Determination of Gerrard Rainbow Trout Stock Productivity at Low Abundance

Final Report

December 2024

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Prepared for

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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 populations 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 2024 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, and counts have occurred since 1957. Juvenile monitoring has occurred every year since 2006, except for 2015, providing information on recruitment. Combined, juvenile recruitment and spawning stock abundance and fecundity provide the necessary information to develop a stock-recruitment relationship for the Gerrard population. Recruitment estimates (below) are derived from the 2023 Gerrard escapement year.

In 2024, age-1 abundance for the Lardeau and Duncan rivers was estimated to be 27,324 (95% CRI 18,500 -42,083). Age-2 abundance for the Lardeau and Duncan rivers was estimated to be 14,011 (95% CRI 8,862 -21,118). The observed variation in recruitment in the time series is partly due to changes in total spawner returns and fecundity associated with in-lake Kokanee abundance. The 2024 juvenile recruitment estimates are the progeny from the 2023 spawners estimated at 331 using AUC method. These escapement estimates are much lower than the record high of >1,500 fish observed in 2012 and are some of the lowest recorded since 1957.

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 a relatively minor increase in recruitment in the age-1 juvenile abundance at egg deposition above 1,000,000. Based on the SR analysis, the maximum reproductive rate (α_s), survival from egg to age-1, was approximated to 0.36 (95% CRI 0.18—0.92). Information on the maximal reproductive rate (the number of spawners per spawner at low abundance without fishing indicates the Gerrard stock is highly productive. The

lifetime maximum reproductive rate (not accounting for fishing mortality) increased from around 10 adults per recruit in the early to mid-2000s to over 20 adults per recruit in 2007 before dropping to under 5 adults per recruit in 2015. The Gerrard stock indicates time variation in in-lake survival that alters the productivity of the stock over time.

Biological reference point (BRP) defining the conservation thresholds for this population were developed. The limit reference point (LRP) for the Gerrard stock is an AUC based spawner abundance of 99 fish (80% CRI 38-197) or 297,000 eggs (80% CRI 115,000-593,000). The LRP is defined as the spawner abundance or egg deposition that produces 50% of the maximum recruitment, known as the half saturation constant.

Our modelling approach also evaluated the proportional change in age-at-return of the spawners in the time series within the stock-recruitment analysis. Age-at-return demonstrated a slight change in the age of spawners over the time series, with a downward shift in median age after 2012 (WLRS on file). However, results of the sensitivity analysis demonstrate that, following the collapse of Kootenay Lake, the upward trend in both LMRR and in-lake survival persist regardless of changes in the assumed age-at-return.

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 following the collapse in 2012. However, the status provides a unique opportunity to assess population dynamics at low abundance and assist with developing BRPs for the stock.

Acknowledgements

Funding for this project was provided by the Habitat Conservation Trust Foundation (HCTF).

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. Jen Sarchuk, Evan Amies-Galonski, Kerry Reed, Emmanuel Abecia, Jeff Berdusco and Gillian Sanders formed a great working team that made the work much easier than otherwise it could have been. Evan Amies-Galonski entered the data into the database and performed spatial data checks and preliminary analysis.

The Province of BC is also gratefully acknowledged for their support in allowing staff to contribute to the collection of this information detailed in this report. Shannon Harris and Harvey andrusak are also acknowledged for their review of this technical report. In addition, Molly Teather and Eric Hegerat provided data on size and condition, spawner counts, KLRT catch and size data use to determine egg deposition. Will Warnock provided data on predator reduction numbers and final escapement numbers used in stock recruitment analysis.

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 be obtained when stock abundances decline to low levels, is essential in managing exploited populations (Myers et al. 1999). Stock productivity (i.e. lifetime maximum reproductive rate-LMRR) and carrying 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 unprecedented collapse of Kootenay Lakes’ Kokanee (*Oncorhynchus nerka*) population has created serious problems for the predator populations on Kootenay Lake (Warnock et al. 2021). The Gerrard Rainbow Trout (*Oncorhynchus mykiss*) population abundance has undergone a severe decline as a result of extremely low Kokanee abundance (Warnock et al. 2021). 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 variable stock abundance but is also expected to assist with recovery initiatives for Kootenay Lake (WLRS on file). Stock abundance (spawner numbers) is expected to be at or near record lows over the coming years with the implementation of a predator reduction program to assist Kokanee recovery on the lake (WLRS on file). Obtaining Gerrard juvenile production information will provide effectiveness monitoring for the predator reduction program implemented on the lake. An outcome of the effectiveness monitoring will be an improved understanding of the population dynamics for this unique population (Keeley et al. 2005, 2007). Moreover, information will assist future fisheries biologists and managers in developing an abundance based management framework (i.e. reference points) for this population, similar to that for Steelhead in BC (MFLNRO 2016b).

Project objectives:

- Estimate the spring abundance of age-1 fish.

- Estimate the stock-recruitment relationship between the egg deposition and the abundance of age-1 recruits the following spring.
- Estimate the maximum reproductive rate (spawners per spawner at low density).
- Assist with Kootenay Lake recovery initiatives
- Effectiveness monitoring for the predator reduction program
- Conservation and management reference points

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 reaches 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).

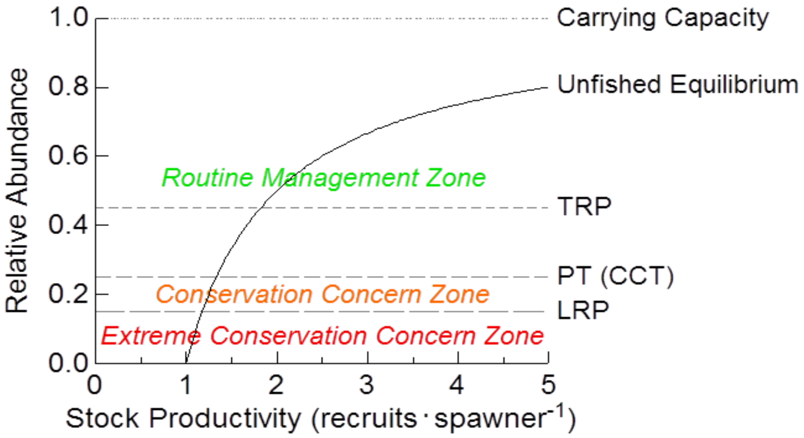

Figure 1. Abundance based reference points and management zones framework in BC, see details in (Johnston et al. 2000; MFLNRO 2016b)

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 (Warnock et al. 2021). Gerrard Rainbow Trout growth, condition, fecundity, survival and abundance have declined in concert with the collapse of the lakes Kokanee population (Andrusak and Andrusak 2015). Understanding how the population is responding to the recovery of their primary prey is critical. Obtaining information at low stock abundance provides an opportunity to assess the stocks reproductive rate, their recovery potential and recovery of the once world-renowned fishery.

Gerrard Rainbow Trout Biology

Gerrard Rainbow Trout are iteroparous 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 (WLRS 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, predominantly occurring in the first fall and winter following emergence. Most fish likely enter Kootenay Lake ≥ age-1 where survival is considered density independent associated with in-lake conditions. 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 of 162 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) including side channels of 196.2 km (Figure 2). However, most of the juvenile recruitment study area is located in the Lardeau River which constitutes 141.6 km of bank from the total of 196.2 km.

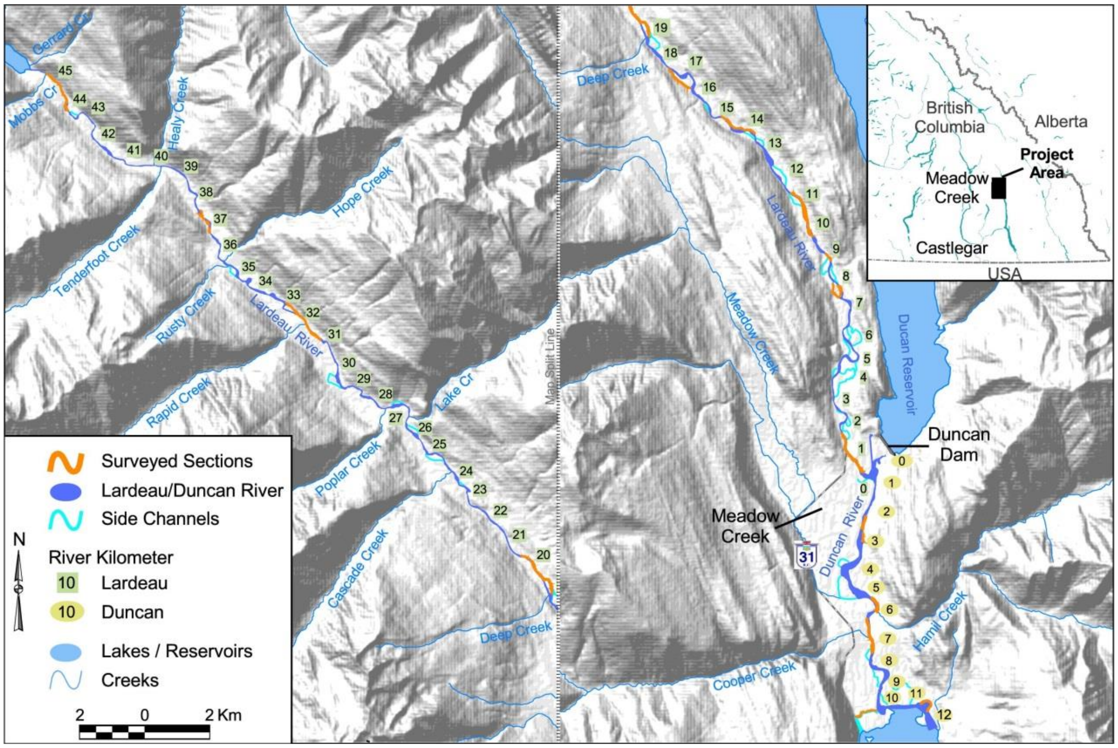

Figure 2. **Location of Kootenay Lake Lardeau and Duncan rivers**

Methods

Gerrard Juvenile Recruitment Surveys

Estimates of Gerrard juvenile recruitment have been obtained using 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 (Wyatt 2003; 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 (2006-2020) 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 (WLRS on file).

For the purposes of our analysis, we use information from 2000-2020. Gerrard Rainbow Trout escapements are estimated using area-under-the-curve (AUC) methodology (English et al. 1992; Irvine et al. 1993) since 1961.

Analysis

Data Preparation

The data was provided by the Ministry of Water, Lands and Resource Stewardship (WLRS). The historical and current snorkel count data was manipulated using R version 4.4.2 (R Core Team 2022) and organized in an SQLite database.

Data Analysis

Model parameters were estimated using Bayesian methods. The estimates were produced using JAGS (Plummer 2003) and STAN (Carpenter et al. 2017). For additional information the reader is referred to (McElreath 2020).

Unless stated otherwise, the Bayesian analyses used weakly informative normal and half-normal prior distributions (Gelman, Simpson, and Betancourt 2017). The posterior distributions were estimated from 1500 Markov Chain Monte Carlo (MCMC) samples thinned from the second halves of 3 chains (Kery and Schaub 2011, 38–40). Model convergence was confirmed by ensuring that the potential scale reduction factor $\hat{R} \leq 1.05$ (Kery and Schaub 2011, 40) and the effective sample size (Brooks et al. 2011) ESS ≥ 150 for each of the monitored parameters (Kery and Schaub 2011, 61).

The parameters are summarised in terms of the point *estimate*, *lower* and *upper* 95% compatibility limits (Rafi and Greenland 2020) and the surprisal *s-value* (Greenland 2019). Together a pair of lower and upper compatibility limits (CLs) are referred to as a compatibility interval (CI). The estimate is the median (50th percentile) of the MCMC samples while the 95% CLs are the 2.5th and 97.5th percentiles. The s-value indicates how surprising it would be to discover that the true value of the parameter is in the opposite direction to the estimate (Greenland 2019). An s-value of $>$ 4.32 bits, which is equivalent to a p-value $<$ 0.05 (Kery and Schaub 2011; Greenland and Poole 2013), indicates that the surprise would be equivalent to throwing at least 4.3 heads in a row on a fair coin.

Variable selection was based on the heuristic of directional certainty Castilho and Prado (2021). Fixed effects were included if their s-value was $>$ 4.32 bits (Kery and Schaub 2011). Based on a similar argument, random effects were included if their standard deviation had a lower 95% CL $>$ 5% of the median estimate.

Model adequacy was assessed via posterior predictive checks (Kery and Schaub 2011). More specifically, the number of zeros and the first four central moments (mean, variance, skewness and kurtosis) for the deviance residuals were compared to the expected values by simulating new residuals. In this context the s-value indicates how surprising each observed metric is given the estimated posterior probability distribution for the residual variation.

Where computationally practical, the sensitivity of the parameters to the choice of prior distributions was evaluated by increasing the standard deviations of all normal, half-normal and log-normal priors by an order of magnitude and then using $\hat{R}$ to evaluate whether the samples were drawn from the same posterior distribution (Thorley and Andrusak 2017).

The results are displayed graphically by plotting the modeled relationships between individual variables and the response 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 average values (expected values of the underlying hyperdistributions) (Kery and Schaub 2011, 77–82).

Unless stated otherwise the typical value is the arithmetic mean. When informative the influence of a particular variables is expressed in terms of the *effect size* (i.e., relative change in the response variable) with the 95% CI (Bradford, Korman, and Higgins 2005).

The analyses were implemented using R version 4.4.2 (R Core Team 2022) and the `embr` family of packages.

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[i]	i^{th}-order polynomial coefficients of effect of river kilometer on bDensity
bDensitySite[i]	Effect of i^{th} Site 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
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.

The condition of fish has been assumed to remain constant since 2021, the most recent year for which length and weight data for individual adults is available.

Table 2. Parameter descriptions

Parameter	Description
bWeight	Intercept of log(eWeight)
bWeightLength	Intercept of effect of log(Length) on bWeight
bWeightYear[i]	Effect of ith Year on bWeight
eWeight[i]	Expected Weight of ith fish
Length[i]	Fork length of ith fish
sWeight	Log standard deviation of residual variation in log(Weight)
sWeightYear	Log standard deviation of bWeightYear
Weight[i]	Recorded weight of ith fish
Year[i]	Year ith 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 ith fish
Fecundity[i]	Fecundity of ith fish (eggs)
sFecundity	SD of residual variation in log(Fecundity)
Weight[i]	Weight of ith 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 (WLRS 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 Beverton-Holt 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 several 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

The relationship between the number of eggs (E) and the abundance of age-1 individuals the following spring (R) was also estimated using a simplified hockey stick stock-recruitment model (Barrowman and Myers 2000). The relationship is fit as a single regression with a slope $a > 0$ at the origin which is constrained to be horizontal beyond a break point of some estimated level of spawner abundance, E* (Mesnil and Rochet 2010):

$$R = \begin{cases} aE, & E < E^* \\ R = aE^*, & E \geq E^* \end{cases}$$

Key assumptions of the hockey stick stock-recruitment model include:

- The ratio of the number of recruits to the number of eggs the previous year is between zero and one.
- The expected number of recruits does not change beyond the breakpoint E*.
- The expected number of recruits increases linearly with the number of eggs until the break point.
- 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.

Age-1 to Age-2 Survival

The relationship between the number of age-1 individuals and the number of age-2 individuals the following year was estimated using a linear regression through the origin where the slope was constrained to lie between 0 and 1 by a logistic transformation.

Key assumptions of the survival rate model include:

- The residual variation in the number of age-2 individuals is log-normally distributed.

Calculated In-lake Survival

The in-lake survival of each recruit cohort was calculated by dividing the number of spawners in a given year by the number of age-1 recruits 6 years previous, assuming all spawners return at age-7.

Modelled In-lake Survival

The in-lake survival was estimated by modelling the relationship between the number of spawners in each year and the number of age-1 recruits four, five, and six years prior. The number of years indexed back is a key assumption and input to the model implying different ages of return. A proportional value was then assigned to each age class describing the proportion of recruits adopting each return strategy, for the pre and post collapse periods separately.

The survival in each year was fit as the fractional multiplier required to produce the expected number of spawners given the assumed proportions of each return strategy. Each estimate of year survival was effectively informed by the age-1 to spawner survival of all sets of recruits that passed through a given year. The sensitivity of the survival estimates to the proportion of fish adopting each return strategy was evaluated by refitting the model assuming different sets of proportions for each strategy in the pre and post collapse periods separately. The cohort survival was estimated by summing the proportional subsets of spawners returning at the three different ages assumed to originate from a single recruit cohort, and dividing that sum by the number of recruits in the original cohort.

An additional Beverton-Holt stock-recruitment model was used to analyse the relationship between spawners (E) and subsequent age-1 recruits (R), facilitating the estimation of recruit numbers prior to the availability of actual recruit data, and enabling the estimation of survival rates throughout the entire time-series of spawner counts. Key assumptions of the in-lake survival model include:

- Spawning fish return at age five, six, or seven.
- Spawning fish intend to return in some fixed proportion of age classes across all years in each period.
- Each spawning fish produces the same number of eggs in each year.
- The collapse of Kootenay Lake Kokanee occurred in 2013.
- The residual variation in the number of spawners is log-normally distributed

Expected Spawners

The expected spawners without in-river and/or in-lake variation was calculated from the stock-recruitment relationship. The mean value from the calculated age-1 to spawner survival (0.79%) was used in deriving the numbers of expected spawners in the scenarios of no in-lake variation.

Lifetime Maximal 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 fish adopt the strategy of intending to return at age 5, 6 and 7.

Results

2024 Juvenile Surveys

Surveys conducted in the spring of 2024 covered approximately 5% of the Lardeau River and of the Duncan River combined (Table 5). Mark re-sight effort information used in determining observer efficiency for age-1- & 2-year-old fish is shown in Table 5.

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 2006-2023, excluding 2015.

Year	Sites	SurveyLength	SurveyPercent	Fish	Marked	Resighted
2006	32	1.8	1	567	83	42
2007	46	2.6	1	251	0	0
2008	97	7.5	4	605	102	47
2009	83	5	3	390	0	0
2010	44	2.3	1	258	0	0
2011	238	14.3	7	1617	0	0
2012	231	13.5	7	1455	33	6
2013	397	22.1	12	1813	123	39
2014	344	19.8	10	1241	110	31
2016	283	16.1	8	330	16	3
2017	599	35.2	18	1614	51	6
2018	213	11.5	6	933	54	11
2019	299	16.2	8	322	29	2
2020	258	13.5	7	450	67	10
2021	229	11.4	6	194	22	10
2022	211	10.5	5	220	24	3
2023	181	9.1	5	360	46	8
2024	196	9.7	5	205	21	7

Juvenile Abundance

In 2024, age-1 abundance for the Lardeau and Duncan rivers was estimated to be 27, 324 (95% CRI 18,500 -842,083), down from 2023 (Table 6;Figure 3). Apart from 2006, the total age-1 abundance (both rivers) has averaged approximately 90,000. Parameter estimates for the abundance analysis is available in Appendix 2.

In 2024, age-2 abundance for the Lardeau and Duncan rivers was estimated to be 14,011 (95% CRI 8,862 -21,118), down from 2023 (Table 7;Figure 4). Age-2 abundance (both rivers) has averaged approximately 23,000. 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 & 2016-2024.**

Year	Estimate	Lower 95% CRI	Upper 95% CRI
2006	208,059	120,016	374,927
2007	90,347	52,415	159,292
2008	67,529	42,726	109,428
2009	64,808	38,051	114,127
2010	78,374	44,550	140,344
2011	181,077	132,155	257,651
2012	173,063	126,654	241,678
2013	109,221	80,990	149,404
2014	76,614	57,621	105,029
2016	26,774	19,221	37,954
2017	53,150	39,252	73,146
2018	97,249	70,656	136,961
2019	27,231	19,632	39,569
2020	58,645	41,749	85,170
2021	29,174	19,974	43,691
2022	33,669	23,258	49,746
2023	56,272	39,272	84,474
2024	27,324	18,500	42,083

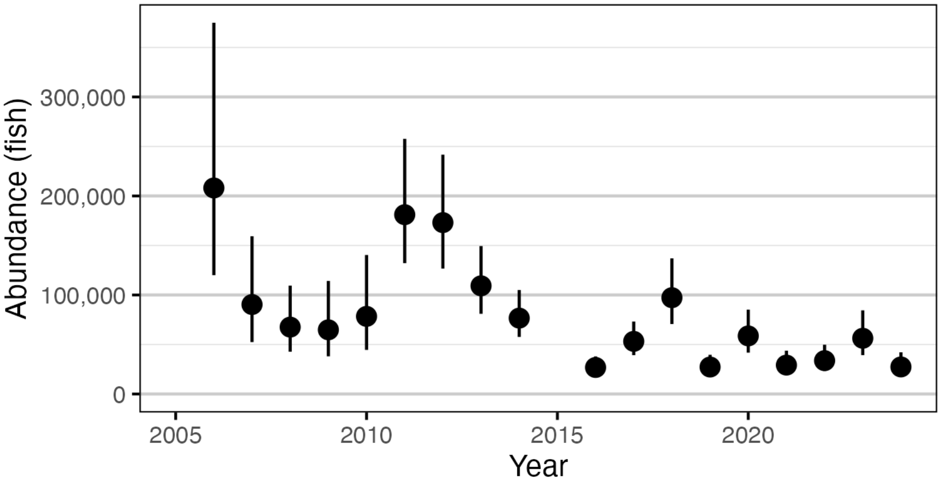

Figure 3. **Predicted abundance of Rainbow Trout age-1 by year (with 95% CRIs) in Lardeau and Duncan rivers combined from 2006-2014 & 2016-2024. No sampling was conducted in 2015.**

Table 7. Estimated age-2 abundance in Lardeau and Duncan rivers from 2006-2014 & 2016-2024.

Year	Estimate	Lower 95% CRI	Upper 95% CRI
2006	12,734	6,623	24,368
2007	40,905	21,740	80,319
2008	15,807	9,485	27,277
2009	25,181	14,288	45,351
2010	24,398	13,012	45,276
2011	37,992	24,864	57,186
2012	41,602	28,281	62,927
2013	43,907	31,006	63,476
2014	20,723	14,599	31,175
2016	24,096	16,186	35,636
2017	9,930	6,894	14,521
2018	20,617	13,954	30,632
2019	12,549	8,693	18,733
2020	11,965	7,871	19,060
2021	15,591	10,255	24,109
2022	14,322	9,480	22,519
2023	20,771	13,660	31,238
2024	14,011	8,862	21,118

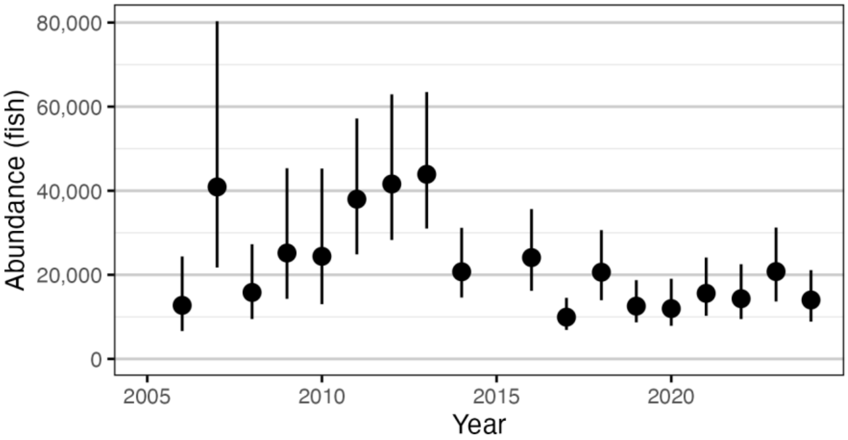

Figure 4. Predicted abundance of Rainbow Trout age-2 by year (with 95% CRIs) in Lardeau and Duncan rivers combined from 2006-2014 & 2016-2023. No sampling was conducted in 2015.

Spawner Escapement

The 2024 Gerrard AUC escapement estimate was 502, higher than the 2023 estimate of 331. The estimate does not include the removal of 726 pre-spawners as part of predator reduction efforts on Kootenay Lake. Escapement estimates since 2000 have ranged from a low of 153 in 2018 to a high of 1,532 in 2012 (Figure 5). The escapement time series now displays the AUC estimate of the total number of returning fish in addition to the number of spawning fish. The difference between the two is the pre-spawner removals associated with the predator reduction program (Figure 5).

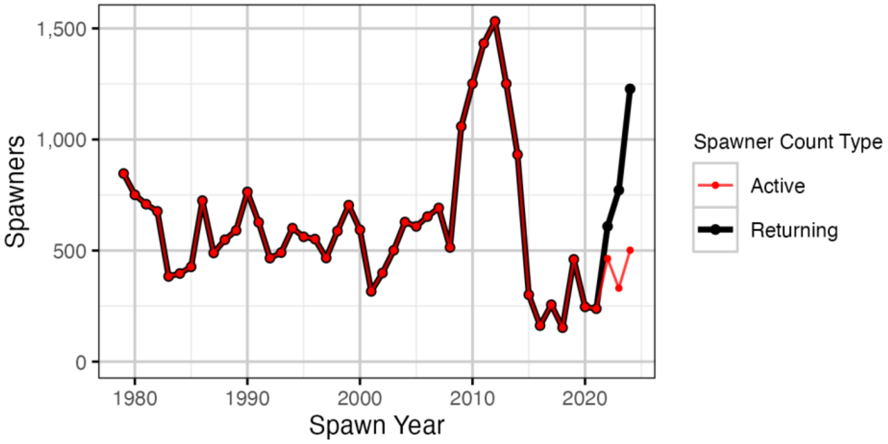

Figure 5. **Gerrard Rainbow Trout spawner escapement estimates (AUC) at Gerrard from 1961-2024 (WLRS on file). The red and black dots show the difference between active and returning spawners. The difference is accounted for by the fish removed during predator removal program.**

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; MWLRS on file). Information demonstrates drastic changes in fish condition because of the recent collapse of Kokanee on Kootenay Lake starting in 2012 (Figure 6). Based on KLRT catch information, the average size of Gerrard Rainbow Trout drastically declined starting in 2014 (Figure 7).

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 8; MWLRS on file). Parameter estimates for the condition analysis are available in Appendix 3.

Average size and weight of spawners at Gerrard (MWLRS on file) was used to predict the changes in fecundity from the fecundity relationship (Figure 9), 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 after 2014, shortly following the collapse of Kokanee in 2012 (Figure 10). Parameter estimates for the condition analysis are available in Appendix 4.

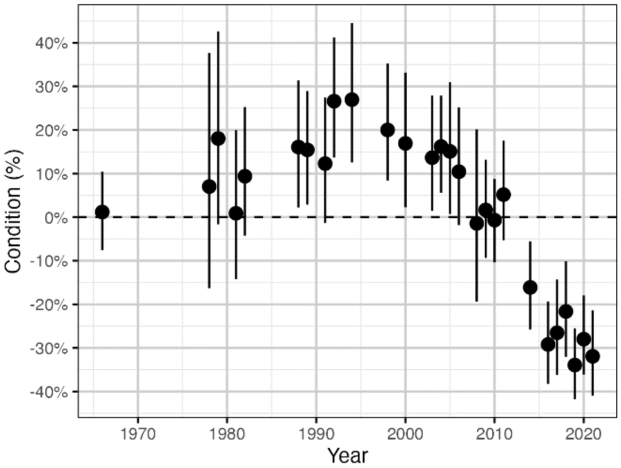

Figure 6. **Condition of Rainbow Trout ≥ 500 mm on Kootenay Lake overtime 1966-2022 (Andrusak and Andrusak 2015).**

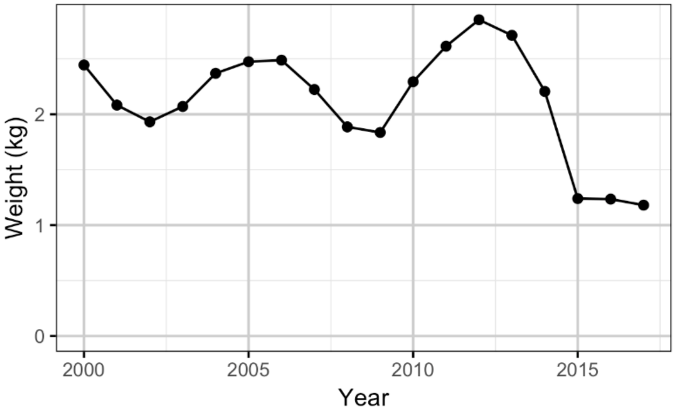

Figure 7. **The mean weight of Rainbow Trout in the KLRT by year**

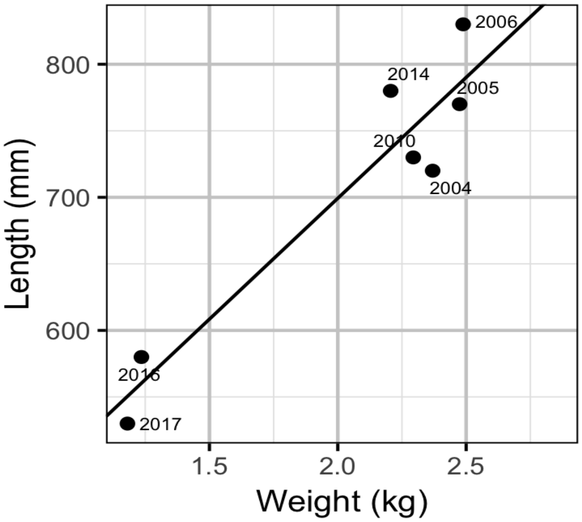

Figure 8. **The mean length of spawning Rainbow Trout by the mean weight of Rainbow Trout in the KLRT**

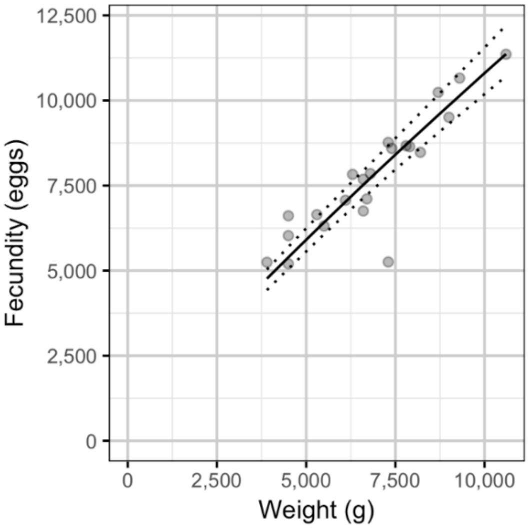

Figure 9. **The fecundity-weight relationship (with 95% CRIs) from (Andrusak and Andrusak 2006).**

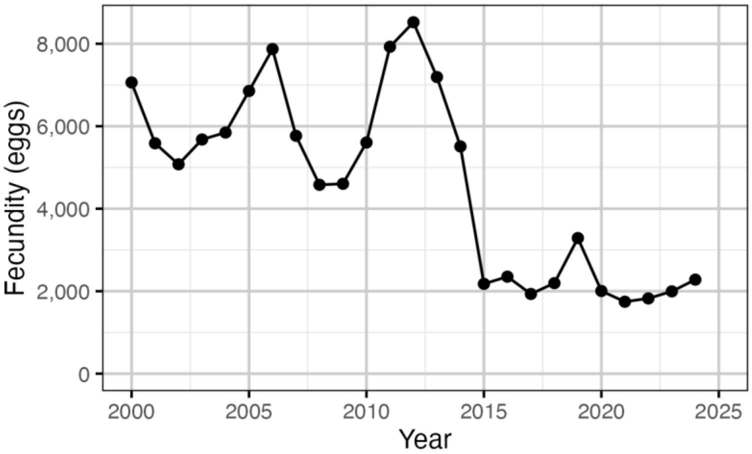

Figure 10. **Estimated Gerrard Rainbow Trout spawner fecundity from 2000-2024 (WLRS on file).**

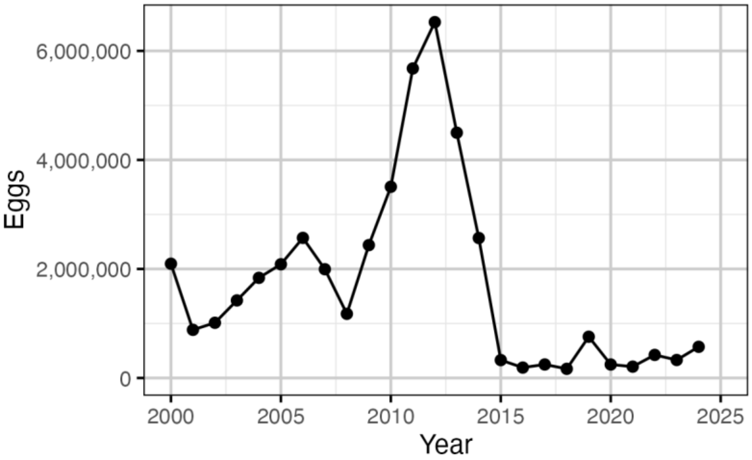

Figure 11. **The egg deposition by year at Gerrard from 2000-2024**

Total egg deposition at the Gerrard spawning grounds is provided for each year (Figure 11). Following the changes in fecundity per-spawner (2000-2022), egg deposition at the Gerrard spawning grounds also changed as abundance and condition of Gerrard spawners changed (Table 8). Egg deposition information demonstrates a drastic decline beginning in 2015 (Figure 11).

Table 8. The estimate total egg deposition by spawn year

Year	Length (cm)	Weight (g)	Condition	Fecundity	Spawners	FishRemoved	Eggs
2000	780	6158	1.08	7069	593	NA	2,097,246
2001	714	4704	1.09	5595	316	NA	884,394
2002	687	4214	1.11	5087	399	NA	1,014,980
2003	712	4795	1.12	5689	501	NA	1,425,576
2004	717	4951	1.13	5849	628	NA	1,837,515
2005	772	5928	1.07	6837	609	NA	2,080,499
2006	830	6948	1	7856	653	NA	2,564,901
2007	740	4866	1.01	5762	692	NA	1,992,937
2008	679	3730	1.02	4577	514	NA	1,176,432
2009	670	3756	1.07	4606	1059	NA	2,438,265
2010	734	4713	1	5605	1251	NA	3,507,115
2011	811	6994	1.08	7902	1432	NA	5,659,580
2012	855	7604	0.99	8499	1532	NA	6,510,435
2013	829	6266	0.9	7176	1251	NA	4,488,169
2014	779	4620	0.81	5508	932	NA	2,566,754
2015	561	1570	0.79	2177	301	NA	327,930
2016	581	1715	0.77	2349	162	NA	190,451
2017	528	1367	0.84	1931	256	NA	247,371
2018	544	1584	0.88	2193	153	NA	167,627
2019	634	2540	0.87	3289	460	NA	757,137
2020	538	1426	0.82	2003	246	NA	246,799
2021	519	1212	0.78	1742	238	NA	207,455
2022	528	1277	0.78	1822	464	145	422,456
2023	545	1417	0.78	1992	331	441	329,440
2024	572	1655	0.78	2278	502	726	571,219

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 a relatively minor increase in recruitment in the age-1 juvenile abundance at egg deposition above 1,000,000 (Table 9). 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 fish each spring when egg disposition is at or above 1,000,000 eggs. A simpler hockey stick stock-recruitment model was also fit to the data to provide supplementary estimation of the carrying capacity. The hockey stick model estimated that no additional recruitment is expected beyond an egg deposition of 836,000 (95% CRI 109,000 – 3,550,000).

The stock-recruitment analyses also provided a summary of the effect of predator removals prior to spawning for the 2022 and 2023 brood years. In 2022 and 2023, the predator program resulted in a ~11% and 43% reduction in recruitment. However, information also demonstrates that the reduced recruitment was compensated for by increased survival of the recruits each year.

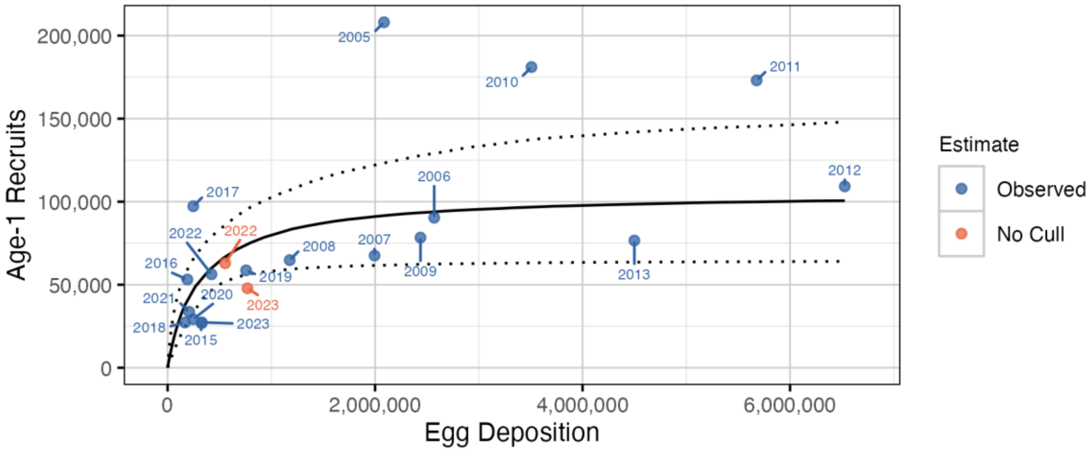

Figure 12. **Predicted Beverton-Holt stock-recruitment relationship (with 95% CRIs). Recruitment of Rainbow Trout age-1s and spawners based on AUC from Gerrard. Year is associated with brood year (2005-2024). Estimates are broken out by color to demonstrate the effect of predator removals for 2022-2024.**

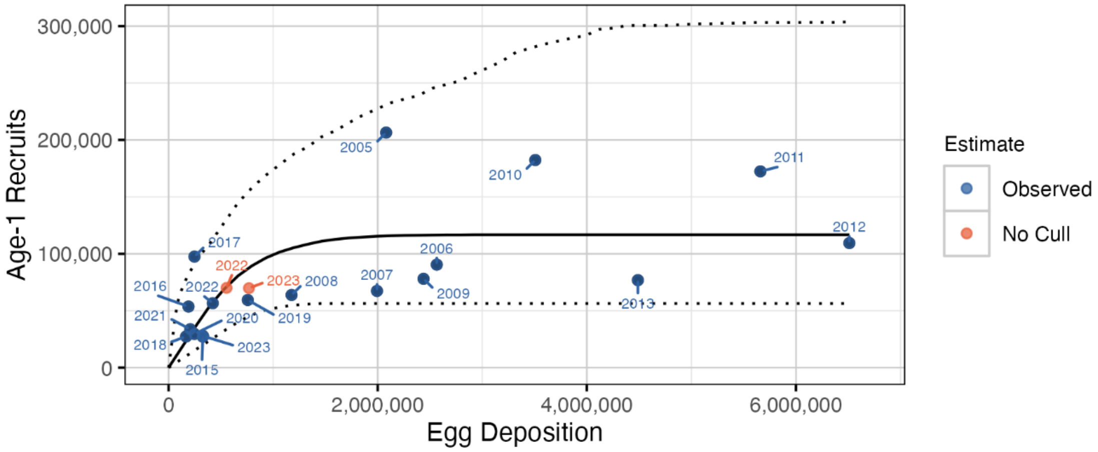

Figure 13. **Predicted 'Hockey Stick' stock-recruitment relationship (with 95% CRIs). Recruitment of Rainbow Trout age-1s and spawners based on AUC from Gerrard. Year is associated with brood year (2005-2024). Estimates are broken out by color to demonstrate the effect of predator removals for 2022-2024.**

Based on the SR analysis, the maximum reproductive rate (α_s), survival from egg to age-1, was approximated to be 0.36 (95% CRI 0.18—0.92; Figure 14). Similarly, the carrying capacity (K) of the river to support age-1 juveniles was estimated to be 106,000 (95% CRI 65,400-165,000) recruits (Table 9). The 'Hockey Stick' SR provides a supplementary carrying capacity (K) estimate of 116,000 (95% CRI 54,000-305,000) recruits.

Table 9. Posterior predictions from BH stock-recruitment model

Parameter	Estimate	Lower 95% CRI	Upper 95% CRI
a	0.36	0.18	0.92
b	3.40E-06	1.2E-06	1.1E-05
K	106,000	65,400	165,000

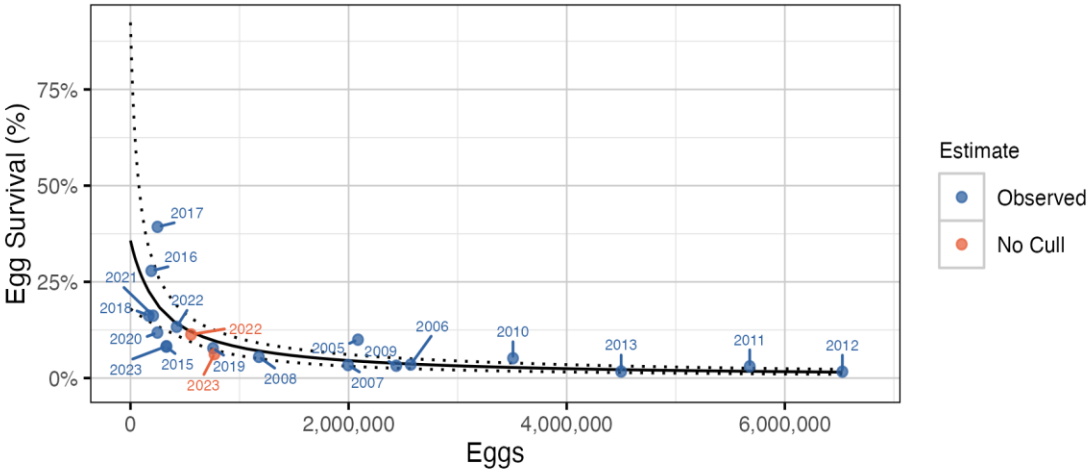

Figure 14. Predicted egg survival by egg deposition from 2005-2024 (with 95% CRIs). The labels indicate brood year. Estimate demonstrates effect of predator removals for 2022-2024.

Age-1 to Age-2 Survival

A general relationship for in-river abundance between age-1 to age-2 is displayed in Figure 15. Survival between spring age-1 recruits and age-2 recruits demonstrates significant variability over the time series, declining in the most recent year (Figure 16). Age-2 recruitment has averaged ~23,000 since 2005 (Table 10).

Table 10. Estimated survival between age-1 and age-2 recruits.

Spawn Year	Recruits (age-2)	Stock (age-1)	Survival
2005	40,905	208,059	0.20
2006	15,807	90,347	0.17
2007	25,181	67,529	0.37
2008	24,398	64,808	0.38
2009	37,992	78,374	0.48
2010	41,602	181,077	0.23
2011	43,907	173,063	0.25
2012	20,723	109,221	0.19
2013	NA	NA	NA
2014	NA	NA	NA
2015	9,930	26,774	0.37
2016	20,617	53,150	0.39
2017	12,549	97,249	0.13
2018	11,965	27,231	0.44
2019	15,591	58,645	0.27
2020	14,322	29,174	0.49
2021	20,771	33,669	0.62
2022	14,012	56,272	0.25
Avg	**23,142**	**84,665**	**0.33**

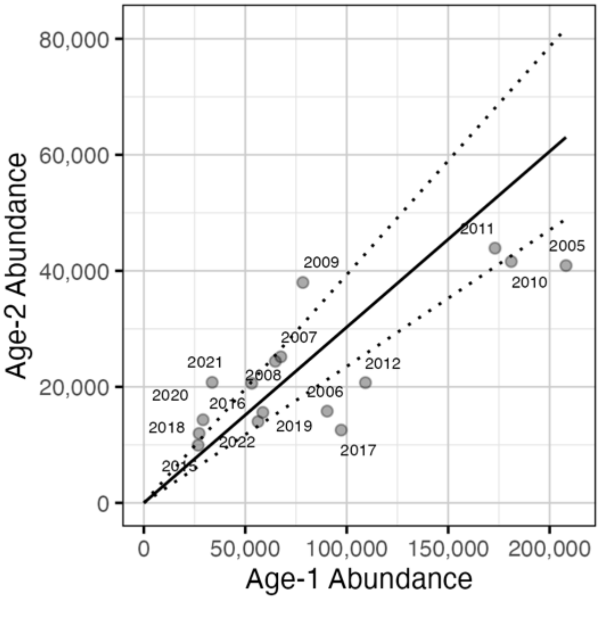

Figure 15. **Predicted relationship between age-1 and age-2 abundance (with 95% CRIs)**

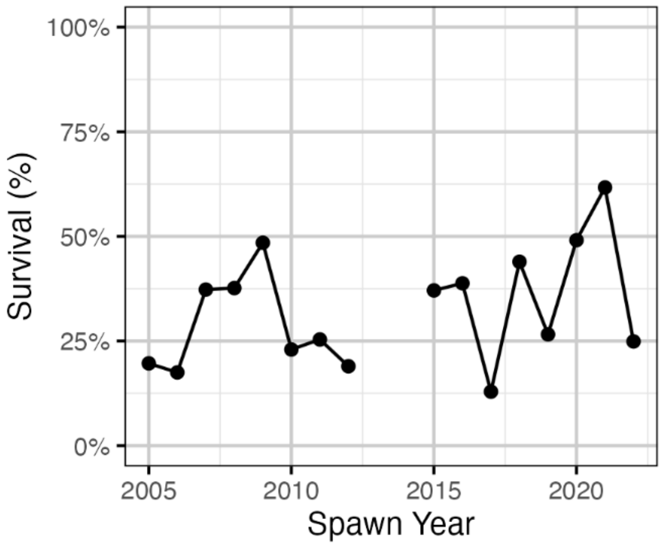

Figure 16. **In-lake survival from age-1 and age-2 to spawning by spawn year**

Calculated In-lake Survival

Survival of age-1 recruits to a returning spawner can also be predicted, demonstrating a significant increase in in-lake survival from 2006 to 2011 (Figure 17). The in-lake survival of each recruit cohort was calculated by dividing the number of spawners in a given year by the number of age-1 recruits 6 years previous, assuming all spawners return at age-7 and is unadjusted for changes in age-at-return.

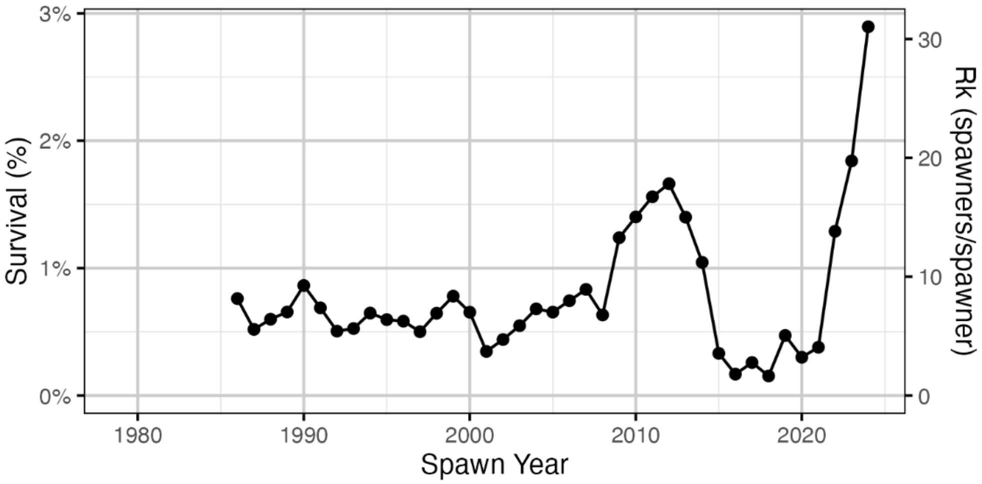

Figure 17. **Survival from expected age-1 to spawners by return year and untransformed maximum reproductive rate (unadjusted for fishing mortality) by spawn year.**

Modelled In-lake Survival

An assessment of age structure in the stock-recruitment analysis was conducted. Using a sensitivity analysis, we incorporated changes in age-at-return (i.e., spawning) within the spawning stock. The goal was to evaluate how time-dependent changes in spawning age affected key variables such as survival, reproductive rate and BRPs in the population, given variable age-at-return observed (WLRS on file). Our sensitivity analysis reviewed annual survival and cohort survival based on varying proportions of age-at-return within the spawning population over the time-period to assess the impacts on key parameters.

Table 11. Sensitivity analysis scenarios for changes in age-at-return

Scenario	Age-at-return
1	all 5 (pre & post)
2	all 6 (pre & post)
3	all 7 (pre & post)
4	All equal (pre & post)
5	Pre all 7, Post all 6
6	Pre all 7, Post half 5 and half 6

Our modelling approach evaluated the proportional change in age-at-return of the spawners in the time series within the stock-recruitment analysis. Age-at-return demonstrated a slight change in the age of spawners over the time series, with a downward shift in median age after 2012 (WLRS on file). However, results of the sensitivity analysis demonstrate that, following the collapse, the upward trend in both LMRR and in-lake survival persists regardless of changes in the assumed age-at-return (Figure 18). Our information indicated that scenarios 5 were the most probable based on observed patterns in Appendix 6.

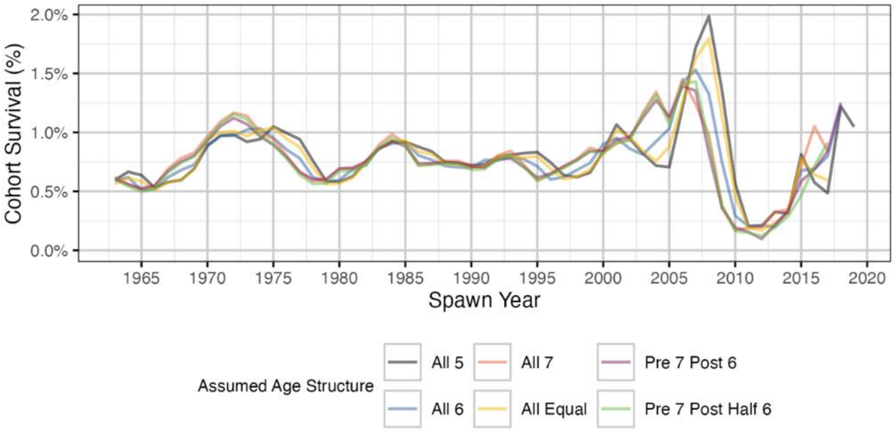

Figure 18 **Estimated cohort survival by the spawn year each cohort originated from, colored by the various assumed proportions of spawner age classes returning.**

Expected Spawners

The expected number of spawners presents a unique insight into factors regulating the Gerrard population over time. Analysis demonstrates that density independent in-lake survival rates for age 1 & 2 recruits are more variable than the density dependent in-river survival factors (Figure 19; Figure 20), suggesting the stock productivity is heavily influenced by in-lake conditions.

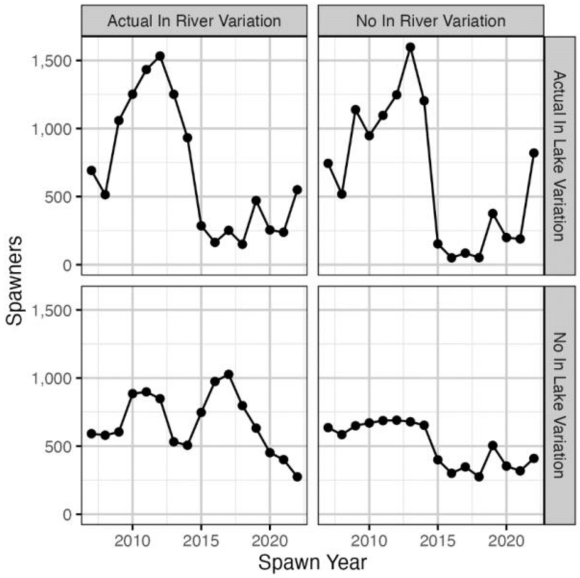

Figure 19. **Expected spawners by return year and in river and in-lake variation based on age-1 recruitment 2007-2024.**

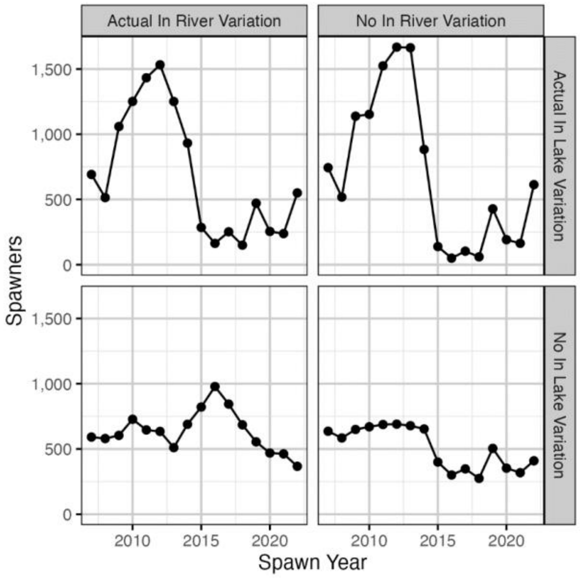

Figure 20 **Expected spawners by return year and in river and in-lake variation based on age-2 recruitment 2007-2024.**

Lifetime Maximal Reproductive Rate and Survival

Information on the lifetime 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 21). The maximum reproductive rate (increased from around 10 adults per recruit in the early to mid-2000s to over 20 adults per recruit in 2007 before dropping to under 5 adults per recruit in 2010. The Gerrard stock indicates time variation in in-lake survival that alters the productivity of the stock over time.

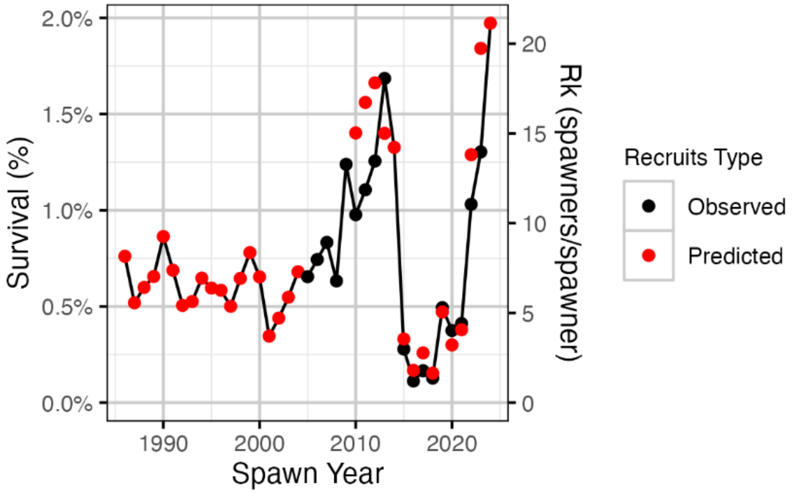

Figure 21. **Survival from expected age-1 to spawners by return year and untransformed maximum reproductive rate (unadjusted for fishing mortality) by spawn year.**

Stock Reference Points

The analysis indicates that a conservation threshold or Limit Reference Point (LRP) for the Gerrard stock is 99 fish (80% CRI 38-197) or 297,000 eggs (80% CRI 115,000-593,000) 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).

Discussion

Determining a stock's reproductive capacity and productivity is essential for managing exploitation (Hilborn and Walters 1992; Walters and Martell 2004). Obtaining estimates of the in-river Gerrard juvenile abundance for 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 (Ayllón et al. 2012; 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 (Tsoukali et al. 2016). 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.

The combined information on survival from the two separate phases in the life history stages provides the ability to derive estimates of the LMRR. Based on analysis of the SR relationship, the maximum reproductive rate (not accounting for fishing mortality) for the Gerrard stock was around 10 (log transformed ~2.3 spawners per spawner) in the early to mid-2000s, increasing to over 20 adults per recruit (log-transformed ~3 adults per recruit) in 2007. It also appears that the productivity in the riverine stage not only shows relatively little variability but is also stationary in the sense of not exhibiting long-term patterns. In contrast, adult productivity is highly variable and non-stationary (Figure 16), similar to ocean survival observed for steelhead (Johnston 2013) and Atlantic salmon (*Salmo salar*) (Chaput 2015). Nonetheless, while the non-stationarity in the in-lake productivity means upper reference points are more difficult to estimate, the riverine environment provides the ability to define the conservation thresholds for the population. Mace (1994) indicated that the degree of resilience (density dependence) is the most appropriate for defining the LRP. In our study, the majority of density dependent regulation occurs prior to age-1, similar to many other riverine salmonids (Elliott 2001; Johnston and Post 2009), supporting the derivation of the LRP for this population. 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 99 fish and/or 297,000 eggs was defined as the LRP.

Incorporating age structure has been shown to have some benefits of reducing time series or errors in variable bias but appears to have only small benefits for deriving information on BRPs (Fleischman et al. 2013). The observed changes in the median age-at-return are believed to be associated with food limitations following the collapse of the Kokanee population on Kootenay Lake (Warnock et al. 2021). The downward shift in age of return is supported by the observed changes in growth, size-at-age, condition and fecundity following the collapse of the Kokanee population on the lake (Andrusak and Andrusak 2015). Nonetheless, the analysis with variable age-at-return demonstrated minimal effect on the estimates of in-lake survival and our ability to accurately estimate LMRR.

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.

The stock-recruitment analysis also provided a summary of the effect of predator removals prior to spawning for the 2022 and 2023 brood years. In 2022 and 2023, predator program removed 145 and 441 spawners prior to spawning which resulted in an estimated ~11% and 43% reduction in recruitment, respectively. However, information also demonstrated that the reduced recruitment was compensated in increased survival of the recruits within the river, likely meditated through increased egg incubation success and/or reduced competition. While it is uncertain at which life stage the compensatory response occurred and why, our study was able to track changes demonstrating some foundational principles in ecology within the salmonid biology (Ward and Slaney 1993; Elliott 2001; Vincenzi et al. 2008; Johnston and Post 2009). Importantly, the compensatory response observed could potentially pose challenges to the predator reduction program and for the future recovery of Kootenay Lake.

Considering recent events on Kootenay Lake, and eventual recovery, development of a management framework will be valuable to the management of for Gerrard Rainbow Trout on Kootenay Lake in future. The information collected from this research will provide important information biological reference points for conservation and management of this unique stock. Importantly, the framework will provide support for decision making in the future and provide guidance on conservation and/or management actions if needed.

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. Redfish Consulting Ltd. contract report submitted to Ministry of Environment.

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.

Ayllón, D., Almodóvar, A., Nicola, G.G., Parra, I., and Elvira, B. 2012. Modelling carrying capacity dynamics for the conservation and management of territorial salmonids. Fish. Res. **134–136**: 95–103. doi:10.1016/j.fishres.2012.08.004.

Barrowman, N.J., and Myers, R.A. 2000. Still more spawner-recruitment curves; the hockey stick and its generalizations. Can J Fish Aqaut Sci **57**: 665–676.

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

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.

Fleischman, S.J., Catalano, M.J., Clark, R.A., and Bernard, D.R. 2013. An age-structured state-space stock–recruit model for Pacific salmon (*Oncorhynchus* spp.). Can. J. Fish. Aquat. Sci. **70**(3): 401–414. doi:10.1139/cjfas-2012-0112.

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. 2005. Ecotypic differentiation of native rainbow trout (Oncorhynchus mykiss) populations from British Columbia. Can. J. Fish. Aquat. Sci. **62**(7): 1523–1539.

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.

McElreath, R. 2020. A Bayesian Course with Examples in R and Stan. *In* 2nd edition. Taylor; Francis, CRC Press, Boca Raton, Fla.

Mesnil, B., and Rochet, M.-J. 2010. A continuous hockey stick stock–recruit model for estimating MSY reference points. ICES J. Mar. Sci. **67**(8): 1780–1784. doi:10.1093/icesjms/fsq055.

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.

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. 2003. JAGS: A Program for Analysis of Bayesian Graphical Models Using Gibbs Sampling,. Vienna, Austria. Available from http://www.ci.tuwien.ac.at/Conferences/DSC-2003/.

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.

Tsoukali, S., Olsson, K.H., Visser, A.W., and MacKenzie, B.R. 2016. Adult lifetime reproductive value in fish depends on size and fecundity type. Can. J. Fish. Aquat. Sci. **73**(9): 1405–1412. doi:10.1139/cjfas-2015-0378.

Vincenzi, S., Crivelli, A.J., Jesensek, D., and De Leo, G.A. 2008. The role of density-dependent individual growth in the persistence of freshwater salmonid populations. Oecologia **156**(3): 523–534. doi:10.1007/s00442-008-1012-3.

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

Ward, B.R., and Slaney, P.A. 1993. Egg-to-smolt survival and fry-to-smolt density dependence of Keough River steelhead trout. Can. Spec. Publ. Fish. Aquat. Sci.: 209–217.

Warnock, W.G., Thorley, J.L., Arndt, S.K., Weir, T.J., Neufeld, M.D., Burrows, J.A., and Andrusak, G.F. 2021. Kootenay Lake kokanee (Oncorhynchus nerka) collapse into a predator pit. Can. J. Fish. Aquat. Sci.: cjfas-2020-0410. doi:10.1139/cjfas-2020-0410.

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.

Wyatt, R.J. 2003. Mapping the abundance of riverine fish populations: integrating hierarchical Bayesian models with a geographic information system (GIS). Can. J. Fish. Aquat. Sci. **60**(8): 997–1006. doi:10.1139/f03-085.

Appendix 1. Gerrard spawner escapement 1957-2024

Year	**Peak Count**	**Peak X 3.08**	**AUC (fish*days)**	***AUC (N)***
2024	297	915	5969	*502
2023	308	949	3994	*336
2022	284	875	5519	*464
2021	195	601	2835	238
2020	199	613	3032	255
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
1960	150	NA	NA	NA
1959	220	NA	NA	NA
1958	110	NA	NA	NA
1957	56	NA	NA	NA

- Note-estimated escapement differs from actual due to predator removal program.

Appendix 2. Age-1 and age-2 model coefficients

Age-1

term	estimate	Lower	upper	svalue
bDensity	-1.3743281	-1.8258968	-0.9303509	10.5517083
bDensityRkm[1]	-0.1612247	-0.3034501	-0.0151078	4.82378781
bDensityRkm[2]	0.56984858	0.36599289	0.78179768	10.5517083
bDensityRkm[3]	-0.1297692	-0.2034507	-0.0631312	10.5517083
bDensityRkm[4]	-0.2589458	-0.3258539	-0.1919248	10.5517083
bEfficiency	-1.7790018	-2.0489025	-1.5103778	10.5517083
bEfficiencyIndex	0.394527	-0.2418596	1.01439518	2.27093749
bEfficiencyMarking	0.53444031	0.32767822	0.74080859	10.5517083
bEfficiencyMarkingIndex	0.8102509	0.19377372	1.44193314	6.46424542
sDensitySite	0.69831069	0.63402981	0.76807582	10.5517083
sDensityYear	0.71445744	0.49663756	1.09657647	10.5517083
sDispersion	1.31629586	1.19958531	1.4580268	10.5517083
sEfficiencySwimmer	0.36509038	0.21570196	0.69008032	10.5517083

Age-2

term	estimate	Lower	upper	svalue
bDensity	-2.270383266	-2.703719626	-1.840281689	10.55170826
bDensityRkm[1]	-0.250753623	-0.43796536	-0.05504514	7.092276643
bDensityRkm[2]	0.087129938	-0.173730592	0.333729994	0.957383658
bDensityRkm[3]	0.048528841	-0.04488019	0.135775916	1.800164203
bDensityRkm[4]	-0.100665662	-0.182099846	-0.017052741	5.597511951
bEfficiency	-1.94052637	-2.294015599	-1.569619888	10.55170826
bEfficiencyIndex	0.54770412	-0.064670186	1.211775287	3.563023575
bEfficiencyMarking	0.897336307	0.606029788	1.194313374	10.55170826
bEfficiencyMarkingIndex	1.925116227	0.894442242	3.022924026	10.55170826
sDensitySite	0.859943214	0.777985212	0.945552686	10.55170826
sDensityYear	0.516249404	0.360765498	0.799932193	10.55170826
sDispersion	1.212526768	1.049180812	1.389426069	10.55170826
sEfficiencySwimmer	0.298113555	0.173246183	0.523833668	10.55170826

Appendix 3. Condition model coefficients

term	estimate	Lower	upper	svalue
bWeight	-12.74540517	-13.13383422	-12.33889284	10.55170826
bWeightLength	3.213729946	3.15220343	3.272080418	10.55170826
sWeight	-1.926025486	-1.966229695	-1.885348864	10.55170826
sWeightYear	-1.991493466	-2.264443516	-1.672420015	10.55170826

Appendix 4. Fecundity model coefficients

term	estimate	Lower	upper	svalue
bFecundity	3.843798944	1.565207226	4.960868612	10.55170826
bFecundityWeight	0.862038022	0.831241122	0.964490583	10.55170826
sFecundity	0.128354758	0.094622728	0.184270399	10.55170826

Appendix 5. Stock-recruitment model coefficients

term	estimate	Lower	upper	svalue
a	0.3573298	0.1800010	0.9239662	10.55171
b	0.0000034	0.0000012	0.0000121	10.55171
sScaling	2.6643747	1.8981738	4.0219737	10.55171

Appendix 6. Sensitivity Analysis -Age structure

All return at age 5

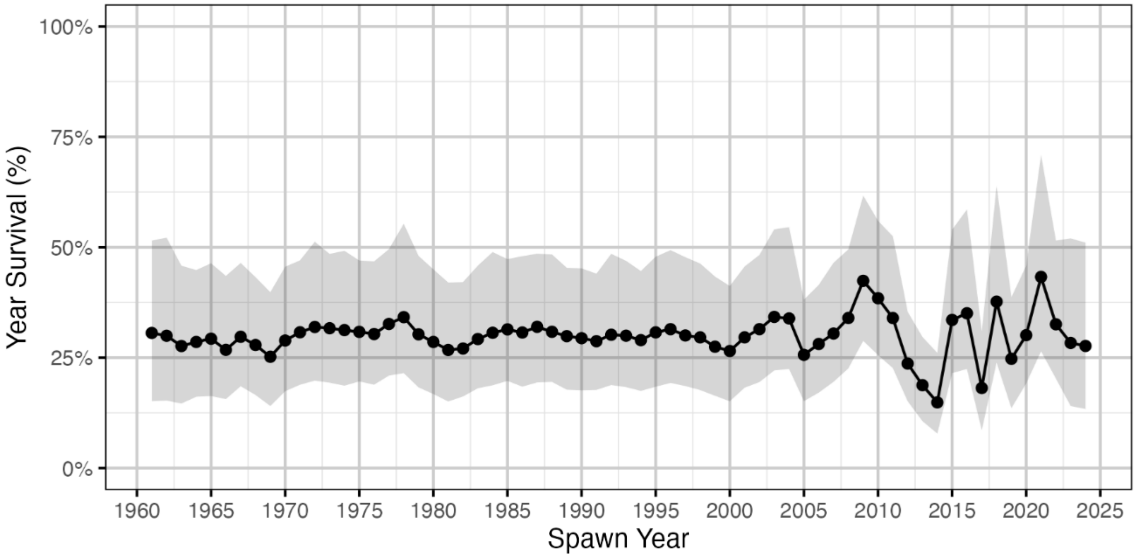

Figure 22. Estimated survival in each year given the assumed proportions of age classes returning.

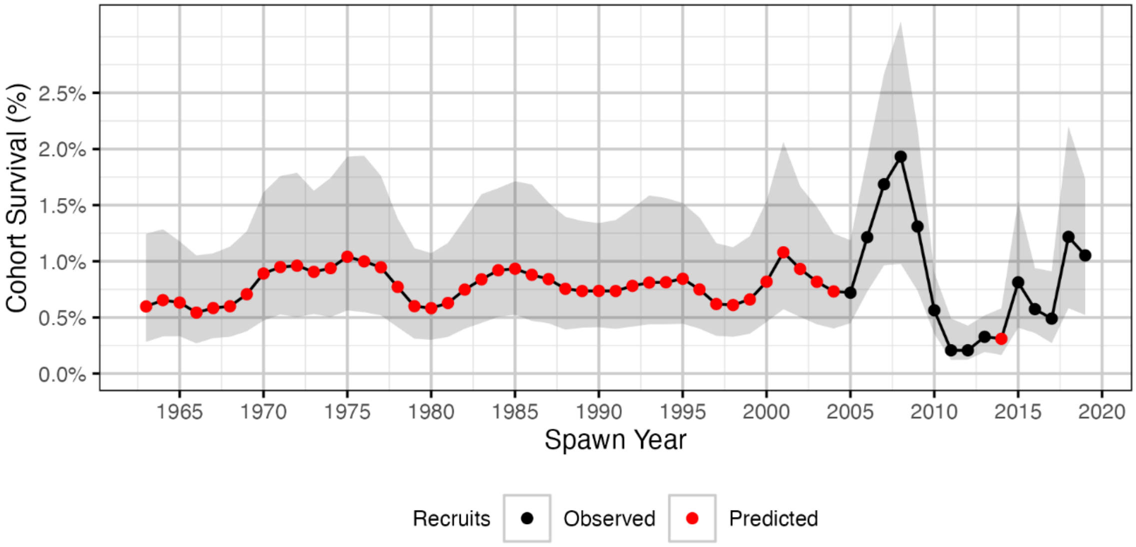

Figure 23. Estimated cohort survival given the assumed proportions of age classes returning.

All return at age 6

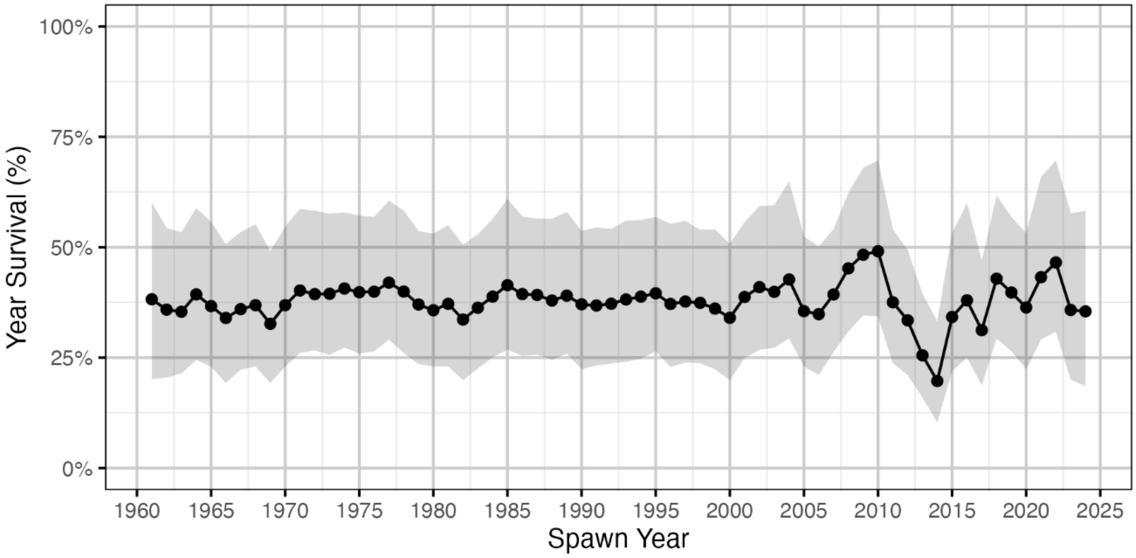

Figure 24. Estimated survival in each year given the assumed proportions of age classes returning.

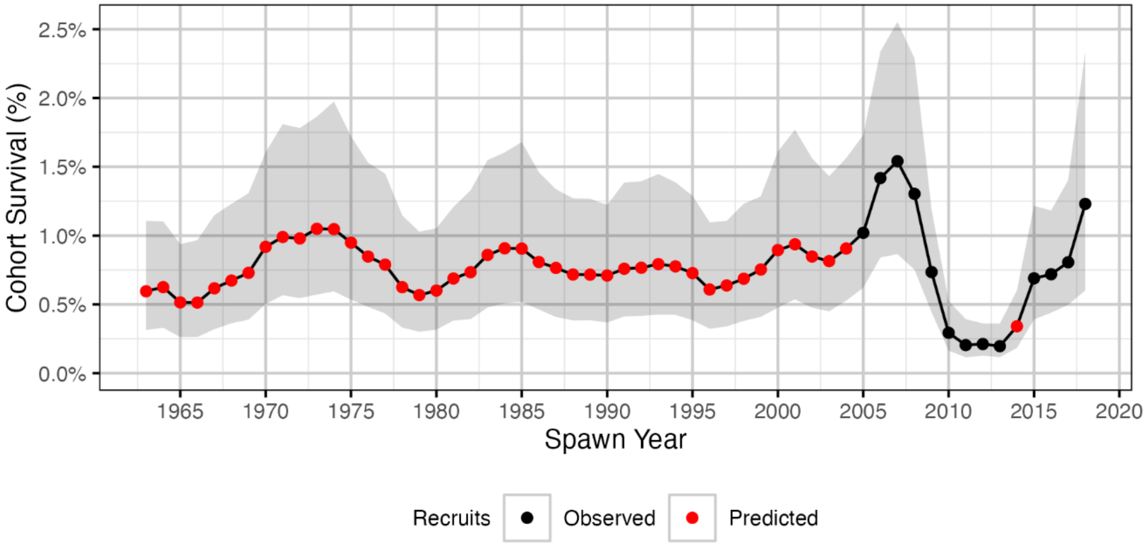

Figure 25. Estimated cohort survival given the assumed proportions of age classes returning.

All return at age 7

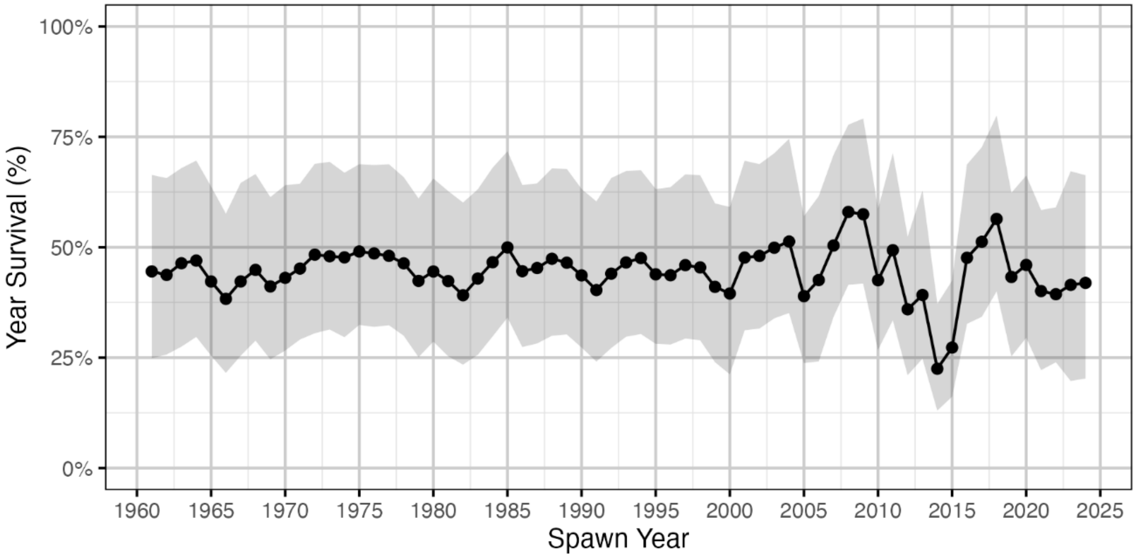

Figure 26. Estimated survival in each year given the assumed proportions of age classes returning.

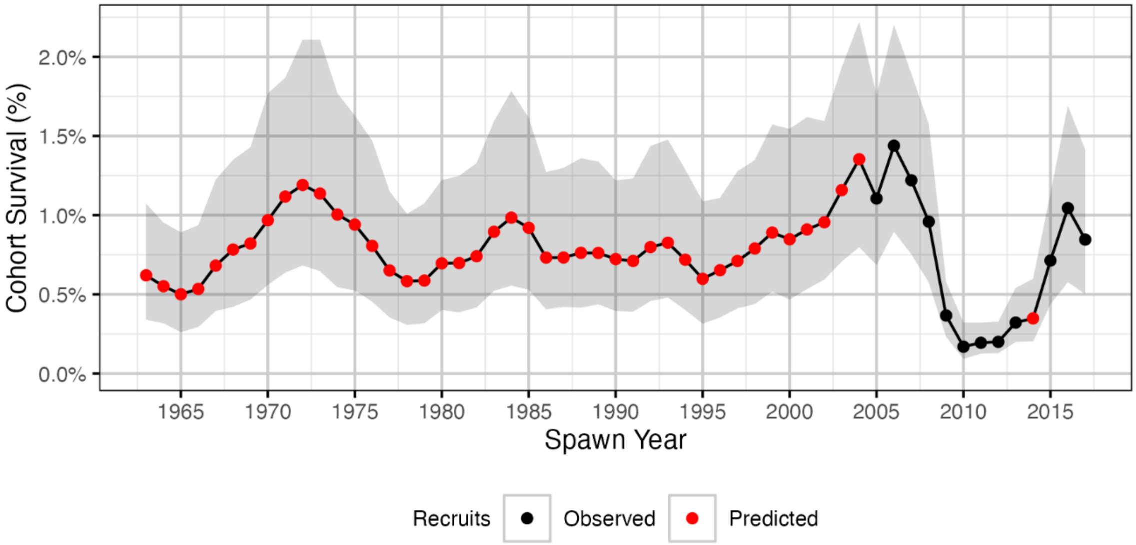

Figure 27. Estimated cohort survival given the assumed proportions of age classes returning.

All return in equal proportion (age 5, 6, & 7)

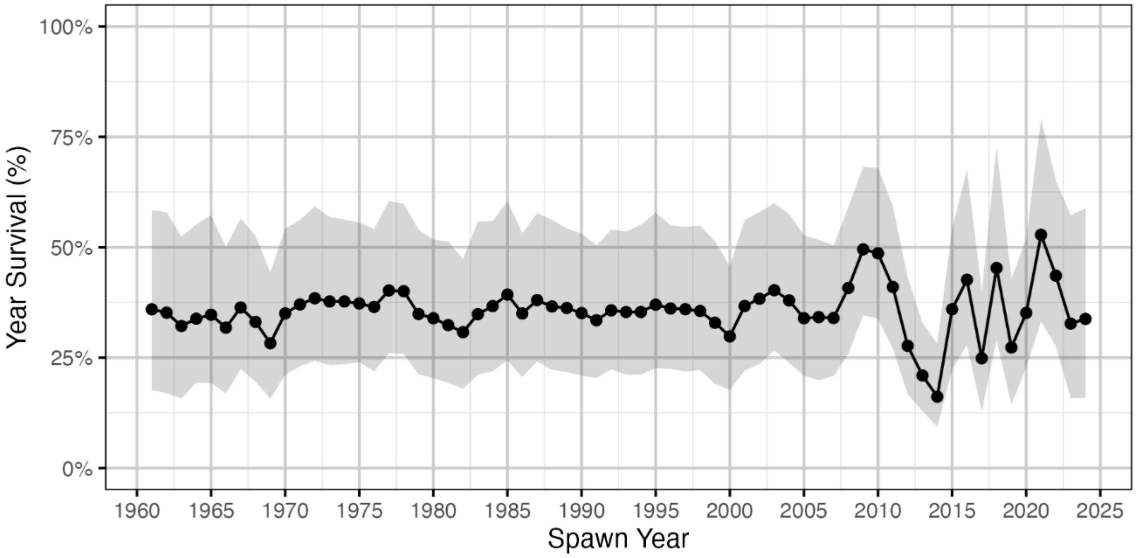

Figure 28. Estimated survival in each year given the assumed proportions of age classes returning.

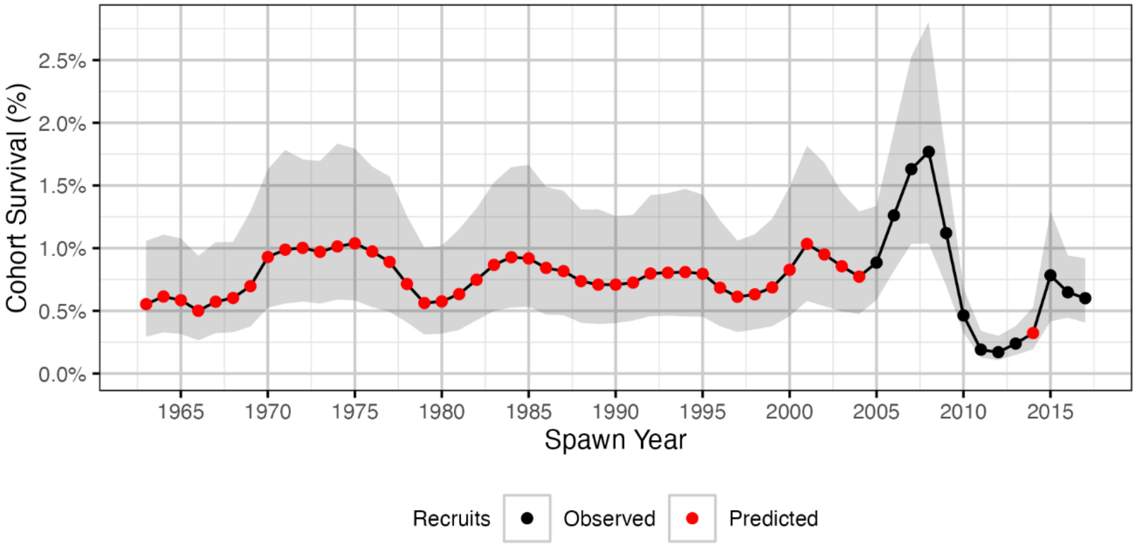

Figure 29. Estimated cohort survival given the assumed proportions of age classes returning.

Pre-collapse all return at age 7 and Post-collapse all return at age 6

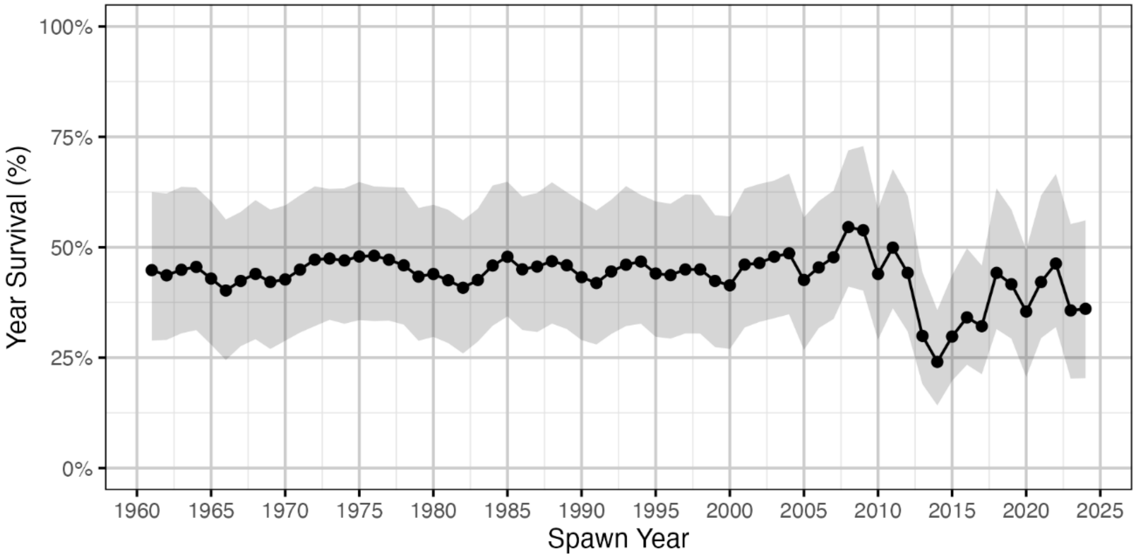

Figure 30. Estimated survival in each year given the assumed proportions of age classes returning.

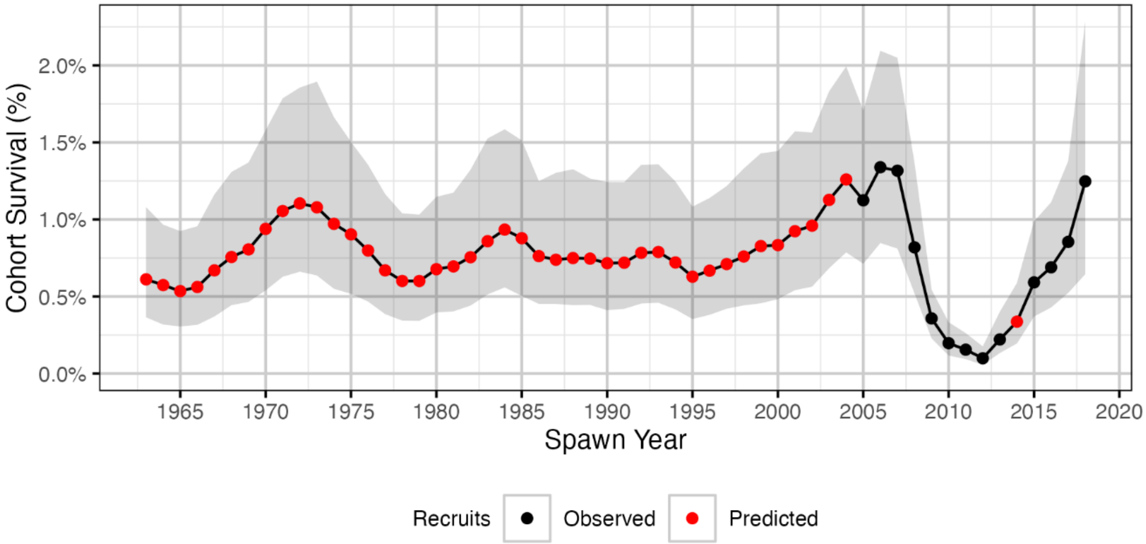

Figure 31. Estimated cohort survival given the assumed proportions of age classes returning.

Pre-collapse all return at age 7 and post-collapse equal return at age 5 & 6

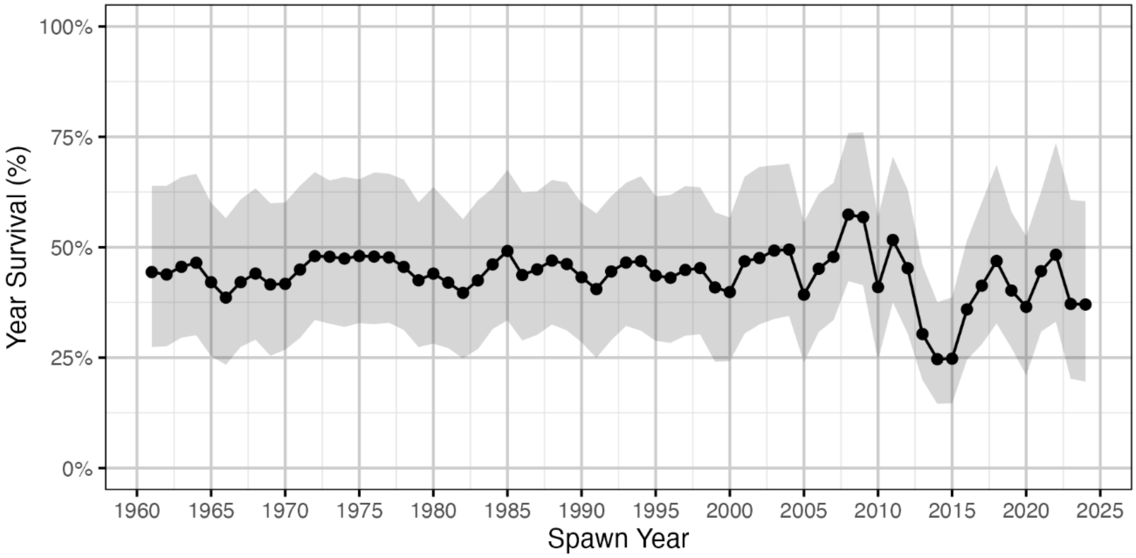

Figure 32. Estimated survival in each year given the assumed proportions of age classes returning.

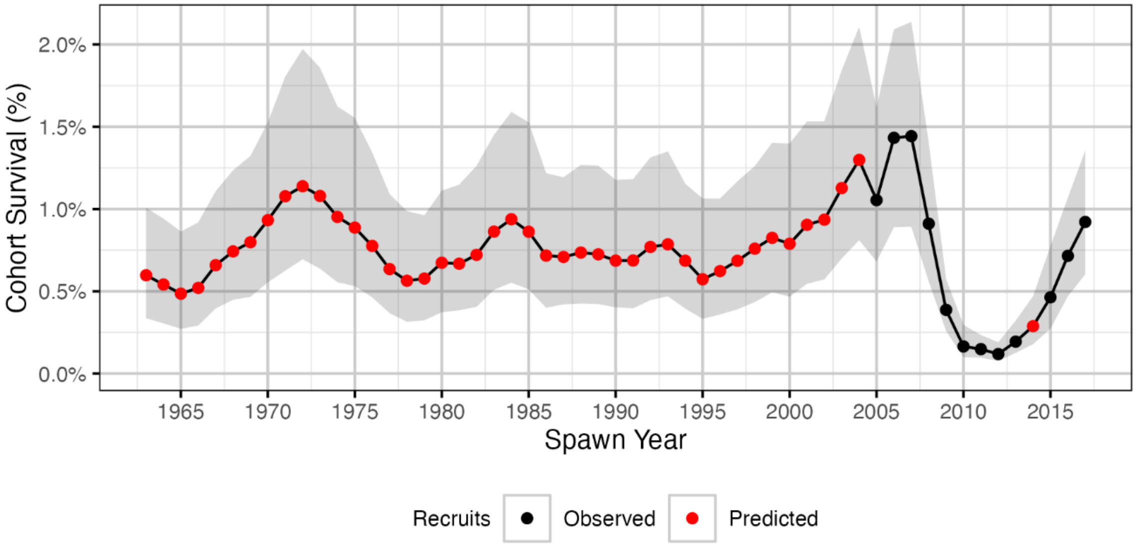

Figure 33. Estimated cohort survival given the assumed proportions of age classes returning.