in egg deposition related to variation in size at maturity associated with food limitations related to collapse of Kokanee. The 2018 and 2019 juvenile recruitment estimates are the progeny from the 2017 and 2018 spawn of Gerrard Rainbow Trout was estimated to be 252 and 153 AUC, respectively. These escapement estimates are well off the record highs of >1,500 AUC observed in 2012 and are some of the lowest recorded since 1961.

Data analysis fitted a Beverton Holt stock-recruit (SR) curve for Gerrard Rainbow Trout based on river recruit and spawner data converted to egg production. Preliminary results suggest no appreciable increase in recruitment in the age 1 juvenile abundance at egg deposition above 1,000,000. Information on the maximal reproductive rate (the number of spawners per spawner at low abundance without fishing indicates the Gerrard stock has a high degree of resilience. The maximum reproductive rate (not accounting for fishing mortality) increased from around 12.5 adults per recruit (log-transformed ~2.5 adults per recruit) in the early to mid-2000s to over 30 adults per recruit (log-transformed ~3.5 adults per recruit) in 2007 before dropping to under 5 adults per recruit (log-

transformed ~1.6 adults per recruit) in 2010. The Gerrard stock appears to indicate time variation in in-lake survival that alters the productivity of the stock over time.

Based on the degree of resiliency from the stock, the limit reference point (LRP) for the Gerrard stock is defined as a spawner abundance of 108 AUC ($S_{0.5R_{max}}$) and/or egg deposition of 326,000 ($E_{0.5R_{max}}$) and defined as the spawner abundance or egg deposition that produces 50% of the maximum recruitment, known as the half saturation constant. Based on the defined reference point, it appears that egg deposition ($E_{0.5R_{max}}$) has fallen below the LRP since 2015.

The recent collapse of Kootenay Lakes’ Kokanee population has had a severe impact on the Gerrard Rainbow Trout population. Expectedly, abundance, size and condition of fish in the sport fishery and returning spawners have also declined. However, the current status provides a unique opportunity to assess population dynamics at low abundance and assist with developing biological reference points (BRPs) for the stock. Development of BRPs will improve fisheries management associated with stock abundance needed for conservation and management. Lastly, development of a framework (harvest and/or abundance based) will provide critical thresholds that that can provide insight and information for adaptive management at various stock levels.

The work follows priority actions and objectives outlined in FWCPs Large Lake Action Plan and Species of Interest Action Plan; including research and acquisition of critical population information and monitoring and evaluation of species. These actions follow under objectives 1); ensure a productive and diverse aquatic; ecosystem and 2) provide sustainable use opportunities. As well, Sub-objectives include 1); maximizing them viability of indicator species and 2) optimize fishery values.

Acknowledgements

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Field work related to this project was conducted under some very difficult and adverse weather conditions. Extraordinary effort by the snorkel survey crew is gratefully acknowledged. Stefan Himmer, Kyle Mace, Kerry Reed, Jeff Berdusco and Jillian Sanders formed a great working team that made the work much easier than otherwise it could have been.

In memory-in May 2017 we lost an integral part of our assessment team to a battle with cancer. Gary Pavan was as a mentor, leader and friend. Along with his field experience, Gary was instrumental in developing the database, data entry, data QA/QC and GIS support for this project. We will miss you.

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Introduction

Assessing and determining a stock's productivity, which can only be obtained when stock abundances decline to low levels, is essential in managing exploited populations (Myers et al. 1999). Estimates of stock productivity (i.e. maximum reproductive rate) and carry capacity are two of the most important parameters in population dynamics (Myers 2001), crucial for defining biological reference points for stock management (Johnston et al. 2002). Use of stock-recruitment (SR) relationships is extensively used to assess the stock's productivity and capacity for defining important biological reference points (BRP) for management (Chaput et al. 2012). Moreover, assessment of the reproductive performance of a stock is essential in determining whether various levels of mortality are sustainable over time.

The recent unprecedented collapse of Kootenay Lakes' Kokanee (*Oncorhynchus nerka*) population has created serious problems for the predator populations on Kootenay Lake (MFLNRO 2016a). The Gerrard Rainbow Trout (*Oncorhynchus mykiss*) population abundance has undergone a severe decline as a result of extremely low Kokanee abundance (MFLNRO 2016a). The decline in the Rainbow Trout population provides a unique opportunity to obtain information on the population dynamics at low stock abundance, a crucial piece of information in stock assessment for the management of many fish stocks and recovery time for the population (Myers et al. 1999; Walters and Martell 2004).

This study focused on obtaining information on the recruitment of Gerrard Rainbow Trout under low stock abundance. Stock abundance (spawner numbers) is expected to be at or near record lows over the next 3-5 years, due to the near collapse in the Kokanee population on the lake (MFLNRO 2016a). Obtaining estimates of juvenile production from the low abundance of spawners is expected to be highly informative in understanding the population dynamics of these unique trout population. Such information will provide necessary data in developing a SR relationship for this ecotype and assist fisheries managers in future using an abundance based management framework, similar to that for Steelhead in BC (MFLNRO 2016b).

Project objectives:

- Estimate the spring abundance of age-1 fish by year.
- Estimate the egg deposition.
- Estimate the stock-recruitment relationship between the egg deposition and the abundance of age-1 recruits the following spring.

- Estimate a Limit Reference Point (LRP) for the egg deposition (and number of spawners).
- Estimate the maximum reproductive rate (spawners per spawner at low density).

Background

Overview

The Gerrard Rainbow Trout that inhabit Kootenay Lake constitute a distinct population (Keeley et al. 2007) of large piscivorous rainbow trout and are an important sport species sought after in the intensive recreational fishery (Andrusak and Andrusak 2012).

Determining the long-term sustainability of exploited wild fish stocks in many recreational fisheries is an important goal for fisheries management in BC. Management actions are often initiated (i.e. harvest policy, fixed escapement) by comparing stock status with specific biological reference points (BRP's) that set limits on mortality imposed on a fish population (Johnston et al. 2002), displayed in Figure 1. BRP's are targets derived from indices of stock status that are used to initiate management actions to meet particular management objectives (Johnston et al. 2000, 2002; Johnston 2013). The objectives of reference point management is to invoke actions when stock abundance exceeds critical thresholds, primarily where a population cannot sustain itself as a result of increasing levels of harvest mortality (Gabriel and Mace 1999; Williams and Shertzer 2003).

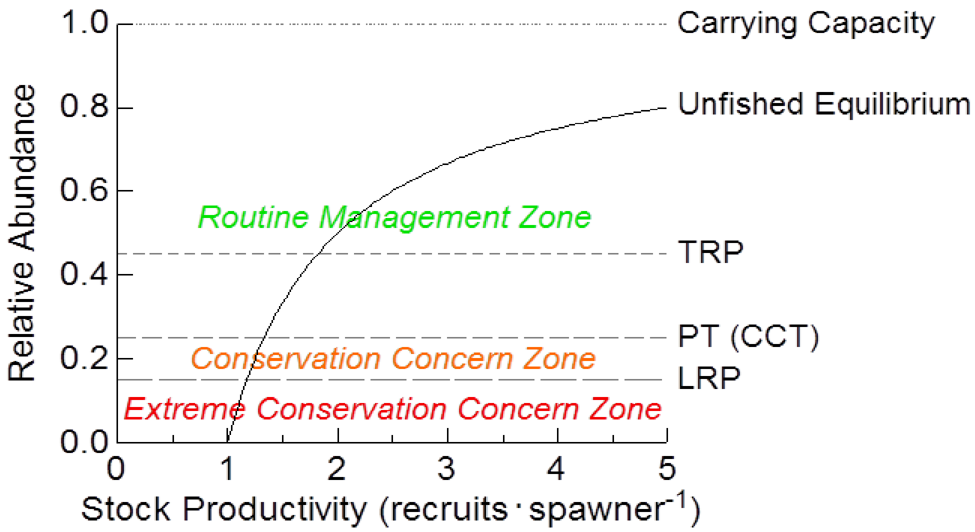

Figure 1. **Abundance based reference points and management zones framework in BC, see details in (Johnston et al. 2000; MFLNRO 2016b)**

The recent collapse of Kootenay Lakes' Kokanee population has created serious problems for piscivorous predators that rely on them as their primary prey starting in 2012 (MFLNRO 2016). Gerrard Rainbow Trout growth, condition, fecundity, survival and abundance have declined in concert with the collapse of the lakes Kokanee population. Understanding how the population is responding to the recovery of their primary prey is critical. Obtaining information at low stock abundance and provides an opportunity to assess the stocks reproductive rate, their recovery potential and recovery of the once world renown fishery.

Gerrard Rainbow Trout Biology

Gerrard Rainbow Trout are iteroparous (can spawn multiple times) but the dominant component of the annual spawning stock is comprised of first time spawners with limited but variable contributions from repeat spawners (Hagen et al. 2007; Thorley and Andrusak 2017). The stock is characterized as a late maturing stock with maiden spawners predominantly returning as age 5-7 (range age 4-8) with a median age of return of approximately 6.5 (MFLNRORD on file).

Gerrard Rainbow Trout utilize two distinct freshwater environments to complete their life cycle and their population structuring is highly evolved and selective to one river system at the north end of Kootenay Lake (Andrusak 2017). Density-dependent population regulation is well established in the riverine phase of the life cycle, occurring in the first year or two of riverine residency. The majority of fish likely enter Kootenay Lake as age 1 where survival is considered density independent. Although, the recent collapse of the Kokanee population in 2012 indicates some density dependence via growth mediation may also regulate the population at increased abundance (Kurota et al. 2016).

Study Area

The Lardeau and Duncan rivers are located at the northern end of Kootenay Lake. Kootenay Lake lies between the Selkirk and Purcell mountain ranges in the southeast corner of British Columbia (Figure 2). The Lardeau River forms at the outlet of Trout Lake and flows approximately 45 km in southeastern direction to its confluence with the regulated Duncan River near Meadow Creek, BC. The unregulated Lardeau River is the largest tributary to the Duncan River and contributes approximately one third of the total discharge historically observed in the Duncan River. The Lardeau River has a mean annual discharge of 58 m^3/s and is monitored by an Environment Canada gauge (08N007) located above the confluence with the Duncan River.

The Duncan River is regulated by the Duncan Dam located approximately 1 km upstream with the confluence of the Lardeau River. The Duncan and Lardeau River confluence is located 10 km upstream of Kootenay Lake. The Duncan River has a relatively wide floodplain at the north end of Kootenay Lake at the Duncan River delta, where the valley widens to about 4 km. The Duncan River, regulated by the Duncan Dam, has a mean annual discharge of162 m^3/s and has target flows requirements (BC Hydro 2005). Discharge is monitored by an Environment Canada gauge (08N118) located below the confluence of the Duncan River.

Both the Lardeau and Duncan rivers are relatively low gradient systems varying from <1% to 2% and are active geo-morphologically, with meandering broad floodplains, large wood accumulations (log jams), alluvial bar development, and extensive bank erosion (Slaney and Andrusak 2003).

The study area includes the Lardeau and Duncan rivers with a total lineal length (both banks) of 196.2 km (Figure 2). However, the majority of the juvenile recruitment study area is located in the Lardeau River which constitutes 141.6 km of river bank from the total of 196.2 km.

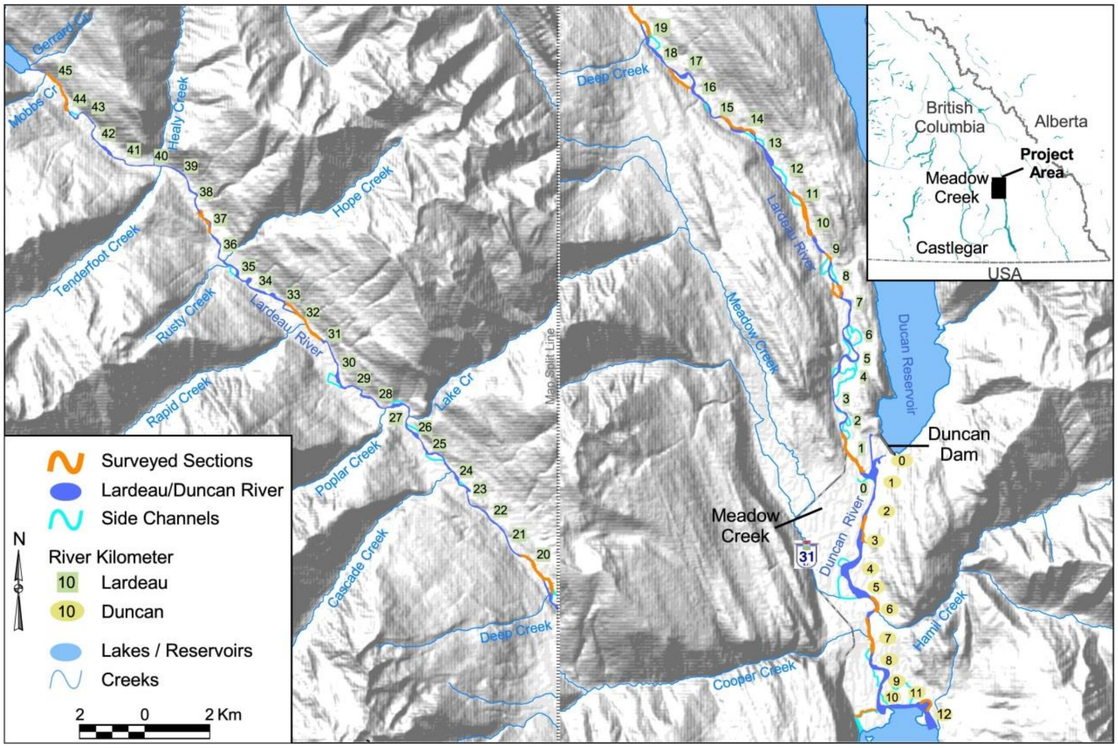

Figure 2. **Location of Kootenay Lake Lardeau and Duncan rivers**

Methods

Gerrard Juvenile Recruitment Surveys

Estimates of Gerrard juvenile recruitment were obtained utilizing calibrated springtime nighttime snorkel surveys methods since 2006, detailed in Andrusak (2017). Nighttime snorkel surveys have been proven to be a preferred and reliable method for obtaining accurate and precise estimates of abundance in medium to large rivers (Korman et al. 2010, 2016; Hagen et al. 2010).

A two stage sampling approach is often employed to account for observational error arising from variation within sites and process error associated with across site variation (Hankin 1984; Korman et al. 2016). Mark recapture (herein mark-resight) is employed to estimate detection probability (herein observer efficiency) at a limited number of sites, which is then used to obtain abundance at the site level (Korman et al. 2016). The second stage increased sampling effort to a larger number of sites and obtains estimates of abundance by expanding these counts with information on observer efficiency from the first stage. River-wide abundance was computed as the sum of the population estimates across sampled shoreline length and the estimates of the population in the unsampled shoreline length (Korman et al. 2016).

The entire study period (2006-2019) was divided into two separate time periods: 1) the first time period (2006-2010) implemented a design that was primarily designed as an index assessment (herein “Index”) in obtaining juvenile abundance estimates (Decker and Hagen 2009), and 2) the second time period implemented a design, herein “GPS” design, that allowed greater total coverage in an attempt to improve the precision of in-river estimates of abundance (Korman et al. 2016). Based on the simulation results of Korman et al. (2016) at least 9.8 km of the 196.2 km of shoreline habitat is sampled each year Total available habitat, needed to determine river-wide abundance, was quantified in a GIS using GEO BC 1:20,000 Freshwater atlas base data.

Gerrard Escapement

A high quality time series of escapement data from shore based counts at the primary spawning grounds at Gerrard BC exists since 1961 (Appendix 1). Information includes daily counts during the spawning run (April-May) to obtain an index of escapement using peak count, expansion of peak count (x 3.08) and more recently use of area-under-curve (AUC) as index of stock abundance (English et al. 1992; Parken et al. 2003). Detailed review available in Hagen et al. (2007) with historic data (MFLNRORD on file).

Analysis

Data Preparation

The data were provided by the Ministry of Forests, Lands and Natural Resource Operations (MFLNRO). The historical and current snorkel count data were manipulated using R version 3.5.0 (R Core Development Team 2017) and organised in an SQLite database.

Data Analysis

Hierarchical Bayesian models were fitted to the data using R version 3.5.0 (R Core Development Team 2017), Stan 2.16.0 (Carpenter et al. 2017) and JAGS 4.2.0 (Plummer 2015) and the mbr family of packages.

Unless indicated otherwise, the models used prior distributions that were vague in the sense that they did not affect the posterior distributions (Kéry and Schaub 2011). The posterior distributions were estimated from 2,000 Markov Chain Monte Carlo (MCMC) samples thinned from the second halves of three chains (Kéry and Schaub 2011). Model convergence was confirmed by ensuring that ^R<1.1 (Kéry and Schaub 2011) for each of the monitored parameters in the model (Kéry and Schaub 2011). Where relevant, model adequacy was confirmed by examination of residual plots.

The posterior distributions of the fixed (Kéry and Schaub 2011) parameters are summarised in terms of the point estimate, standard deviation (sd), the z-score, lower and upper 95% confidence/credible limits (CLs) and the p-value (Kéry and Schaub 2011). The estimate is the median (50th percentile) of the MCMC samples, the z-score is sd/mean and the 95% CLs are the 2.5th and 97.5th percentiles. A p-value of 0.05 indicates that the lower or upper 95% CL is 0.

Variable selection was achieved by dropping fixed (Kéry and Schaub 2011) variables with two-sided p-values ≥ 0.05 (Kéry and Schaub 2011) and random variables with percent relative errors ≥ 80%.

The results are displayed graphically by plotting the modelled relationships between particular variables and the response with 80% or 95% credible intervals (CIs) with the remaining variables held constant. In general, continuous and discrete fixed variables are held constant at their mean and first level values respectively while random variables are held constant at their typical values (expected values of the underlying hyper-distributions) (Kéry and Schaub 2011). Where informative the influence of particular variables is expressed in terms of the effect size (i.e., percent change in the response variable) with 95% CIs (Bradford et al. 2005).

Length Correction

The annual bias (inaccuracy) and error (imprecision) in observer's fish length estimates when spotlighting (standing) and snorkeling were quantified from the divergence of their length distribution from the length distribution for all observers (including measured fish) in that year. More specifically, the length correction that minimised the Jensen-Shannon divergence (Lin 1991) between the two distributions provided a measure of the inaccuracy while the minimum divergence (the Jensen-Shannon divergence was calculated with log to base 2 which means it lies between 0 and 1) provided a measure of the imprecision.

After correcting the fish lengths, age-1 individuals were assumed to be those with a fork length ≤ 100 mm.

Abundance

The abundance was estimated from the count data using an over-dispersed Poisson model (Kéry and Schaub 2011). The annual abundance estimates represent the total number of fish in the study area.

Key assumptions of the abundance model include:

- The lineal fish density varies with year, useable width and river kilometer as a polynomial, and randomly with site.
- The observer efficiency at marking sites varies by study design (GPS versus Index).
- The observer efficiency also varies by visit type (marking versus count) within study design and randomly by snorkeller.
- The expected count at a site is the expected lineal density multiplied by the site length, the observer efficiency and the proportion of the site surveyed.
- The residual variation in the actual count is gamma-Poisson distributed.

Table 1. Parameter descriptions

Parameter	Description
bDensity	Intercept for log(eDensity)
bDensityRkm[x]	x^{th}-order polynomial coefficients of effect of river kilometer on bDensity
bDensitySite[i]	Effect of i^{th} Site on bDensity
bDensityWidth	Effect of Width on bDensity
bDensityYear[i]	Effect of i^{th} Year on bDensity
bEfficiency	Intercept of logit(eEfficiency)
bEfficiencyIndex	Effect of Index on bEfficiency
bEfficiencyMarking	Effect of Marking on bEfficiency
bEfficiencyMarkingIndex	Effect of Marking and Index on bEfficiency
bEfficiencySwimmer[i]	Effect of i^{th} Swimmer on bEfficiency
eAbundance[i]	Expected abundance of fish at site of i^{th} visit
eCount[i]	Expected total number of fish at site of i^{th} visit
eDensity[i]	Expected lineal density of fish at site of i^{th} visit
eEfficiency[i]	Expected observer efficiency on i^{th} visit
Index	Whether the i^{th} visit was to an index site
Marking[i]	Whether the i^{th} visit was to a site with marked fish
Rkm[i]	River kilometer of i^{th} visit
sDensitySite	SD of bDensitySite
sDispersion	Overdispersion of Count[i]
sEfficiencySwimmer	SD of bEfficiencySwimmer
Site[i]	Site of i^{th} visit
SiteLength[i]	Length of site of i^{th} visit
SurveyProportion[i]	Proportion of site surveyed on i^{th} visit
Swimmer[i]	Snorkeler on i^{th} site visit
Width[i]	Useable width of site on i^{th} visit
Year[i]	Year of i^{th} site visit

Condition

The condition of fish with a fork length ≥ 500 mm was estimated via an analysis of mass-length relations (He et al. 2008).

More specifically the model was based on the allometric relationship

$$W = \alpha_c L^{\beta_c}$$

where

W is the weight (mass), α_c is the coefficent, β_c is the exponent and L is the length. To improve chain mixing the relation was log-transformed, i.e.,

$$\log(W) = \log(\alpha_c) + \beta_c \log(L).$$

Key assumptions of the condition model include:

- α_c can vary randomly by year.
- The residual variation in weight is log-normally distributed.

Table 2. **Parameter descriptions**

Parameter	Description
bWeight	Intercept of log(eWeight)
bWeightLength	Intercept of effect of log(Length) on bWeight
bWeightYear[i]	Effect of i^{th} Year on bWeight
eWeight[i]	Expected Weight of i^{th} fish
Length[i]	Fork length of i^{th} fish
sWeight	Log standard deviation of residual variation in log(Weight)
sWeightYear	Log standard deviation of bWeightYear
Weight[i]	Recorded weight of i^{th} fish
Year[i]	Year i^{th} fish was captured

Fecundity

The fecundity of females with a fork length ≥ 500 mm was estimated via an analysis of fecundity-mass relations (Andrusak and Andrusak 2006).

More specifically the model was based on the allometric relationship.

$$F = \alpha_f W^{\beta_f}$$

where

F is the fecundity, α_f is the coefficent, β_f is the exponent and W is the weight. To improve chain mixing the relation was log-transformed.

Key assumptions of the fecundity model include:

- The residual variation in fecundity is log-normally distributed.

Table 3. Parameter descriptions

Parameter	Description
bFecundity	Intercept of eFecundity
bFecundityWeight	Effect of log(Weight) on log(bFecundity)
eFecundity[i]	Expected Fecundity of i^{th} fish
Fecundity[i]	Fecundity of i^{th} fish (eggs)
sFecundity	SD of residual variation in log(Fecundity)
Weight[i]	Weight of i^{th} fish (mm)

Spawner Size

The average length of the spawners in each year (for years for which it was unavailable) was estimated from the mean weight of Rainbow Trout in the Kootenay Lake Rainbow Trout Mailout Survey (KLRT) using a linear regression (MFLNRORD data on file).

Egg Deposition

The egg deposition in each year was estimated by

1. converting the average length of spawners to the average weight using the condition relationship for a typical year
2. adjusting the average weight by the annual condition effect (interpolating where unavailable)
3. converting the average weight to the average fecundity using the fecundity relationship
4. multiplying the average fecundity by the AUC based estimate of the number of females (assuming a sex ratio of 1:1)

Stock-Recruitment

The relationship between the number of eggs (E) and the abundance of age-1 individuals the following spring (R) was estimated using a Beverton-Holt stock-recruitment model (Walters and Martell 2004):

$$R = \frac{\alpha_s \cdot E}{1 + \beta_s \cdot E} \quad ,$$

where α_s is the maximum number of recruits per egg (egg survival), and β_s is the density dependence.

Key assumptions of the stock-recruitment model include:

- The residual variation in the number of recruits is log-normally distributed with the standard deviation scaling with the uncertainty in the number of recruits.

The age-1 carrying capacity (K) is given by:

$$K = \frac{\alpha_s}{\beta_s} \quad .$$

and the $E_{K/2}$Limit Reference Point (Mace 1994, $E_{0.5Rmax}$), which corresponds to the stock (number of eggs) that produce 50% of the maximum recruitment (K), by;

$$E_{K/2} = \frac{1}{\beta_s}$$

The LRP was also converted into a number of spawners in a typical year (assuming 6,000 eggs per spawner and a sex ratio of 1:1).

Table 4. **Parameter descriptions**

Parameter	Description
a	Recruits per Stock at low density
b	Density-dependence
eRecruits[i]	Expected number of recruits from ith spawn year
esRecruits[i]	Expected SD of residual variation in Recruits
Recruits[i]	Number of recruits from ith spawn year
SDLogRecruits[i]	Standard deviation of uncertainty in log(Recruits[i])
sScaling	Scaling term for SD of residual variation in log(eRecruits)
Stock[i]	Number of egg in ith spawn year

Reproductive Rate

The maximum reproductive rate (the number of spawners per spawner at low density) not accounting for fishing mortality was calculated by multiplying β_s (number of recruits per egg at low density) from the stock-recruitment relationship by the in-lake survival and by the average number of eggs per spawner in a typical year (assumed to be 3,000 based on 6,000 eggs per spawner and a sex ratio of 1:1). The in-lake survival from age-1 to spawning was calculated by dividing the subsequent number of spawners by the number of recruits assuming that equal numbers of fish spawn at age 5, 6 and 7.

Results

Juvenile Surveys

Surveys conducted in the spring of 2019 covered approximately 9% of the Lardeau River and of the Duncan River combined (Table 5). The 2018 sampling effort was reduced due to funding constraints which forced the surveys to be conducted in April, in comparison to March in previous years, when site conditions are more variable and difficult due to dam operations which can reduce the visibility on the Duncan River.

Table 5. **Number of sites total survey length (km), percent coverage and fish marked and re-sighted each year on the Lardeau and Duncan rivers 2006-2019**

Year	Sites	SurveyLength	SurveyPercent	Fish	Marked	Resighted
2006	34	2	1	620	36	22
2007	47	2.7	1	260	0	0
2008	97	7.5	4	618	102	54
2009	83	5	3	390	0	0
2010	48	2.5	1	303	0	0
2011	296	17.6	9	2124	0	0
2012	328	19	10	2210	43	6
2013	425	25.1	13	2077	217	40
2014	350	21.1	11	1287	172	31
2016	327	18.3	10	458	16	3
2017	602	35.6	19	1625	59	5
2018	216	11.8	6	933	93	15
2019	299	16.7	9	322	38	3

Mark re-sight effort information used in determining observer efficiency is shown in Table 5. Estimated observer efficiency is approximately 0.16 based on the new study ("GPS") design starting in 2012, substantially differing from the previous study design ("Index") from 2006-2010.

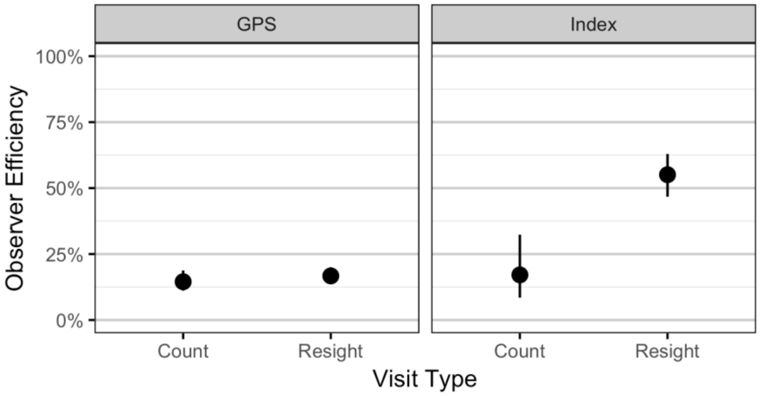

Figure 3. **Predicted observer efficiency for age-1 Rainbow Trout by visit type and study design (with 95% CRIs).**

Juvenile Abundance

Due to the length biases when associated with nighttime snorkel methods, length-corrected estimates of abundance were derived which improved the accuracy and precision of age 1 abundance estimates (Figure 4).

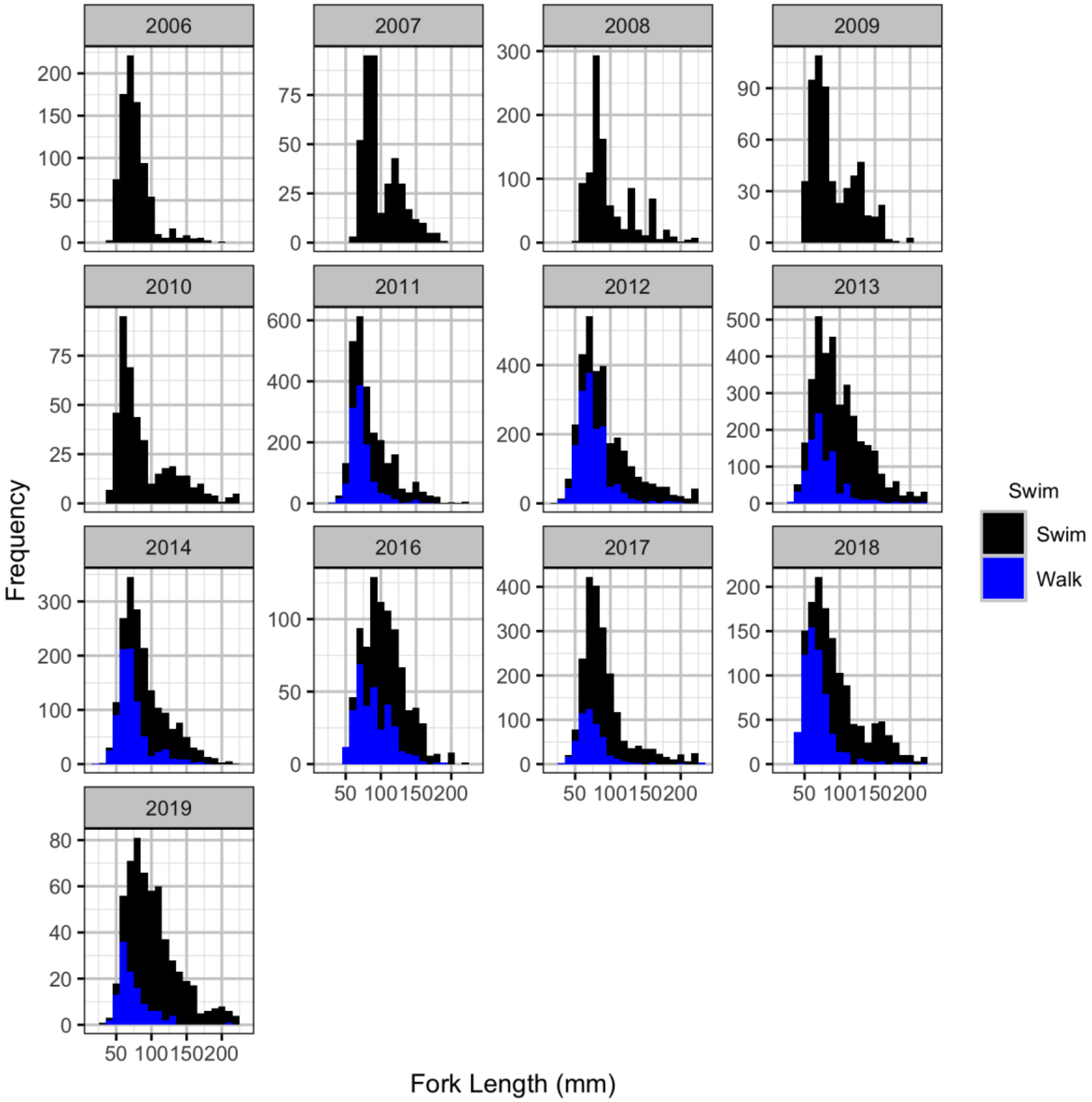

Figure 4. **Corrected length-frequency histogram by year and observation type from 2006-2019.**

In 2019, age 1 abundance for the Lardeau and Duncan rivers was estimated to be 28,296 (95% CRI 18,564-41,642, down significantly from 2018 (Table 6;Figure 5). Age 1 abundance was highest in 2006 at ~260,000, however, this data point is associated with high uncertainty due to large measurement error and may be unreliable. With the exception of 2006 data, the total age 1 abundance (both rivers) has averaged approximately 92,000. Parameter estimates for the abundance analysis is available in Appendix 2.

Table 6. Estimated age 1 abundance in Lardeau and Duncan rivers from 2006-2014 & 2016-2019

Year	Estimate	Lower 95% CRI	Upper 95% CRI
2006	268,331	129,955	567,104
2007	106,428	53,246	235,516
2008	77,715	42,613	144,482
2009	75,920	37,197	154,029
2010	104,183	49,512	221,375
2011	163,185	110,884	236,848
2012	165,922	115,439	238,095
2013	115,388	82,183	165,249
2014	79,281	54,969	112,677
2016	31,261	21,403	44,897
2017	58,411	40,752	83,121
2018	97,967	67,940	142,639
2019	28,296	18,564	41,642

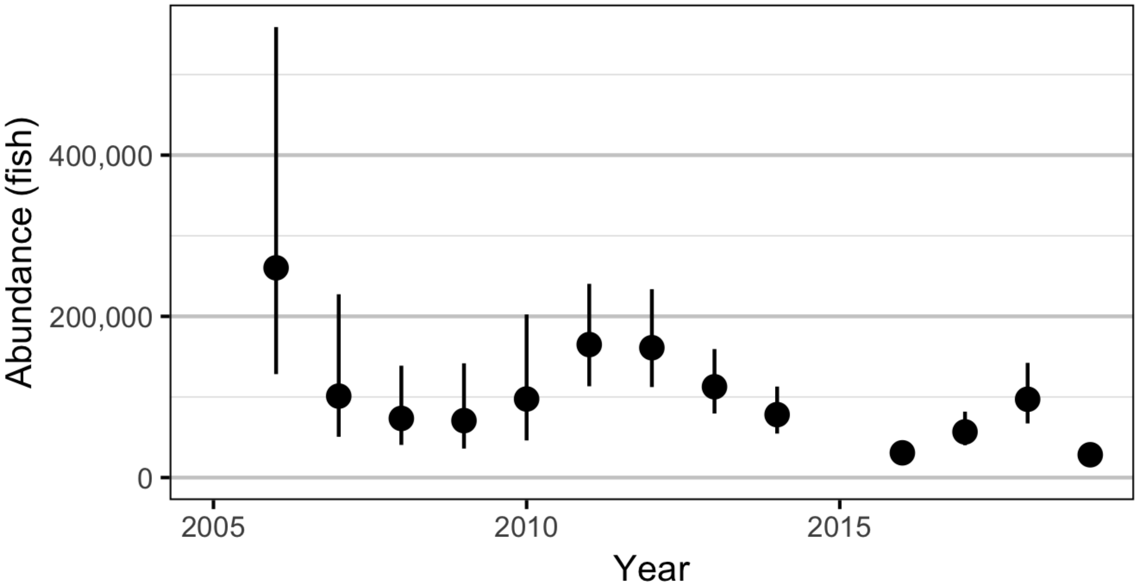

Figure 5. Predicted abundance of Rainbow Trout age 1 by year (with 95% CRIs) in Lardeau and Duncan rivers combined from 2006-2014 & 2016-2019. No sampling was conducted in 2015.

Spawner Escapement

The historic escapement time series since 1961 is available in Appendix 1. For the purposes of our analysis we use information from 2000-2019.

Gerrard Rainbow Trout escapements using AUC methodology have varied widely in the since 2000, ranging from a low 163 in 2014 to a high of 1,532 in 2012 (Figure 6) Escapement in 2018 was 153 based on AUC and the corresponding juveniles surveys are the progeny from the 2018 escapements. Commencing in 2009, escapements began to increase substantially until they reached a historic high in 2012. Spawner estimates from 2009-2012 indicate escapements that are almost double the historic average which was approximately 500 spawners based on the time period 1961-2008.

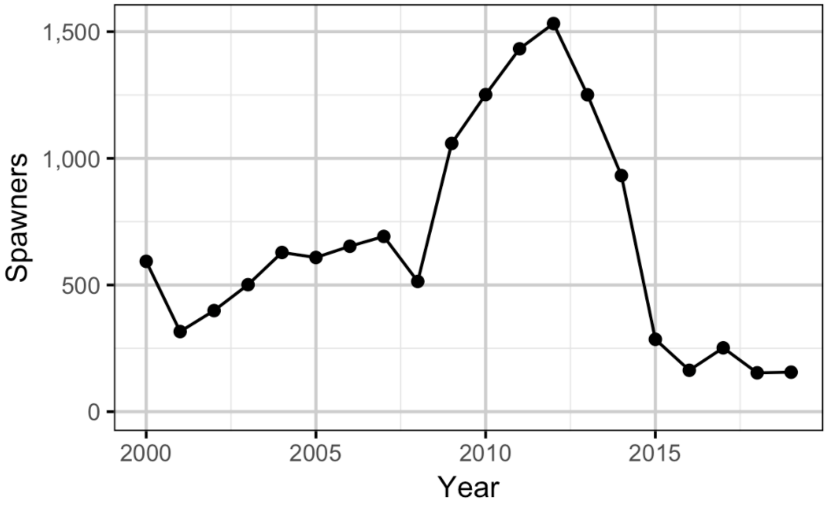

Figure 6. **Gerrard Rainbow Trout spawner escapement estimates from area-under the curve (AUC) at Gerrard from 1961-2019 (MFLNRO on file).**

Condition, Fecundity, Spawner Size and Egg Deposition

The condition of fish with a fork length ≥ 500 mm was estimated via an analysis of mass-length relations from available catch information on Kootenay Lake over time (Andrusak and Andrusak 2015; MFLNRORD on file). Information demonstrates drastic changes in fish condition as a result of the recent collapse of Kokanee on Kootenay Lake starting in 2012 (Figure 7). Based on KLRT catch information, the average size of Gerrard Rainbow Trout drastically declined starting in 2014 (Figure 8).

Based on select years of spawner size information, linear regression analysis demonstrated a decline in average spawner size in agreement with the decline in the average size of Gerrard Rainbow Trout from the KLRT catch information on Kootenay Lake

(Figure 9; MFLNRORD on file). Parameter estimates for the condition analysis is available in Appendix 3.

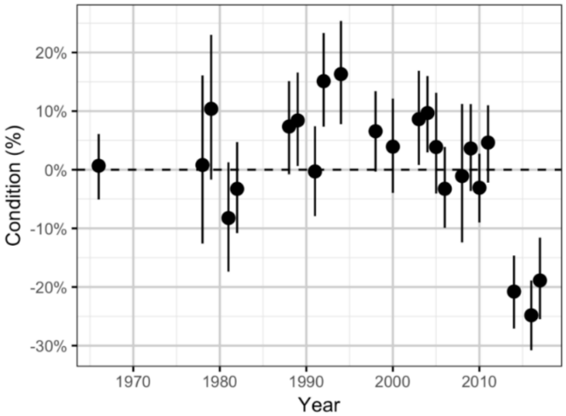

Figure 7. **Condition of Rainbow Trout ≥ 500 mm on Kootenay Lake overtime 1966-2014 (Andrusak and Andrusak 2015).**

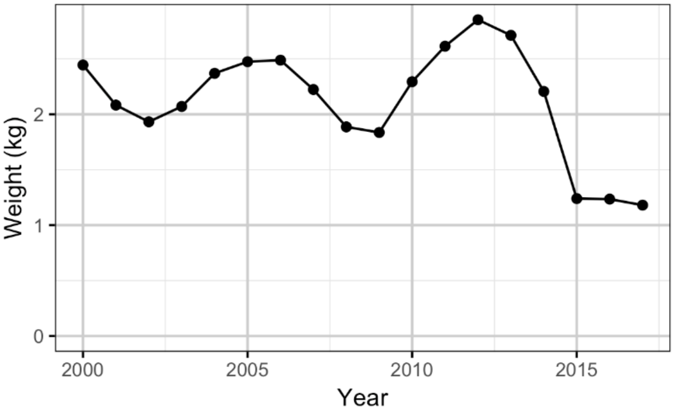

Figure 8. **The mean weight of Rainbow Trout in the KLRT by year**

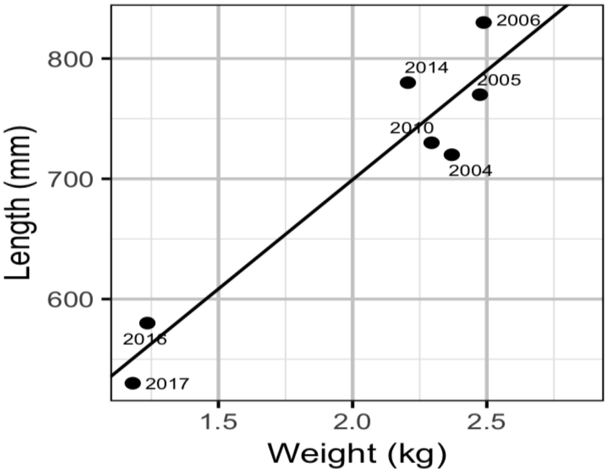

Figure 9. **The mean length of spawning Rainbow Trout by the mean weight of Rainbow Trout in the KLRT**

Average size and weight of spawners at Gerrard (MFLNRORD on file) was used to predict the changes in fecundity from the fecundity relationship (Figure 10), multiplied by the AUC based estimate of the number of females (assuming a sex ratio of 1:1). Based on the weight-fecundity relationship, data indicates that spawner fecundity in the Gerrard population dropped substantially after 2014, shortly following the collapse of Kokanee in 2012 (Figure 11). Parameter estimates for the condition analysis is available in Appendix 4

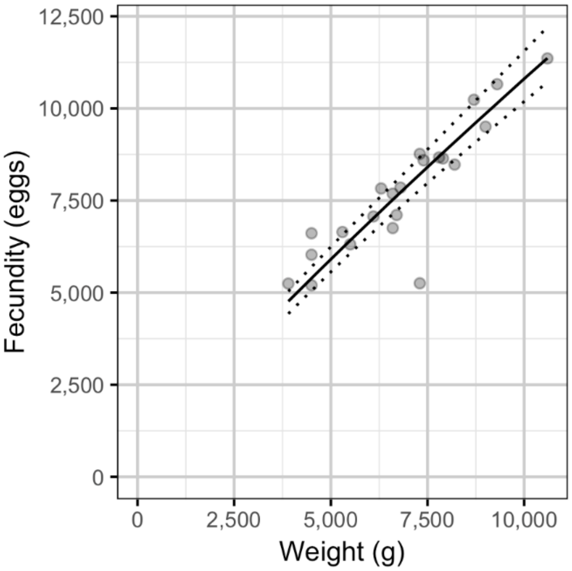

Figure 10. **The fecundity-weight relationship (with 95% CRIs) from (Andrusak and Andrusak 2006).**

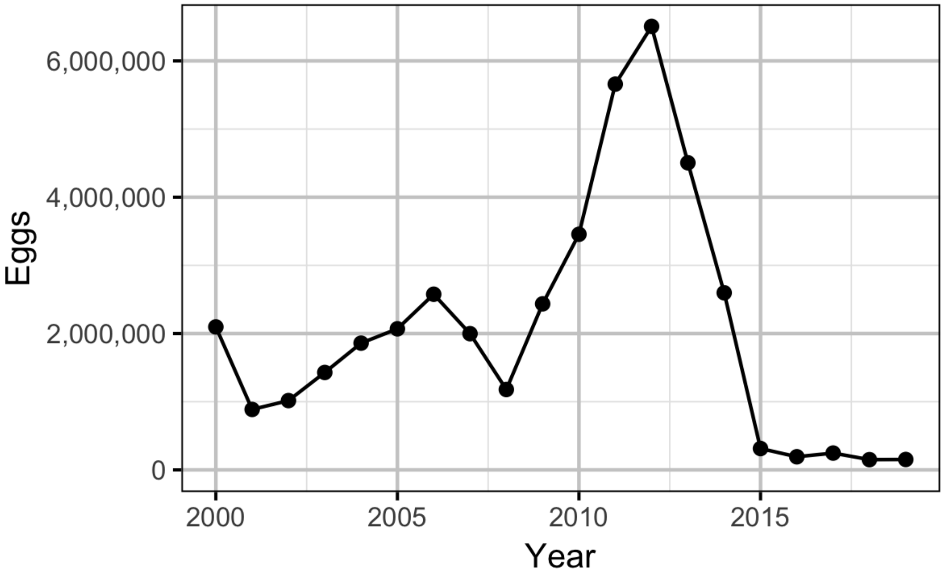

Figure 11. **Estimated Gerrard Rainbow Trout spawner fecundity from 2000-2019 (MFLNRO on file).**

Following the changes in fecundity per-spawner over time, egg deposition at the Gerrard spawning grounds also changed substantially as abundance and condition of Gerrard spawners changed (Table 7). Egg deposition information demonstrates a drastic decline beginning in 2015, well below the peak observed in 2012 (Figure 12). Size and egg deposition information for 2018 & 2019 were not available at the time, so information from 2017 was assumed to be representative of 2017 data (Table 7).

Table 7. The estimate total egg deposition by spawn year

Year	Length (cm)	Condition	Weight (g)	Fecundity	Spawners	Eggs
2000	780	1.04	6139	7060	593	2,094,685
2001	714	1.05	4699	5594	316	884,259
2002	687	1.07	4207	5082	399	1,013,924
2003	712	1.09	4790	5688	501	1,425,385
2004	720	1.10	5010	5916	628	1,858,853
2005	770	1.04	5885	6804	609	2,070,318
2006	830	0.97	6968	7882	653	2,573,158
2007	740	0.98	4877	5778	692	1,998,279
2008	679	0.99	3739	4589	514	1,179,361
2009	670	1.04	3752	4602	1059	2,436,185
2010	730	0.97	4628	5521	1252	3,454,744
2011	811	1.05	6994	7908	1433	5,664,160
2012	854	0.96	7594	8494	1532	6,506,177
2013	829	0.88	6283	7204	1251	4,505,842
2014	780	0.79	4678	5572	932	2,596,511
2015	561	0.77	1589	2202	301	331,737
2016	580	0.75	1720	2356	162	191,089
2017	530	0.81	1391	1963	256	251,519
2018*	530	1	1391	1956	153	152,394
2019*	530	1	1391	1956	153	152,394

Note-*2018 &2019 are constants used from 2017

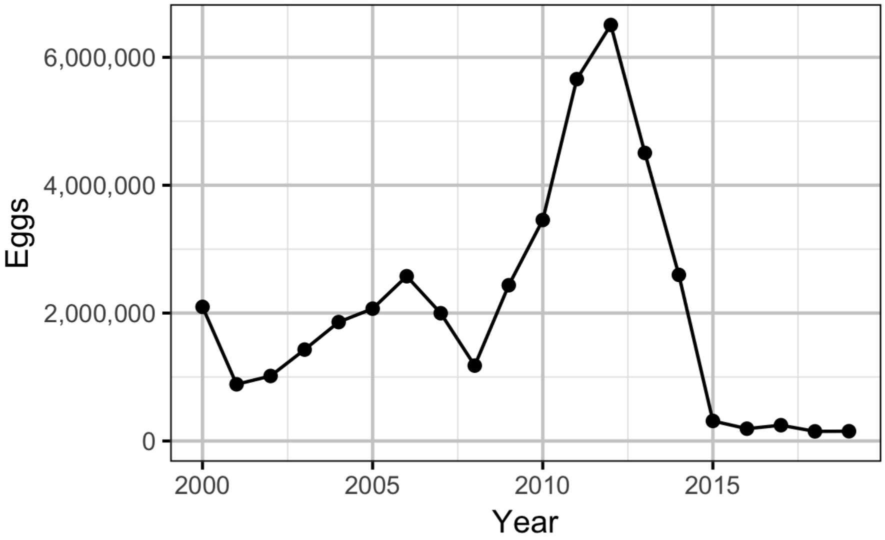

Figure 12. Estimated annual egg deposition of Gerrard Rainbow 2000-2019.

Stock-Recruitment

A Beverton-Holt (Beverton and Holt 1957) stock recruitment curve was fitted to the Gerrard Rainbow Trout population using information from egg deposition and subsequent recruitment to age 1. Preliminary results suggest no appreciable increase in recruitment in the age 1 juvenile abundance at egg deposition above 1,000,000 (Figure 13). The SR relationship also suggests that most of the density dependent mortality in the early life stages occurs prior to age 1 with an average recruitment near 100,000 age 1 each spring when egg disposition at or above 1,000,000 eggs.

The 2005 data point has little influence on the stock recruitment relationship overall (Figure 13). Analysis of the SR was conducted using two scenarios; 1) “all” and 2) “reduced” to indicate the relative influence of the 2005 data point. Analysis revealed that the 2005 data point had a minimal increase in the uncertainty in the SR relationship. Here we report the parameter estimates for the reduced model. Parameter estimates for the condition analysis is available in Appendix 5.

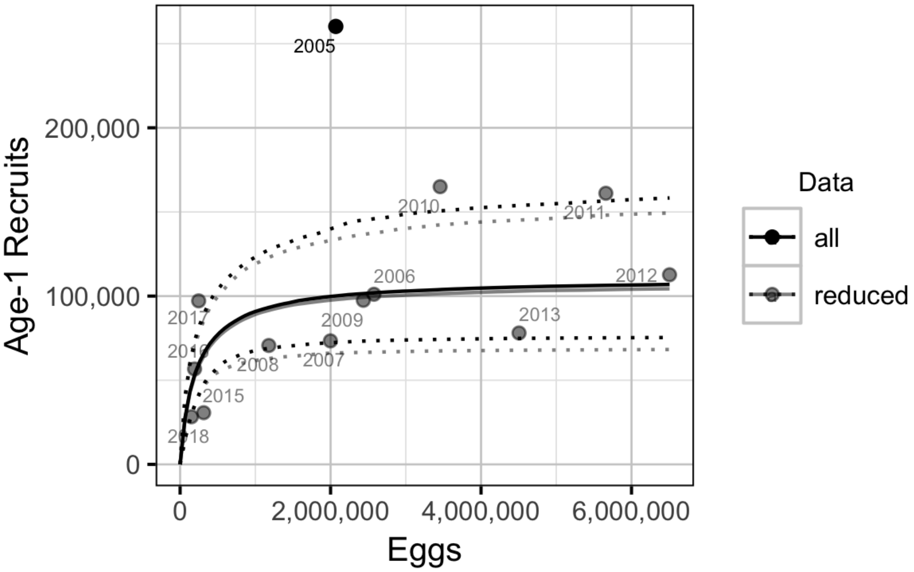

Figure 13. **Predicted Rainbow Trout stock-recruitment relationship (with 95% CRIs). Recruitment of spring age 1 and spawners based on AUC from Gerrard. Year is associated with brood year. All includes the 2005 data point and reduced removes the 2005 data point for assessment of influence on the SR.**

Based on the SR analysis, the maximum reproductive rate (α_s), survival from egg to age 1, was approximated to be 0.56 (95% CRI 0.26—0.96) for the reduced model analysis (Figure 14). Similarly, the carry capacity (K) of the river to support age 1 juveniles was estimated to be 108,000 (95% CRI 69,500-158,000) recruits (Table 8).

Table 8. **Posterior predictions from BH stock recruitment model**

Parameter	Estimate	Lower 95% CRI	Upper 95% CRI
a	0.56	0.26	0.96
b	0.0000052	0.0000018	0.0000125
K	108,000	69,500	158,000

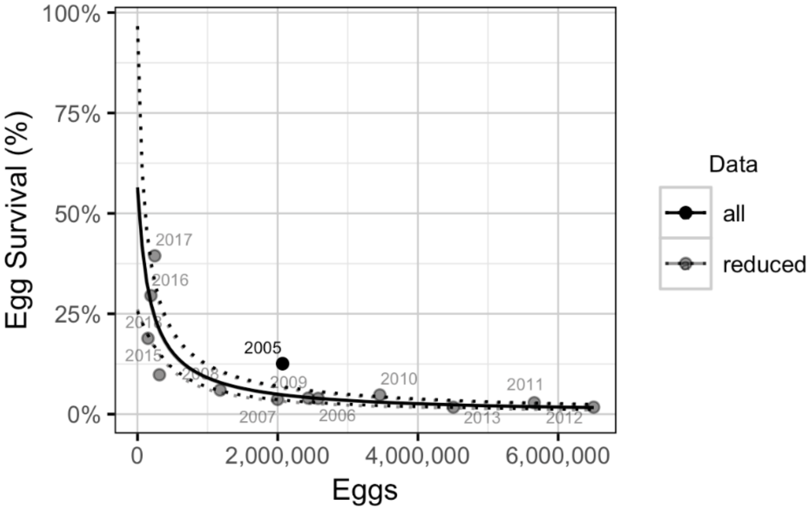

Figure 14. **Predicted egg survival by egg deposition by data set (with 95% CRIs). The labels indicate the spawn year.**

Information from age 1 abundance to a returning spawner can be used to predict average in-lake survival of each successive cohort returning a (age 5, 6 and 7) over time (Figure 15). Information suggests that cohorts entering the lake beginning in 2006 experienced increased in-lake survival which peaked in 2007 before declining (Figure 15)

Figure 15. **In-lake survival from age-1 to spawning by recruitment year**

Maximal Reproductive Rate

Information on the maximal reproductive rate (the number of spawners per spawner at low abundance without fishing), from the stock recruitment relationship, indicates that the Gerrard stock is highly productive (Rk) and has high compensatory ability to changes in mortality (Figure 16). The maximum reproductive rate (not accounting for fishing mortality) increased from around 12.5 adults per recruit (log-transformed ~2.5 adults per recruit) in the early to mid-2000s to over 30 adults per recruit (log-transformed ~3.5 adults per recruit) in 2007 before dropping to under 5 adults per recruit (log-transformed ~1.6 adults per recruit) in 2010. The Gerrard stock appears to indicate time variation in in-lake survival that alters the productivity of the stock over time.

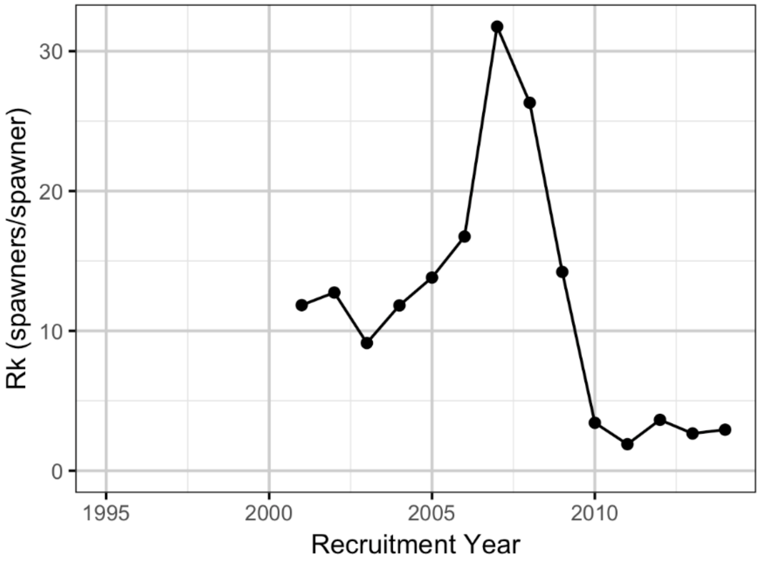

Figure 16. Untransformed maximum reproductive rate (unadjusted for fishing mortality) by recruitment year.

Stock Reference Points

The analysis indicates that a conservation threshold or Limit Reference Point (LRP) for the Gerrard stock is 55 spawners AUC (80% CRI 35-108) or 165,000 eggs (80% CRI 106,000-326,000) at the Gerrard spawning grounds based on fecundity in a typical year. However, we utilized a more conservative approach by utilizing the upper range of the 80% CRI as the LRP. As a result, the LRP is defined as 108 spawners (AUC) or 326,000 eggs at the Gerrard spawning grounds based on fecundity in a typical year. The LRP used for the Gerrard stock is defined as the spawner abundance that produces 50% of the maximum recruitment, known as the half saturation constant (Mace 1994; Chaput 2015). The egg deposition has been below the LRP since 2015 (Figure 12). For the purposes of our reporting, 108 AUC will be considered $S_{0.5R_{max}}$ and 326,000 eggs will be considered $E_{0.5R_{max}}$.

The preliminary upper reference point can also be derived for this population based on parameter inputs using an equilibrium based yield per recruit analysis (YPR). We developed an upper reference under maximum sustainable yield (MSY) when the population was stable (1992-2005). Based on the YPR analysis, the upper reference point indicates a spawner abundance of 490-550 AUC at the Gerrard spawning grounds based on fecundity in a typical year. YPR details are provided in Appendix 6.

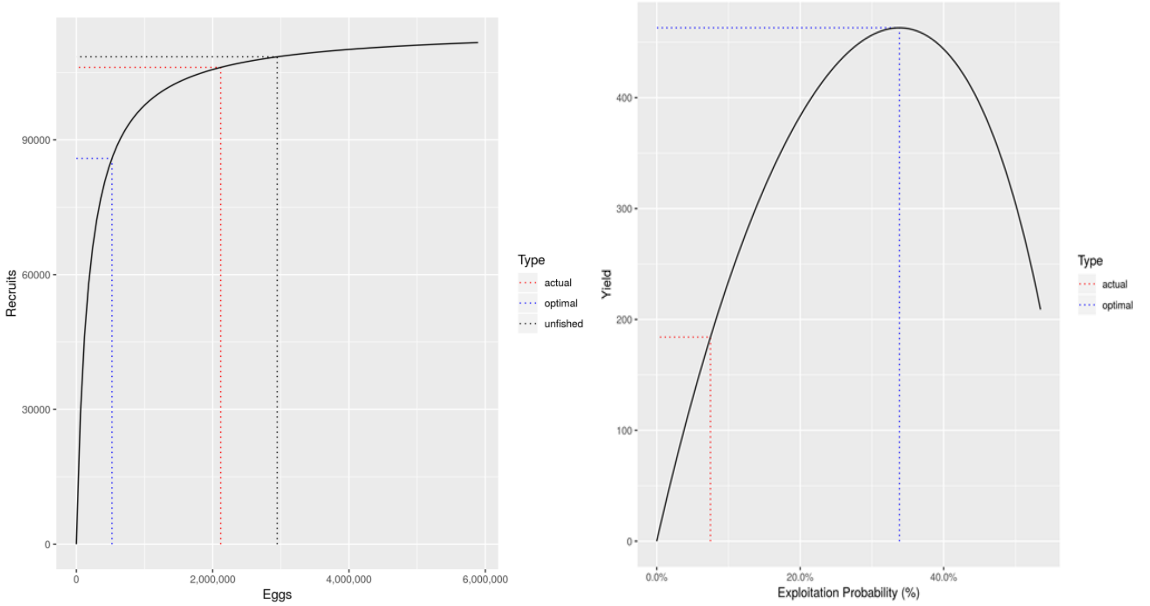

Figure 17. **Equilibrium based yield per analysis used to develop upper reference point for Gerrard population.**

Discussion

Determining a stock's reproductive capacity and productivity is essential for managing this highly exploited population (Hilborn and Walters 1992; Walters and Martell 2004). Obtaining estimates of the in-river Gerrard juvenile abundance from the Lardeau and Duncan rivers provides a critical component for developing a stock-recruitment relationship used to assess the population dynamics and defining biological useable reference points for stock management (Mace 1994; Johnston et al. 2002; Johnston 2013; Chaput 2015). The recent unprecedented collapse of the lakes’ Kokanee population (MFLNRO 2016a) has provided a unique opportunity to obtain information on the population dynamics at low stock abundance

The development of the stock recruitment (SR) relationship is considered a key piece for developing a conservation and management framework for the Gerrard population on Kootenay Lake. Nighttime snorkel surveys have been employed to assess recruitment, providing accurate and precise estimates of abundance often difficult to obtain on medium to large rivers such as the Lardeau and Duncan rivers. Meanwhile, escapement information has been collected and analyzed using AUC as a measure of stock abundance since 1961. Despite the well understood shortcomings and limitations of developing stock recruitment relationships (Walters and Martell 2004), the available data has provided a unique time series of stock abundance and recruitment since 2006.

Stock productivity is a crucial parameter obtained in the SR analysis which can only be obtained when stock abundance is low (Myers 2001). The parameter is vital for developing conservation and management reference points but requires the full life cycle, including the density dependent (riverine) and density independent (in-lake) stages (Chaput 2015). However, changes in spawner sizes, fecundity, repeat spawning and variation in density dependent survival make SR analysis using full life cycle difficult, especially when data is limited. To reduce uncertainty in parameter estimates, egg production was used as a measure of stock abundance (Michielsens and McAllister 2004) in the SR analysis to account for changes in size, condition and fecundity which has changed drastically as a result of changes with food availability and collapse of Kokanee on Kootenay Lake.

Based on analysis of the SR, maximum reproductive rate (not accounting for fishing mortality) for the Gerrard stock was around 12.5 (log transformed ~2.5 adults per recruit) in the early to mid-2000s, increasing to over 30 adults per recruit (log-transformed ~3.5 adults per recruit) in 2007. It also appears that the productivity in the riverine stage is relatively stationary (i.e. no changes in productivity) in comparison to adult productivity which appears to vary substantially over time due to changes in in-lake survival (Figure 15), similar to ocean survival observed for steelhead (Johnston 2013) and Atlantic salmon

(*Salmo salar*) (Chaput 2015). While variations in environmental conditions in the riverine stage can be as important as those in the in-lake stages, there is limited evidence of productivity changes in the riverine stages in comparison to the in-lake stage. As a result, defining upper reference points for the stock is more difficult since adult productivity appears to demonstrate non-stationarity. Nevertheless, Mace (1994) indicated that the degree of resilience or compensatory ability is the most appropriate for defining the LRP. Moreover, since density dependent regulation occurs prior to age 1 in the Gerrard stock, similar to many other riverine salmonids (Elliott 2001; Johnston and Post 2009), the riverine life stage can be used to derive the LRP for this stock.

The LRP used for the Gerrard stock is defined as the spawner abundance that produces 50% of the maximum recruitment, known as the half saturation constant (Mace 1994; Chaput 2015). The reference point was chosen because it can be generated from riverine dynamics that considers stock resilience and generally produces robust values above the lowest conservation thresholds (Chaput 2015). Therefore, the spawner abundance of 108 AUC ($S_{0.5R_{max}}$) and/or 326,000 eggs ($E_{0.5R_{max}}$) was defined as the LRP. Although it important to note, the egg deposition ($E_{0.5R_{max}}$) has fallen below the LRP since 2015.

The choice of optimal reference point for the stock depends upon the management objective for Kootenay Lake, such as maximizing harvest or maximizing opportunity (Andrusak 2005) and needs to ensure long-term genetic diversity is maintained (Rieman and Allendorf 2001). One of the key drivers for the intensive sport fishery on Kootenay Lake, prior to the collapse, was the unique opportunity to catch a trophy sized Gerrard Rainbow Trout that often exceeded > 9 kg (Andrusak 1972, 1974, 1981, 1987, 2010; Andrusak and Andrusak 2012). In addition, an upper reference point is also required to ensure the Kokanee population does not collapse again in the future due to increased predator numbers. Regardless of the objective of the fishery management, information on the productivity of this stock is essential for determining fishing mortality rates which maximize the yield. (i.e. F_{MSY}) or provide escapement targets (i.e. S_{MSY}) used for determining upper reference points. Developing the upper reference point will improve fisheries management associated with stock abundance needed for conservation and management.

In light of recent events on Kootenay Lake, development of a management framework will provide key conservation and management targets to maintain the Gerrard population in future. Importantly, the framework will provide support for decision making in future and provide critical information to precipitate conservation and/or management actions when the thresholds are exceeded.

References

Andrusak, G. 2010. Implementation of a Conservation Plan for Gerrard Rainbow Trout: Stock Assessment of Juvenile Gerrard Rainbow Trout in the Lardeau River.

Andrusak, G.F. 2017. Determination of Gerrard Rainbow Trout Stock Productivity at Low Abundance-2017. Ministry of Forest, Lands and Natural Resources and Rural Development, Victoria, BC.

Andrusak, G.F., and Andrusak, H. 2015. Gerrard Rainbow Trout Growth and Condition with Kokanee Prey at Low Densities. RD, Fish and Wildlife Compensation Program-Columbia, Nelson, BC.

Andrusak, H. 1972. Kootenay Lake Sport Fishery 1970-71.

Andrusak, H. 1974. Kootenay Lake sport fishery. British Columbia Ministry of Environment. Nelson. Br. Columbia.

Andrusak, H. 1981. Kootenay Lake Sportfishery Statistics, 1978-80. British Columbia Fish and Wildlife Branch.

Andrusak, H. 1987. Kootenay Lake Sport Fishery 1984-86 unpublished MS, Fisheries Branch, Nelson, BC Report No. KO-19.

Andrusak, H. 2005. Kootenay Lake Gerrard Rainbow Trout Management Plan. Habitat Conservation Trust Fund, Nelson, BC.

Andrusak, H., and Andrusak, G. 2006. Analysis of Gerrard rainbow trout size, age, fecundity and growth data. Contract Rep. Submitt. BC Minist. Water Land Air Prot. Redfish Consult. Ltd. Nelson BC.

Andrusak, H., and Andrusak, G. 2012. Kootenay Lake Angler Creel Survey 2011. Redfish Consulting Ltd, Report prepared for Fish and Wildlife Compensation Program – Columbia Basin, Nelson, BC.

Beverton, R.J.H., and Holt, S.J. 1957. On the Dynamics of Exploited Fish Populations. Chapman and Hall, London, UK.

Bradford, M.J., Korman, J., and Higgins, P.S. 2005. Using confidence intervals to estimate the response of salmon populations (*Oncorhynchus* spp.) to experimental habitat alterations. Can. J. Fish. Aquat. Sci. **62**(12): 2716–2726. doi:10.1139/f05-179.

Carpenter, B., Gelman, A., Hoffman, M.D., Lee, D., Goodrich, B., Betancourt, M., Brubaker, M., Guo, J., Li, P., and Riddell, A. 2017. *Stan* : A Probabilistic Programming Language. J. Stat. Softw. **76**(1). doi:10.18637/jss.v076.i01.

Chaput, G. 2015. Considerations for defining reference points for Atlantic Salmon that conform to the Precautionary Approach. DFO (Doc. 2015/074): +46.

Chaput, G., Cass, A., Grant, S., Huang, M.A., and Veinott, G. 2012. Considerations for defining refernce points for semelparous species, with emphasis on anadramous salmonid species including iteroparous salmonids. Research Document 2012/146, DFO.

Decker, S., and Hagen, J. 2009. Stock Assessment of Juvenile Gerrard Rainbow Trout in the Lardeau/Duncan System: Feasibility Study 2005-2008. Habitat Conservation Trust Foundation, Victoria, BC.

Elliott, J.M. 2001. The relative role of density in the stock-recruitment relationship of salmonids. *In* E. Prevost and G. Chaput (Eds.). Paris. p. pg 25-66.

English, K.K., Bocking, R.C., and Irvine, J.R. 1992. A robust procedure for estimating salmon escapement based on the area-under-the-curve method. Can. J. Fish. Aquat. Sci. **49**(10): 1982–1989.

Gabriel, W.L., and Mace, P.M. 1999. A review of biological reference points in the context of the precautionary approach. In Proceedings of the fifth national NMFS stock assessment workshop: providing scientific advice to implement the precautionary approach under the Magnuson-Stevens fishery conservation and management act. NOAA Tech Memo NMFS-F/SPO-40, Northeast Fisheries Science Center.

Hagen, J., Baxter, J., Burrows, J.A., and Bell, J. 2007. Gerrard Rainbow Trout (Oncorhynchus mykiss) Spawner Migration and Residence Time as Estimated by Radio and Sonic Telemetry, 2004-2006. Fish and Wildlife Compensation Program, Nelson, Ministry of Environment, Nelson and BC Hydro, Castlegar, Castlegar, BC.

Hagen, J., Decker, S., Korman, J., and Bison, R.G. 2010. Effectiveness of Night Snorkeling for Estimating Steelhead Parr Abundance in a Large River Basin. North Am. J. Fish. Manag. **30**(5): 1303–1314. doi:10.1577/M09-160.1.

Hankin, D.G. 1984. Multistage Sampling Designs in Fisheries Research: Applications in Small Streams. Can. J. Fish. Aquat. Sci. **41**(11): 1575–1591. doi:10.1139/f84-196.

Hilborn, R., and Walters, C.J. 1992. Quantitative fisheries stock assessment: choice, dynamics, and uncertainty. Chapman and Hall, New York.

Irvine, J.R. 1978. The Gerrard Rainbow Trout of Kootenay Lake, British Columbia: A Discussion of Their Life History with Management, Research and Enhancement Recommendations. BC Ministry of Recreation and Conservation.

Johnston, F.D., and Post, J.R. 2009. Density-dependent life-history compensation of an iteroparous salmonid. Ecol. Appl. **19**(2): 449–467. doi:10.1890/07-1507.1.

Johnston, N.T. 2013. Management reference points for the Thompson and Chilcotin late summer-run steelhead (Onchorhynchus mykiss) stock aggregates. Fisheries Project Report, Ministry of Forests, Lands and Natural Resource Operations-BC Fish and Wildlife Branch, Vancouver, B.C.

Johnston, N.T., Parkinson, E.A., Tautz, A.F., and Ward, B.R. 2000. Biological reference points for the conservation and management of steelhead, Oncorhynchus mykiss. Department of Fisheries and Oceans, Vancouver, BC.

Johnston, N.T., Parkinson, E.A., Tautz, A.F., and Ward, B.R. 2002. Biological Reference Points from Deterministic Stock Recruitment Relations. BC Fisheries Branch: Research and Development Section, Ministry of Water, Land and Air Protection, Vancouver, B.C.

Keeley, E.R., Parkinson, E.A., and Taylor, E.B. 2007. The origins of ecotypic variation of rainbow trout: a test of environmental vs. genetically based differences in morphology. J. Evol. Biol. **20**(2): 725–736. doi:10.1111/j.1420-9101.2006.01240.x.

Kéry, M., and Schaub, M. 2011. Bayesian population analysis using WinBUGS: a hierarchical perspective. *In* 1st ed. Academic Press, Boston.

Korman, J., Decker, A.S., Mossop, B., and Hagen, J. 2010. Comparison of electrofishing and snorkeling mark–recapture estimation of detection probability and abundance of juvenile steelhead in a medium-sized river. North Am. J. Fish. Manag. **30**(5): 1280–1302.

Korman, J., Schick, J., and Mossop, B. 2016. Estimating Riverwide Abundance of Juvenile Fish Populations: How Much Sampling is Enough? North Am. J. Fish. Manag. **36**(2): 213–229. doi:10.1080/02755947.2015.1114542.

Kurota, H., McAllister, M.K., Parkinson, E.A., and Johnston, N.T. 2016. Evaluating the influence of predator-prey interactions on stock assessment and management reference points for a large lake ecosystem. Canadian Journal of Fisheries and Aquatic Sciences.

Lin, J. 1991. Divergence measures based on the Shannon entropy. IEEE Trans. Inf. Theory **37**(1): 145–151. doi:10.1109/18.61115.

Mace, P.M. 1994. Relationships between Common Biological Reference Points Used as Thresholds and Targets of Fisheries Management Strategies. Can. J. Fish. Aquat. Sci. **51**(1): 110–122. doi:10.1139/f94-013.

MFLNRO. 2016a. Kootenay Lake Action Plan. Ministry of Forest, Lands and Natural Resources, Nelson, BC.

MFLNRO. 2016b. Provincial Framework for Steelhead Management In BC. Ministry of Forests, Lands and Natural Resource Operations, Victoria, BC.

Michielsens, C.G., and McAllister, M.K. 2004. A Bayesian hierarchical analysis of stock–recruit data: quantifying structural and parameter uncertainties. Can. J. Fish. Aquat. Sci. **61**(6): 1032–1047. doi:10.1139/f04-048.

Myers, R. 2001. Stock and recruitment: generalizations about maximum reproductive rate, density dependence, and variability using meta-analytic approaches. ICES J. Mar. Sci. **58**(5): 937–951. doi:10.1006/jmsc.2001.1109.

Myers, R.A., Bowen, K.G., and Barrowman, N.J. 1999. Maximum reproductive rate of fish at low population sizes. Can. J. Fish. Aquat. Sci. **56**(12): 2404–2419. Available from http://www.nrcresearchpress.com/doi/abs/10.1139/f99-201 [accessed 2 April 2013].

Parken, C.K., Bailey, R.E., and Irvine, J.R. 2003. Incorporating uncertainty into area-under-the-curve and peak count salmon escapement estimation. North Am. J. Fish. Manag. **23**(1): 78–90.

Plummer, M. 2015. {JAGS} version 3.3.0 user manual. Available from http://sourceforge.net/projects/mcmc-jags/files/Manuals/3.x/.

R Core Development Team. 2017. A language and environment for statistical computing. R Foundation for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Rieman, B.E., and Allendorf, F. 2001. Effective population size and genetic conservation criteria for bull trout. North Am. J. Fish. Manag. **21**(4): 756–764.

Slaney, P.A., and Andrusak, H. 2003. Fish Habitat Assessments of the Lardeau River (2002) Integrated with Habitat Assessments of the Duncan River. Ministry of Water, Land and Air Protection Nelson, B.C.

Thorley, J.L., and Andrusak, G.F. 2017. The fishing and natural mortality of large, piscivorous Bull Trout and Rainbow Trout in Kootenay Lake, British Columbia (2008–2013). PeerJ **5**: e2874. doi:10.7717/peerj.2874.

Walters, C.J., and Martell, S.J.D. 2004. Fisheries ecology and management. Princeton University Press, Princeton, N.J.

Williams, E.H., and Shertzer, K.W. 2003. Implications of life-history invariants for biological reference points used in fishery management. Can. J. Fish. Aquat. Sci. **60**(6): 710–720. doi:10.1139/f03-059.

Appendix 1. Gerrard spawner escapement 1961-2019

Year	Peak Count	Peak X 3.08	AUC (fish*days)	*AUC (N)*
2019	186	573	1854	156
2018	149	459	1827	154
2017	181	557	2994	252
2016	114	351	1945	163
2015	188	579	3398	301
2014	711	2190	11091	932
2013	750	2310	14886	1251
2012	1068	3289	18231	1532
2011	995	3065	17047	1432
2010	725	2233	14893	1251
2009	589	1814	12599	1059
2008	514	1583	6117	514
2007	464	1429	8231	692
2006	438	1349	7770	653
2005	426	1312	7242	609
2004	406	1250	7478	628
2003	303	933	5964	501
2002	227	699	4748	399
2001	244	752	3762	316
2000	340	1047	7061	593
1999	399	1229	8382	704
1998	367	1130	6997	588
1997	344	1060	5551	466
1996	275	847	6564	552
1995	286	881	6684	562
1994	275	847	7149	601
1993	257	792	5841	491
1992	219	675	5544	466
1991	280	862	7460	627
1990	382	1177	9091	764
1989	363	1118	7028	591
1988	340	1047	6531	549
1987	294	906	5821	489
1986	378	1164	8623	725
1985	241	742	5077	427
1984	220	678	4721	397
1983	270	832	4564	384
1982	417	1284	8051	677
1981	453	1395	8435	709
1980	440	1355	8933	751
1979	618	1903	10076	847
1978	473	1457	8099	681
1977	347	1069	5878	494
1976	272	838	6726	565
1975	346	1066	6505	547
1974	287	884	6168	518
1973	258	795	4979	418
1972	238	733	3747	315
1971	176	542	3371	283
1970	203	625	3599	302
1969	237	730	6275	527
1968	178	548	4597	386
1967	180	554	3575	300
1966	249	767	7380	620
1965	377	1161	8297	697
1964	234	721	3715	312
1963	251	773	6234	524
1962	258	795	5977	502
1961	214	659	3534	297

Appendix 2. Abundance model coefficients

term	estimate	sd	zscore	lower	upper	pvalue
bDensity	-0.7607636	1.1561023	-0.6742722	-3.0319881	1.4261906	0.5160
bDensityRkm1	-0.2002844	0.0951455	-2.0646251	-0.3793614	-0.0093872	0.0413
bDensityRkm2	0.6990284	0.1085313	6.4447752	0.4845076	0.9071412	0.0007
bDensityRkm3	0.0241088	0.0384032	0.6044451	-0.0527287	0.0981108	0.5600
bDensityRkm4	-0.3066138	0.0359931	-8.5345925	-0.3760614	-0.2386546	0.0007
bDensityWidth	0.0881415	0.0277506	3.2091328	0.0353163	0.1445341	0.0013
bDensityYear1	0.7532300	1.1889240	0.6455826	-1.5275878	3.0814713	0.5360
bDensityYear2	-0.1646217	1.1860415	-0.1416503	-2.4764562	2.1312142	0.8867
bDensityYear3	-0.4705407	1.1694619	-0.4179577	-2.7677794	1.8060433	0.6627
bDensityYear4	-0.5263892	1.1805706	-0.4529708	-2.8168709	1.8274796	0.6520
bDensityYear5	-0.2024856	1.1892890	-0.1756103	-2.5324501	2.1645429	0.8640
bDensityYear6	0.3048713	1.1607872	0.2713507	-1.9038821	2.6645695	0.7800
bDensityYear7	0.2629078	1.1622348	0.2451026	-1.9307674	2.6324490	0.8120
bDensityYear8	-0.1037340	1.1612491	-0.0641941	-2.2425239	2.2436714	0.9413
bDensityYear9	-0.4565983	1.1625668	-0.3775051	-2.6516372	1.8593701	0.7173
bDensityYear10	-1.3886294	1.1597552	-1.1853318	-3.5680948	0.9357530	0.2347
bDensityYear11	-0.7832372	1.1630077	-0.6568957	-2.9540413	1.5620239	0.5267
bDensityYear12	-0.2509581	1.1627343	-0.1943220	-2.4014962	2.1040140	0.8480
bDensityYear13	-1.4624000	1.1641541	-1.2519882	-3.6598846	0.8674248	0.2080
bEfficiency	-1.7781440	0.1451762	-12.2554187	-2.0623369	-1.5044287	0.0007
bEfficiencyIndex	0.2754663	0.4242570	0.6229875	-0.5725449	1.1101548	0.5360
bEfficiencyMarking	0.1306282	0.1029821	1.2974438	-0.0599982	0.3351911	0.1973
bEfficiencyMarkingIndex	1.5835704	0.4167981	3.8087252	0.7942319	2.4185364	0.0013
sDensitySite	0.6377221	0.0370255	17.2431886	0.5677290	0.7104917	0.0007
sDispersion	1.2487283	0.0632765	19.7436554	1.1344972	1.3756299	0.0007

Appendix 3. Condition model coefficients

term	estimate	sd	zscore	lower	upper	pvalue
bWeight	-12.658203	0.2086329	-60.67838	-13.084986	-12.263615	7e-04
bWeightLength	3.204790	0.0315039	101.73624	3.145275	3.270979	7e-04
sWeight	-1.906059	0.0216453	-88.04412	-1.948303	-1.863327	7e-04
sWeightYear	-2.120613	0.1657116	-12.76173	-2.446724	-1.778655	7e-04

Appendix 4. Fecundity model coefficients

term	estimate	sd	zscore	lower	upper	pvalue
bFecundity	3.8012790	0.9834289	3.688632	1.5490640	4.9584933	7e-04
bFecundityWeight	0.8628457	0.0365621	23.891517	0.8314001	0.9654232	7e-04
sFecundity	0.1248082	0.0215635	5.936688	0.0958774	0.1802509	7e-04

Appendix 5. Stock recruitment model coefficients

term	estimate	sd	zscore	lower	upper	pvalue
a	0.5645723	0.2037437	2.861395	0.2559306	0.9664123	7e-04
b	0.0000050	0.0000025	2.197717	0.0000017	0.0000110	7e-04
sScaling	2.2198954	0.5589822	4.154955	1.5307592	3.7323148	7e-04

Appendix 6. Equilibrium yield per recruit

tmax	The maximum age (yr).
k	The VB growth coefficient (per yr).
Linf	The VB mean maximum length (cm).
t0	The (theoretical) age at zero length (yr).
Wb	The weight (as a function of length) scaling exponent.
Ls	The length at which 50% mature (cm).
Sp	The maturity (as a function of length) power.
es	The annual probability of a mature fish spawning.
Sm	The spawning mortality probability.
fb	The fecundity (as a function of weight) scaling exponent.
tR	The age from which survival is density-independent (yr).
BH	Recruitment follows a Beverton-Holt (1) or Ricker (0) relationship.
Rk	The spawners per spawner or if less than 1 the egg to age tR survival at low density.
M	The instantaneous mortality rate (per yr).
Mb	The instantaneous mortality rate (as a function of length) scaling exponent.
Lv	The length at which 50% vulnerable to harvest (cm).
Vp	The vulnerability to harvest (as a function of length) power.
Llo	The lower harvest slot length (cm).
Lup	The upper harvest slot length (cm).
Nc	The slot limits non-compliance probability.
pi	The annual capture probability.
rho	The release probability.
Hm	The hooking mortality probability.
Rmax	The number of recruits at the carrying capacity (ind).
A0	The initial post age tR density independent mortality probability.
Wa	The (extrapolated) weight of a 1 cm individual (g).
fa	The (theoretical) fecundity of a 1 g female (eggs).
q	The catchability (annual probability of capture) for a unit of effort.