Fisheries and Oceans Canada / Pêches et Océans Canada
Ecosystems and Oceans Science / Sciences des écosystèmes et des océans

Canadian Science Advisory Secretariat (CSAS)

Research Document 2016/099

Central and Arctic Region

Recovery Potential Modelling of Bull Trout (*Salvelinus confluentus*) (Saskatchewan – Nelson rivers populations) in Alberta

Amanda L. Caskenette, Jennifer A.M. Young, and Marten A. Koops

Fisheries and Oceans Canada
Great Lakes Laboratory for Fisheries and Aquatic Sciences
867 Lake Shore Rd.
Burlington, ON L7S 1A1 Canada

November 2016

Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

Research documents are produced in the official language in which they are provided to the Secretariat.

Published by:

Fisheries and Oceans Canada
Canadian Science Advisory Secretariat
200 Kent Street
Ottawa ON K1A 0E6

http://www.dfo-mpo.gc.ca/csas-sccs/
csas-sccs@dfo-mpo.gc.ca

ISSN 1919-5044

Correct citation for this publication:

Caskenette, A.L., Young, J.A.M., and Koops, M.A. 2016. Recovery Potential Modelling of Bull Trout (*Salvelinus confluentus*) (Saskatchewan – Nelson rivers populations) in Alberta. DFO Can. Sci. Advis. Sec. Res. Doc. 2016/099. iv + 40 p.

TABLE OF CONTENTS

ABSTRACT

The Committee on the Status of Endangered Wildlife in Canada (COSEWIC) has assessed the Saskatchewan – Nelson rivers populations of Bull Trout (*Salvelinus confluentus*) as Threatened in Canada. Here we present population modelling in support of the recovery potential assessment of the species. Results include a sensitivity analysis, determination of allowable harm, and minimum viable population estimates to inform recovery targets for population abundance and required habitat. The analyses demonstrate that the dynamics of Bull Trout populations are particularly sensitive to perturbations that affect survival of immature individuals. Harm to these portions of the life cycle should be minimized to avoid jeopardizing the survival and future recovery of Saskatchewan – Nelson rivers populations. To achieve demographic sustainability (i.e., a self-sustaining population over the long term) under conditions with a 15% chance of catastrophic mortality event per generation and a quasi-extinction threshold of 50 adults at 1% probability of extinction, the adult Bull Trout abundance needs to be at least 1.9 million adult Bull Trout, requiring 510 km^2 of suitable habitat. Estimates for alternative risk scenarios ranged from ~95 adults to ~10 million adults and ~14,000 m^2 to ~4,300 km^2 of suitable habitat, and are highly sensitive to the extinction threshold, the probability of catastrophic mortality, and the ratio of individuals from small and large-bodied growth trajectories in the population.

Modélisation du potentiel de rétablissement de l’omble à tête plate (*Salvelinus confluentus*) (populations des rivières Saskatchewan et Nelson) en Alberta

RÉSUMÉ

Le Comité sur la situation des espèces en péril au Canada (COSEPAC) a évalué les populations d’omble à tête plate (*Salvelinus confluentus*) de la rivières Saskatchewan et Nelson et déterminé qu’il s’agit d’une espèce menacée au Canada. Nous présentons ci-après la modélisation de la population afin d’étayer l’évaluation du potentiel de rétablissement de l’espèce. Les résultats comprennent une analyse de sensibilité, la détermination des dommages admissibles et l’estimation de la population minimale viable, afin d’éclairer l’établissement des cibles de rétablissement pour l’abondance de la population et l’habitat nécessaire. Les analyses démontrent que la dynamique des populations d’omble à tête plate est particulièrement sensible aux perturbations qui ont une incidence sur la survie des individus immatures. On doit réduire au minimum les dommages qui surviennent à ces étapes du cycle de vie pour ne pas mettre en péril la survie et le rétablissement futur des populations de la rivière Saskatchewan et du fleuve Nelson. Afin d’assurer la durabilité démographique (c.-à-d. une population autosuffisante à long terme) dans des conditions où la probabilité qu’un épisode de mortalité catastrophique survienne est de 15 % pour chaque génération et où le seuil de quasi-extinction est de 50 adultes à un taux de probabilité d’extinction de 1 %, l’abondance de la population adulte d’omble à tête plate doit être d’au moins 1,9 million d’individus, ce qui requiert un habitat convenable de 510 km^2. Les autres scénarios de risque présentaient des estimations allant de ~95 adultes à ~10 millions d’adultes et de ~14 000 m^2 à ~4 300 km^2 d’habitat convenable, et étaient très sensibles au seuil d’extinction, à la probabilité d’un épisode de mortalité catastrophique et aux proportions d’individus de petite et de grande taille au sein de la population.

INTRODUCTION

Bull Trout (*Salvelinus confluentus*) was assessed by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) in 2012. Bull Trout in Canada were split into five DUs; the Saskatchewan – Nelson Rivers populations (DU 4) were ranked Threatened and are now being considered for listing under the *Species at Risk Act* (SARA). In accordance with the SARA which mandates the development of recovery strategies (and action plans) for the protection and recovery of species that are at risk of extinction or extirpation from Canada, Fisheries and Oceans Canada (DFO) has developed the recovery potential assessment (RPA) (DFO 2007a, 2007b) as a means of providing scientific information and advice. There are three components to each RPA: an assessment of species status, the scope for recovery, and scenarios for mitigation and alternatives to activities. This report contributes to components two and three by identifying population sensitivity and quantifying recovery targets, required habitat, and allowable harm with associated uncertainty for the Saskatchewan - Nelson rivers populations of Bull Trout. This work is based on a demographic approach developed by Vélez-Espino and Koops (2007, 2009a, 2009b) which determines a population-based recovery target based on long-term population projections.

METHODS

The analysis consisted of four parts:

(i) information on vital rates was compiled to build projection matrices using uncertainty in life history to represent variation in the life cycle for stochastic simulations.

With these projection matrices:

(ii) sensitivity of the population growth rate to changes in each vital rate was determined following Vélez-Espino and Koops (2007, 2009a, 2009b);

(iii) risk of extirpation, time to extirpation, minimum viable population (MVP) and the minimum area for population viability (MAPV; i.e., the amount of suitable habitat required to support the MVP) were estimated; and

(iv) the effects of allowable harm on the population growth rate were quantified.

SOURCES

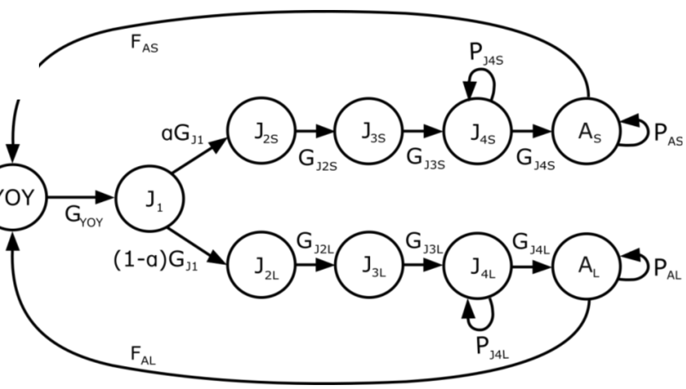
Growth patterns, stage-specific annual mortality, and fecundity-at-stage of Bull Trout were determined using data and estimates from the literature (Appendices 1-3). General trends of population growth were identified for several waterbodies in the Saskatchewan – Nelson rivers DU. All analyses and simulations were conducted using the statistical program R (R Core Team 2015).

THE MODEL

Using a matrix approach, the life cycle of Bull Trout was represented with annual projection intervals and by a post-breeding stage-structured projection matrix (Caswell 2001) (Figure 1). The Saskatchewan – Nelson rivers Bull Trout populations exhibit one or more of the following three life-history types: adfluvial, fluvial, and stream resident (COSEWIC 2012). This results in a variety of growth trajectories (Figure 2) with fish that remain small through their complete lifecycle, fish that grow to large sizes, or a combination of both large and small growth trajectories.

The variety of growth trajectories can be captured by a stage-structured population model with a common young-of-year (YOY) and juvenile stage (J_1); then three stages for each large ($J_{L2\text{-}4}$) and small juveniles ($J_{S2\text{-}4}$) and one adult stage for each small (A_S) and large adults (A_L). When there are both small and large growth trajectories in a population, at the juvenile stage a proportion of individuals (α) will transition to small juveniles, while the remainder (1-α) will transition to large juveniles. Juveniles were divided into multiple stages as they remain juveniles for several years (up to 8, see below) with a marked difference in the survival between early stage and late stage juveniles. The resulting matrix (Figure 1b) represents a mixed population (MP); similar matrices were generated for each of the two growth trajectories (small (SP) and large (LP)) on their own.

a)



b)

$$
M = \begin{pmatrix}
0 & 0 & 0 & 0 & F_{J4S:AS} & 0 & 0 & F_{J4L:AL} & F_{AS} & F_{AL} \\
G_{YOY} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \alpha G_{J1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & G_{J2S} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & G_{J3S} & P_{J4S} & 0 & 0 & 0 & 0 & 0 \\
0 & (1-\alpha)G_{J1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & G_{J2L} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & G_{J3L} & P_{J4L} & 0 & 0 \\
0 & 0 & 0 & 0 & G_{J4S} & 0 & 0 & 0 & P_{AS} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & G_{J4L} & 0 & P_{AL}
\end{pmatrix}
$$

Figure 1. Generalized life cycle (a) and corresponding stage-structured projection matrix (b) used to model the population dynamics of Bull Trout. F_i represents annual effective fecundities, P_i represents the probability of remaining in the current stage, and G_i, represents the probability of moving to the next stage. Note that fecundity is positive for the last juvenile stage class since individuals recorded as immature in census t will mature upon their next birthday (if they survive) and produce offspring that would be counting at census t+1 (Caswell 2001).

Elements of the stage-structured matrix include the fecundity coefficient of stage class *j* (F_j), the stage-specific annual probability of remaining in stage *j* (P_j) and the transition probability of surviving one stage and moving to the next *(G_j).*

Fecundity coefficients (F_j) represent the contribution of an adult in stage class j to the next census of age-0 individuals. Since a post-breeding model is assumed, the coefficient F_j includes the annual survival probability (σ_j), the probability of moving to or remaining in the adult stage, as well as the stage-specific annual number of female offspring for an individual (f_j) such that

$$F_j = \begin{cases} \sigma_j f_j G_j & J_4 \\ \sigma_j f_j P_j & A \end{cases} \quad \text{(Equation 1)}$$

Where f_j is the product of the average fertility (total annual egg count) for a female of stage j (η_j), the proportion of females in the population (φ, assumed to be 0.5 for Bull Trout), the proportion of fish in stage j that reproduce (ρ_j, assumed to be 1 for Bull Trout), and the inverse of the average spawning periodicity (T):

$$f_j = \eta_j \varphi \rho_j \, {}^{1}/_{T} \quad \text{(Equation 2)}$$

The probability of moving from j to j+1 (G_j) is defined as $\sigma_j(\gamma_j)$ and the probability of surviving and remaining in stage j (P_j) is defined as $\sigma_j(1-\gamma_j)$. For the initial four stages (*YOY*, J_1, J_2, and J_3) γ_j was set to 1 as no individuals remained in those stages for more than one year. For the sub-adult and adult stages (J_4 and A), assuming that the age distribution within stages is stable (see Lefkovitch 1965), the term γ_j can be calculated as:

$$\gamma_j = \frac{\left({}^{\sigma_j}/_{\lambda}\right)^{D} - \left({}^{\sigma_j}/_{\lambda}\right)^{D-1}}{\left({}^{\sigma_j}/_{\lambda}\right)^{D} - 1} \quad \text{(Equation 3)}$$

where λ is the largest eigenvalue of the matrix (Caswell 2001) and is set to 1 to represent a population at equilibrium, and D is the duration of the stage (years). For the sub-adult stages (J_4) D is the duration from entering that stage until age at maturation (t_{mat}). For the adult stages (A), D represents the duration between t_{mat} and the maximum age of the population (t_{max}).

PARAMETER ESTIMATES

All model parameters are defined in Table 1.

Individual Growth and Mortality

Estimates of growth were based on length-at-age data for Bull Trout gathered from the literature (Appendix 1) and represent several distinct populations. There are over 1,000 individual records from 17 different sources. When only figures were available, values were approximated using image software (Tummers 2006). When only total length was available, it was converted to fork length (FL) using the following relationship: FL = 0.968TL – 2.018 (Budy et al. 2010).

After separating the length-at-age data into small-sized populations (354 records) and large-sized populations (661 records), growth patterns were determined by fitting a von Bertalanffy growth curve by the method of non-linear least squares (Figure 2). The growth curve relates length and age using the formula: $L_t = L_\infty(1 - e^{-k(t-t_0)})$ where L_t is FL at time t, t_0 is the hypothetical age at which the fish would have had length 0, L_∞ is the asymptotic size, and k is a growth parameter. Estimated von Bertalanffy curves for individual populations in the literature (Rieman and McIntyre 1993, Paul et al. 2003, Johnston and Post 2009, Bowerman 2013) generally fall within the 95% confidence intervals of the resulting von Bertalanffy curve.

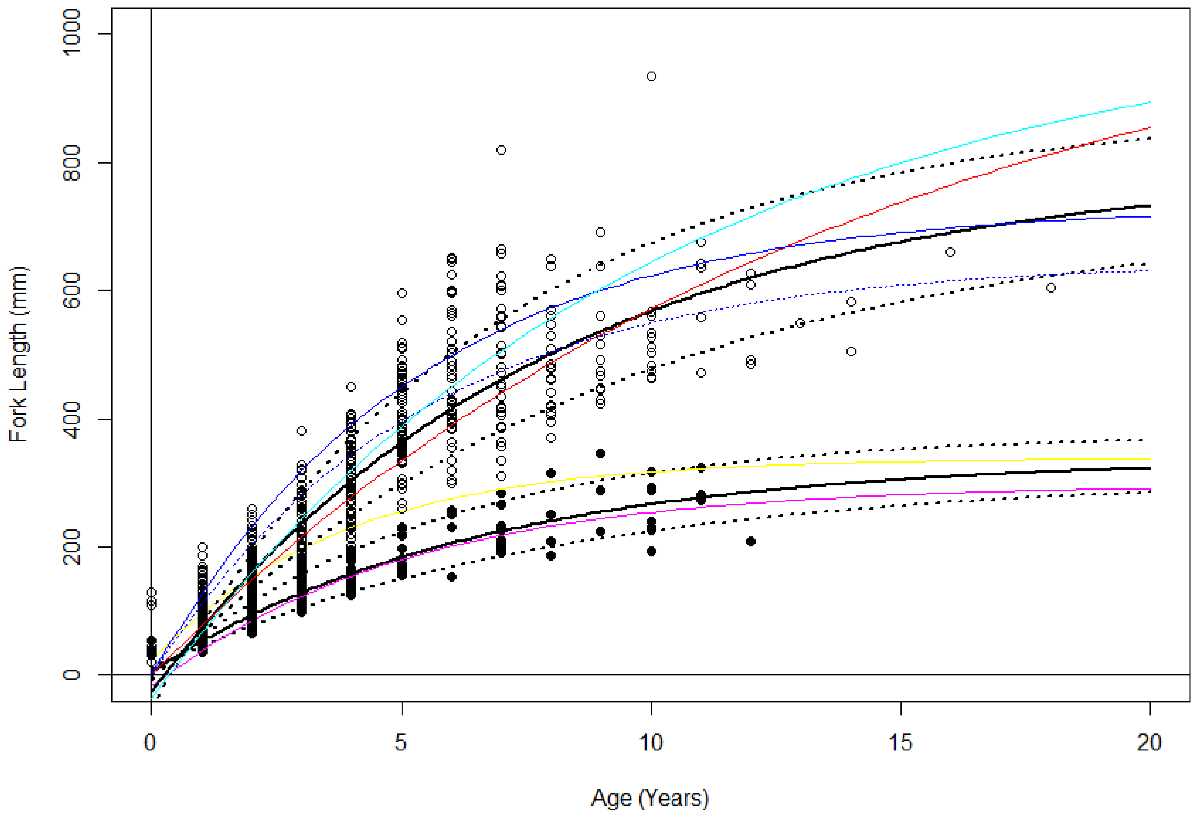


Figure 2. Estimates of fork length at age for Bull Trout from the literature with fitted von Bertalanffy growth curve (solid black lines) and 95% confidence intervals (dashed black lines) for both small (filled circles) and large (empty circles) trajectory growth curves. Fitted von Bertalanffy curves from the literature are added in colour for reference (SP: Rieman and McIntyre 1993 (pink), Paul et al. 2003 (yellow); LP: Rieman and McIntyre 1993 (cyan), Johnston and Post 2009 (low density = solid blue, high density = dashed blue), Bowerman 2013 (red)).

There are several, widely variable, estimates for length and age at maturity in the literature. Individuals in both growth trajectories mature between 3–8 years (Rodtka 2009). Individuals following the SP mature between 150–300 mm in length, where individuals following the LP mature between 240–730 mm (Rodtka 2009). Due to the large variability in estimates, length at maturity (L_{mat}) was calculated for each projection matrix from the following empirically supported relationship

$$L_{mat} = 10e^{\left(0.8979\ \log\left(L_\infty/_{10}\right) - 0.0782\right)} \text{ (Equation 4)}$$

(Froese and Binohlan 2000) and was converted to age-at-maturity (t_{mat}) using the formula for converting length to age:

$$t = \frac{-\log\left(1 - {L_t}/_{L_\infty}\right)}{k} + t_0. \text{ (Equation 5)}$$

Table 1. Range of values, symbols, descriptions, and sources for all parameters used to model Bull Trout.

	Description	Symbol	Estimate			Source / Reference
			Small	Large	Mixed	
Growth	Asymptotic size	L_∞	326–361	768–844	325–850	Figure 1 Appendix 1
	Growth coefficient	k	0.14–0.17	0.12–0.14	0.12–0.17	
	Age at 0 mm	t_0	-0.21–0.01	0.17–0.32	-0.21–0.31	
Survival	Instantaneous mortality at unit size	m_0	22–140	161–353	97–350	Depends on target λ
	Young-of-year (YOY)	σ_{YOY}	0.01–0.55	0.05–0.25	0.05–0.09	Figure 3, Equation 8, Appendix 1
	Juvenile Stages (1–4)	$\sigma_{J1\text{-}4}$	0.15–0.92	0.05–0.75	0.09–0.73	
	Adult Stage	σ_A	0.62–0.95	0.59–0.78	0.48–0.76	
Fecundity	Proportion female	φ		0.5		Assumed
	Spawning periodicity	T		1–2		
	Fertility (egg count)	η_j		0-8000		Figure 4, Appendix 1
	Proportion reproductive	ρ_j		J = 0, A = 1		Assumed
Age	Maximum age	t_{max}		9.01–12.77		Equation 6
	Age at maturity	t_{mat}		5.62–8.51		Equations 4,5
Matrix	Effective fecundity	F_j	196–252	1691–2145	195–2144	Equation 1
	Probability of transitioning	G_j	0.10–0.30	0.05–0.16	0.04–0.21	Equation 3
	Proportion in small trajectory	α	NA		0.5	
Analysis	Annual population growth rate	λ		various		
	Maximum growth rate	λ_{max}	1.8	1.3	1.4	Equation 10
	Generic vital rate	v				
	Elasticity	ε_v				Equation 9
	Allowable chronic harm	H_C				Equation 11
	Allowable transient harm	H_T				
	Minimum viable population	MPA				Equation 14
	Minimum area for population viability	MAPV				Equation 15

The maximum recorded age of Bull Trout was 24 years, however it is thought that Bull Trout rarely reach ages greater than 20 with an average maximum age closer to 10 years (McPhail and Baxter 1996). The oldest fish in the small and large bodied datasets were 12 and 18 respectively. Maximum age (t_{max}) was estimated for each projection matrix using the following the empirically supported relationship with the estimated age at maturity:

$$t_{max} = e^{0.5498 + 0.957 \log(T_{mat})} \text{ (Equation 6)}$$

(Froese and Binohlan 2000).

Survival data (Figure 3) were gathered from four sources (Appendix 1) and represent three large bodied populations across the Bull Trout native range. When only figures were available, values were approximated using image software (Tummers 2006). When length ranges were provided, the mean length in the range was used and converted to age using the von Bertalanffy growth curve estimates from the respective population.

Age-dependent survival was then estimated by combining a size-dependent mortality model (Lorenzen 2000) with the estimated growth parameters. Mortality was assumed to decline proportionally with increases in size (Lorenzen 2000) such that:

$$M_t = \frac{m_0}{L_t} \text{ (Equation 7)}$$

where M_t and L_t are the instantaneous mortality and mean length at time t, and m_0 is the mortality at unit size (i.e., at $L_t = 1$). Since L_t is described by the von Bertalanffy growth curve, survival from age j to age j+1 can be calculated by integrating the above equation and evaluating between j and j+1 (van der Lee and Koops 2016):

$$s_{j \ldots j+1} = \left[\frac{L_j e^{-k}}{L_{j+1}}\right]^{m_0/kL_\infty} \text{ (Equation 8)}$$

The parameter m_0 for the SP and LP was estimated by fitting the above equation by the method of non-linear least squares to the survival data using the mean, upper and lower values for the small and large growth trajectory von Bertalanffy parameter estimates respectively. Stage-specific survival estimates for each projection matrix were calculated using equation 7 with the minimum and maximum estimates of m_0 from the above model fits for each growth trajectory and the stage specific average size. The model was not able to estimate survival for age 0 for the SP and LP; instead the youngest age that could be estimated by the model for SP and LP (0.2 and 0.4) was used for the YOY survival estimate. For stages that represent both SP and LP (YOY and J_1), survival was weighted by the proportion of individuals (α) in the respective growth trajectory.

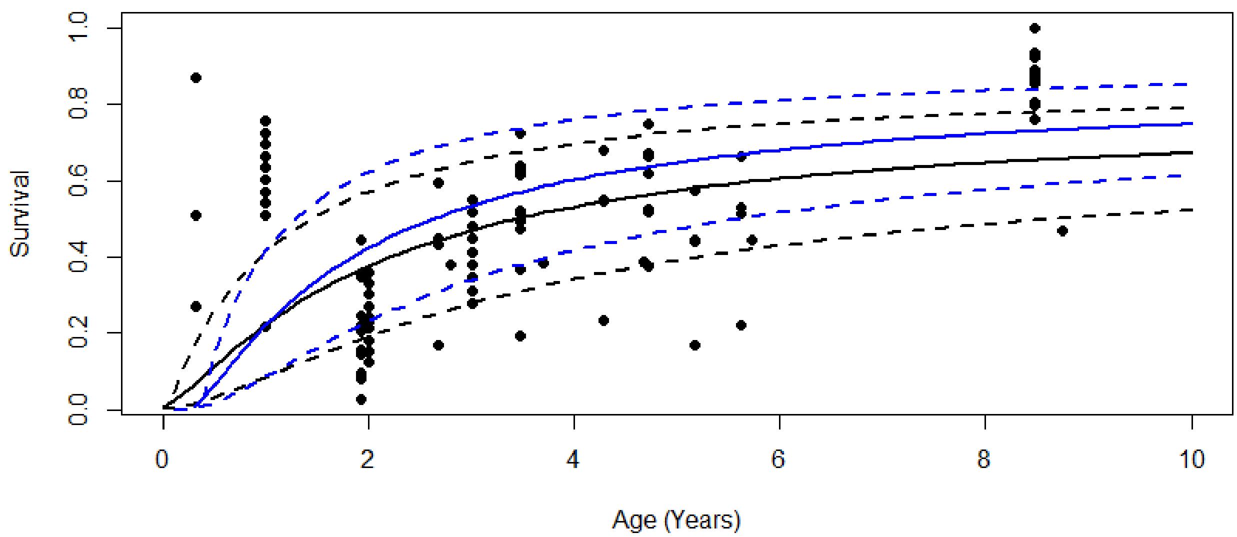


Figure 3. Estimates from the literature for Bull Trout age specific survival probabilities (points) and the estimates from the survival equation (solid lines) with corresponding confidence intervals (dashed lines) for small (black) and large (blue) bodied population types.

Fecundity

Fecundity data, the number of eggs in relation to fork length (mm) were gathered from the literature (Appendix 1). When only figures were available, values were approximated using image software (Tummers 2006). Fecundity at length was determined by fitting ϑ and β from the following relationship: $E = \vartheta FL^{\beta}$ to the data by the method of non-linear least squares (Figure 4). To determine the number of eggs for the adult life stage, the above relationship was applied to the mean fork length between L_{mat} and L_{∞} for each growth trajectory. The resulting fecundity relationship is generally consistent with population specific estimates in the literature (Al-Chokhachy and Budy 2008; Bowerman 2013; Johnston et al. 2007; Rieman and McIntyre 1993). The periodicity of Bull Trout spawning depends on the population. The probability of skipped or alternate year spawning increases in individuals with lower condition, in colder systems, and in populations with higher density (Rodtka 2009). Estimates in the literature range from 100% of the population exhibiting skipped spawning (Rieman and McIntyre 1993) to 93% of the population spawning annually (Downs et al. 2006). Generation time was calculated from the stage-specific survival and fecundity estimates as per Caswell (2001).

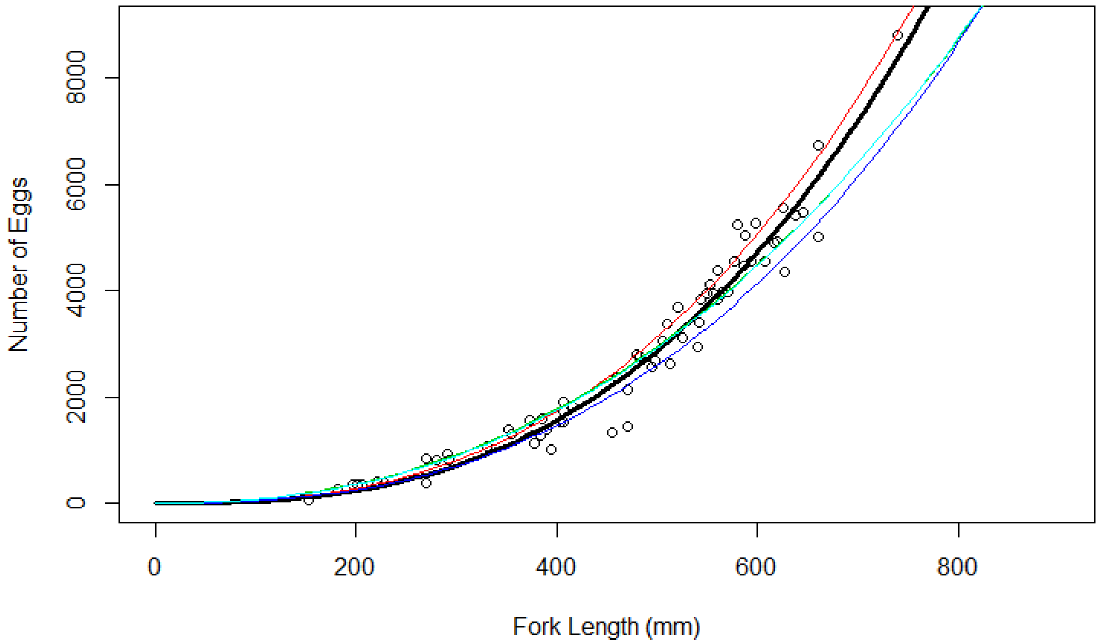


Figure 4. Estimates of the number of eggs at fork length from the literature (Appendix 1, points) and the fit equation (solid black line). Fitted curves from the literature are added in colour for reference (Al-Chokhachy and Budy 2008 (cyan); Bowerman 2013 (red); Johnston et al. 2007 (green); Rieman and McIntyre 1993 (blue)).

Population Trajectory

Thirty-six Bull Trout waterbodies were assessed and provided a conservation ranking by Alberta Environment and Sustainable Resource Development. The waterbodies were evaluated for life history type (i.e., resident, fluvial, or adfluvial), number of subpopulations, population size, occupancy, short-term tends, threats, and recovery potential (Alberta Environment and Sustainable Resource Development 2012). The 36 waterbodies contained 70 extant subpopulations and 3 extirpated subpopulations. Of the extant subpopulations, 33% contained only residents, 18% had only fluvial or adfluvial populations and 45% were mixed; one subpopulation was incidental (Middle Bow River). The estimated size of all the populations in the waterbodies combined is between 6,359 and 21,700 total mature individuals, with the individual population estimates in the waterbodies ranging from 10 to 1,275 mature individuals. Short-term population trends show 54% of the subpopulations in decline, 33% stable, and 9% increasing; one subpopulation was unranked (Upper Bow River).

POPULATION SENSITIVITY

The sensitivity of the population to changes in the environment is determined by the sensitivity of the estimated annual growth rate (λ) to perturbations in the vital rates (v). Annual population growth rate can be estimated as the largest eigenvalue of the projection matrix (Caswell 2001). Model sensitivity is quantified by elasticities which are a measure of the sensitivity of population growth rate to perturbations in vital rate v, and are given by the scaled partial derivatives of λ with respect to the vital rate:

$$\varepsilon_v = \frac{v}{\lambda}\sum_{i,j}\frac{\partial\lambda}{\partial a_{i,j}}\frac{\partial a_{i,j}}{\partial v} \quad \text{(Equation 9)}$$

where a_{ij} are the projection matrix elements.

Variation in vital rates were incorporated to determine effects on population responses from demographic perturbations (see Vélez-Espino and Koops 2007). Computer simulations were used to

(i) generate 5,000 matrices with values for parameters that contribute to the estimation of vital rates (i.e., L_∞, k, t_0, m_0, and T) drawn from uniform distributions according to the confidence intervals of the estimated parameter values;

(ii) calculate λ for each matrix;

(iii) calculate the ε_v for each matrix; and

(iv) estimate mean stochastic elasticities and their 95% confidence intervals.

ALLOWABLE HARM

Allowable harm is defined as harm to the population that will not jeopardize population recovery or survival. Chronic harm refers to a negative alteration to a vital rate (survival, fecundity, etc.) that reduces the annual population growth rate permanently or over the long term. Transient harm refers to a one-time removal of individuals such that survival (and therefore population growth rate) is only affected in the year of the removal.

Estimates of allowable chronic harm are based on the population growth rate and are only calculated for populations with positive growth (9% of Bull Trout waterbody populations). Allowable chronic harm is estimated for each population type (small, large, and mixed) assuming a positive growth rate, and a minimum acceptable population growth rate of stability (λ = 1). A positive growth rate for each population type was achieved by optimizing m_0 (hence survival) to obtain the maximum growth rate for the respective population type defined by

$$\lambda_{max} = e^{2.64\, W_{mat}{}^{-0.35}} \text{ (Equation 10)}$$

where W_{mat} is the weight at maturation (Randall and Minns 2000).

Maximum allowable chronic harm (H_c) was estimated analytically as:

$$H = \left(\frac{1}{\varepsilon_v}\right)\left(\frac{1-\lambda}{\lambda}\right) \text{ (Equation 11)}$$

where ε_v is the elasticity of vital rate v, and λ is the growth rate in the absence of additional harm.

The effects of transient harm were modelled as follows:

(i) annual projection matrices were generated for ten years by randomly drawing vital rates as in the sensitivity analysis;

(ii) survival of one or all of the stages was reduced for one of the random matrices, simulating a one-time removal of individuals;

(iii) the geometric mean population growth rates before and after removal were compared over the timeframe considered;

(iv) this simulation was repeated 5,000 times to create a distribution of changes in population growth rate as a result of removal;

(v) rates of removal (number of individuals as a proportion of total abundance) from 0 to all individuals were considered.

Allowable transient harm was defined as a one-time removal of individuals, within a time-frame of 10 years that does not reduce the average population growth rate over that time-frame more than a pre-determined amount (see Results). The population growth rate was considered to be "reduced" when the lower confidence bound of the distribution of differences in growth rate pre- and post-removal exceeded the designated amount.

RECOVERY TARGETS

Abundance

Demographic sustainability can be used to identify potential recovery targets for Bull Trout. Demographic sustainability is related to the concept of a minimum viable population (MVP) (Shaffer 1981), and was defined as the minimum adult population size that results in a desired probability of persistence over 100 years (approx. 12 generations for Bull Trout).

Since population growth is not sustainable over time, the probability of persistence was simulated for a stable population over the long-term. To achieve stability in the model, m_0 was optimized to achieve a geometric mean growth rate (in stochastic simulations) of $\lambda = 1$.

Recovery targets were estimated as follows:

(i) 50,000 projection matrices were generated by randomly drawing vital rates as in the population sensitivity analysis, based on a geometric mean growth rate of $\lambda=1$;

(ii) projection matrices were drawn at random from these to generate 5,000 realizations of population size per time step (i.e., over 100 years);

(iii) these realizations were used to generate a cumulative distribution function of extinction probability, where a population was said to be extinct if it was reduced to one adult (female) individual

(iv) this process was repeated 10 times, giving an average extinction probability per time step. Catastrophic decline in population size, defined as a 50% reduction in abundance, was incorporated into these simulations, and occurred at a probability (P_k) of 0.10 or 0.15 per generation. From these simulations, the minimum number of adults necessary for the desired probability of persistence (see Results) over 100 years was calculated.

Assuming that populations experience independent and identical catastrophic extirpation risks (Ruckelshaus et al. 2002), the probability of persistence of a group of environmentally discrete populations (P_m) can be calculated using the probability of persistence of each individual population (P_s) and the total number of populations (n) as:

$$P_m = 1 - \prod_{s=1}^{n}(1 - P_s) \quad \text{(Equation 12)}$$

This equation accounts for the probability of catastrophic events reducing a population by 50% however it does not account for a catastrophic extirpation which is defined by (Reed et al. 2003a) as an event that reduces abundance by 95% or more. The probability of catastrophic extirpation (P_e) can be incorporated into equation 12:

$$P'_m = 1 - \prod_{s=1}^{n}(1 - P_s + P_s P_e) \quad \text{(Equation 13)}$$

Habitat: Minimum area for population viability (MAPV)

Following Vélez-Espino et al. (2009), MAPV was estimated as a first order quantification of the amount of habitat required to support a viable population, and calculated for each stage-class in the population as:

$$MAPV_j = MVP_j \cdot API_j \quad \text{(Equation 14)}$$

where MVP_j is the minimum number of individuals per stage-class required to achieve the desired probability of persistence over 100 years, as estimated for the recovery target; and API_j is the area required per individual in class *j*. Individuals were distributed among stage classes according to the stable stage distribution, which is represented by the dominant right eigenvector (w) of the mean projection matrix based on the λ=1 ($Mw = \lambda \cdot w$) (de Kroon et al. 1986). API was estimated using an allometry for river environments from (Minns 2003; Randall et al. 1995). This allometry approximates API_j (m^2) for freshwater fishes based on the mean TL in mm of class *j*:

$$API_j = e^{-13.28} \cdot TL_j^{2.904}$$ (Equation 15)

The MAPV for the entire population was estimated by summing the MAPVs estimated for each stage. MAPV was compared to the area available for the populations in the Saskatchewan – Nelson rivers waterbodies.

RESULTS

POPULATION SENSITIVITY

When considered cumulatively by stage, Bull Trout population growth was most sensitive to changes in the survival of juveniles for each population type. Sensitivity to the survival of juveniles is also highly variable for declining populations, increasing and becoming less variable as population growth increases. Sensitivity to the survival of adults is highly variable for declining population, then decreases and becomes less variable as population growth increases. For the mixed model, sensitivity to the SP growth, fecundity, and juvenile and adult survival decrease as λ increases, with the same sensitivities for the LP increasing as λ increases. In other words, the importance of SP or LP vital rates in the MP switches as λ increases.

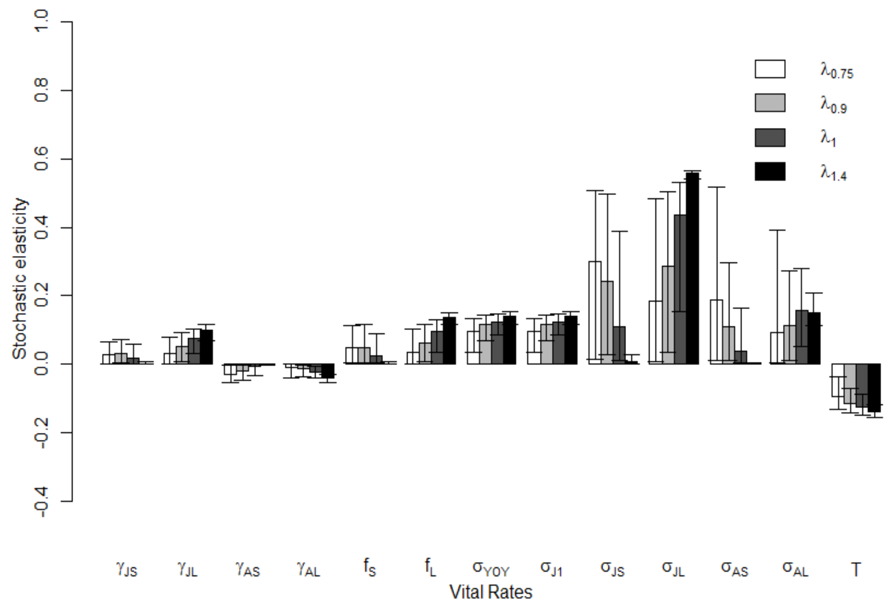


Figure 5. Results of the stochastic perturbations analysis showing elasticities (ε_v) of vital rates for Bull Trout for the mixed population growth trajectory. The vital rates include the growth between stages (γ) for juveniles and adults, fecundity (f), survival (σ) for the young of year, juveniles and adult stages, and spawning periodicity (T). Results for a two declining populations (λ = 0.75 or 0.9), a stable population (λ=1), and a population growing at maximum growth (λ_{max}). Exact values are listed in Table 2.

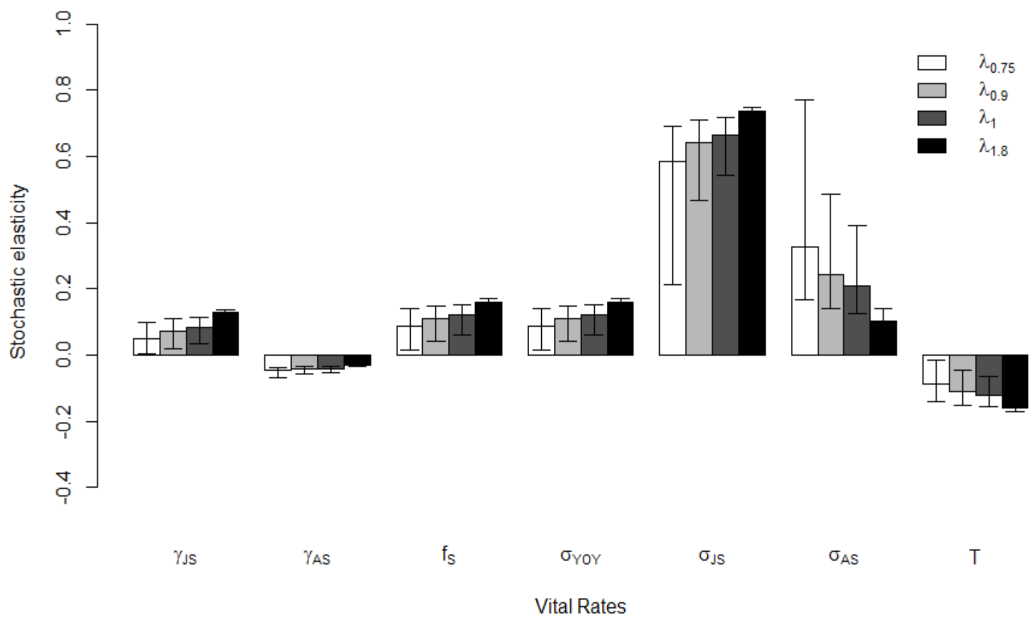


Figure 6. Results of the stochastic perturbations analysis showing elasticities (εv) of vital rates for Bull Trout for the small population growth trajectory. The vital rates include the growth between stages (γ) for juveniles and adults, fecundity (f), survival (σ) for the young of year, juveniles and adult stages, and spawning periodicity (T). Results for a two declining populations (λ = 0.75 or 0.9), a stable population (λ=1), and a population growing at maximum growth (λ_{max}). Exact values are listed in Table 3.

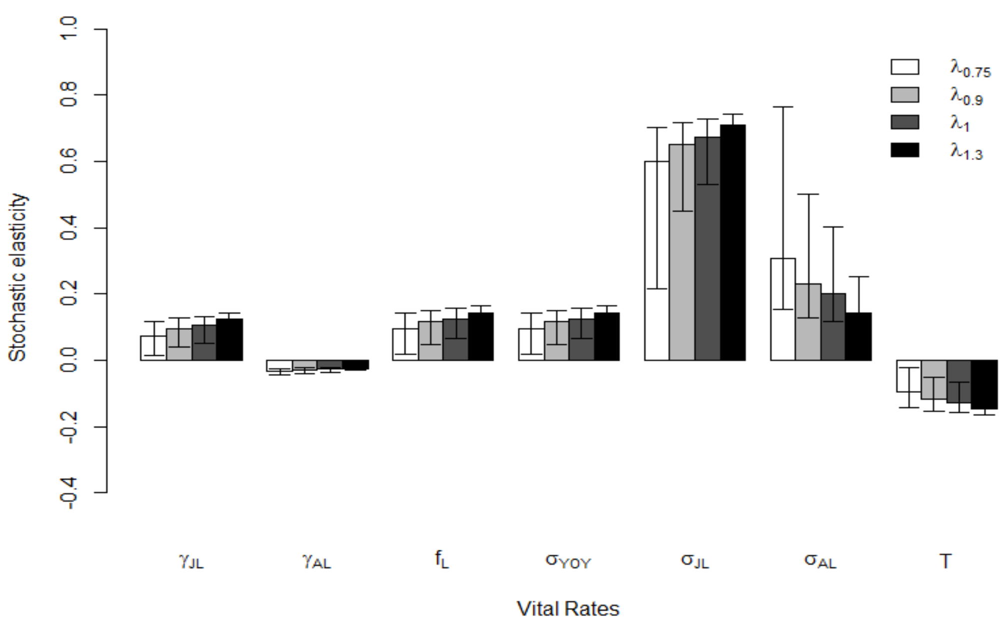


Figure 7. Results of the stochastic perturbations analysis showing elasticities (ε_v) of vital rates for Bull Trout for the large population growth trajectory. The vital rates include the growth between stages (γ) for juveniles and adults, fecundity (f), survival (σ) for the young of year, juveniles and adult stages, and spawning periodicity (T). Results for a two declining populations (λ = 0.75 or 0.9), a stable population (λ=1), and a population growing at maximum growth (λ_{max}). Exact values are listed in Table 4.

Table 2. Summary of elasticities of Bull Trout vital rates (ε_v) for a ***mixed population*** *(MP) at maximum population growth (λ=1.4), a stable population (λ=1) and two declining populations (λ=0.9 and 0.75). Shown are elasticities for: annual survival of YOY (σ_{YOY}), annual survival of the first stage of the juvenile population (σ_{J1}), annual cumulative juvenile survival (σ_{JS} and σ_{JL}) , annual adult survival (σ_{AS} and σ_{AL}), fecundity (f_S and f_L), and spawning periodicity (T).*

Growing Population (λ = 1.4)

Vital Rate	σ_{YOY}	σ_{J1}	σ_{JS}	σ_{JL}	σ_{AS}	σ_{AL}	f_S	f_L	T
Stochastic mean	0.14	0.14	0.01	0.56	1.32×10^{-3}	0.15	1.77×10^{-3}	0.14	-0.14
Lower confidence	0.12	0.12	7.51×10^{-4}	0.54	1.72×10^{-4}	0.11	1.98×10^{-4}	0.12	-0.16
Upper confidence	0.16	0.16	0.03	0.57	0.01	0.21	0.01	0.15	-0.12

Stable Population (λ = 1)

Vital Rate	σ_{YOY}	σ_{J1}	σ_{JS}	σ_{JL}	σ_{AS}	σ_{AL}	f_S	f_L	T
Stochastic mean	0.12	0.12	0.10	0.44	0.04	0.16	0.02	0.10	-0.12
Lower confidence	0.09	0.09	0.01	0.15	4.14×10^{-3}	0.05	2.42×10^{-3}	0.03	-0.15
Upper confidence	0.15	0.15	0.39	0.53	0.16	0.28	0.09	0.13	-0.09

Declining Population (λ = 0.9)

Vital Rate	σ_{YOY}	σ_{J1}	σ_{JS}	σ_{JL}	σ_{AS}	σ_{AL}	f_S	f_L	T
Stochastic mean	0.12	0.12	0.29	0.24	0.13	0.09	0.06	0.05	-0.12
Lower confidence	0.07	0.07	0.04	0.02	0.02	7.55×10^{-3}	8.14×10^{-3}	4.88×10^{-3}	-0.14
Upper confidence	0.14	0.14	0.51	0.50	0.31	0.26	0.12	0.11	-0.07

Declining Population (λ = 0.75)

Vital Rate	σ_{YOY}	σ_{J1}	σ_{JS}	σ_{JL}	σ_{AS}	σ_{AL}	f_S	f_L	T
Stochastic mean	0.10	0.10	0.26	0.23	0.16	0.12	0.04	0.04	-0.10
Lower confidence	0.04	0.04	0.01	9.20×10^{-3}	6.45×10^{-3}	4.56×10^{-3}	1.94×10^{-3}	1.95×10^{-3}	-0.13
Upper confidence	0.13	0.13	0.50	0.49	0.48	0.43	0.11	0.11	-0.0

*Table 3. Summary of elasticities of Bull Trout vital rates (ε_v) for the **small bodied** population (SP) at maximum population growth (λ=1.8), a stable population (λ=1) and two declining populations (λ=0.9 and 0.75). Shown are elasticities for: annual survival of YOY (σ_{YOY}), cumulative annual juvenile survival (σ_J), annual adult survival (σ_A), fecundity (f), and spawning periodicity (T).*

Growing Population (λ = 1.8)

Vital Rate	σ_{YOY}	σ_J	σ_A	f	T
Stochastic mean	0.16	0.74	0.10	0.16	-0.16
Lower confidence	0.14	0.72	0.08	0.14	-0.17
Upper confidence	0.17	0.75	0.14	0.17	-0.14

Stable Population (λ = 1)

Vital Rate	σ_{YOY}	σ_J	σ_A	f	T
Stochastic mean	0.12	0.67	0.21	0.12	-0.12
Lower confidence	0.06	0.55	0.13	0.06	-0.15
Upper confidence	0.15	0.72	0.39	0.15	-0.06

Declining Population (λ = 0.9)

Vital Rate	σ_{YOY}	σ_J	σ_A	f	T
Stochastic mean	0.11	0.64	0.24	0.11	-0.11
Lower confidence	0.04	0.47	0.14	0.04	-0.15
Upper confidence	0.15	0.71	0.49	0.15	-0.04

Declining Population (λ = 0.75)

Vital Rate	σ_{YOY}	σ_J	σ_A	f	T
Stochastic mean	0.09	0.59	0.33	0.09	-0.09
Lower confidence	0.02	0.21	0.17	0.02	-0.14
Upper confidence	0.14	0.69	0.77	0.14	-0.02

Table 4. Summary of elasticities of Bull Trout vital rates (ε_v) for the ***large*** *bodied population (LP) at maximum population growth (λ=1.3), a stable population (λ=1) and two declining populations (λ=0.9 and 0.75). Shown are elasticities for: annual survival of YOY (σ_{YOY}), cumulative annual juvenile survival (σ_J), annual adult survival (σ_A), fecundity (f), and spawning periodicity (T).*

Growing Population (λmax = 1.3)

Vital Rate	σ_{YOY}	σ_J	σ_A	f	T
Stochastic mean	0.15	0.71	0.14	0.15	-0.15
Lower confidence	0.11	0.64	0.09	0.11	-0.16
Upper confidence	0.16	0.74	0.25	0.16	-0.11

Stable Population (λ = 1)

Vital Rate	σ_{YOY}	σ_J	σ_A	f	T
Stochastic mean	0.13	0.67	0.20	0.13	-0.13
Lower confidence	0.07	0.53	0.12	0.07	-0.16
Upper confidence	0.16	0.73	0.41	0.16	-0.07

Declining Population (λ = 0.9)

Vital Rate	σ_{YOY}	σ_J	σ_A	f	T
Stochastic mean	0.12	0.65	0.23	0.12	-0.12
Lower confidence	0.05	0.44	0.13	0.05	-0.15
Upper confidence	0.15	0.72	0.51	0.15	-0.05

Declining Population (λ = 0.75)

Vital Rate	σ_{YOY}	σ_J	σ_A	f	T
Stochastic mean	0.09	0.60	0.31	0.09	-0.09
Lower confidence	0.02	0.21	0.15	0.02	-0.14
Upper confidence	0.14	0.70	0.77	0.14	-0.02

ALLOWABLE HARM

Allowable chronic harm

Since there is a high amount of uncertainty in many of the vital rates, it follows that there is high uncertainty in the allowable harm. From a precautionary perspective, the upper 95% confidence level is applied for allowable harm. If the upper and lower confidence limits cross zero, as is the case for the LP, the uncertainty is too great to set an allowable harm value. Our results suggest that the SP type at maximum population growth (λ_{max}) is most sensitive to changes in the survival of juveniles (SP), with a maximum allowable reduction of 46% in juvenile survival (Table 5). Allowable harm values that do not fall between 0 and -1 (or 0 and 1 in the case of parameters that would increase λ if decreased, i.e., *T*) indicate that the population is not sensitive to changes in these vital rates at λ_{max} if all other vital rates are held constant.

Allowable chronic harm would be lower if the population is growing at a slower rate, and is 0 if it is not growing. Allowable chronic harm for a population with a positive growth rate (λ^+) that is lower than the maximum population growth rate ($\lambda_{max} > \lambda^+ > 1$) can be approximated with Equation 10 by using the λ^+ along with the elasticities from a growing population ($\lambda = \lambda_{max}$) in Table 2. If human activities are such that harm exceeds just one of these thresholds, the future persistence of populations is likely to be compromised. In addition, simulations suggest that recovery time can be severely delayed by any levels of harm within the maximum allowable harm suggested in Table 5 (Young and Koops 2011).

Allowable transient harm

In all population types (mixed, small, and large growth trajectories), for the case where all stages were reduced, the average growth rate and the decline in average growth rate decreased and increased respectively with larger removal rates of individuals (Figure 8, black lines). When individual stages were affected, there was minimal effect on growth rate (Figure 8, grey lines).

Allowable transient harm (allowable one time removal, performed no more frequently than every 10 years) can be extracted from Figure 9 by determining the percent removal that is associated with an acceptable reduction in the population growth rate over that time period (following the curve for the life stage being removed). We suggest that the upper confidence bounds be used, as values in the upper confidence bound represent a change in the population growth rate beyond that which might result simply from environmental stochasticity. Allowable transient harm may also differ depending on the population growth rate; a growing population may be able to sustain a larger removal, without going into decline, than a stable population. For example, for the mixed type, if an acceptable change in the population growth rate is 0.01 for a stable population, the allowable one-time removal every 10 years is ~10% of all individuals Figure 9, top panel, right). An acceptable change in population growth rate for a population growing at a rate of $\lambda=1.4$ may be 0.015, which would yield the same allowable removal of ~10% of all individuals every 10 years Figure 9, top panel, left).

Table 5. A summary of Bull Trout allowable chronic harm (as a proportion of the vital rate, H_c) for mixed, small, and large bodied populations at maximum population growth. Shown are allowable harm for: annual survival of YOY (σ_{YOY}), cumulative annual juvenile survival (σ_J), annual adult survival (σ_{AS} and σ_{AL}), fecundity (f_S and f_L), and spawning periodicity (T).

Mixed Growth Trajectory (λmax = 1.4)

Vital Rate	σ_{YOY}	σ_J	σ_{AS}	σ_{AL}	f_S	f_L	T
Stochastic mean	-2.04	-1.22	-215	-1.89	-161.35	-2.08	2.04
Lower confidence	-2.45	-1.30	-1660	-2.52	-1445	-2.46	1.84
Upper confidence	-1.84	-1.14	-50.16	-1.38	-34.57	-1.89	2.45

Small Growth Trajectory (λmax = 1.8)

Vital Rate	σ_{YOY}	σ_J	σ_{AS}	σ_{AL}	f_S	f_L	T
Stochastic mean	-2.79	-0.61	-4.30		-2.79		2.79
Lower confidence	-3.15	-0.71	-6.59		-3.15		2.25
Upper confidence	-2.25	-0.46	-2.33		-2.25		3.15

Large Growth Trajectory (λmax = 1.3)

Vital Rate	σ_{YOY}	σ_J	σ_{AS}	σ_{AL}	f_S	f_L	T
Stochastic mean	-1.61	-0.33		-1.63		-1.61	1.61
Lower confidence	-2.74	-0.61		-4.86		-2.74	-1.01
Upper confidence	1.01	0.16		0.42		1.01	2.74

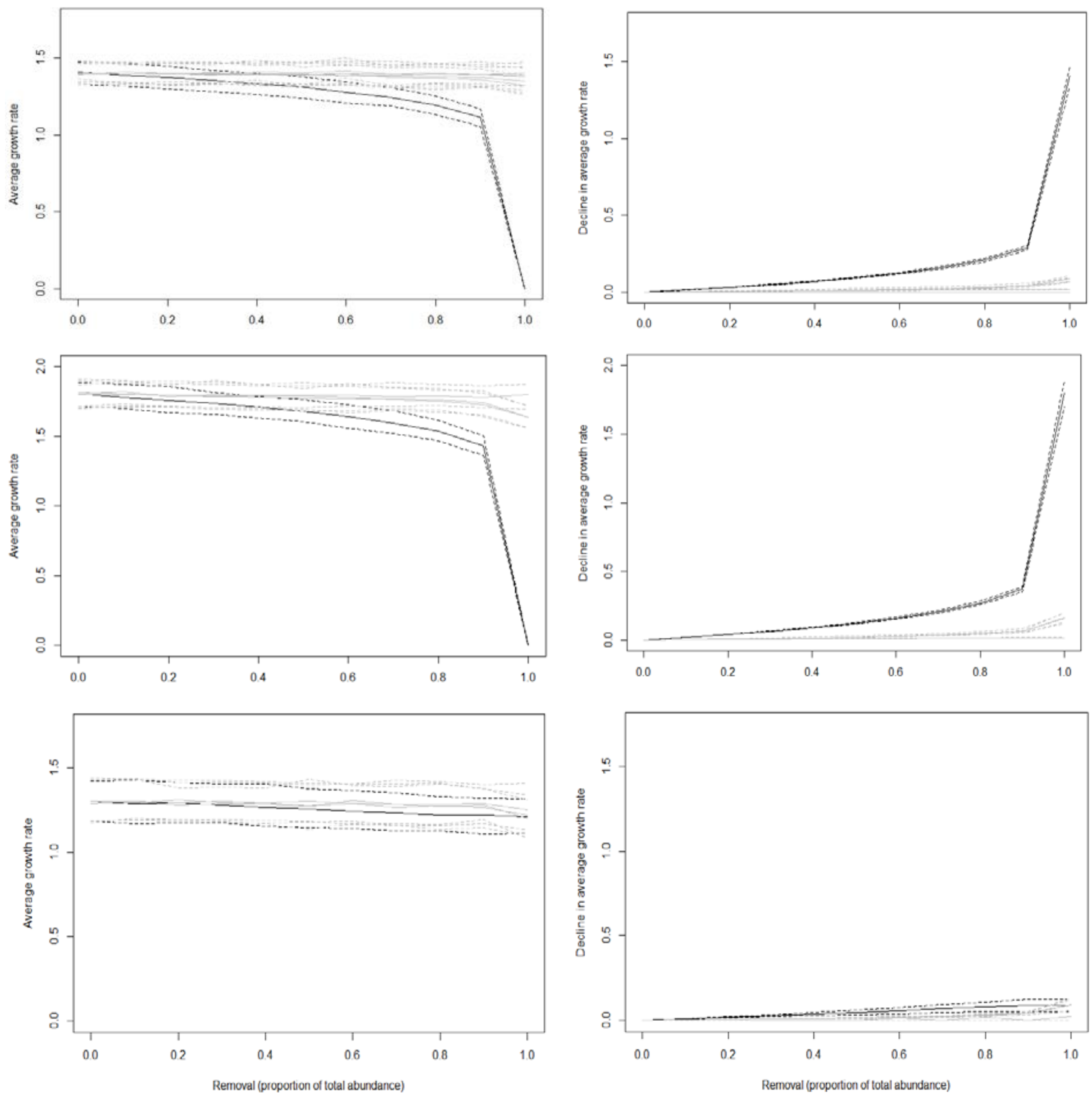


Figure 8. Average growth rate (left) and decline in average growth rate (right) for the mixed (top panel), small (middle panel) and large (bottom panel) bodied population types growing at maximum growth rate over 10 years, as a function of the percent of individuals removed from the population in one of 10 years. Means (solid lines), bootstrap 95% confidence intervals (dashed lines) are shown. Results are for removal of only YOY, juveniles, or adults (grey lines), or all stages (black lines) are compared.

The figures here represent removal rates (i.e., a proportion of the population). Absolute numbers can be determined from the removal rates by multiplying by the population abundance for the appropriate life stage. For example, current numbers for populations that are increasing range from 250 – 25,000 adults (Alberta Environment and Sustainable Resource Development, 2012). Assuming an acceptable reduction in growth rate of 1%, the allowable transient harm would be 25-2,500 adults (harm to all stages) over 10 years. Absolute numbers of individuals can also be calculated deterministically (i.e., ignoring environmental variation) given the population abundance (N0), acceptable change in mean population growth rate (Δλ), and the survival rate of stage class j (σ_j):

$$h_j = \Delta\lambda\, N_0 \sigma_j \text{ (Equation 16)}$$

RECOVERY TARGETS

Recovery Efforts

Similarly, the equation for allowable harm can be used to calculate the amount of change to a vital rate required to increase the population growth rate. For populations with a declining population ($\lambda < 1$) we can calculate the amount of change to a vital rate required to increase the population growth rate to 1 (stable). As outlined in Appendix 2, an increase in the juvenile or adult survival rates (σ_J or σ_A), or a decrease in the spawning periodicity (T) of 24%, 79%, 74% respectively for the SP and 25%, 85%, 74% respectively for the LP could increase a λ of 0.9 to 1. No amount of increase to any individual vital rate could increase a λ of 0.75 or lower to 1 for any population types. It is important, however, to consider that there may be biological limits to increasing vital rates. Recovery efforts that increase vital rates for more than one life stage should be considered preferential over those that only target one life stage.

Abundance targets (MVP)

Probability of extinction decreases as a power function of population size (Figure 10 and Figure 11). Functions of the form $y = ax^b$ were fitted, using non-linear least squares, to the simulated extinction probabilities for each catastrophe scenario.

While choosing a larger recovery target will result in a lower risk of extinction, there are also costs associated with an increased target (increased recovery effort, longer time to recovery, etc.). When determining MVP from the fitted power curves, we attempted to balance the benefit of reduced extinction risk and the cost of increased recovery effort with the following algorithm.

(i) We assumed that the maximum allowable risk of extinction is 10% based on COSEWIC's quantitative criteria (E) that a risk of extinction greater than or equal to 10% within 100 years constitutes Threatened status. We define a maximum MVP (i.e., maximum feasible effort) to be the population that would result in a 0.1% probability of extinction, as this is the most stringent criteria in the literature;

(ii) using these as boundaries, we calculate the average decrease in probability of extinction per individual increase in population size;

(iii) we choose as MVP the population size that would result in this average (i.e., the point on the power curve at which the slope equals the average % decrease in extinction risk per increase in target). This represents the point between the upper and lower boundaries where the reduction in extinction risk per investment in recovery is maximized.

Calculated in this way, the reduction in extinction risk per investment in recovery was maximized at approximately 1% risk of extinction. MVP ranged from 95 to 1300 adults (Table 7), depending on the population type, when the probability of catastrophic decline (50% decline) was assumed to be 10% per generation (1.2% each year). If catastrophes occurred at 15% per generation (1.9% each year), MVP ranged between 360 and 3900 adults (Table 7). P_{ext}, for the 10% or 15% per generation catastrophe scenario can be defined as a function of initial adult population, N, and are described in Table 6.

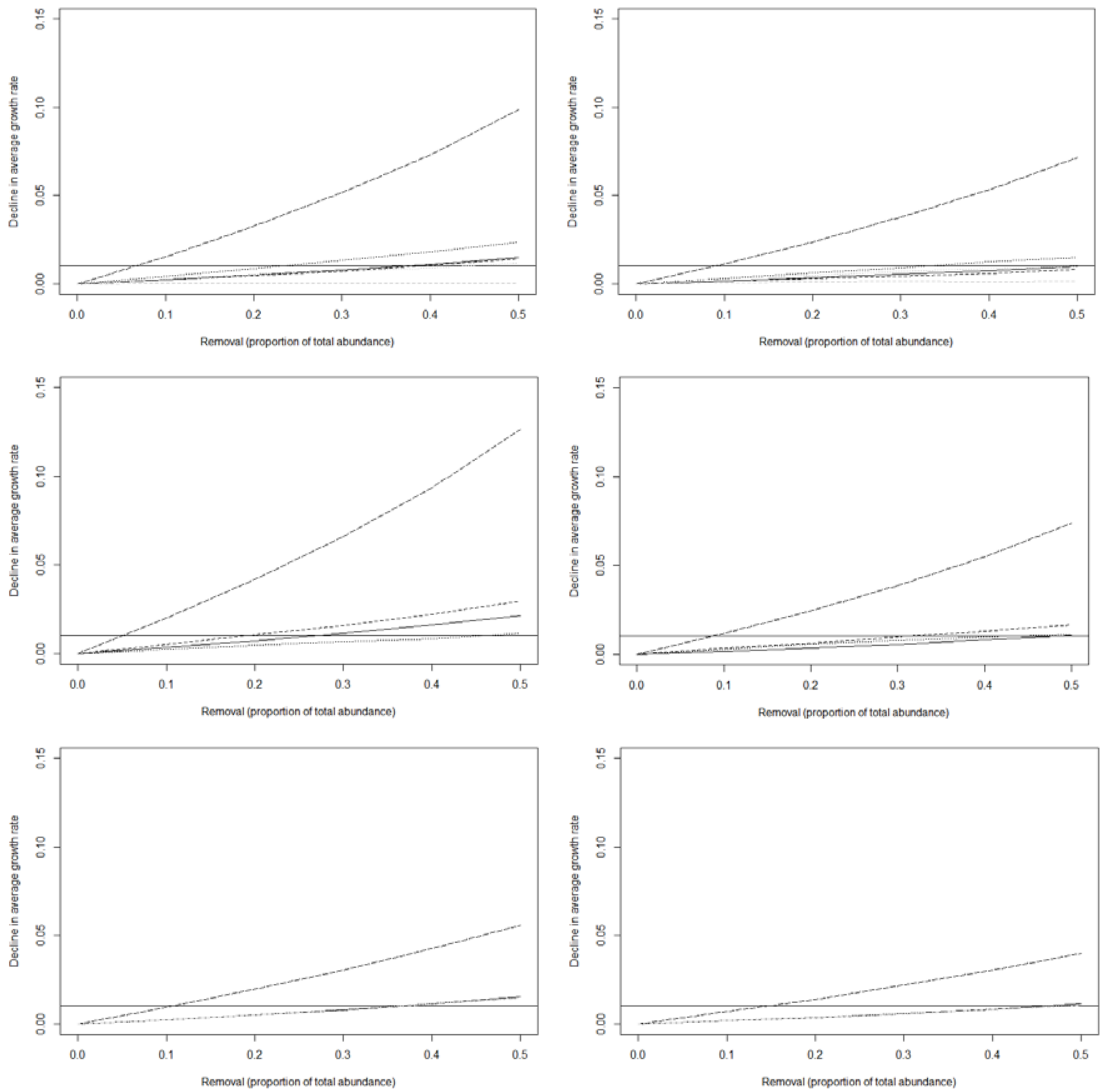


Figure 9. The decline in average growth for the mixed (top panel), small (middle panel) and large (bottom panel) bodied population types of a stable population (right) or a population growing at λmax (left) over 10 years, as a function of the proportion of individuals removed from the population in one of 10 years. Results are for removal of all stages (black, long dashed line), YOY and first juvenile stage (solid) small (dashed)) and large (small dash) juveniles (black) and adults (grey). Values shown are the lower confidence bounds across 5000 runs with 10 randomly drawn population matrices. A horizontal black line at 0.01 represents a possible acceptable change in the population growth rate.

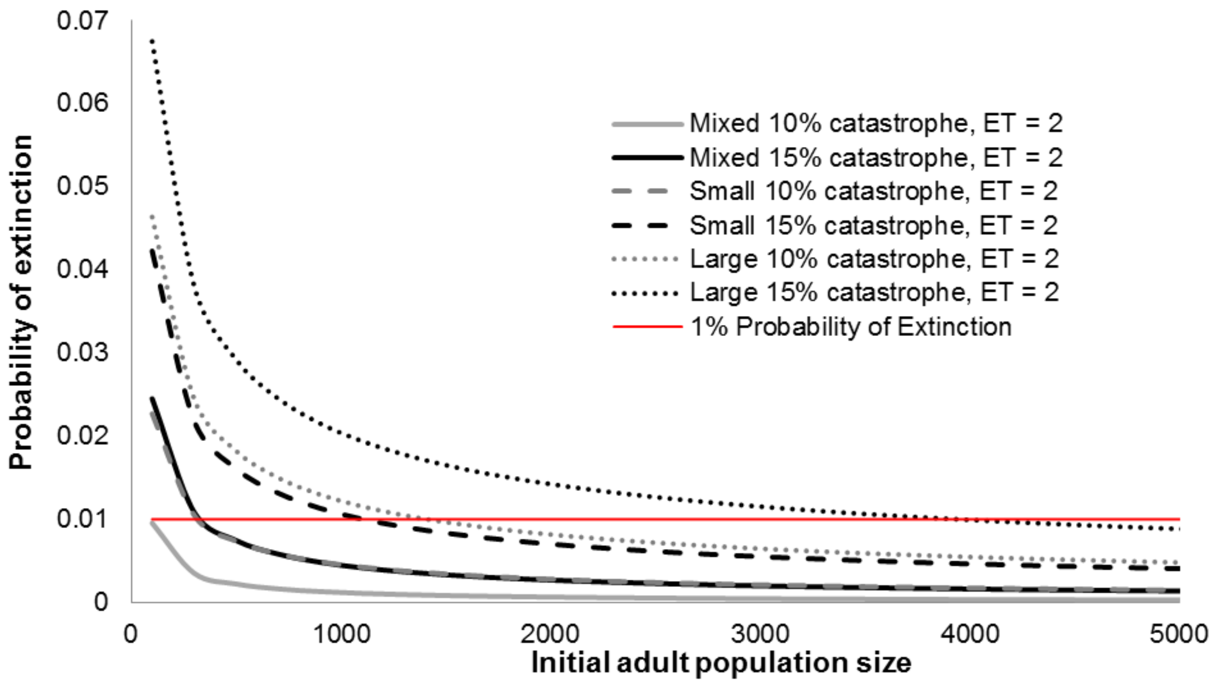


Figure 10. Probability of extinction, at the quasi-extinction thresholds (ET) of 2 adults, within 100 years of 10 simulated Bull Trout populations, at equilibrium, as a function of adult population size. Curves represent different combinations of population type and probability of catastrophe per generation (%). Red horizontal reference line is at 0.01 and intersects curves at the associated MVPs (Table 7).

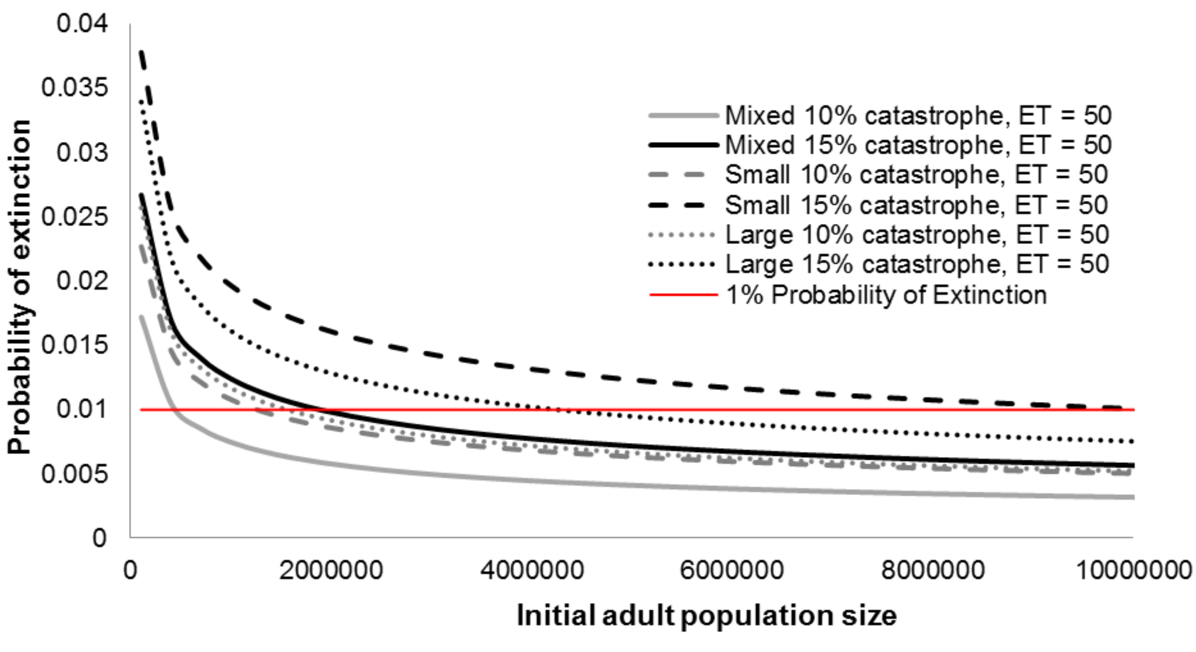


Figure 11. Probability of extinction, at the quasi-extinction thresholds (ET) of 50 adults, within 100 years of 10 simulated Bull Trout populations, at equilibrium, as a function of adult population size. Curves represent different combinations of population type and probability of catastrophe per generation (%). Red horizontal reference line is at 0.01 and intersects curves at the associated MVPs (Table 7).

Table 6. Equations describing probability of extinction (P_{ext}) considered at either 2 or 50 adults after 100 years, at 10% and 15% probability of catastrophe per generation based on the initial number of adults in the population (N).

2 Adults

	10% per generation	15% per generation
Mixed	$P_{ext} = 0.63*N^{-91}$	$P_{ext} = 0.74*N^{-0.74}$
Small	$P_{ext} = 0.57*N^{-0.70}$	$P_{ext} = 0.67*N^{-0.60}$
Large	$P_{ext} = 0.64*N^{-0.58}$	$P_{ext} = 0.74*N^{-0.52}$

50 Adults

	10% per generation	15% per generation
Mixed	$P_{ext} = 1.24*N^{-0.37}$	$P_{ext} = 1.36*N^{-0.34}$
Small	$P_{ext} = 1.03*N^{-0.33}$	$P_{ext} = 1.08*N^{-0.29}$
Large	$P_{ext} = 1.44*N^{-0.36}$	$P_{ext} = 1.54*N^{-0.33}$

If catastrophes occur at 15% per generation and the recovery target is set based on an assumption that catastrophes occur at 10% per generation, the risk of extinction will be between 1.8 and 2.5% instead of 1%, depending on population type.

MVP simulations assumed an extinction threshold of one adult female (or two adults). We observed that assuming a higher, quasi-extinction threshold (i.e., if the population is considered effectively extinct before it declines to one female) results in a large increase in MVP. For example, if the quasi-extinction threshold is increased to 50 adults, and the chance of catastrophe is 10% per generation, for the MP the mean MVP increases from 95 to $1.9x10^6$ (see Table 7 for examples of using these equations to calculate MVP for a different extinction risk). Thus, if the true extinction threshold is greater than one adult female, larger recovery targets should be considered. Equations describing extinction risk at a threshold of 50 adults, and a probability of catastrophe of 10 and 15%, respectively, are described in Table 6. If there is a different acceptable probability of extinction than 0.01, then the MVP estimates will change; using Table 6 alternative MVPs can be generated (for examples see Appendix 2).

MVP for the MP is lower than that for the SP and LP when there is a 50/50 mix of individuals from both population types. Changing the proportion of the population that is represented by small bodies individuals (α) results in a non-linear change in MVP with the highest MVP occurring at around α = 0.25 (Figure 12). The MVP trend across α values is similar for both the extinction threshold of 2 and 50 adults when the risk of catastrophe is at 15%.

The estimated probability of extinction (P_{ext}) for Bull Trout adult population abundance estimates for waterbodies within Saskatchewan-Nelson Rivers DU4 (COSEWIC 2012) are provided for extinction thresholds of two and 50 adults at 15% risk of catastrophe per generation in Appendix 2. The North Saskatchewan River Basin with an estimated abundance greater than 5000 adults, if considered a distinct population, satisfies the COSEWIC viability threshold of less than 10% risk of extinction over 100 years for each extinction target and population type. The Bow River Basin, does not meet the viability threshold for the small and large population types at the extinction threshold of 50 adults. The Oldman River Basin and the Red Deer River Basin do not meet the viability threshold of < 10% risk of extinction over 100 years for the extinction threshold of 50 adults for any of the population types. 77% and 7% of the individual waterbodies, if considered discrete populations, would have a chance of extinction greater than 20% for at least one population type, at the extinction threshold of 50 and 2 adults respectively. 20% is the population viability threshold for endangered species. While Appendix 2 shows the probability of extinction for each extinction threshold (two and 50) it should be emphasized that an extinction threshold of two adults may not be sufficient to maintain genetic diversity and should not be considered equivalent to the more conservative extinction threshold of 50 adults.

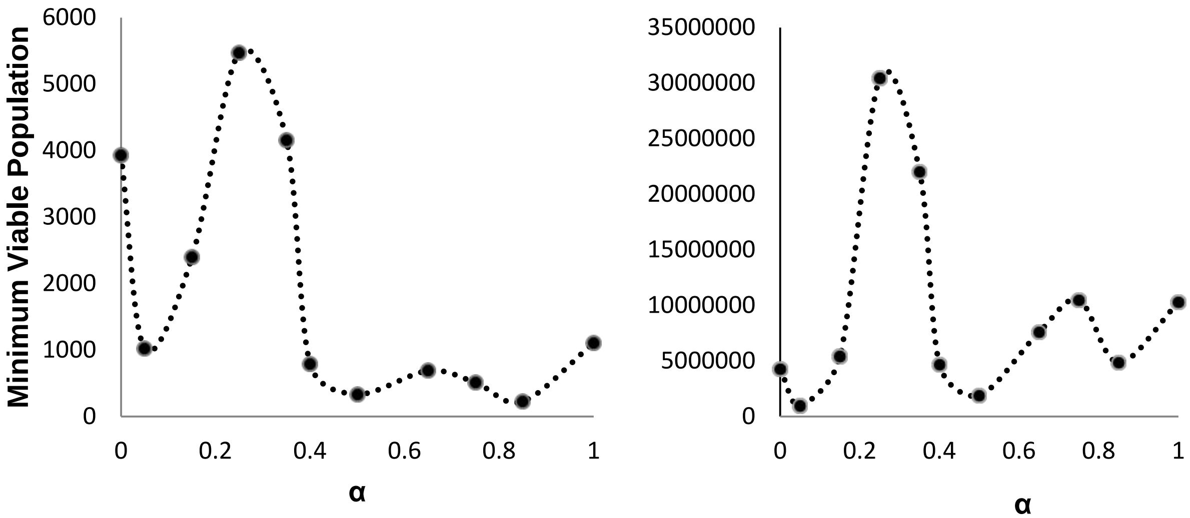


Figure 12. Minimum Viable population estimates at either 2 (left) or 50 (right) adults after 100 years, at 15% probability of catastrophe per generation for increasing proportions of the small bodied population type (α) in a mixed population (MP).

Reed et al. (2003) estimated that when a catastrophe occurs, about 4% of events result in a catastrophic extirpation ($P_{e|k}$ = 0.04). The probability of a catastrophic extinction for Bull Trout over 100 years at a P_k = 0.15 per generation is then: $P_e = 1-(1 - P_{k \cdot Pe|k})100 = 0.073$. At current population levels, considering each basin as a discrete population leads to a meta-basin probability of persistence (P_m and P'_m) ~ 1 for each extinction threshold and population type (range 0.9986 to 1). This is the probability that there is at least one basin that will meet the extinction threshold of two or 50 fish surviving 100 years based on the current basin level population abundance. Similarly, considering each waterbody as a discrete stream leads to a P_m and P'_m ~1, which is the probability that there is at least one waterbody meeting the extinction threshold of two or 50 fish surviving 100 years based on the current waterbody level population abundance.

At the current estimate of abundance, using the most conservative estimate of MVP (extinction threshold of 50 individuals with a 15% generational risk of catastrophe) the minimum number of years it would take to achieve the MVP was estimated for populations growing at λ_{max} (Appendix 2). This is to be taken as the best case scenario; the actual population growth rate will most likely be lower than λ_{max}, and will slow down as the population size increases due to density dependence. For large, mixed, and small population types the average waterbody, at a probability of extinction of 0.01, will take approximately 39, 28, or 19 years, respectively, to obtain the MVP. For large, mixed, and small population types the average basin, at a probability of extinction of 0.01, will take approximately 29, 20, or 15 years, respectively, to obtain the MVP. For large, mixed, and small population types the total population, at a probability of extinction of 0.01, will take approximately 23, 16, or 12 years, respectively to obtain the MVP.

Habitat targets (MAPV)

The stable stage distribution of Bull Trout for each population type is listed in Table 8. Note that this distribution assumes a post-breeding census such that the YOY class consists of individuals that are newly hatched; the age-1 class have just had their first birthday, etc. For the MP, MAPV ranged from 6.9×10^3 (ha) for an MVP of 95 adults to 1.4×10^8 (ha) for a target of 1.9×10^6 adults (Table 7). The MAPV that corresponds to a probability of catastrophe of 15%, an extinction threshold of 50 adults, and an extinction risk of ~1% is the most conservative scenario. These MAPV assume that each individual requires the area (API) listed in Table 8, and does not account for any overlapping of individual habitats (sharing) that may occur. It is important to note that this area is based on an allometry of fish density per fish size and does not include any additional space requirements for the completion of life stages.

The estimated historical distribution of Bull Trout was 24,000 km of stream habitat, which has reduced over the years and is currently estimated at approximately 16,000 km. Assuming an average stream width of 10 m, the total available habitat for Bull Trout is between 160 km^2 and 240 km^2, which is enough for the extinction threshold of two adults, however it is only enough for the mixed population at 10% risk of extinction for the extinction threshold of 50 adults and so does not meet the requirements for the most conservative MVP estimates. With the current available habitat falling short of the MAPV targets, it is possible that the most conservative MVP may be unattainable. Furthermore, this MAPV estimate assumes that the entire area is suitable habitat. If certain areas of the current available habitat are deemed partially unsuitable, the total minimum required area should be increased.

Table 7. Number of individuals by stage required to support a minimum viable population (MVP), and associated habitat required, based on estimated area per individual (Table 8). Results for all three population types, two different extinction thresholds, and two probabilities of generational catastrophe (GC) are shown. Stages shown are young of year (YOY), juvenile (stages 1-4), and adult. The most conservative MVP and MAVP estimates for conservation are highlighted in grey.

Extinction Threshold	GC	Stage	Mixed		Small		Large	
			MVP	MAPV (m^2)	MVP	MAPV (m^2)	MVP	MAPV (m^2)
2 adults	10%	YOY	5.0×10^4	3.9 x10	4.0×10^5	4.6×10^2	1.6×10^6	1.4×10^3
		J	5.6×10^3	1.9×10^4	7.3×10^4	7.8×10^3	2.9×10^5	1.1×10^6
		A	95	6.9×10^3	3.2×10^2	5.9×10^3	1.3×10^3	2.3×10^5
		Total		2.6×10^4		1.4×10^4		1.3×10^6
2 adults	15%	YOY	1.8×10^5	1.4×10^2	1.6×10^5	1.6×10^3	4.9×10^6	4.1×10^3
		J	2.0×10^4	6.6×10^4	1.3×10^4	2.7×10^4	8.6×10^6	3.3×10^6
		A	3.4×10^2	2.4×10^4	1.1×10^3	2.0×10^4	3.9×10^3	6.9×10^5
		Total		9.1×10^4		4.9×10^4		4.0×10^7
50 adults	10%	YOY	2.4×10^8	1.9×10^5	1.9×10^8	1.9×10^6	1.2×10^9	1.0×10^6
		J	2.7×10^7	9.0×10^7	1.5×10^7	3.2×10^7	2.2×10^8	8.3×10^8
		A	4.6×10^5	3.3×10^7	1.3×10^6	2.4×10^7	9.9×10^5	1.7×10^8
		Total		1.2×10^8		5.0×10^8		1.0×10^9
50 adults	15%	YOY	1.0×10^9	7.7×10^5	1.5×10^9	1.4×10^7	5.4×10^9	4.4×10^6
		J	1.1×10^8	3.7×10^8	1.3×10^8	2.4×10^8	9.3×10^8	3.6×10^9
		A	1.9×10^6	1.4×10^8	1.0×10^7	1.8×10^8	4.3×10^6	7.5×10^8
		Total		5.1×10^8		4.4×10^8		4.3×10^9

Table 8. Stable stage distribution (SSD; proportion of the population in each stage, assuming a pre-breeding census. i.e., the YOY class is nearly 1 year old, age 1 class is nearly 2 years old, etc.) and required area per individual (API) for each stage.

Stage	Mixed		Small		Large	
	SSD	API (m^2)	SSD	API (m^2)	SSD	API (m^2)
YOY	$9.0x10^{-1}$	$8.7x10^{-4}$	$9.1x10^{-1}$	$9.7x10^{-3}$	$8.5x10^{-1}$	$8.4\ x10^{-4}$
J_1	$7.2x10^{-2}$	0.4	$5.2\ x10^{-2}$	$2.3\ x10^{-1}$	$1.2x10^{-1}$	$5.7\ x10^{-1}$
J_{2S}	$7.4x10^{-3}$	1.1	$1.5\ x10^{-2}$	1.1		
J_{3S}	$3.1x10^{-3}$	2.8	$7.0\ x10^{-3}$	2.8		
J_{4S}	$3.7\ x10^{-3}$	8.6	$1.2\ x10^{-2}$	8.6		
A_S	$1.1x10^{-3}$	18.3	$6.2\ x10^{-3}$	18.4		
J_{2L}	$7.4x10^{-3}$	5.2			$1.9x10^{-2}$	5.2
J_{3L}	$2.4x10^{-3}$	15.9			$5.7x10^{-3}$	15.9
J_{4L}	$2.7x10^{-3}$	69.1			$4.5x10^{-3}$	69.1
A_L	$5.8x10^{-4}$	176.4			$6.8x10^{-4}$	176.5

DISCUSSION

Our results show that to avoid jeopardizing the survival and future recovery of Bull Trout, human-induced harm to the annual survival of juveniles should be minimal. This is consistent with the known threats to the Bull Trout population which include low juvenile survival and possible overexploitation (COSEWIC 2012). A similar elasticity analysis for Bull Trout (Bowerman 2013) also determined that the Bull Trout population modelled was most sensitive to the probability of juveniles surviving and moving to the next stage. In addition, the elasticities for fecundity were greater for the LP than for the SP, which was seen here in the MP model.

Analyses of chronic harm show that if the Bull Trout population is growing at maximum population growth (λ_{max}), a removal of 46% of the juveniles for populations with the small growth trajectory, will bring population growth down to λ=1. At maximum population growth, if all other vital rates are held constant, the population growth rate will not be reduced to 1 by changes in vital rates for the other stages in the SP and MP. For declining populations (λ<1), recovery efforts that target a single life-history stage may not be sufficient to raise λ to 1.

Transient harm may be applied without jeopardizing survival or recovery if the population is not in decline. For small and mixed bodied population types, removal of ~10% and for the large bodied population type removal of ~15%, of the total population will result in a 1% decline in population growth rate for a stable population. Removal of 25% of all individuals for the mixed 30% for the large, and 35% for the small bodied population type of every 10 years will reduce the growth rate to 1 if the population is growing at λ_{max} (i.e., this removal will result in a stable population). Absolute numbers for removal should be chosen based on the population abundance. Allowable transient harm may be smaller if the population is growing at a slower rate. We caution that any removal affects population growth rate and will delay recovery, and that current population abundance estimates are very uncertain.

Potential recovery targets, based on the concept of MVP, were presented for a variety of risk scenarios. The MVP for Bull Trout ranged from $1.9x10^6$ to $4.3x10^6$ adults across population types if the probability of a catastrophic (50%) decline was 0.15 per generation with an extinction threshold of 50 adults. Associated total MAPV for Bull Trout ranged from 440 to 4300 km^2 of suitable habitat. This required area is not met when assuming the strictest MVP estimates. At the current estimates of population size, only the North Saskatchewan River Basin has a probability of extinction less than the COSEWIC viability threshold of 10% chance of extinction within 100 years for all population types and extinction thresholds.

We emphasize that the choice of recovery target is not limited to the scenarios presented (Table 7). Required adult population sizes can be calculated for any alternative probability of extinction using one of equations in Table 6 depending on which risk scenario (probability of catastrophe and extinction threshold) best represents the Saskatchewan – Nelson rivers populations of Bull Trout, and what level of risk is considered acceptable (see Appendix 2 for examples).

Demographic sustainability was highest (i.e., the lowest MVP) for the mixed population type at intermediate α values. The presence of multiple life-history types is thought to be advantageous in dealing with variable environments (Jonsson and Jonsson 1993) and coincides here with a reduced risk of extinction. However, it is important to note that an α of approximately 0.25 has the lowest demographic sustainability, meaning it is not as simple as having a mixed population. The current mixing of life-histories for the Saskatchewan-Nelson rivers populations is unknown. Habitat fragmentation in the Saskatchewan-Nelson rivers populations (COSEWIC 2012) may lead, however, to a decline of the migratory population type for Bull trout; as observed in other locations across their range (Nelson et al. 2002).

According to Reed et al. (2003), catastrophic events (a one-time decline in abundance of 50% or more) occur at a probability of 0.14 per generation in vertebrates. It is uncertain at what frequency catastrophic events occur for the Bull Trout population. We therefore modelled recovery targets assuming a stable population with the most conservative catastrophe scenario, based on Reed et al. (2003), of 15%. The underlying pattern of decline will need to be determined to ensure the persistence of Bull Trout.

We also emphasize that recovery targets based on MVP can be easily misinterpreted as a reference point for exploitation or allowable harm. A recovery target is neither of these things because it pertains exclusively to a minimum abundance level for which the probability of long-term persistence within a recovery framework is high. Therefore, abundance-based recovery targets are particularly applicable to populations that are below this threshold, and are useful for optimizing efforts and resources by selecting those populations that are in the greatest need of recovery. We stress that these MVP targets refer to adult numbers only. If juveniles are being included in abundance estimates, then the MVP should include these age classes as well (see Table 7).

UNCERTAINTIES

Some elements of the life history of Bull Trout are unknown. While individual growth and fecundity of Bull Trout has been well studied and seems consistent over time, estimates of annual mortality are highly variable for all age classes, and so was estimated for this model using an allometry based on growth patterns. This has a large effect on the certainty of allowable harm estimates; uncertainty around life history parameters should be reduced. Some life-history parameters for Bull Trout have been shown to be density dependent (i.e., spawning periodicity, survival and growth rates). There was not enough information, however, to include density-dependence in the model, and may result in changes in the estimates of probability of extinction. Further, MVP estimates differed dramatically based on the assumed population growth trajectory type (mixed, LP, or SP), frequency of catastrophic decline, and extinction threshold. If recovery targets are set based on an incorrect population type or rate of catastrophes, then risk of extirpation may be greater. Further research in this area is warranted.

Current population connectivity and abundance estimates for Bull Trout are very uncertain. Incorrect assumptions regarding abundance will affect estimates of probability of extinction, and may result in profound changes in allowable harm advice. Uncertainty in population abundance should be reduced. Predictions from this model assume random mating and complete mixing of the population (i.e., all individuals interact and can reproduce with one another). One of the main potential threats to the Bull Trout population is habitat fragmentation (COSEWIC 2012), implying that there may not be complete mixing. This assumption should be considered when applying MVP to the setting of recovery targets, and larger total targets should be set if the assumption does not hold.

Finally, estimates of MAPV are based on a general relationship between fish density and area (API) and may not effectively represent a migratory fish like Bull Trout. Species specific estimates of area per individual that are based on Bull Trout, or similar migratory salmonid, movements and habitat use will reduce uncertainty in this estimate. Our estimates of required habitat (MAPV) assume that habitat is of high quality throughout the range of Bull Trout. We did not have sufficient data to either confirm, or provide an alternative to this assumption. However, one of the main potential threats to the Bull Trout population is habitat degradation; the extent of Bull Trout habitat is declining due to climate change and anthropogenic pollution (COSEWIC 2012). Further study is needed to assess the extent of suitable of habitat for Bull Trout.

REFERENCES CITED

Alberta Environment and Sustainable Resource Development. 2012. Bull Trout conservation management plan 2102-2017. Species at Risk Conservation Management Plan No. 8. Alberta Sustainable Resource Development, Edmonton, AB.

Al-Chokhachy, R., and Budy, P. 2008. Demographic characteristics, population structure, and vital rates of a fluvial population of bull trout in Oregon. Trans. Am. Fish. Soc. 137: 1709–1722. doi:10.1577/T07-247.1

Bowerman, T.E. 2013. A multi-scale investigation of factors limiting bull trout viability. Utah State University. 193 p.

Budy, P., Bowerman, T., and Thiede, G. 2010. Bull trout population assessment in northeastern Oregon: a template for recovery planning. 2009 Annual Progress Report to US Fish and Wildlife Research Service. UTCFWRU. 48 p.

Caswell, H. 2001. Matrix population models: construction, analysis, and interpretation. Sinauer Associates. 722 p.

COSEWIC. 2012. COSEWIC Assessment and Status Report on the Bull Trout (*Salvelinus confluentus*). Committee on the Status of Endangered Wildlife in Canada, Ottawa.

de Kroon, H., Plaisier, A., van Groenendael, J., and Caswell, H. 1986. Elasticity: the relative contribution of demographic parameters to population growth rate. Ecology 67: 1427. doi:10.2307/1938700

DFO. 2007a. Documenting habitat use of species at risk and quantifying habitat quality. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2007/038.

DFO. 2007b. Revised protocol for conducting recovery potential assessments. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2007/039.

Downs, C.C., Horan, D., Morgan-Harris, E., and Jakubowski, R. 2006. Spawning demographics and juvenile dispersal of an adfluvial Bull Trout population in Trestle Creek, Idaho. North Am. J. Fish. Manag. 26: 190–200. doi:10.1577/M04-180.1

Froese, R., and Binohlan, C. 2000. Empirical relationships to estimate asymptotic length, length at first maturity and length at maximum yield per recruit in fishes, with a simple method to evaluate length frequency data. J. Fish Biol. 56: 758–773. doi:10.1111/j.1095-8649.2000.tb00870.x

Hagen, J., and Baxter, J.S. 1992. Bull trout populations of the North Thompson River basin, British Columbia: initial assessment of a biological wilderness. B.C. Min. Environ., Lands and Parks, Fish. Br., Kamloops, B.C.

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

Johnston, F.D., Post, J.R., Mushens, C.J., Stelfox, J.D., Paul, A.J., and Lajeunesse, B. 2007. The demography of recovery of an overexploited bull trout, *Salvelinus confluentus*, population. Can. J. Fish. Aquat. Sci. 64: 113–126. doi:10.1139/f06-172

Jonsson, B., and Jonsson, N. 1993. Partial migration: niche shift versus sexual maturation in fishes. Rev. Fish Biol. Fish. 3: 348–365. doi:10.1007/BF00043384

Lefkovitch, L.P. 1965. The study of population growth in organisms grouped by stages. Biometrics 21: 1–18. doi:10.2307/2528348

Lorenzen, K. 2000. Allometry of natural mortality as a basis for assessing optimal release size in fish-stocking programmes. Can. J. Fish. Aquat. Sci. 57: 2374–2381. doi:10.1139/f00215.

McPhail, J.D., and Baxter, J.S. 1996. A review of bull trout (*Salvelinus confluentus*) life-history and habitat use in relation to compensation and improvement opportunities. Ministry of Environment, Lands and Parks.

Minns, C.K. 2003. An Area-Per Individual (API) Model for estimating critical habitat requirements in Aquatic Species-At Risk DFO Can. Sci. Advis. Sec. Res. Doc. 2003/074. i + 21 p.

Mochnacz, N.J., Reist, J.D., Cott, P., Low, G., and Wastle, R. 2004. Biological and habitat data for bull trout (*Salvelinus confluentus*) and associated species from stream surveys conducted in the southern and central Mackenzie River Valley, Northwest Territories, 2000 to 2001 Can. Data Rep. Fish. Aquat. Sci. 1131. iv + 38 p.

Mullen, J.W., Williams, K.R., Rhodus, G., Hillman, T.W., and McIntyre, J.D. 1992. Production and habitat of salmonids in mid-Columbia river tributary streams. U.S. Fish and Wildlife Service (Monograph No. I). 489 p.

Nelson, M.L., McMahon, T.E., and Thurow, R.F. 2002. Decline of the migratory form in bull charr, *Salvelinus confluentus*, and implications for conservation. Env. Bio. Of Fish. 64: 321–332.

Parker, B.R., Schindler, D.W., Wilhelm, F.M., and Donald, D.B. 2007. Bull Trout population responses to reductions in angler effort and retention limits. North Am. J. Fish. Manag. 27: 848–859. doi:10.1577/M06-051.1

Paul, A.J., Post, J.R., Sterling, G.L., and Hunt, C. 2000. Density-dependent intercohort interactions and recruitment dynamics: models and a bull trout (*Salvelinus confluentus*) time series. Can. J. Fish. Aquat. Sci. 57: 1220–1231. doi:10.1139/f00-048

Paul, A.J., Post, J.R., and Stelfox, J.D. 2003. Can anglers influence the abundance of native and nonnative salmonids in a stream from the Canadian Rocky Mountains? North Am. J. Fish. Manag. 23: 109–119. doi:10.1577/1548-8675(2003)023<0109:CAITAO>2.0.CO;2

Randall, R.G., and Minns, C.K. 2000. Use of fish production per unit biomass ratios for measuring the productive capacity of fish habitats. Can. J. Fish. Aquat. Sci. 57: 1657–1667.

Randall, R.G., Minns, C.K., and Kelso, J.R.M., 1995. Fish production in freshwaters: Are rivers more productive than lakes? Can. J. Fish. Aquat. Sci. 52: 631–643. doi:10.1139/f95-063

Ratliff, D.E., Thiesfeld, S.L., Weber, W.G., Stuart, A.M., Riehle, M.D., and Buchanan, D.V. 1996. Distribution, life history, abundance, harvest, habitat, and limiting factors of bull trout in the Metolius River and Lake Billy Chinook, Oregon, 1983-94 (No. OFIINFR), Information reports; 96-7. Oregon. Fish Division, Portland, Oregon.

R Core Team. 2015. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Reed, D.H., O'Grady, J., Ballou, J.D., and Frankham, R. 2003. The frequency and severity of catastrophic die-offs in vertebrates. Anim. Conserv. 6: 109–114. doi:10.1017/S1367943003003147

Rieman, B.E., and McIntyre, J.D. 1993. Demographic and habitat requirements for conservation of bull trout. U.S. Dept. Agriculture. Gen.Tech. Rep. INT-302. 38 p.

Rodtka, M. 2009. Status of Bull Trout in Alberta: Update 2009 (Alberta Wildlife Status Report No. 39). Alberta Sustainable Resource Development; Alberta Conservation Association, Edmonton, Alberta.

Ruckelshaus, M., McElhan, P., and Ford, M.J. 2002. Recovering species of conservation concern: are populations expendable? *In* The importance of species: perspectives on expendability and triage. Edited by P. Kareiva and S. Levin. Princeton University Press, Princeton, N.J. p. 305–329.

Shaffer, M.L. 1981. Minimum Population Sizes for Species Conservation. BioScience 31: 131–134. doi:10.2307/1308256

Tummers, B. 2006. Data Thief III.

van der Lee, A.S., and Koops, M.A., 2016. Are small fishes more sensitive to habitat loss? A generic size-based model. Can. J. Fish. Aquat. Sci. 73: 1–11. doi:10.1139/cjfas-2015-0026

Vélez-Espino, L.A., and Koops, M.A. 2007. Assessing allowable harm and recovery efforts in Lake Ontario Atlantic salmon (*Salmo salar*). DFO Can. Sci. Advis. Sec. Res. Doc. 2007/083. iv + 27 p.

Vélez-Espino, L.A., and Koops, M.A. 2009a. Recovery potential assessment for Lake Sturgeon in Canadian designatable units. North Am. J. Fish. Manag. 29: 1065–1090. doi:10.1577/M08-034.1

Vélez-Espino, L.A., and Koops, M.A. 2009b. Quantifying allowable harm in species at risk: application to the Laurentian black redhorse (*Moxostoma duquesnei*). Aquat. Conserv. Mar. Freshw. Ecosyst. 19: 676–688. doi:10.1002/aqc.1023

Vélez-Espino, L.A., Randall, R.G., and Koops, M.A. 2009. Quantifying habitat requirements of four freshwater species at risk in Canada: Northern Madtom, Spotted Gar, Lake Chubsucker, and Pugnose Shiner. DFO Can. Sci. Advis. Sec. Res. Doc. 2009/115. vi + 21 p.

Warnock, W.G. 2012. Examining Brook Trout invasion into Bull Trout streams of the Canadian rockies. Thesis (PhD). University of Lethbridge. 184 p.

Young, J.A., and Koops, M.A. 2011. Recovery potential modelling of Lake Chubsucker (*Erimyzon sucetta*) in Canada. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/049. vi + 20 p.

APPENDIX 1: DATA SOURCES

Table A1-1. Source, waterbody name, adult body size, description and number of samples for length-at-age data used to calculate von Bertalanffy growth trajectories for the models.

Source	Waterbody	Adult Size	Description	n
(Al-Chokhachy and Budy 2008)	South Fork of Walla Walla River	Large	Mean length-at-age estimated from figure	7
(Bjornn 1961 in (Warnock 2012))	Lower Priest Lake	Large	Mean length-at-age	4
	Upper Priest Lake	Large		4
(Bowerman 2013)	South Fork of Walla Walla River	Large	Individual length-at-age data estimated from figure	54
(Carl 1989 in (Warnock 2012))	Pinto Lake	Large	Mean length-at-age	4
(Fraley and Shepard 1989 in (Warnock 2012))	Coal Creek	Large	Mean length-at-age	4
	North Fork Drainage	Small		4
	Red Meadow Creek	Large		4
	Trail Creek	Small		4
	Whale Creek	Large		3
(Goetz 1989 in (Rieman and McIntyre 1993))	Multiple	Large	Mean-length-at-age estimated from graph	37
(Hagen and Baxter 1992)	North Thompson River	Large	Mean length-at-age	4
(Johnston and Post 2009)	Lower Kananaskis Lake	Large	Individual length-at-age estimated from figure	171
(Mochnacz et al. 2004)	Drum L Outlet	Large	Individual length-at-age	13
	Funeral Creek	Small		14
	Irvine Creek	Large		2
	Keele River	Large		3
	South Nahanni	Small		1

Source	Waterbody	Adult Size	Description	n
	River			
	Unnamed Creek B	Small		2
(Mullen et al. 1992)	Methow River Drainage	Small	Individual length-at-age estimated from figure (using uniform random sampling from range and sample size at age provided in figure)	306
(Oliver 1979 in (Warnock 2012))	Ram creek	Large	Mean length-at-age	4
	Wigwam River	Small		3
(Parker et al. 2007)	Harrison Lake	Large	Individual length-at-age estimated from figure	57
	Osprey lake	Large		29
(Paul et al. 2000)	Eunice Creek	Small	Mean length-at-age	10
(Paul et al. 2003)	Quirk Creek	Small	Mean length-at-age estimated from figure	7
(Ratliff et al. 1996)	Metolius River basin	Large	Mean length-at-age	17
(Underwood et al. 1991 in (Warnock 2012))	Mill Creek	Large	Individual length-at-age	21
	Tucannon River	Large		44
	Wolf-Fork	Large		12
(Warnock 2012)	Camp Creek	Large	Individual length-at-age	11
	Carbondale River	Large		3
	Castle River	Large		5
	Crowsnest River	Large		6
	Daisy Creek	Large		8
	Dutch Creek	Large		24
	Gardiner Creek	Large		6
	Hidden Creek	Small		3
	Livingstone River	Large		9

Source	Waterbody	Adult Size	Description	n
	Lost Creek	Large		20
	Mill Creek	Large		3
	North Racehorse Creek	Large		16
	Oldman River	Large		16
	Racehorse Creek	Large		12
	Smith-Dorrien Creek	Large		10
	South Racehorse Creek	Large		10
	Vicary Creek	Large		4

Table A1-2. Source, waterbody name, description and number of samples for survival data used to calculate stage specific survival for the models.

Source	Waterbody	Adult Size	n	Description
(Bowerman 2013)	South Fork of Walla Walla River	large adults	27	Age and length based survival estimates. Where length ranges were provided, the mean was converted to appropriate age.
(Al-Chokhachy and Budy 2008)	South Fork of Walla Walla River	large adults	48	Length based estimates of survival, the mean of the length ranges were converted to the appropriate age
(Johnston et al. 2007)	Lower Kananaskis Lake	large adults	12	Survival estimates for adult fish, the mean length between their minimum cut off (400 mm) and the estimated maximum length were used then converted to age.
(Paul et al. 2000)	Eunice Creek	large adults	27	Age based estimates from fitted equations for survival and density for ages 1 to 3 within the range of observed density values

Table A1-3. Source, waterbody name, description and number of samples for fecundity-at-length data used to calculate fecundity for the models.

Source	Waterbody	n	Description
(Parker et al. 2007)	Harrison Lake	5	Post fishery closure Bull trout number of eggs at FL estimated from figure
(Al-Chokhachy and Budy 2008)	South Fork of Walla Walla River	3	Mean number of eggs at FL estimated from figure
(McPhail and Baxter 1996)	Mackenzie Creek	3	
	Upper Flathead River	1	
	S.E. Washington	2	Mean egg number and mean female size and range
	Bull River	3	
	Clarck Fork	3	
	Sun Creek	3	
(Johnston and Post 2009)	Lower Kananaskis Lake	25	Number of eggs at FL estimated from figure
(Bowerman 2013)	South Fork of the Walla Walla River	22	Number of eggs at FL estimated from figure

APPENDIX 2: ADDED INFORMATION TO SUPPORT RECOVERY ESTIMATION

Table A2-1. Estimated probability of extinction (P_{ext}) in 100 years for Bull Trout adult population abundance estimates within Saskatchewan-Nelson Rivers DU4 (COSEWIC, 2012) provided for extinction thresholds of 2 and 50 adults at 15% risk of catastrophe per generation; shown in red when P_{ext} ≥10%.

	Abundance Estimate	P_{ext} (ET=2)			P_{ext} (ET = 50)		
		Small	Mixed	Large	Small	Mixed	Large
Oldman River Basin	1940	0.01	0.00	0.01	0.12	0.10	0.13
Waterton River	40	0.07	0.05	0.11	0.37	0.39	0.46
Drywood Creek	40	0.07	0.05	0.11	0.37	0.39	0.46
Lower Oldman River	60	0.06	0.04	0.09	0.33	0.34	0.40
Belly River	250	0.02	0.01	0.04	0.22	0.21	0.25
Upper Livingstone River	280	0.02	0.01	0.04	0.21	0.20	0.24
Castle River and Oldman Reservoir	310	0.02	0.01	0.04	0.20	0.19	0.23
Upper Oldman River	410	0.02	0.01	0.03	0.19	0.18	0.21
St Mary River	550	0.02	0.01	0.03	0.17	0.16	0.19
Bow River Basin	2623	0.01	0.00	0.01	0.11	0.09	0.11
Middle Bow River	10	0.17	0.13	0.22	0.55	0.62	0.72
Jumpingpound Creek	15	0.13	0.10	0.18	0.49	0.54	0.63
Canyon Creek	20	0.11	0.08	0.16	0.45	0.49	0.57
Flat Creek	40	0.07	0.05	0.11	0.37	0.39	0.46
Upper Spray River	40	0.07	0.05	0.11	0.37	0.39	0.46
Lake Minnewanka	58	0.06	0.04	0.09	0.33	0.34	0.40
Lower Elbow River	105	0.04	0.02	0.07	0.28	0.28	0.33
Upper Elbow River	115	0.04	0.02	0.06	0.27	0.27	0.32
Highwood River	190	0.03	0.02	0.05	0.24	0.23	0.27
Ghost River	385	0.02	0.01	0.03	0.19	0.18	0.22
Sheep River	445	0.02	0.01	0.03	0.18	0.17	0.21
Upper Kananaskis River	1200	0.01	0.00	0.02	0.14	0.12	0.15
Red Deer River Basin	540	0.02	0.01	0.03	0.17	0.16	0.19
Little Red Deer River	10	0.17	0.13	0.22	0.55	0.62	0.72
Red Deer River Basin	530	0.02	0.01	0.03	0.18	0.16	0.19
North Saskatchewan River Basin	5115	0.00	0.00	0.01	0.09	0.07	0.09
Baptiste River	50	0.06	0.04	0.10	0.35	0.36	0.42
Lower North Saskatchewan River	75	0.05	0.03	0.08	0.31	0.31	0.37
Nordegg River	105	0.04	0.02	0.07	0.28	0.28	0.33
Clearwater River	390	0.02	0.01	0.03	0.19	0.18	0.22
Middle North Saskatchewan River	400	0.02	0.01	0.03	0.19	0.18	0.21
Blackstone River	720	0.01	0.01	0.02	0.16	0.15	0.18
Upper North Saskatchewan River	950	0.01	0.00	0.02	0.15	0.13	0.16
Pinto Lake and Cline River	1150	0.01	0.00	0.02	0.14	0.12	0.15
Brazeau River	1275	0.01	0.00	0.02	0.14	0.12	0.15
Total	10218	0.00	0.00	0.01	0.07	0.06	0.07

Table A2-2. The proportional change of population vital rates required to raise the population growth rate (λ) to 1 (stable) from a declining λ. Highlighted in grey are vital rates that, if changed by the specified amount, could theoretically raise λ to 1 if all other rates were held constant.

Mixed Growth Trajectory

				λ = 0.9								**λ = 0.75**			
Vital Rate	σ_{YOY}	σ_J	σ_{AS}	σ_{AL}	f_S	f_L	T	σ_{YOY}	σ_J	σ_{AS}	σ_{AL}	f_S	f_L	T
Stochastic mean	0.93	0.93	0.38	0.46	0.85	1.23	1.85	3.33	3.33	1.28	1.45	2.08	2.78	8.33
Upper confidence	1.59	1.59	2.78	5.56	5.56	14.72	13.65	8.33	8.33	33.33	36.23	51.68	73.10	171.82
Lower confidence	0.79	0.79	0.22	0.22	0.36	0.43	0.93	2.56	2.56	0.67	0.68	0.69	0.78	3.03

Small Growth Trajectory

				λ = 0.9								**λ = 0.75**			
Vital Rate	σ_{YOY}	σ_J	σ_{AS}	σ_{AL}	f_S	f_L	T	σ_{YOY}	σ_J	σ_{AS}	σ_{AL}	f_S	f_L	T
Stochastic mean	1.01	0.17	0.46		1.01		-1.01	3.70	0.56	1.01		3.70		-3.70
Upper confidence	2.78	0.24	0.79		2.78		-0.74	16.67	1.59	1.96		16.67		-2.38
Lower confidence	0.74	0.16	0.23		0.74		-2.78	2.38	0.48	0.43		2.38		-16.67

Large Growth Trajectory

				λ = 0.9								**λ = 0.75**			
Vital Rate	σ_{YOY}	σ_J	σ_{AS}	σ_{AL}	f_S	f_L	T	σ_{YOY}	σ_J	σ_{AS}	σ_{AL}	f_S	f_L	T
Stochastic mean	0.93	0.17		0.48		0.93	-0.93	3.70	0.56		1.08		3.70	-3.70
Upper confidence	2.22	0.25		0.85		2.22	-0.74	16.67	1.59		2.22		16.67	-2.38
Lower confidence	0.74	0.15		0.22		0.74	-2.22	2.38	0.48		0.43		2.38	-16.67

Table A2-3. Number of individuals by stage required to support a minimum viable population (MVP). Results for the ***mixed*** *population type, two different extinction thresholds, five different probabilities of extinction (P_{ext}), and two probabilities of generational catastrophe (GC) are shown. Stages shown are young of year (YOY), juvenile (stages 1-4), and adult. The MVP estimates that correspond to the estimates in Table 7 are highlighted in grey.*

Extinction Threshold	GC	Stage	MVP					
			P_{ext}	0.001	0.01	0.03	0.05	0.08
2 adults	10%	YOY		$6.4x10^5$	$5.1E\ x10^4$	$1.5\ x10^4$	$8.7\ x10^3$	$5.2\ x10^3$
		J		$7.0x10^4$	$5.6E\ x10^3$	$1.7\ x10^3$	$9.5\ x10^2$	$5.7\ x10^2$
		A		$1.2\ x10^3$	95	28	16	10
2 adults	15%	YOY		$4.0\ x10^6$	$1.8\ x10^5$	$4.1\ x10^4$	$2.0\ x10^4$	$1.1\ x10^4$
		J		$4.4\ x10^5$	$2.0\ x10^4$	$4.5\ x10^3$	$2.2\ x10^3$	$1.2\ x10^3$
		A		$7.5\ x10^3$	$3.4\ x10^2$	76	38	20
50 adults	10%	YOY		$1.2\ x10^{11}$	$2.4\ x10^8$	$1.3\ x10^7$	$3.1\ x10^6$	$8.8\ x10^5$
		J		$1.3\ x10^{10}$	$2.7\ x10^7$	$1.4\ x10^6$	$3.4\ x10^5$	$9.7\ x10^4$
		A		$2.3\ x10^8$	$4.5\ x10^5$	$2.3\ x10^4$	$5.9\ x10^3$	$1.6\ x10^3$
50 adults	15%	YOY		$8.8\ x10^{11}$	$1.0\ x10^9$	$4.0\ x10^7$	$8.9\ x10^6$	$2.2\ x10^6$
		J		$9.7\ x10^{10}$	$1.1\ x10^8$	$4.4\ x10^6$	$9.7\ x10^5$	$2.4\ x10^5$
		A		$1.6\ x10^9$	$1.9\ x10^6$	$7.4\ x10^4$	$1.7\ x10^4$	$4.2\ x10^3$

Table A2-4. Number of individuals by stage required to support a minimum viable population (MVP). Results for the ***small*** *population type, two different extinction thresholds, five different probabilities of extinction (P_{ext}), and two probabilities of generational catastrophe (GC) are shown. Stages shown are young of year (YOY), juvenile (stages 1-4), and adult. The MVP estimates that correspond to the estimates in Table 7 are highlighted in grey.*

Extinction Threshold	GC	Stage	MVP					
			P_{ext}	0.001	0.01	0.03	0.05	0.08
2 adults	10%	YOY		$1.3\ x10^6$	$4.7\ x10^4$	$9.9\ x10^3$	$4.7\ x10^3$	$2.4\ x10^3$
		J		$5.1\ x10^5$	$1.9\ x10^4$	$3.9\ x10^3$	$1.9\ x10^3$	$9.7\ x10^2$
		A		$8.6\ x10^3$	$3.2\ x10^2$	67	32	17
2 adults	15%	YOY		$7.5\ x10^6$	$1.6\ x10^5$	$2.6\ x10^4$	$1.1\ x10^4$	$5.1\ x10^3$
		J		$6.2\ x10^5$	$1.3\ x10^4$	$2.1\ x10^3$	$9.2\ x10^2$	$4.2\ x10^2$
		A		$5.1\ x10^4$	$1.1\ x10^3$	$1.8\ x10^2$	76	35
50 adults	10%	YOY		$2.0\ x10^{11}$	$1.8\ x10^8$	$6.6\ x10^6$	$1.4\ x10^6$	$3.4\ x10^5$
		J		$1.6\ x10^{10}$	$1.5\ x10^7$	$5.5\ x10^5$	$1.2\ x10^5$	$2.8\ x10^4$
		A		$1.3\ x10^9$	$1.3\ x10^6$	$4.5\ x10^4$	$9.6\ x10^3$	$2.3\ x10^3$
50 adults	15%	YOY		$4.2\ x10^{12}$	$1.5\ x10^9$	$3.4\ x10^7$	$5.9\ x10^6$	$1.2\ x10^6$
		J		$3.5\ x10^{11}$	$1.2\ x10^8$	$2.8\ x10^6$	4.8E+05	$9.6\ x10^4$
		A		$2.9\ x10^{10}$	$1.0\ x10^7$	$2.3\ x10^5$	$4.0\ x10^4$	$7.9\ x10^3$

*Table A2-5: Number of individuals by stage required to support a minimum viable population (MVP). Results for the **large** population type, two different extinction thresholds, five different probabilities of extinction (P_{ext}), and two probabilities of generational catastrophe (GC) are shown. Stages shown are young of year (YOY), juvenile (stages 1-4), and adult. The MVP estimates that correspond to the estimates in Table 7 are highlighted in grey.*

Extinction Threshold	GC	Stage	MVP					
			P_{ext}	0.001	0.01	0.03	0.05	0.08
2 adults	**10%**	**YOY**		8.6×10^{7}	1.6×10^{6}	2.4×10^{5}	1.0×10^{5}	4.5×10^{4}
		J		1.5×10^{7}	2.9×10^{5}	4.3×10^{4}	1.8×10^{4}	7.9×10^{3}
		A		6.9×10^{4}	1.3×10^{3}	2.0×10^{2}	81	36
2 adults	**15%**	**YOY**		4.1×10^{8}	4.9×10^{6}	5.9×10^{5}	2.2×10^{5}	9.0×10^{4}
		J		7.2×10^{7}	8.6×10^{5}	1.0×10^{5}	3.9×10^{4}	1.6×10^{4}
		A		3.3×10^{5}	3.9×10^{3}	4.8×10^{2}	1.8×10^{2}	72
50 adults	**10%**	**YOY**		7.4×10^{11}	1.2×10^{9}	5.8×10^{7}	1.4×10^{7}	3.8×10^{6}
		J		1.3×10^{11}	2.2×10^{8}	1.0×10^{7}	2.5×10^{6}	6.7×10^{5}
		A		5.9×10^{8}	9.9×10^{5}	4.7×10^{4}	1.1×10^{4}	3.1×10^{3}
50 adults	**15%**	**YOY**		5.7×10^{12}	5.3×10^{9}	1.9×10^{8}	4.1×10^{7}	9.8×10^{6}
		J		1.0×10^{12}	9.3×10^{8}	3.3×10^{7}	7.1×10^{6}	1.7×10^{6}
		A		4.6×10^{9}	4.3×10^{6}	1.5×10^{5}	3.2×10^{4}	7.8×10^{3}

Table A2-6. Number of years required to achieve the minimum viable population (MVP) size (adults) for large, mixed and small population types, with an extinction threshold of 50 individuals, five different probabilities of extinction (P_{ext}), and a probability of generational catastrophe (GC) of 15%.

Waterbody	Current Abundance Estimate	Large					Mixed					Small				
		0.001	0.01	0.03	0.05	0.08	0.001	0.01	0.03	0.05	0.08	0.001	0.01	0.03	0.05	0.08
Oldman River Basin	1940	55.9	29.3	16.6	10.7	5.3	40.6	20.4	10.8	6.4	2.3	28.1	14.6	8.1	5.1	2.4
Waterton River	40	70.7	44.1	31.4	25.5	20.1	52.1	32.0	22.4	17.9	13.8	34.7	21.2	14.7	11.8	9.0
Drywood Creek	40	70.7	44.1	31.4	25.5	20.1	52.1	32.0	22.4	17.9	13.8	34.7	21.2	14.7	11.8	9.0
Lower Oldman River	60	69.2	42.6	29.9	24.0	18.6	50.9	30.8	21.2	16.7	12.6	34.0	20.5	14.1	11.1	8.3
Belly River	250	63.7	37.1	24.4	18.5	13.1	46.7	26.5	16.9	12.5	8.4	31.6	18.1	11.6	8.6	5.9
Upper Livingstone River	280	63.3	36.7	24.0	18.1	12.7	46.3	26.2	16.6	12.1	8.0	31.4	17.9	11.4	8.4	5.7
Castle River and Oldman Reservoir	310	62.9	36.3	23.6	17.7	12.3	46.0	25.9	16.3	11.8	7.7	31.2	17.7	11.3	8.3	5.5
Upper Oldman River	410	61.8	35.2	22.6	16.7	11.2	45.2	25.1	15.5	11.0	6.9	30.7	17.2	10.8	7.8	5.0
St Mary River	550	60.7	34.1	21.4	15.5	10.1	44.3	24.2	14.6	10.1	6.0	30.2	16.7	10.3	7.3	4.5
Bow River Basin	2623	54.8	28.2	15.5	9.6	4.2	39.7	19.5	9.9	5.5	1.4	27.6	14.1	7.6	4.6	1.9
Middle Bow River	10	76.0	49.4	36.7	30.8	25.4	56.2	36.1	26.5	22.0	17.9	37.1	23.6	17.1	14.1	11.4
Jumpingpound Creek	15	74.4	47.9	35.2	29.3	23.8	55.0	34.9	25.3	20.8	16.7	36.4	22.9	16.4	13.4	10.7
Canyon Creek	20	73.4	46.8	34.1	28.2	22.7	54.2	34.0	24.4	20.0	15.9	35.9	22.4	15.9	12.9	10.2
Flat Creek	40	70.7	44.1	31.4	25.5	20.1	52.1	32.0	22.4	17.9	13.8	34.7	21.2	14.7	11.8	9.0
Upper Spray River	40	70.7	44.1	31.4	25.5	20.1	52.1	32.0	22.4	17.9	13.8	34.7	21.2	14.7	11.8	9.0
Lake Minnewanka	58	69.3	42.7	30.0	24.1	18.7	51.0	30.9	21.3	16.8	12.7	34.1	20.6	14.1	11.1	8.4
Lower Elbow River	105	67.0	40.4	27.7	21.8	16.4	49.2	29.1	19.5	15.0	10.9	33.1	19.6	13.1	10.1	7.4
Upper Elbow River	115	66.7	40.1	27.4	21.5	16.1	49.0	28.8	19.2	14.8	10.7	32.9	19.4	13.0	10.0	7.2
Highwood River	190	64.8	38.2	25.5	19.6	14.2	47.5	27.3	17.7	13.3	9.2	32.0	18.5	12.1	9.1	6.3
Ghost River	385	62.1	35.5	22.8	16.9	11.5	45.4	25.2	15.6	11.2	7.1	30.8	17.3	10.9	7.9	5.1
Sheep River	445	61.5	34.9	22.2	16.3	10.9	44.9	24.8	15.2	10.8	6.6	30.6	17.1	10.6	7.7	4.9
Upper Kananaskis River	1200	57.7	31.2	18.5	12.6	7.1	42.0	21.9	12.3	7.8	3.7	28.9	15.4	9.0	6.0	3.2

Waterbody	Current Abundance Estimate	Large					Mixed					Small				
		0.001	0.01	0.03	0.05	0.08	0.001	0.01	0.03	0.05	0.08	0.001	0.01	0.03	0.05	0.08
Red Deer River Basin	540	60.8	34.2	21.5	15.6	10.2	44.4	24.2	14.6	10.2	6.1	30.3	16.8	10.3	7.3	4.6
Little Red Deer River	10	76.0	49.4	36.7	30.8	25.4	56.2	36.1	26.5	22.0	17.9	37.1	23.6	17.1	14.1	11.4
Red Deer River Basin	530	60.9	34.3	21.6	15.7	10.3	44.4	24.3	14.7	10.2	6.1	30.3	16.8	10.4	7.4	4.6
North Saskatchewan River Basin	5115	52.2	25.6	12.9	7.0	1.6	37.7	17.6	8.0	3.5	0.0	26.4	12.9	6.5	3.5	0.7
Baptiste River	50	69.9	43.3	30.6	24.7	19.2	51.4	31.3	21.7	17.2	13.1	34.3	20.8	14.4	11.4	8.6
Lower North Saskatchewan River	75	68.3	41.7	29.0	23.1	17.7	50.2	30.1	20.5	16.0	11.9	33.6	20.1	13.7	10.7	7.9
Nordegg River	105	67.0	40.4	27.7	21.8	16.4	49.2	29.1	19.5	15.0	10.9	33.1	19.6	13.1	10.1	7.4
Clearwater River	390	62.0	35.4	22.7	16.8	11.4	45.3	25.2	15.6	11.1	7.0	30.8	17.3	10.9	7.9	5.1
Middle North Saskatchewan River	400	61.9	35.3	22.7	16.8	11.3	45.3	25.1	15.5	11.1	7.0	30.8	17.3	10.8	7.8	5.1
Blackstone River	720	59.7	33.1	20.4	14.5	9.1	43.5	23.4	13.8	9.3	5.2	29.8	16.3	9.8	6.8	4.1
Upper North Saskatchewan River	950	58.6	32.0	19.4	13.5	8.0	42.7	22.6	13.0	8.5	4.4	29.3	15.8	9.4	6.4	3.6
Pinto Lake and Cline River	1150	57.9	31.3	18.6	12.7	7.3	42.1	22.0	12.4	7.9	3.8	29.0	15.5	9.0	6.0	3.3
Brazeau River	1275	57.5	30.9	18.2	12.3	6.9	41.8	21.7	12.1	7.6	3.5	28.8	15.3	8.9	5.9	3.1
Total	10218	49.6	23.0	10.3	4.4	0.0	35.6	15.5	5.9	1.4	0.0	25.3	11.8	5.3	2.3	0.0