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Recovery Potential Modelling of Redside Dace (*Clinostomus elongatus)* in Canada

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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.

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ABSTRACT

The Committee on the Status of Endangered Wildlife in Canada (COSEWIC) has assessed Redside Dace (*Clinostomus elongatus*) as Endangered in Canada. Here a population model is presented to determine population-based recovery targets, assess allowable harm, and conduct long-term projections of population recovery in support of a recovery potential assessment (RPA). The analyses demonstrate that the dynamics of Redside Dace populations are particularly sensitive to perturbations that affect survival of immature individuals (from hatch to age-2) and population-level fecundity. Harm to these portions of the life cycle should be minimized to avoid jeopardizing the survival and future recovery of Canadian populations. Meta-population structure was incorporated into analyses. The manner in which catastrophes impacted segments of the meta-population influenced recovery target estimates, indicating that understanding the extent of meta-population structure throughout the species range is needed to refine recovery targets. To achieve demographic sustainability, (i.e., a self-sustaining population over the long term) under conditions with a catastrophe probability of 0.15/generation and a quasi-extinction threshold of 50 adults at a 1% probability of extinction over 100 years, population sizes ranging from 18,000 to 75,000 were required. This required between 3.2 and 13.2 ha of suitable Redside Dace habitat. Three recovery effort strategies were simulated that focused on improving vital rates (survival and fecundity). A declining population ($\lambda = 0.89$) required considerable improvement to individual vital rates (> 40%) to cease population decline. If, however, survival of all age-classes could be augmented simultaneously an improvement of only 13% was required. Depending on the strategy employed, recovery occurred after 48 to 120 years. Recovery efforts affecting survival of all age-classes provided the greatest improvement to population growth rate and therefore resulted in quickest recovery (48 years).

INTRODUCTION

Redside Dace (*Clinostomus elongatus*) was previously assessed by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) in 2007 and was designated as Endangered (COSEWIC 2007). Redside Dace was re-assessed by COSEWIC in 2017 again as Endangered (COSEWIC 2017), and was subsequently listed as Endangered under Schedule 1 of the Canadian *Species at Risk Act* (SARA). In accordance with the *Species at Risk Act* (SARA), which mandates the development of strategies for the protection and recovery of species that are at risk of extinction or extirpation in Canada, Fisheries and Oceans Canada (DFO) has developed the recovery potential assessment (RPA; DFO 2007a, 2007b) as a means of providing information and scientific 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 - that are further broken down into 22 elements. This report contributes to components two and three and elements 3, 12, 13, 14, 15, 19, 20, 21, and 22 by identifying recovery targets, assessing allowable harm, projecting recovery timeframes and identifying mitigation strategies with associated uncertainty for Canadian populations of Redside Dace.

A previous RPA was conducted for Redside Dace in 2008 following its initial assessment by COSEWIC (Vélez-Espino and Koops 2008). The previous analysis estimated abundance-based recovery targets with the use of a predictive relationship. Results indicated that 4,711 adult fish was an acceptable recovery target, which would require 17,308 m^2 of suitable habitat per population. Allowable harm analysis indicated that population recovery may be impeded if mortality of any age class was increased by greater than 5% or if fecundity was reduced by greater than 18%. An update to the previous RPA is provided utilizing new methodological approaches to estimating recovery targets and allowable harm as well as incorporating new data for Canadian populations of Redside Dace collected since the previous assessment (Poesch unpublished data). This work is based on a demographic approach developed by Vélez-Espino and Koops (2009, 2012) and Vélez-Espino et al. (2010), which determines a population-based recovery target based on long-term population projections.

METHODS

The analysis consisted of five 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) stochastic sensitivity of population growth rate to changes in each vital rate was determined and used to estimate allowable chronic harm following Vélez-Espino and Koops (2009);

(iii) simulations were used to estimate the impact of transient harm (a one-time removal of fish of various age-classes) on population growth;

(iv) stochastic simulations were conducted to estimate the minimum viable population (MVP) and the minimum area for population viability (MAPV; i.e., the amount of suitable habitat required to support the MVP); and

(v) using MVP as a recovery target, simulations were conducted to estimate the probability of recovery over a given time frame though application of potential recovery efforts.

SOURCES

Redside Dace were collected from various tributaries in southern Ontario between July 2007 and October 2008 (Poesch unpublished data). These data provided information to inform estimates of growth, survival, fecundity, dispersal, and abundance. Additional life history and population information was sourced from the primary literature. All analyses and simulations were conducted using the statistical program R 3.3.2 (R Core Team 2016).

THE MODEL

The life cycle of Redside Dace was modelled using a birth-pulse (all spawning occurs on the assumed birth date of the population), post-breeding, age-structured matrix model with annual projection intervals (Caswell 2001). Matrix population models use estimates of vital rates (growth, survival, and fecundity) to project age- or stage-specific population size. The dominate eigenvalue of the matrix represents the population growth rate (λ) and indicates the long term status of the population based on current conditions (Caswell 2001). A $\lambda > 1$ indicates that the population is growing exponentially, a $\lambda = 1$ indicates a population that is stable, and a $\lambda < 1$ indicates a population that is declining towards 0. The dominant right eigenvector of the matrix represents the stable stage structure of the population and indicates the proportional distribution of individuals among stages/ages. This can be used to estimate the number of individuals in all other stages/ages if one is known.

The matrix structure is defined by Redside Dace longevity (t_{max}) and age-at-first-maturity (t_{mat}). Redside Dace is assumed live to a maximum age of 4 years and reach maturity at age-2 (Koster 1939, McKee and Parker 1982). The life cycle of Redside Dace is represented in Figure 1.

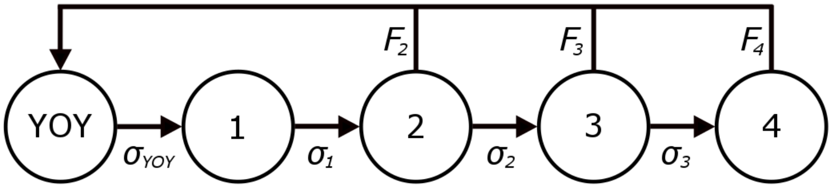

Figure 1. Generalized life cycle used to model the population dynamics of Redside Dace. F_t represents age-specific annual fertility and σ_t represents the age-specific annual survival.

Elements within the age-structured matrix include age-specific annual survival (σ_t) and fertility rate (F_t). Fertility coefficients (F_t) represent the contribution from an adult in age class t to the next census of age-0 individuals. Multiple variables are incorporated into estimates of annual age-specific fertility rate. Fertility is dependent on mean age-specific fecundity (f_t) or the mean number of eggs produced per spawning event per individual female in age class t. It also accounts for the proportion of the population that is female (φ; assumed to be 0.5 for Redside Dace populations) and the proportion of the population that is mature at age-t (ρ_t). As well, fertility includes spawning periodicity (T) or the number of years between spawning events (1 year for Redside Dace). Finally, because a post-breeding matrix structure is incorporated, the survival coefficient is included to account for mortality occurring between the population census and the next spawning event. Fertility is calculated as:

$$F_t = \frac{\varphi \rho_t f_t \sigma_t}{T}. \tag{1}$$

The matrix has 5 columns representing young-of-the-year (YOY), age-1, age-2, age-3, and age-4 Redside Dace:

$$\mathbf{B} = \begin{bmatrix} 0 & F_2 & F_3 & F_4 & 0 \\ \sigma_0 & 0 & 0 & 0 & 0 \\ 0 & \sigma_1 & 0 & 0 & 0 \\ 0 & 0 & \sigma_2 & 0 & 0 \\ 0 & 0 & 0 & \sigma_3 & 0 \end{bmatrix}. \qquad (2)$$

Because the population census occurs just after reproduction has occurred, individuals grow and mature over the course of the year and spawn just before the next census. To account for this timing, the fertility coefficients for age-*t*+1 are incorporated into column *t* of the projection matrix (i.e., fertility of age 2 fish is represented in the age-1 column of the matrix). As well, the matrix structure includes a column of 0s to represent age-4 fish. This allows for age-4 fish to exist but not survive to the next census or spawn as age-5 fish.

Redside Dace populations may function as meta-populations with several sub-populations occupying distinct pools separated by a well-defined but passable migration barrier (i.e., a riffle; Poos and Jackson 2012). Meta-population structure may affect Redside Dace resilience to catastrophes or susceptibility to recovery measures if sub-populations are independently affected. To explore these effects, two population models for Redside Dace were constructed: one as a single population model; and, a second incorporating meta-population structure with distinct sub-populations and defined movement among them.

In matrix form a meta-population model consists of two components: an $s \times s$ (where *s* is the number of stages) demographic projection matrix ($\boldsymbol{B_p}$**;** equation 2); and a $p \times p$ (where *p* is the number of patches (sub-populations)) dispersal matrix $\boldsymbol{M_s}$ (Hunter and Caswell 2005). $\boldsymbol{B_p}$ represents the life history characteristics of the patch *p* and $\boldsymbol{M_s}$ represents the probability of movement between patches by fish in stage *s*. $\boldsymbol{M_s}$ is structured as:

$$\boldsymbol{M_s} = \begin{bmatrix} r_1 & d_{2\to1} & d_{3\to1} & d_{4\to1} \\ d_{1\to2} & r_2 & d_{3\to2} & d_{4\to2} \\ d_{1\to3} & d_{2\to3} & r_3 & d_{4\to3} \\ d_{1\to4} & d_{2\to4} & d_{3\to4} & r_4 \end{bmatrix}, \qquad (3)$$

where *r* represents the probabilty of fish in patch *p* remaining in that patch and *d* repesents the probability of dispersing from one patch to another. The columns in ***M*** represent the movement probability from a patch and must sum to 1 and the rows represent the probability of movement to a patch.

The patch- and stage-sepcific matrices ($\boldsymbol{B_p}$ and $\boldsymbol{M_s}$) are organized in to block diagonal matrices ($\mathbb{B}$ and $\mathbb{M}$) to represent the meta-population as a whole, where:

$$\mathbb{B} = \left[\begin{array}{c|c|c|c} \boldsymbol{B_1} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \hline \mathbf{0} & \boldsymbol{B_2} & \mathbf{0} & \mathbf{0} \\ \hline \mathbf{0} & \mathbf{0} & \boldsymbol{B_3} & \mathbf{0} \\ \hline \mathbf{0} & \mathbf{0} & \mathbf{0} & \boldsymbol{B_4} \end{array}\right], \qquad (4)$$

and:

$$\mathbb{M} = \left[\begin{array}{c|c|c|c|c} \boldsymbol{M_0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \hline \mathbf{0} & \boldsymbol{M_1} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \hline \mathbf{0} & \mathbf{0} & \boldsymbol{M_2} & \mathbf{0} & \mathbf{0} \\ \hline \mathbf{0} & \mathbf{0} & \mathbf{0} & \boldsymbol{M_3} & \mathbf{0} \\ \hline \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \boldsymbol{M_4} \end{array}\right]. \qquad (5)$$

The **0**s represent $s \times s$ and $p \times p$ matrices of 0s. Because of a lack of information on patch-specific vital rates and age-specific movements the same parameter values were used for all patch-specific $\boldsymbol{B_p}$ and age-specific $\boldsymbol{M_s}$ matrices, except for YOY movement where no movement was assumed with $\boldsymbol{M_0}$ represented by an identity matrix. This assumes that Redside Dace experience the same vital rates in all patches and that movement patterns are independent of age for ages > 0.

Finally, from the $\mathbb{B}$ and $\mathbb{M}$ matrices the meta-popuation projection matrix (***A***) is calculated as (Hunter and Caswell 2005):

$$\boldsymbol{A} = \boldsymbol{P}^T \mathbb{M} \boldsymbol{P} \mathbb{B}. \qquad (6)$$

Where ***A*** has dimensions *of* $sp \times sp$, ***P*** represents the vec-permutation matrix, and T represents the transposition operator. The vec-permutation matrix (Hunter and Caswell 2005) is a matrix of 0s and 1s with $sp \times sp$ dimenstions and serves to combine and organize the demographic and dispersal matrices in to the final projection matrix with appropriate dimenstions. The formation of ***A*** allows for dispersal to be implimented before demographic changes (i.e., mortality and reproduction) take place. Alternative forms can be used where dispersal follows demography (Hunter and Caswell 2005).

Parameter Estimates

All model parameters are outlined in Table 1.

Growth

Length-at-age data were available from otolith-derived ages of Redside Dace captured from southern Ontario populations. The data were fit with a von Bertalanffy growth curve (Figure 2):

$$L_t = L_\infty (1 - e^{-K(t - t_0)}), \qquad (7)$$

Where L_t is total length (TL) in mm at age-*t*, t_0 is the hypothetical age at which the fish would have had a length of 0, L_∞ is the asymptotic size, and *K* is a growth parameter. To properly represent early life growth the relationship was forced through predicted length-at-hatch at age-0. Length-at-hatch was estimated from a relationship with egg diameter (Duarte and Alcaraz 1989). Redside Dace egg diameter ranges from 1.2 to 2.4 mm (Scott and Crossman 1973) producing a median hatch size of 5.79 mm. This resulted in an L_∞ value of 95.9, a *K* value of 0.48 and a t_0 value of -0.13 (Table 1).

Length-weight data were compiled for Redside Dace captured in Ontario (Figure 3). These data were fit as a $\log_e$ transformed linear model which was re-transformed as a power curve to predict the expected weight, in grams, for a given length, in mm, resulting in the relationship:

$$W_t = 3.46 \times 10^{-6} {L_t}^{3.203} . \qquad (8)$$

Table 1. Values, symbols, descriptions, and sources for all parameters used to model Redside Dace.

	Symbol	Description	Value	Source/Location
Age	t_{max}	Longevity	4	Koster (1939); NY
	t_{mat}	Age-at-first-maturity	2	McKee and Parker (1982); ON
	ζ	Generation time	2.8	ON
Growth	L_{∞}	Asymptotic length	95.88	Poesch (unpublished); ON
	K	Growth coefficient	0.48	
	t_0	Age at 0 mm	-0.13	
Fecundity	α_F	Fecundity allometric exponents	2.54×10^{-5}	Poesch (unpublished); ON
	β_F	Fecundity allometric intercept	3.98	
	sd_F	log standard deviation of fecundity	0.12	
	φ	Proportion female	0.5	McKee and Parker (1982); ON
	T	Spawning periodicity	1	
	ρ_0	Proportion reproductive at age 0	0	
	ρ_1	Proportion reproductive at age 1	0	
	ρ_2	Proportion reproductive at age 2	0.75	
	ρ_3	Proportion reproductive at age 3	1	
	ρ_4	Proportion reproductive at age 4	1	
Weight	α_W	Length-weight allometric exponents	3.46×10^{-6}	Poesch (unpublished); ON
	β_W	Length-weight allometric intercept	3.20	
Mortality	M_{min}	Instantaneous adult mortality with $\lambda = 0.89$	1.13	Fitted / Poesch (unpublished); ON
	M_{equil}	Instantaneous adult mortality with $\lambda = 1$	1.07	
	M_{mean}	Instantaneous adult mortality with $\lambda = 1.19$	0.99	
	M_{est}	Instantaneous adult mortality from catch curve analysis with $\lambda = 1.46$	0.90	
	M_{max}	Instantaneous adult mortality with $\lambda = 1.91$	0.78	
	cv_M	Coefficient of variation of mortality	0.2	Mertz and Myers (1995)
Dispersal	r_1	Probability of remaining in patch 1	0.60	Drake and Poesch (unpublished); Rouge River tributaries (Berczy Creek)
	$d_{1 \rightarrow 2}$	Probability of dispersing from patch 1 to 2	0.32	
	$d_{1 \rightarrow 3}$	Probability of dispersing from patch 1 to 3	0.05	
	$d_{1 \rightarrow 4}$	Probability of dispersing from patch 1 to 4	0.03	
	r_2	Probability of remaining in patch 2	0.71	
	$d_{2 \rightarrow 1}$	Probability of dispersing from patch 2 to 1	0.15	
	$d_{2 \rightarrow 3}$	Probability of dispersing from patch 2 to 3	0.06	
	$d_{2 \rightarrow 4}$	Probability of dispersing from patch 2 to 4	0.08	
	r_3	Probability of remaining in patch 3	0.65	
	$d_{3 \rightarrow 1}$	Probability of dispersing from patch 3 to 1	0.1	
	$d_{3 \rightarrow 2}$	Probability of dispersing from patch 3 to 2	0.07	
	$d_{3 \rightarrow 4}$	Probability of dispersing from patch 3 to 4	0.18	
	r_4	Probability of remaining in patch 4	0.88	
	$d_{4 \rightarrow 1}$	Probability of dispersing from patch 4 to 1	0.06	
	$d_{4 \rightarrow 2}$	Probability of dispersing from patch 4 to 2	0.01	
	$d_{4 \rightarrow 3}$	Probability of dispersing from patch 4 to 3	0.05	

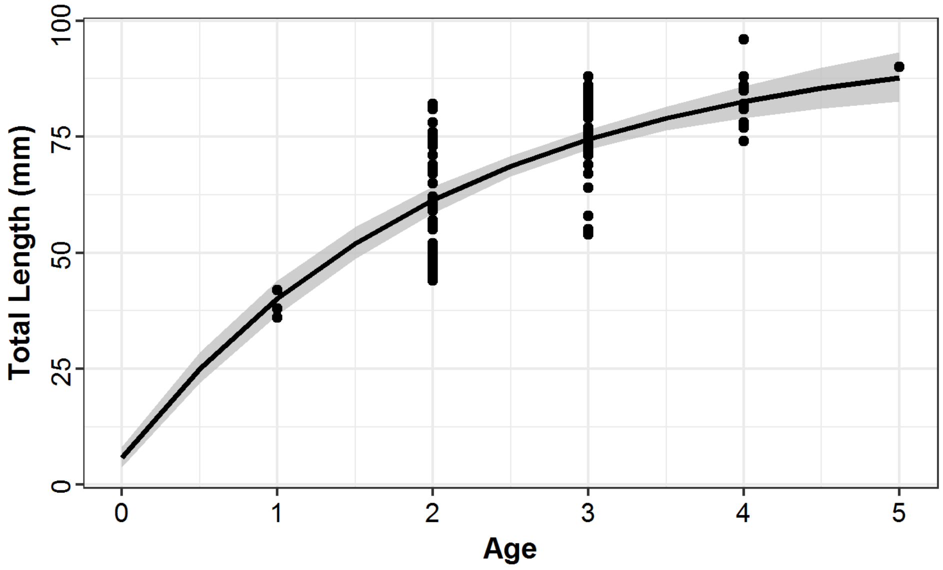

Figure 2. Length-at-age data for Redside Dace captured from southern Ontario tributaries. The black line represents the best fit of the von Bertalanffy growth curve forced through size-at-hatch (5.79 mm) and the grey region represents bootstrapped 95% confidence intervals. $L_t = 95.9(1 - e^{-0.48(t+0.13)})$.

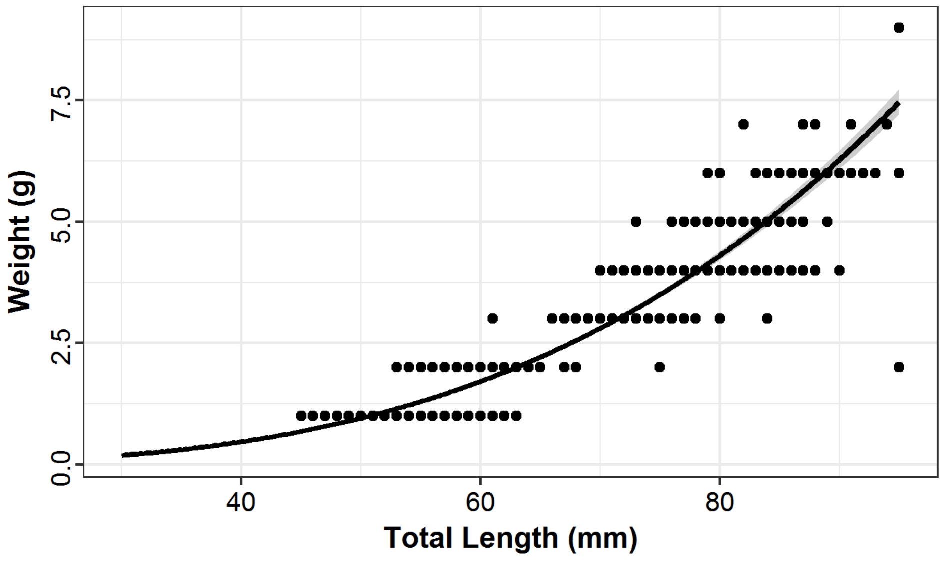

Figure 3. Length-weight data for Redside Dace captured from southern Ontario tributaries. The black line represents the best fit relationship and the grey region represents 95% confidence intervals. $W = 3.46 \times 10^{-6} L^{3.203}$.

Reproduction

Limited empirical data were available from southern Ontario to inform aspects of Redside Dace reproduction. Redside Dace are believed to spawn once annually in late May and maintain a sex ratio of approximately 1:1 (McKee and Parker 1982). First spawning typically occurs after individuals have passed through two winters (Koster 1939), based on observations in New York State. McKee and Parker (1982) found all age-1+ individuals to be immature, while most age-2+ individuals and all age-3+ individuals were mature. As a result, the maturation schedule incorporated into the model had 0% of age-1 fish, 75% of age-2 fish and all age-3+ fish as mature (Table 1).

Few fecundity estimates exist for Redside Dace. Fecundity estimates in the literature were 409–1,526 (Koster 1939) and 423-1,971 (McKee and Parker 1982) eggs/individual. Nine additional measurements were made for females captured from southern Ontario and ranged from 690-1,272 eggs/individual (Poesch unpublished data). All available fecundity data were compiled and fit as a $\log_e$ transformed linear model with length, which was re-transformed as a power function producing the relationship (Figure 4):

$$f_t = 2.54 \times 10^{-5} {L_t}^{3.98}, \tag{9}$$

where L_t represents length at age-t estimated from Equation 7.

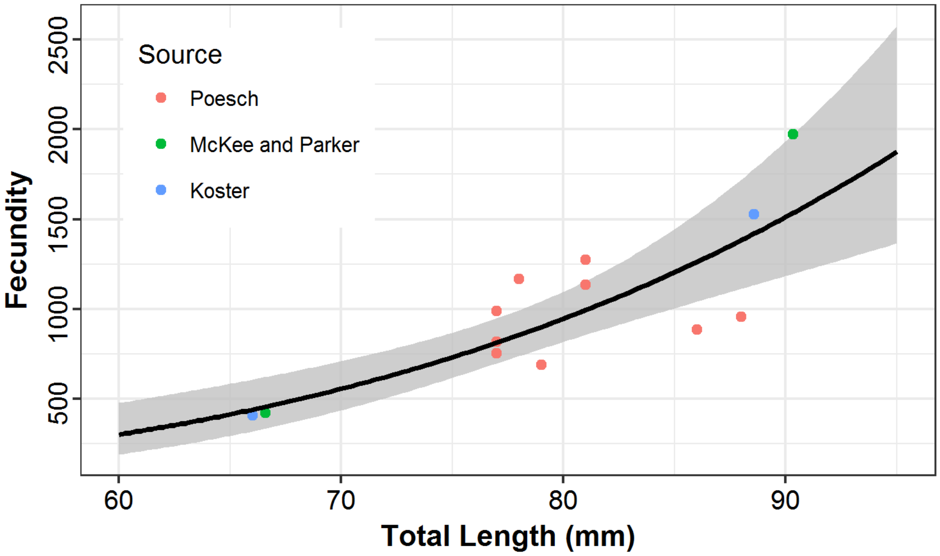

Figure 4. Fecundity data for Redside Dace captured from southern Ontario (McKee and Parker 1982; Poesch unpublished data) and New York State (Koster 1939). The black line represents the best fit relationship with length and the grey region represents 95% confidence intervals. $f = 2.54 \times 10^{-5} L^{3.98}$.

Mortality

A single estimate of adult mortality was available from catch-curve analysis of otolith-aged fish captured from southern Ontario populations (Figure 5). Weighted catch curve regression analysis was performed to decrease potential bias from rarer, older fish (Maceina and Bettoli 1998). This resulted in an estimated instantaneous adult mortality of 0.90. Constant adult mortality (ages 2 and 3) was assumed and survival of younger age classes was estimated from a size-dependent relationship (Lorenzen 2000):

$$M_t = \frac{m_0}{L_t}, \tag{10}$$

where m_0 is the mortality at a single unit of length. If L_t is described by the von Bertalanffy growth curve (Equation 7), survival from age-t to $t+1$ can be calculated by combining Equations 7 and 10 and integrating (see Appendix A in van der lee and Koops 2016); resulting in:

$$\sigma_t = \left[\frac{L_t e^{-K}}{L_{t+1}}\right]^{m_0/KL_\infty}. \tag{11}$$

Equation 11 was used to estimate YOY and age-1 survival.

Incorporating the estimated adult mortality (M = 0.90) into the projection matrix and back calculating for younger age classes resulted in a population growth rate of 1.46. This is likely not a representative estimate of Redside Dace population growth as only one observation of mortality was made and some assumptions of catch-curve analysis, such as constant year class strength, and equal vulnerability of all age-classes to the sampling gear, may have been violated. Consequently, the projection matrix was used to solve for additional mortality rates that resulted in various population growth rates. An optimization procedure was used to solve for the adult mortality (and back-calculated YOY and age-1 survival) that resulted in the expected minimum, equilibrium, mean, and maximum populations growth rates (Table 1).

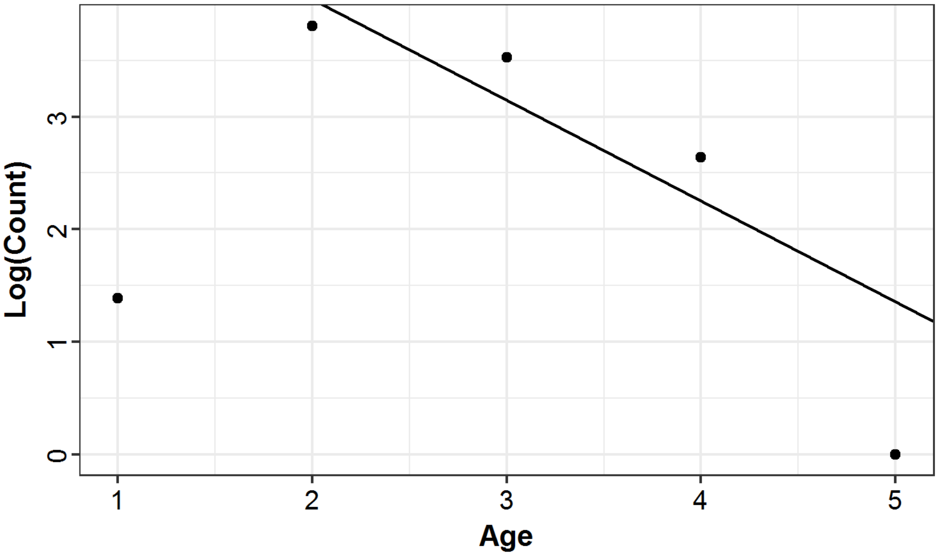

Figure 5. Weighted catch curve analysis of age frequency data of Redside Dace captured from southern Ontario tributaries. Instantaneous adult mortality was estimated to be 0.90 which resulted in a population growth rate (λ) of 1.46.

Minimum population growth rate was calculated based on interpreting COSEWIC's assessment criteria. Based on criterion A1, COSEWIC defines an endangered species as one where there is indication of a 70% decline in population size over the previous 10 years or 3 generations, whichever is longer. Generation time (ζ) for Redside Dace was estimated from the projection matrix to be 2.8 years. From this minimum population growth rate was estimated as: $\lambda_{min} = 0.3^{1/10}$ resulting in a λ_{min} of 0.89 and a M_{min} of 1.12. Equilibrium population growth, when λ equals 1, resulted in a M_{equil} of 1.07. Maximum population growth rate, reflecting the greatest possible rate of population increase for the species under ideal environmental conditions, was estimated from an allometric relationship (Randall and Minns 2000):

$$\lambda_{max} = e^{2.64W^{-0.35}}, \quad (12)$$

where W represents average adult weight. As a conservative estimate the lower prediction interval from the fitted relationship (Randall and Minns 2000) was used giving a λ_{max} of 1.91 and a M_{max} of 0.78. Mean population growth rate was estimated through balancing conservative and optimistic estimates of λ by taking the geometric mean of minimum, equilibrium, and maximum λ (Vélez-Espino and Koops 2007). This resulted in a population growth rate of 1.19 and an estimated M_{mean} of 0.99. This mean value can be considered as the midpoint between the rate of population decline at the time of COSEWIC assessment and the highest rate of population growth possible under ideal environmental conditions.

Meta-population

Within-tributary populations of Redside Dace may function as meta-populations (Poos and Jackson 2012). A meta-population consists of distinct sub-populations occupying defined patches separated by a passable migration barrier (i.e., riffle), allowing for some level of connectivity and movement among patches.

Abundance and dispersal data were available for Berczy Creek, a relatively undisturbed tributary of the Rouge River (Poos and Jackson 2012, Drake and Poesch unpublished data). Mark-recapture sampling was conducted in Berczy Creek from 2007 to 2008. The creek was sub-divided into pools with 13 intensively sampled sites and 5 extended sites upstream and downstream from the intensively sampled sites; data from the 5 upstream and downstream extended sites were pooled and termed pool 0 and 14 respectively. Individual fish captured within an intensively sampled pool were marked with pool- and season-specific markings and released. Recapture events allowed for the quantification of site-fidelity and movement probabilities among pools based on the summed annual number of captures of fish between origin and destination pools. Pool-specific abundance estimates were made with multi-pass removal method estimates (Poos et al. 2012). These data were used to define the meta-population structure and parameterize the dispersal matrix (Equation 3) for the meta-population model.

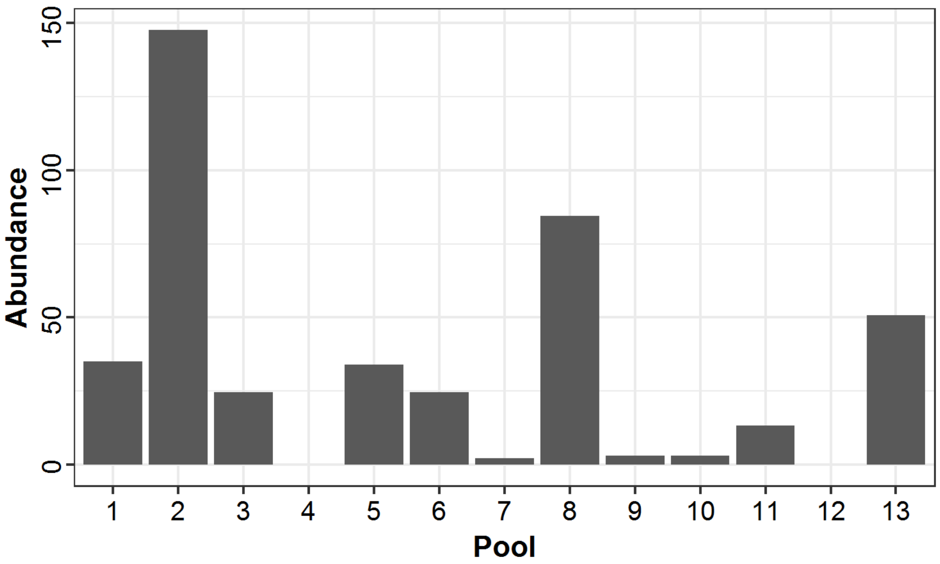

Figure 6. Pool-specific abundance estimates of Redside Dace in Berczy Creek. Abundance estimates were made using multi-pass removal method estimates (Poos et al. 2012).

The meta-population consisted of 4 patches (sub-populations). Within Berczy Creek 3 pools (pool 2, 8 and 13) maintained the greatest abundance (Figure 6). These pools also had the greatest site fidelity with 59, 65 and 53% of fish that originated in each pool being recaptured there respectively (Figure 7). As a result, the defined patches (sub-populations) were centred around these pools. In addition, pool 1 and the upstream extended pools were considered to be a patch because there was considerable movement upstream from pool 1. The spatial extent of each patch was defined by visual examination of Figure 7 and determination of the likely destination of fish from each patch; i.e., pools with fish likely to move towards pool 2 were considered to be in patch 2 while pools with fish that moved towards patch 8 were considered to be in patch 3. The patches were defined as: patch 1 – pools 0 to 1; patch 2 – pools 2 to 5; patch 3 – pools 6 to 10; and patch 4 – pools 11 to 14. Movements within and among patches were summed to give estimates of the annual probability of movement among patches which were incorporated into the ***M*** matrix. The representation of a Redside Dace meta-population was not meant to be a detailed representation of a specific Redside Dace population or apply broadly to all Redside Dace populations. Rather, it is intended to help identify the potential significance of a meta-population structure to Redside Dace persistence and recovery.

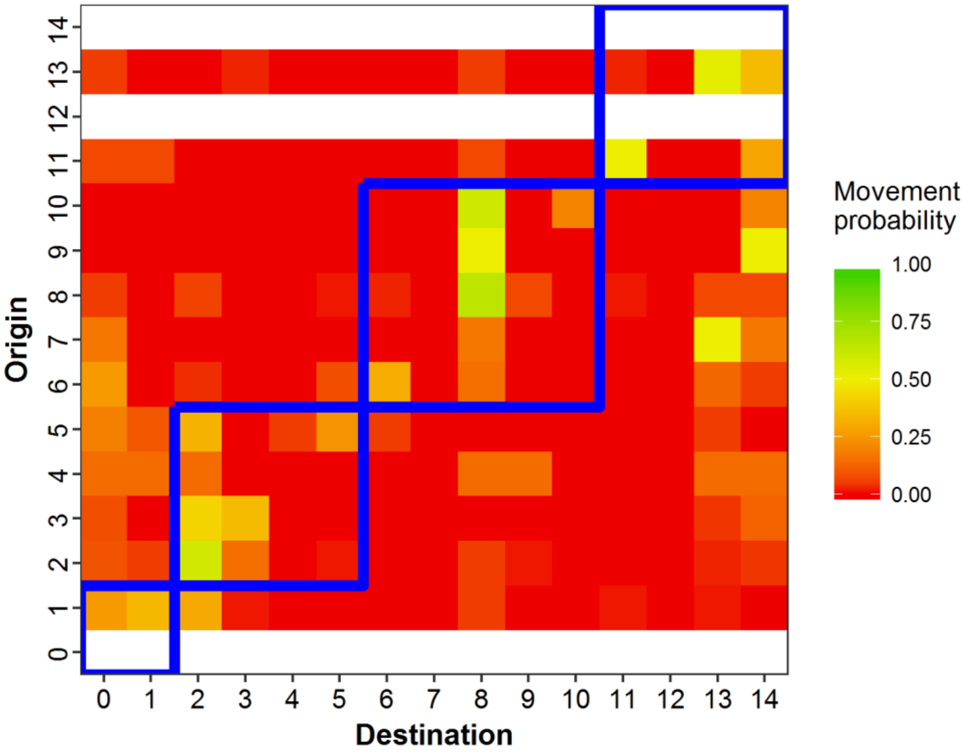

Figure 7. The movement probability of Redside Dace between origin and destination pools in Berczy Creek. Origins represent the pools in which the fish were marked and destinations represent the pools in which the fish were recaptured. The origin-specific values were calculated by dividing the number of recaptures within each pool by the total number of captures from each origin pool. Pools 0 and 14 represent the 5 upstream and 5 downstream extended pools. White indicates that the origin pool did not provide any recaptured fish. The blue lines represent patch definitions used in the meta-population model: Patch 1 – pools 0 to 1; patch 2 – pools 2 to 5; patch 3 – pools 6 to 10; and patch 4 – pools 11 to 14.

STOCHASTICITY

Random, inter-annual variability was incorporated into simulations to account for the influence of environmental stochasticity on demographic factors experienced by populations of Redside Dace. Variability was incorporated into age-specific fecundity and mortality (Figure 8). Age-specific variables were assumed to vary independently among ages and between years.

Fecundity

In stochastic simulations, random mean population-level fecundity values were generated assuming fecundity follows a lognormal distribution. The age-specific means were generated from Equation 9 and half the residual standard error (RSE) from the model fit (on a $\log_e$ scale) was used as the standard deviation (*sd* = 0.12). Half the RSE was used because it resulted in a reasonable range of population fecundity values (Figure 8 left panel). For example, age-4 mean fecundity was 1,078 eggs/female/year and 50,000 random fecundities had a range of approximately 600 to 1,879 eggs/female/year. This corresponds well with the observed ranges of Redside Dace fecundity in New York State and southern Ontario (Koster 1939, McKee and Parker 1982; Poesch unpublished).

Mortality

Independent stochastic simulations were run using each estimate of *M*. The amount of inter-annual variability in Redside Dace mortality was unknown. Bradford (1992) found that across species and life-stages the variance in mortality increases as a function of *M* ($sd(M) = 0.39M^{1.12}$). Mertz and Meyers (1995) determined that the variance estimate was likely inflated by error from field estimates of *M* and proposed that inter-annual variability in *M* could be represented by a normal distribution with a constant coefficient of variation (CV) of 0.2. A CV of 0.2 applied to YOY mortality rates results in a very broad distribution for population growth rates (when mean λ = 1) often with values < 0.5 (which constitutes a catastrophe in the MVP simulations). To account for this the CV of YOY mortality rate was solved for such that λ values of 0.5 were outside of the 99% confidence intervals, giving a value of 0.165. Stochastic instantaneous mortality rates were generated assuming a normal distribution with CVs of 0.165 for YOY aged fish and 0.2 for age-1+ fish (Figure 8 right panel).

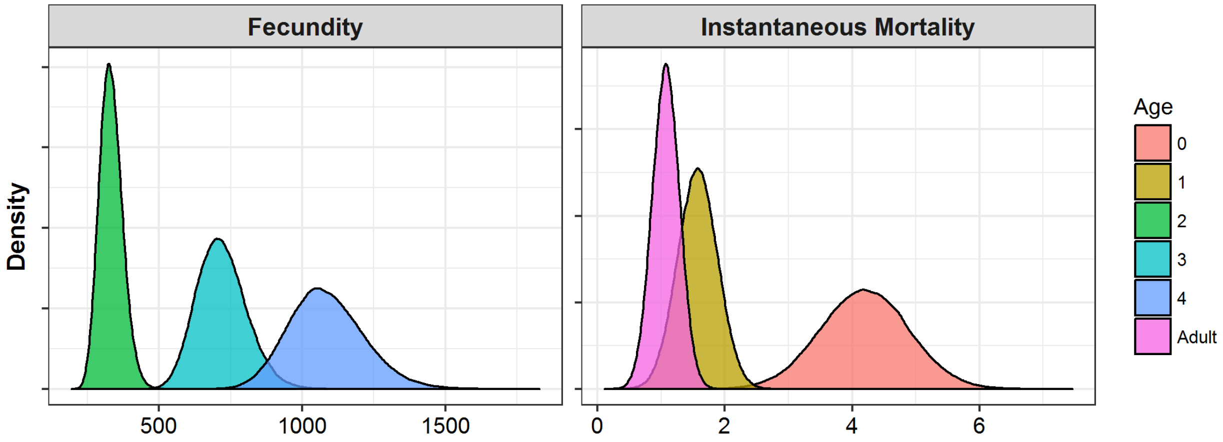

Figure 8. Density graph representing the realized probability density functions for age-specific stochastic parameters (fecundity and instantaneous mortality) incorporated into model simulations. NOTE: age increases along the x-axis from left to right for fecundity but decreased from left to right for mortality.

Population Growth Rate

Incorporating inter-annual variability of vital rates within projection matrices results in a distribution of λ values dependent on the timeframe over which lambda is measured (Figure 9). On an annual basis, λ is log-normally distributed and Redside Dace populations with a geometric mean λ of 1 had a $\log_e(sd) = 0.277$. On a longer-term (i.e., 10 or 100 years) average annual population growth rate has an approximately normal distribution; with a mean λ of 1 the standard deviation over 10 years was 0.089 and over 100 years was 0.028 (i.e., variance in λ declines as the period over which it is measured increases). Over 100 years the range of average annuals λ was 0.93 to 1.08. Therefore, although on average the population experiences a growth rate of 1, due to stochastic environmental variation over a period as long as 100 years individual populations may experience population declines of up to 7% or increases up to 8%.

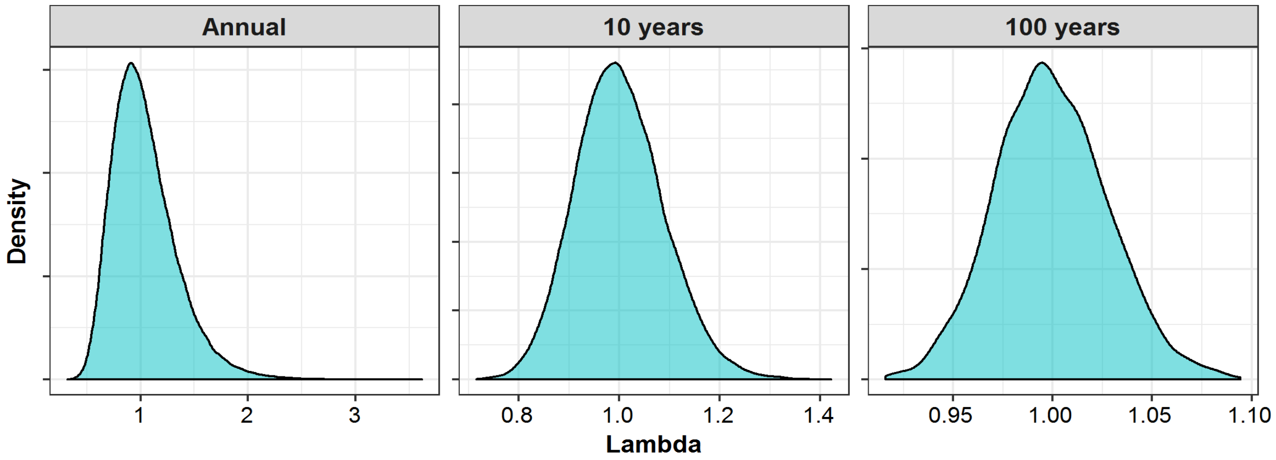

Figure 9. Density graphs of the annual and long term average values of population growth rate (λ) that result from stochastic variation in vital rates. The annual values represent the distribution of λ values for any given year. The long term average values represent the distribution of the geometric mean of λ values over 100 years. The distributions were based on matrices with an average λ of 1.

SENSITIVITY ANALYSIS

Sensitivity analysis of matrix population models was used to determine the impact of changes to vital rates and lower level parameters on annual population growth rate (λ). Sensitivities were quantified though estimation of elasticities (ε_v) which describe the proportional change in λ following a proportional perturbation in a vital rate (v). For example, an elasticity value of 0.2 for adult survival (ε_a) would indicate that a 20% increase in adult survival would result in a 4% ($20\% \times 0.2 = 4\%$) increase λ (i.e., a λ of 1.5 would increase to 1.56 ($1.5 \times (1 + 0.04) = 1.56$). Elasticities are calculated by taking the scaled partial derivatives of λ with respect to the vital rate:

$$\varepsilon_v = \frac{v}{\lambda}\sum_{i,j}\frac{\partial\lambda}{\partial a_{i,j}}\frac{\partial a_{i,j}}{\partial v} \qquad (13)$$

where a_{ij} are the projection matrix elements in row i and column j. Elasticities are additive; as such, the effect of perturbations acting on multiple vital rates can be assessed by summing the elasticities of the affected vital rates.

Variation in vital rates was 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 vital rates (σ_t and f_t) drawn from distributions with means and variances described above;
(ii) calculate the ε_v of λ with respect to σ_t and f_t for each matrix;
(iii) estimate mean stochastic elasticities and their 95% confidence intervals; and
(iv) repeat steps i to iii for matrices with λs of 0.89, 1, 1.19, 1.46, 1.91.

RECOVERY EFFORT AND ALLOWABLE HARM

Allowable harm and minimum required recovery effort were assessed within a demographic framework following Vélez-Espino and Koops (2009). Recovery effort is defined as the minimum vital rate improvement that will allow a population to begin recovery. Allowable harm is defined as the maximum change in a vital rate that will not prevent population recovery. Recovery effort applies when a population has an initial λ < 1 and allowable harm applies when a population has an initial λ > 1 (when λ < 1, there is no scope for allowable harm as any harm can be interpreted as jeopardizing survival or recovery). Estimates of allowable chronic harm and transient harm are provided. Chronic harm refers to a permanent negative alteration to vital rate(s) (including repeated yearly perturbations) while transient harm refers to a one time (temporary) mortality event affecting one or more life stage.

Recovery effort (ψ_v) and allowable chronic harm (τ_v) were estimated analytically as:

$$\psi_v \ or \ \tau_v = \left(\frac{1}{\varepsilon_v}\right)\left(\frac{\lambda_T-\lambda}{\lambda}\right) \qquad (14)$$

where ε_v is the elasticity of vital rate *v,* λ is the current population growth rate, and λ_T is the target population growth rate. If the recovery effort or harm impacts more than one vital rate it is calculated by summing the elasticity values (ε_v) of each vital rate before inclusion in Equation 14.

The effects of transient harm were modelled as follows:

(i) annual projection matrices were generated for three generations (~8 years) by randomly drawing vital rates as in the sensitivity analysis;
(ii) survival of one or all stages was reduced in the first random matrix, simulating a one-time removal of individuals;
(iii) the average population growth rates with and without 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 resulting from removal; and
(v) rates of removal (number of individuals as a proportion of total abundance) from 0.01 to 0.99 (all individuals) with increments of 0.02 were considered.

Allowable transient harm was defined as a one-time removal of individuals within a time-frame of 3 generations 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: Minimum Viable Population (MVP)

Demographic sustainability was used to identify potential recovery targets for Redside Dace using the single population (Equation 2) and meta-population (Equation 6) models with multiple catastrophe scenarios. 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 (> 35 generations for Redside Dace).

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, adult mortality (*M*, affecting the entire mortality schedule (Equation 11)) was optimized to achieve a geometric mean growth rate (in stochastic simulations) of λ = 1, resulting in *M* = 1.072.

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 λ = 1;

(ii) Individual simulations were conducted by randomly drawing projection matrices and projecting the population with various initial adult densities over 100 years with impacts from random catastrophes;

(iii) Catastrophes were simulated based on a pre-defined probability of occurrence and resulted in a 50% decline to total population abundance;

(iv) Simulations were repeated 500 times and the number of extinctions (when the adult population dropped below a given threshold) were counted;

(v) This process was repeated 10 independent times and these realizations were used to fit a model predicting extinction probability;

(vi) Simulations were replicated using a factorial design with a probability of catastrophe of 0.10 or 0.15/generation and with quasi-extinction thresholds of 2 or 50 adults;

From these simulations, the minimum number of adults necessary for the desired probability of persistence (see Results) over 100 years (MVP) was calculated.

MVP estimates were made using the single population structure (Equation 2) as well as the meta-population structure (Equation 6) with multiple (3) catastrophe scenarios. The single population model assumes the entire population is affected simultaneously when a catastrophe occurs. Use of a meta-population structure allows for other assumptions to be explored. Simulations incorporated three meta-population catastrophe scenarios:

i) Linked catastrophes: each sub-population is affected by a catastrophe simultaneously. This should produce similar results to the single population model.

ii) Rescue catastrophe: One sub-population (patch 2) is affected by catastrophes independently while the other three (patches 1, 3 and 4) are affected by catastrophe simultaneously. Patch 2 was chosen as the rescue sub-population arbitrarily.

iii) Independent catastrophe: each sub-population is affected by independent catastrophes.

Independent simulations and MVP values were calculated for each of the four catastrophe scenarios describe above.

Table 2. Stable stage distributions of the age-structured single and meta-population matrix models for Redside Dace. The meta-population values are separated by patch (sub-population). Summing the patch-specific values within an age will total the single population value.

Age	Single population	Meta-population			
		Patch 1	Patch 2	Patch 3	Patch 4
0	0.9750	0.1876	0.2520	0.1282	0.4072
1	0.0200	0.0039	0.0052	0.0026	0.0084
2	0.0037	0.0007	0.0010	0.0005	0.0015
3	0.0010	0.0002	0.0003	0.0001	0.0004
4	0.0003	0.00006	0.00007	0.00004	0.0001

Critical Habitat: Minimum Area for Population Viability (MAPV)

Following Velez-Espino et al. (2010) and Young and Koops (2014), the minimum area for population viability (MAPV) was estimated as a first order quantification of the amount of habitat required to support a viable population. MAPV represents the total area requirement of a population assuming independent stage-specific habitat use (e.g., YOY habitat is entirely separate from adult habitat), and calculated as:

$$MAPV = \sum_{t=0}^{t_{max}} MVP_t \cdot API_t, \quad (15)$$

where MVP_t is the age-specific minimum number of individuals required to achieve the desired probability of persistence over 100 years, as estimated for the recovery target; and API_t is the area required per individual of age-*t*. Individuals were distributed among age classes according to the stable stage distribution, which is represented by the dominant right eigenvector (*w*) of the mean projection matrix based on the $\lambda = 1$ ($\boldsymbol{A}w = \lambda w$) (de Kroon et al. 1986, Table 2). API_t was estimated from an allometric relationship with length (Equation 7), in mm, based on fish community densities (Randall et al. 1995, Minns 2003):

$$API_t = e^{a_{api}} \cdot {L_t}^{b_{api}}, \quad (16)$$

with a_{api} = -13.28 and b_{api} = 2.904. MAPV values using these parameters provide estimates of Redside Dace exclusive habitat requirements. In natural environments, interactions with other species will result in increased spatial requirements per individual fish. Density measurements for Redside Dace were available from 7 tributaries in southern Ontario (n = 40, Poesch unpublished data). The density data were assumed to represent only adult fish and estimates of the average and minimum species-specific adult Redside Dace APIs were made. Average adult API was estimated using the median values of the samples and minimum API was estimated using the 5th percentile of the values. APIs of YOY and juvenile Redside Dace were made by augmenting the API allometry by assuming the same slope (b_{api}) but altering the intercept (a_{api}) based on adult APIs and the geometric mean adult length. This resulted in a_{api} values of -11.42 and -12.68 for the minimum and median API relationships respectively.

Space requirements of an age class can increase or decrease throughout the year depending on the age-specific mortality and growth schedules. The required space for a given cohort can be described as a function of age by combining Equations 7, 11, 15, and 16 as follows:

$$MAPV_t = MVP_t \left(\frac{L_t e^{-Kt}}{L_{t+1}}\right)^{m_0/KL_\infty} e^{a_{api}} {L_t}^{b_{api}}. \quad (17)$$

By taking the derivative of this function the age at which space requirements of a cohort are maximal (t_{area}) can be estimated (Young and Koops 2014):

$$t_{area} = t_0 - \frac{1}{K} log_e \frac{m_0}{b_{api} K L_\infty}. \quad (18)$$

The required space by a cohort increased until age t_{area} and decreased afterwards. To ensure sufficient space for growth of an age-class the length (L_t) and density (MVP_t) values used to estimate MAPV incorporate t_{area}. When $t < t_{area}$ values reflect the end of the age class, when $t > t_{area}$ values reflect the start of the age class, and when t_{area} falls within age class *t* area usage is estimates at t_{area}. This is accomplished by accounting for survival from *t* to t_{area} in the MVP_t value incorporated.

RECOVERY STRATEGIES AND TIMES

The effects of three hypothetical recovery scenarios were compared using the single and meta-population catastrophe scenarios with improvements to YOY survival (σ_0), adult survival (σ_2 and σ_3) and survival of all ages ($\sigma_0, \sigma_1, \sigma_2,$ and σ_3). As Redside Dace are considered Endangered an initial population growth rate < 1 (λ_{min} = 0.89) was assumed, reflecting the presumed rate of population decline at time of COSEWIC assessment. Each survival type was improved by a proportion that allowed for positive population growth. Within independent simulations, YOY survival was improved by 75%, adult survival was improved by 75%, and survival of all age classes was improved by 25%, resulting in average population growth rates of 1.08, 1.06, and 1.10 respectively.

Simulations were conducted similarly to MVP simulations. Random matrices were generated using the improved vital rates as mean values and the previously specified variance and distributional assumptions. An initial abundance was chosen and populations were simulated over 100 years with the impacts of catastrophes incorporated at a rate of 0.10 and 0.15/generation. Simulations were repeated 500 times with the whole process replicated 10 times. The number of successful recoveries after each time step were counted with a recovery defined as a population ≥ MVP. The results were fit using logistic regression to predict the probability of recovery over time.

The initial abundance was chosen based on estimated tributary-specific abundances in southern Ontario (Poos et al. 2012). As a conservative estimate the lower confidence interval of abundance estimates were used with a low proportion of optimal habitat assumed. This gave a geometric mean of 737 adults which was used as the initial abundance in simulations.

RESULTS

SENSITIVITY ANALYSIS

Redside Dace population growth rate was primarily sensitive to the survival rate of immature age classes. Sensitivities for YOY and age-1 survival were equal (Table 3, Figure 10). The sensitivity of λ to both survival and fecundity declined with age. The extent of this decline, however, was dependent on the value of λ with populations that had greater λs more sensitive to perturbations of vital rates of younger age classes and less sensitive to that of older age classes.

Table 3. Summary of the stochastic sensitivity analysis of Redside Dace population growth rate (λ) to perturbation of stage-specific (YOY (y), juvenile (j), and adult (a)) vital rates (survival (σ) and fecundity (ƒ; sum of f_t values in Figure 10)). The results are reported as elasticity (ε_v) values (mean, lower and upper confidence intervals (LCI and UCI) and were estimated for various values of λ.

Population Growth Rate (*λ*)		**Estimate**	**Elasticity**			
			σ_y	σ_j	σ_a	f
Minimum	0.886	Mean	0.352	0.352	0.295	0.346
		LCI	0.316	0.316	0.247	0.300
		UCI	0.399	0.399	0.336	0.408
Equilibrium	1	Mean	0.356	0.356	0.287	0.351
		LCI	0.319	0.319	0.242	0.206
		UCI	0.400	0.400	0.328	0.410
Mean	1.191	Mean	0.363	0.363	0.273	0.359
		LCI	0.328	0.328	0.230	0.315
		UCI	0.405	0.405	0.312	0.415
Estimated	1.464	Mean	0.372	0.372	0.257	0.368
		LCI	0.338	0.338	0.218	0.326
		UCI	0.410	0.410	0.294	0.419
Maximum	1.907	Mean	0.382	0.382	0.235	0.380
		LCI	0.350	0.350	0.200	0.339
		UCI	0.417	0.417	0.271	0.428

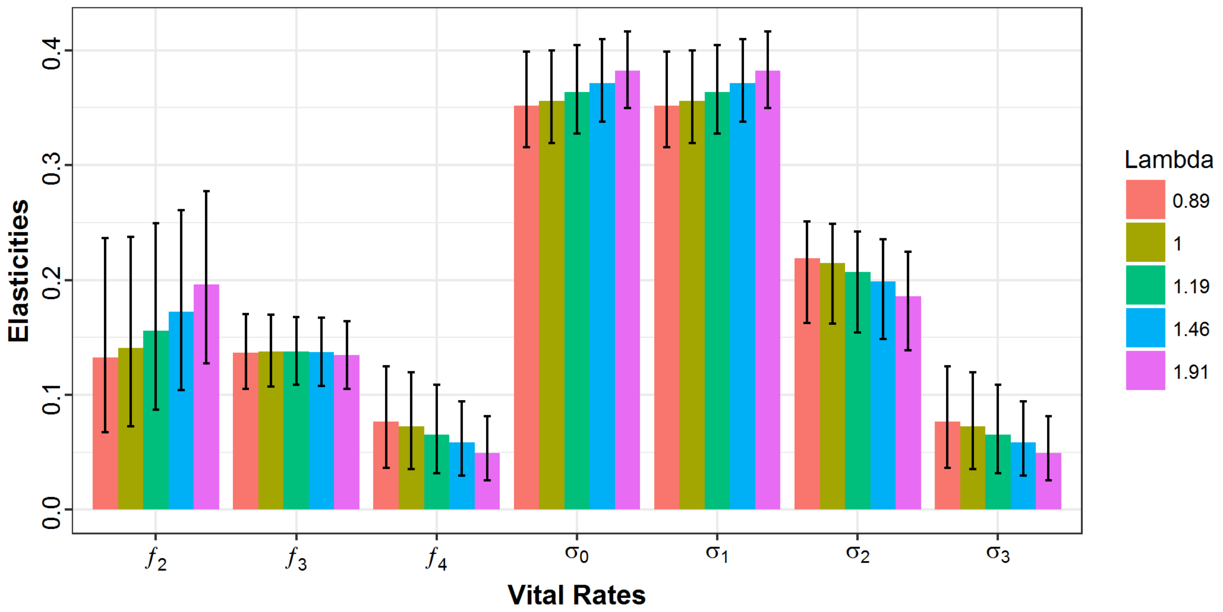

Figure 10. Results of the stochastic sensitivity analysis of Redside Dace population growth rate (λ) to perturbation of age-specific vital rates (survival (σ) and fecundity (ƒ)). The results are reported as elasticities (ε_v; mean, upper and lower confidence intervals) and were estimated for various values of λ, representing minimum, equilibrium, mean, estimated, and maximum λ respectively.

RECOVERY EFFORT AND ALLOWABLE HARM

Recovery effort and allowable chronic harm

Recovery effort and allowable chronic harm estimates (Table 4) were based on the lower and upper confidence intervals of stage-specific elasticity values from stochastic sensitivity analysis respectively, following a precautionary approach. Values represent the proportional change to vital rates that would result in λ = 1. This provided an estimate of the recovery effort (i.e., increase in survival or fertility) needed to build a stable population from the rate of decline at time of COSEWIC assessment (i.e., λ = 0.89), as well as the estimated allowable harm (i.e., decreases in survival and fertility) that could be applied to a growing population (i.e., λ = 1.19, 1.46, 1.91) and result in λ = 1. Allowable harm values below -1 indicate a lack of significant impacts of harm to that vital rate if all others are held constant for a given level of population growth. Values of allowable chronic harm are presented for 3 values of population growth (λ = 1.19, 1.47, and 1.91); however, over the long term, large population growth rates are unlikely to be maintained by a population in a natural environment and, as a result, the harm values are likely unrepresentative of natural populations.

A declining population (λ = 0.89) required considerable improvement to individual vital rates (> 40%) to cease the population decline. If, however, survival of all age-classes could be augmented simultaneously an improvement of only 13% was required.

The level of allowable chronic harm to a population depended on the assumed population growth rate; however, the trends among stages were similar. The adult population was the least susceptible to harm while the other stages (YOY and juvenile survival and fecundity) were similarly affected by harm. Assuming the estimate of mean population growth rate (λ = 1.19) is the most reasonable representation of long term growth, allowable harm affecting survival of all age-classes could be only as high as 15%.

Table 4. Summary of recovery effort and allowable chronic harm estimates of individual vital rates for Redside Dace. Recovery effort applies to populations with population growth rates below 1 and allowable harm applies to populations with population growth rates above 1. Values were estimated using the lower (recovery effort) or upper (allowable chronic harm) confidence intervals of vital rate elasticities (Table 3).

Population Growth Rate (λ)	**Vital Rate**				
	σ_y	σ_j	σ_a	σ	f
Recovery Effort					
0.886	0.406	0.406	0.518	0.134	0.426
Allowable harm					
1.191	-0.397	-0.397	-0.515	-0.154	-0.387
1.464	-0.773	-0.773	-1.079	-0.305	-0.756
1.907	< -1	< -1	< -1	-0.460	< -1

To further examine the effects on harm simulations of Redside Dace populations under varying levels of harm were conducted. Various levels of harm (deaths per 100 individuals per year) to specific life stages (YOY, age-1+, and all age-class) were applied to a Redside Dace population with a initial mean λ of 1.19 and the probability of population decline (λ < 1) on an annual (1 year), 10-year, and 100-years basis was estimated. The harm applied ranged from 1 to 99 deaths per 100 individuals. The harm implemented in simulations was in addition to the mean natural mortality rates of an unharmed population and did not take into account density dependence. Therefore estimates likely represent ‘worst case’ scenarios in the absence of compensatory processes. This may be of particular importance in relation to harm to YOY individuals.

50,000 stochastic projection matrices were generated in the same manner as in the sensitivity analysis. The λ of each projection matrix was estimated and the geometric mean λ over 10 year (5,000 replicates) and 100 year (500 replicates) time frames calculated. The proportion of λs < 1 provides an estimate of the probability of population decline over each time frame under various types and levels of harm to the population for the given amount of variability incorporated in the simulation at the initial λ value.

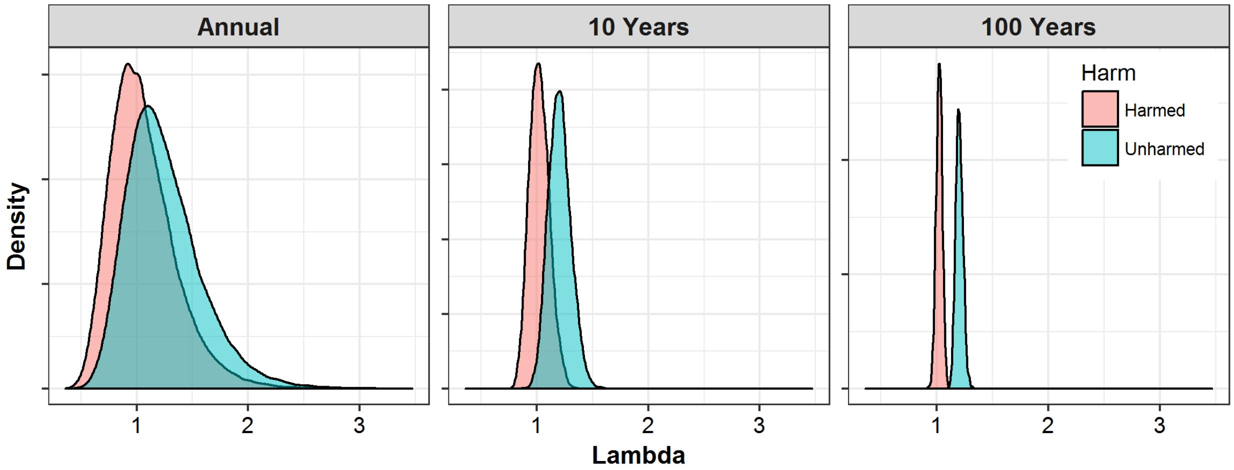

Figure 11. Probability distributions of λ over three times frames (annual, 10 years, and 100 years) for an unharmed (average λ = 1.19) and harmed (maximum allowable harm; average λ ≈ 1.02) Redside Dace population.

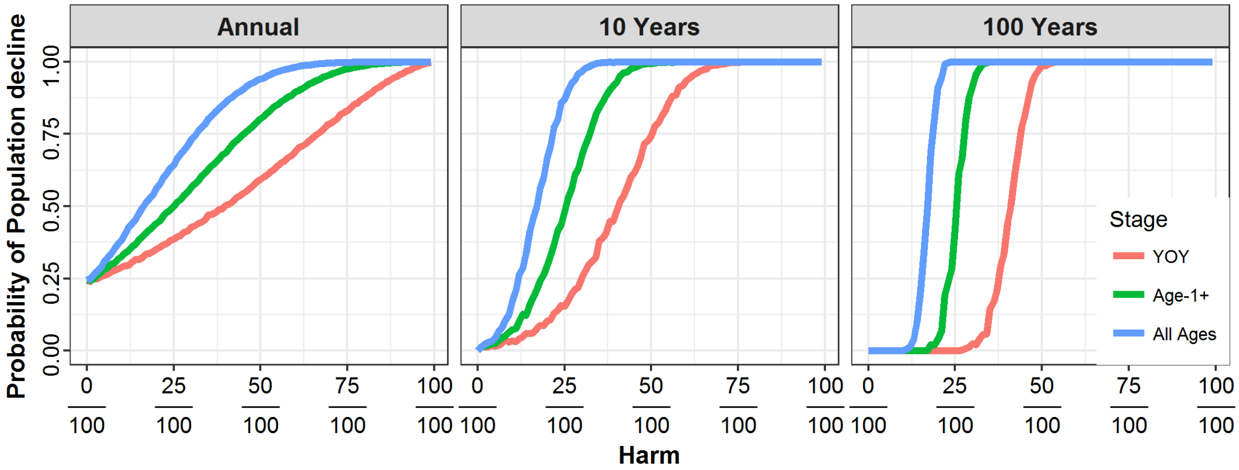

Figure 12. The probability of Redside Dace population decline (λ < 1) after experiencing increasing levels of harm (deaths per 100 individuals per year) to YOY, age-1+ and all age-classes over three timeframes.

Comparing the probability distributions of λ for each time frame (Figure 11) for an unharmed population (λ = 1.19) and a population experiencing maximum allowable chronic harm (Table 4) demonstrates the change in λ associated with harm relative to the length of time over which the effects of harm are measured. The probability of observing a population decline of an unharmed population over 1, 10, and 100 years was 24, 0.1 and 0%, given a starting population growth rate λ = 1.19. At allowable harm (~15 deaths per 100 fish) there was a 48% probability of population decline each year. Over 10 years the probability of decline decreased to 41% and over 100 years was 21%.

The probability of population decline, to various life stages (YOY, age-1+, and all age-class), increases with the level of harm (Figure 12). From Figure 12 the risk (in the form of probability of decline) associated with rates of fish death can be determined on an annual, 10 year and 100 year time frame. The rate of increase in the likelihood of decline depends on the timeframe over which λ is measured; more slowly on an annual basis and sharply over 100 years. This indicates that with extended periods of chronic harm (i.e., 100 years) with rather small increases in harm, the risk to population recovery increases greatly. Over 10 years, the probability of population decline exceeded 50% following 18 deaths per 100 individuals per year of all age classes, 26 deaths per 100 individuals of age classes 1+, and 41 deaths per 100 individuals of YOY Redside Dace. These values reached 100% following proportional deaths of 35, 53, and 73 per 100 individuals respectively.

Transient allowable harm

Allowable transient harm (allowable one time removal, performed no more frequently than once every 3 generations) can be extracted from Figure 13 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). Allowable transient harm may differ depending on the population growth rate; a growing population will be able to sustain a larger removal without going into decline than a stable population. 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. Absolute numbers of individuals can also be calculated deterministically (i.e., ignoring environmental variation) given the population abundance (N_0), acceptable change in mean population growth rate (Δλ), and the survival rate of age class t (σ_t).

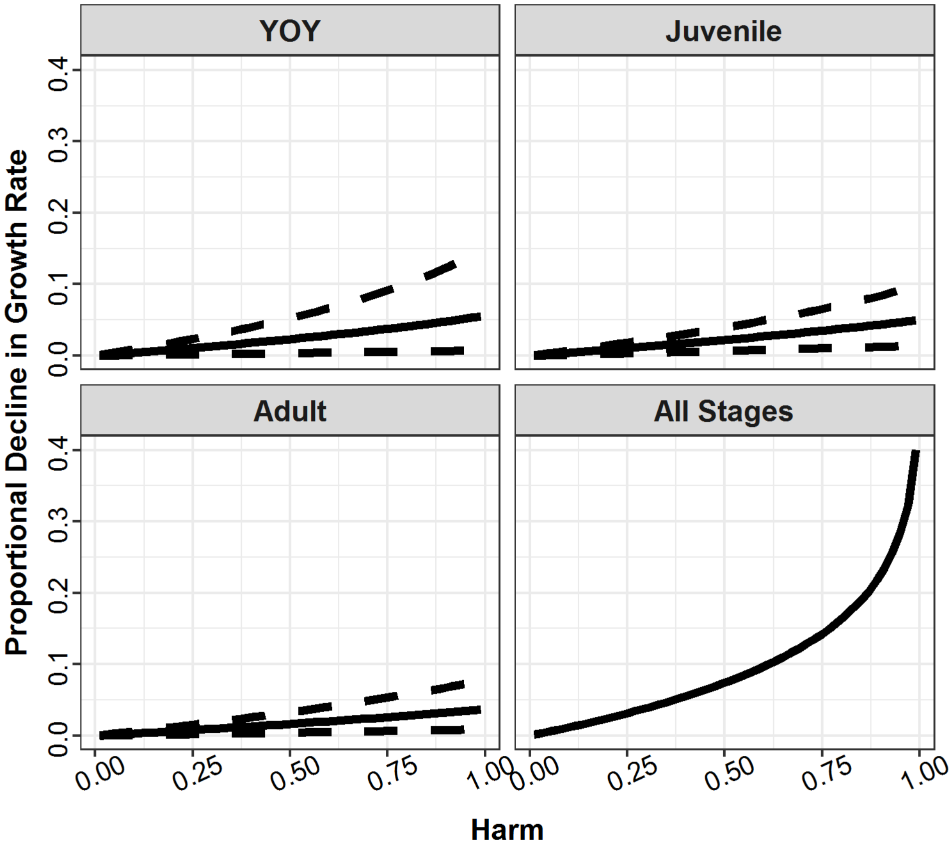

Figure 13. The proportional decline in population growth rate due to transient harm (simulated as a one-time removal of individuals) impacting specified stage(s). The solid line represents mean impacts and the dashed lines represent 95% confidence intervals. Simulations were conducted with an initial λ of 1.19.

RECOVERY TARGETS

Abundance: Minimum Viable Population (MVP)

The probability of extinction (*P[ext.]*) decreases as a power function of adult population size (N_a) (Figure 14). Functions of the form: $P[ext.] = a_{MVP}{N_a}^{b_{MVP}}$, were fitted using non-linear least squares to the predict extinction probabilities for each combination of quasi-extinction thresholds, catastrophe rate, and catastrophe scenario (Table 5). These equations can be rearranged and used to estimate minimum recovery targets for a desired probability of persistence over 100 years given the pre-defined population, catastrophe and extinction criteria. In choosing recovery targets, the risks associated with extinction probability must be balanced with the costs associated with an increased target (increased recovery effort, longer time to recovery, etc.). Recovery target values, for all simulated scenarios, are presented for a 5% and 1% risk of extinction (Table 6, Appendix 1); however, additional targets can be estimated for other extinction risks with use of the functional relationships (Table 5) and stable stage distribution (Table 2). MVP estimates increased greatly with greater quasi-extinction thresholds, greater catastrophe rates, and lower extinction probability (Appendix 1). The more conservative approach would utilize a quasi-extinction threshold of 50 adults, catastrophe probability of 0.15/generation and extinction probability of 1% (Table 6). This conservative approach allows for a more reasonable definition of population extinction, a catastrophe rate in line with other vertebrates, and conservative extinction probability.

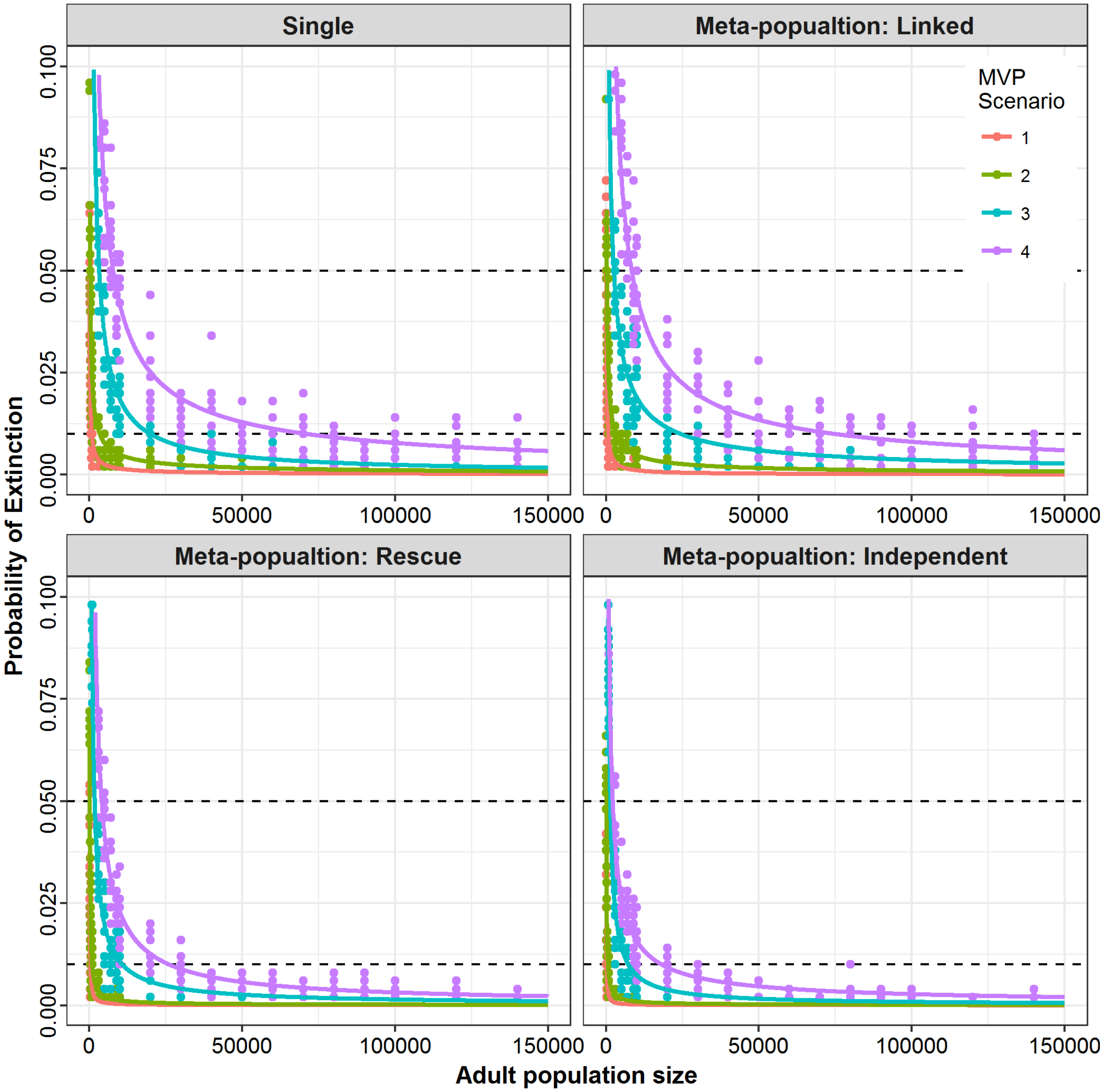

Figure 14. The probability of population extinction from recovery target simulations. Simulations were run for four catastrophe scenarios and four MVP scenarios. The catastrophe scenarios were a single population model (Single) and three a meta-population models with catastrophes acting on all sub-populations simultaneously (Linked), catastrophes affecting one sub-population independently (Rescue), and catastrophes affecting each sub-population independently (Independent). The MVP scenarios considered the probability of catastrophe per generation and quasi-extinction threshold: 1 – 0.10 and 2 adults; 2 – 0.15 and 2 adults; 3 – 0.1 and 50 adults; and 4 – 0.15 and 50 adults.

Population structure and the catastrophe scenario simulated had an important influence on MVP estimates (Table 6). As expected, the single population model and the meta-population model with linked catastrophes produced similar recovery target estimates, with conservative MVP estimates of approximately 75,000 adults. This value decreased markedly when alternative catastrophe scenarios were incorporated. The Rescue scenario, where one sub-population (in this case patch 2) was subject to catastrophes independently while the other three patches experience catastrophes simultaneously, resulted in an MVP estimate of approximately 26,000 adults. The Independent scenario, where each patch was affected by catastrophes independently, had a considerably smaller MVP value of 18,000 adults. These catastrophe scenarios provided a representation of potential alternative scenarios to the single population dynamics. These simulations are meant to provide insight into the potential importance of maintaining meta-population structure and the habitat complexity that allows for it, as well as the relative vulnerability of different population structures to catastrophic decline.

Table 5. Parameter values for the extinction probability relationships ($P[ext.] = a_{MVP} N_a{}^{b_{MVP}}$) used to estimate minimum viable population (MVP, Table 6, Appendix 1). Values are provided for various catastrophe scenarios: the single population model; a meta-population model with linked catastrophes; a meta-population with one rescue sub-population; and a meta-population model with independent catastrophes. Within the catastrophe scenarios, relationships were fit for simulation with quasi-extinction thresholds of 2 or 50 adults and probabilities of catastrophe of 0.10 and 0.15/generation.

Catastrophe Scenario	Catastrophe Rate	Extinction Threshold	α_{MVP}	β_{MVP}
Single population	0.10	2	1.538	-0.753
	0.15	2	2.081	-0.656
	0.10	50	64.097	-0.885
	0.15	50	34.234	-0.729
Meta-population: Linked	0.10	2	3.014	-0.860
	0.15	2	2.207	-0.666
	0.10	50	14.048	-0.717
	0.15	50	39.448	-0.738
Meta-population: Rescue	0.10	2	4.301	-1.029
	0.15	2	4.323	-0.889
	0.10	50	35.303	-0.880
	0.15	50	65.436	-0.864
Meta-population: Independent	0.10	2	4.037	-1.081
	0.15	2	2.946	-0.875
	0.10	50	50.060	-0.957
	0.15	50	17.969	-0.764

Critical Habitat: Minimum Area for Population Viability (MAPV)

Estimates of required critical habitat (MAPV) assume independent habitat use by YOY, juvenile, and adult stages and account for the change in space requirements over the course of the year from the interactive effects of growth and mortality through estimates of t_{area} (Equation 18). The value of t_{area} was estimated to be 0.95 years of age (Figure 15). This represents the age of a cohort when space requirements is at its maximum. As a result, the stage-specific MAPV was made at the age of 0.95 years for YOY fish; at age 1 for juvenile fish, and at ages 2, 3, and 4 summed for adult fish. MAPV was estimated by multiplying the age-specific MVP at the time of maximum space requirement for that age by the area-per-individual (API) at that time. Three estimates of API were used (Table 7). MAPV values were estimated for conservative MVP simulations (Table 8) and all other simulations (Appendix 2) using each API estimate. MAPV estimates assuming a catastrophe rate of 0.15/generation and a quasi-extinction threshold of 50 adults depended on the simulated catastrophe scenario and API estimate and ranged from 1.7 to 46.3 ha. Smaller MAPV estimates were estimated using API values generated using the Minns (2003) allometry, which is a generic relationship from the literature based on measurements of fish assemblage densities. These values would therefore be representative of Redside Dace exclusive habitat and not account for competition for habitat with other species or life stages. The other API relationships were based on measured Redside Dace densities and may be a better reflection of required habitat of a Redside Dace population within a species assemblage. However, as the populations of Redside Dace are expected to be in decline, their densities maybe lower than that of a stable or growing population, resulting in overestimates of API for a recovering population. Values, therefore, are presented using the median and 5th percentile of estimated APIs to provide a more conservative habitat requirement estimate (these estimates are inclusive of the larger species assemblage). As well, the density observations, although measured in several southern Ontario tributaries, were made over the course of a single year and do not account for the potential of inter-annual variation in population size and habitat requirements.

Table 6. Estimates of the stage-specific minimum viable population (MVP) for Redside Dace for two probabilities of extinction (P[ext.]).Values are provided for various catastrophe scenarios: the single population model; a meta-population model with linked catastrophes; a meta-population with one rescue sub-population; and a meta-population model with independent catastrophes. Results are presented with MVP simulation scenarios using a quasi-extinction threshold of 50 adults and a catastrophe probability of 0.15/generation. Results from other MVP simulation scenarios are presented in the Appendix 1 (Table A1.1)

Catastrophe Scenario	**Stage**	**MVP**	
		***P[ext]* = 5%**	***P[ext]* = 1%**
Single population	YOY	1,992,413	18,142,236
	Juvenile	32,294	294,058
	Adult	7,791	70,943
Meta-population: Linked	YOY	2,156,758	19,099,783
	Juvenile	34,958	309,578
	Adult	8,434	74,687
Meta-population: Rescue	YOY	1,036,993	6,681,718
	Juvenile	16,808	108,300
	Adult	4,055	26,128
Meta-population: Independent	YOY	566,769	4,660,889
	Juvenile	9,186	75,546
	Adult	2,216	18,226

RECOVERY STRATEGIES AND TIMES

Simulations were conducted to investigate the probability of recovery of a population over time and estimated the time required for a likely recovery to occur under three recovery strategy scenarios: a 75% improvement to YOY survival; a 75% improvement to adult survival; and a 25% improvement to survival of all age-classes. Simulations began with a population size of 737 adults and populations were deemed to be recovered when the population size reached MVP. Simulations were run for all MVP and catastrophe (meta-population) scenarios (Appendix 3) and the number of successful recoveries over time were fit as a logistic regression using the relationship: $P[rec.] = \frac{1}{1+e^{-(a_{rec}+b_{rec}\log_e(year))}}$, where *P[rec.]* is the probability of recovery (Figure 16). This relationship was rearranged and used to predict time to a 95% probability of recovery (Table 9).

Table 7. Area per individual (API) values (m^2) used to estimate minimum area for population viability (MAPV). Values within each stage are provided at the age in which MAPV is the greatest.

Stage	Age	Fish Length	API Relationship		
			Minns	Minimum	Median
YOY	0.95	38.8	0.070	0.128	0.450
Juvenile	1	40.1	0.077	0.141	0.495
	2	61.4	0.266	0.486	1.701
Adult	3	74.5	0.467	0.854	2.990
	4	82.7	0.631	1.154	4.041

The relative success of each recovery strategy was related to the average population growth rate that resulted from the strategy. Improving survival of all age-classes resulted in the most rapid recovery (λ = 1.10), followed by improving YOY survival (λ = 1.08), with improving adult survival the slowest (λ = 1.06). Recovery was generally slow and time to recovery increased as the recovery target increased. The minimum time to recovery with a catastrophe rate of 0.15/generation, quasi-extinction threshold of 50 adults and a probability of persistence of 1% was 48.1 years for a meta-population with independent catastrophes; if catastrophes affecting sub-populations were linked this value increased to 73.1 years.

Figure 15. Relative habitat area occupied by a cohort over time. The vertical dashed lines indicate the age of maximal area usage for each age class.

DISCUSSION

ELEMENTS

Element 3: Estimate the current or recent life-history parameters for Redside Dace

The best available data were assembled to provide life-history parameters for Redside Dace. The value for each life-history parameter used in recovery modelling is presented in Table 1. Details regarding how the parameters were estimated and source data used are outlined in the Methods section of this report.

Table 8. Stage-specific minimum area for population viability (MAPV) estimates (ha) for Redside Dace with a probability of extinction (P[ext.]) of 1%. MAPV was estimated using three estimates of area pre individual (API): using an allometry from the literature (Minns 2003), using a low (5th percentile), and median estimate from Redside Dace densities (Table 7). Values are provided for various catastrophe scenarios: the single population model; a meta-population model with linked catastrophes; a meta-population with one rescue sub-population; and a meta-population model with independent catastrophes. Results are presented with MVP simulation scenarios using a quasi-extinction threshold of 50 adults and a catastrophe probability of 0.15/generation. Results from other MVP simulation scenarios and quasi-extinction thresholds are presented in the Appendix 2 (Table A2.1)

Catastrophe Scenario	Stage	MAPV		
		Minns API	Minimum API	Median API
Single Population	YOY	2.164	3.955	13.852
	Juvenile	2.162	3.950	13.837
	Adult	2.544	4.649	16.285
	Total	6.871	12.555	43.975
Meta-Population: Linked	YOY	2.279	4.164	14.583
	Juvenile	2.276	4.159	14.567
	Adult	2.679	4.895	17.145
	Total	7.233	13.217	46.296
Meta-population: Rescue	YOY	0.797	1.457	5.102
	Juvenile	0.796	1.455	5.096
	Adult	0.937	1.712	5.998
	Total	2.530	4.624	16.196
Meta-population: Independent	YOY	0.556	1.016	3.559
	Juvenile	0.555	1.015	3.555
	Adult	0.654	1.194	4.184
	Total	1.765	3.225	11.297

Element 12: Propose candidate abundance and distribution target(s) for recovery

More conservative abundance targets based on minimum viable population (MVP) analysis using a quasi-extinction threshold of 50 adults with a catastrophe probability of 0.15/generation and a probability of extinction of 1% over 100 years are recommended. MVP estimates are provided (Table 6) for four catastrophe scenarios, which depended on population structure (single population or meta-population) and how catastrophes impact sub-populations. These scenarios included the single population model (Single population); a meta-population model with catastrophes affecting each sub-population simultaneously (Linked Meta-population); a meta-population model with catastrophes affecting three sub-populations simultaneously and one independently (Rescue Meta-population); and a meta-population model with catastrophes affecting each sub-population independently (Independent Meta-population).

The Single population and Linked Meta-population scenarios resulted in similar MVP estimates of approximately 75,000 adults. Application of alternative catastrophe scenarios resulted in large reductions in MVP estimates. The Rescue Meta-population scenario gave an MVP estimate of 26,000 adults and the Independent Meta-population scenario resulted in an MVP estimate of 18,000. These catastrophe scenarios are meant as representations of potential alternative scenarios to the single population dynamics and may not be directly representative of Redside Dace populations in Canada. Instead these simulations are intended to provide insight into the potential importance of maintaining meta-population structure and the habitat complexity that allows for it. As well, the estimates of MVP of a meta-population will likely be sensitive to the number of sub-populations included in the simulation, and in the Rescue scenario, MVP estimates will likely be sensitive to the choice of independent patch and movement probabilities among patches.

Table 9. Time required (in years) for a population to have a 95% probability of reaching recovery targets (MVP; Table 6) given an initial population growth rate of 0.89 for three recovery strategies. The recovery strategies investigated were: increasing YOY survival by 75%; increasing adult survival by 75%; and increasing survival of all age classes by 25%. Values were estimated from probability of recovery relationships (Appendix 3). Results are presented with MVP simulation scenarios using a quasi-extinction threshold of 50 adults and a catastrophe probability of 0.15/generation.

Catastrophe Scenario	**Strategy**	**Years to Recovery**	
		***P[ext.]* = 5%**	***P[ext.]* = 1%**
Single population	YOY	65.7	97.0
	Adult	82.3	118.8
	All	46.8	71.1
Meta-population: Linked	YOY	68.6	100.2
	Adult	84.7	120.3
	All	48.4	73.1
Meta-population: Rescue	YOY	48.9	74.0
	Adult	59.2	89.2
	All	35.1	54.8
Meta-population: Independent	YOY	35.2	63.2
	Adult	43.4	78.6
	All	25.9	48.1

The previous recovery potential assessment of Redside Dace (Vélez-Espino and Koops 2008) provided an MVP estimate of 4,711 adults. This value was estimated with a predictive relationship from the literature (Reed et al. 2003b) based on MVP estimates of 102 vertebrate species with MVP defined as an 1% probability of extinction over 40 generations; however, only one fish species was included in the analysis. Vélez-Espino and Koops (2012) included Redside Dace in their assessment of MVP for freshwater fishes and estimated Redside Dace MVP at 24 614 for a 5% probability of extinction over 250 years (~83 generations). Updated estimates were based on species-specific simulation modelling with updated life history information and are likely a better representation of Redside Dace population dynamics.

The choice of recovery target is not limited to the scenarios presented here. Additional MVP estimates for alternative quasi-extinction thresholds and catastrophe probabilities are listed in Appendix 1 and estimates for additional persistence probabilities can be made using the parameters values listed in Table 5.

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

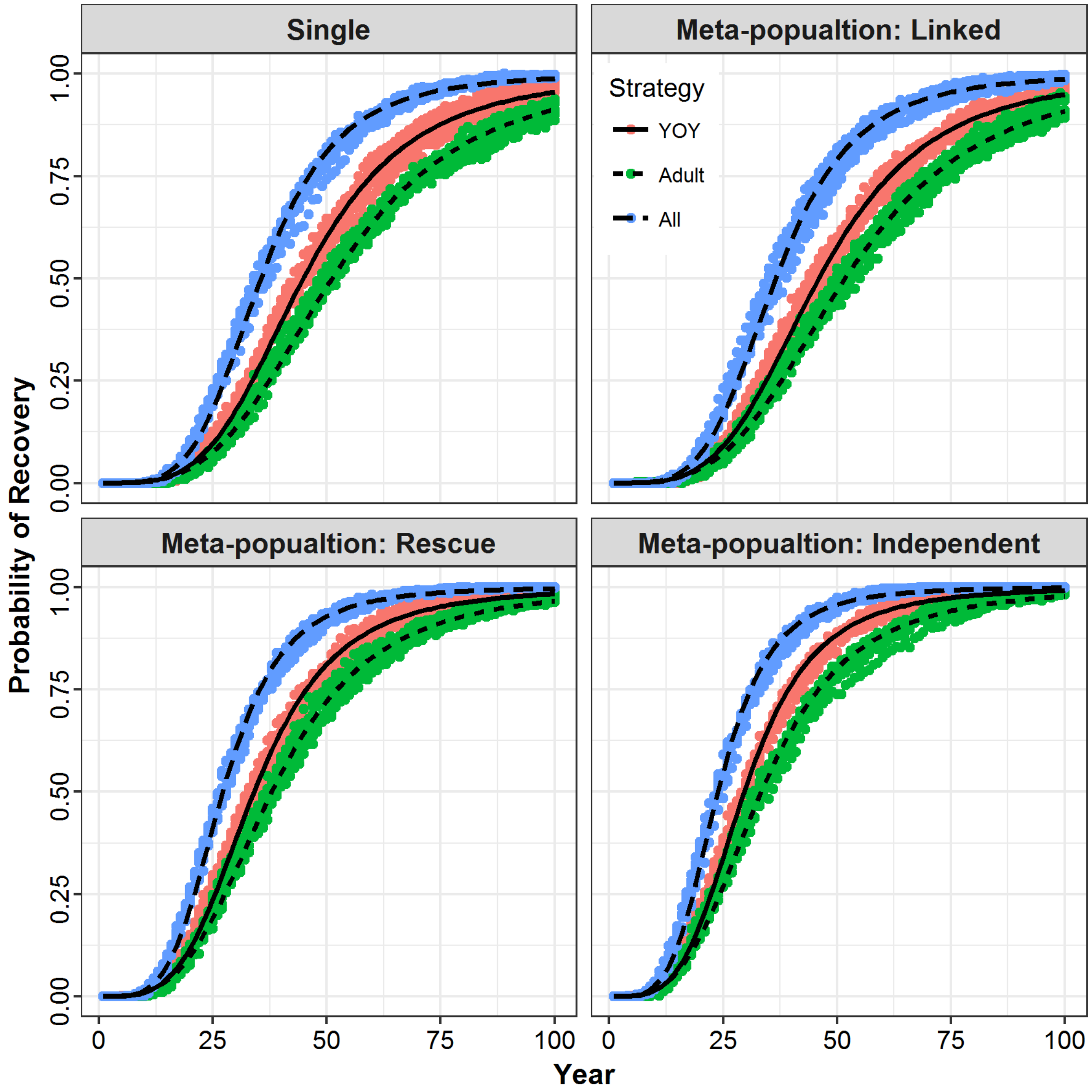

Figure 16. The probability of recovery through time for a Redside Dace population with an initial abundance of 737 adults with recovery defined as reaching MVP abundances (Table 6). Simulations were run with a catastrophe rate of 0.15/generation and an MVP target with a 1% probability of extinction and a 50 adult quasi-extinction threshold for each catastrophe scenario. The lines represented fitted relationships using logistic regression; logistic regression parameter values for all simulation scenarios are presented in Appendix 3.

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.

These MVP targets refer to adult numbers only. If juveniles are being included in abundance estimates, then the MVP must include these age classes as well.

Additionally, MVP estimates for Redside Dace were made using a post-breeding matrix model. This means that abundance estimates were made directly after spawning has occurred and before age-specific mortality has acted. Therefore abundance estimates from MVP analysis represent maximum annual abundances for a given population. When compared to field observations of abundance, sampling date relative to spawning date should be considered and the expected mortality over this time period accounted for.

Element 13: Project expected population trajectories over a scientifically reasonable time frame (minimum 10 years), and trajectories over to the potential recovery target(s), given current Redside Dace population dynamics parameters.

Current population trajectories of Redside Dace populations in Canada are unknown due to the lack of standardized monitoring data across the species range, which led to recovery potential being explored under a series of assumed scenarios of population decline and growth. In recovery projections, the assumption was made that initially populations may be in decline following the COSEWIC definition of an Endangered species: a decline in population size of 70% in the previous 10 years resulting in an estimated population growth rate of 0.89. Under this assumption populations will continue to decline and there will be no chance of recovery unless mitigation actions are taken. The same conclusion exists for any population growth rate < 1.

Element 14: Provide advice on the degree to which supply of suitable habitat meets the demands of the species both at present and when the species reaches the potential recovery target(s) identified in element 12.

Currently, Redside Dace populations appear to be at lower densities than the current supply of habitat could support (Poos et al. 2012); however, the extent of optimal habitat within the current Redside Dace distribution is unknown (Poos et al. 2012) and continued urbanization throughout southern Ontario will further degrade suitable Redside Dace habitat through several mechanisms (COSEWIC 2017).

The area required to support an MVP population size (MAPV) was calculated for each MVP and catastrophe scenario (Appendix 2) using three estimates of individual area requirements (API). The first API estimate, based on an allometry from the literature (Minns 2003), gives an estimate of Redside Dace exclusive habitat, and is consistent with previous RPA reports. The other estimates were based on distributions of Redside Dace area requirements (using density estimates) and provide the minimum (5th percentile) and median area requirements. As Redside Dace populations are expected to be at low abundance the median API estimate may overestimate the area requirements of a healthy population. These values, however, provide estimates of area requirements inclusive of entire species assemblage and may better reflect natural habitat requirements. The estimated MAPVs for Redside Dace using the minimum API estimate from Redside Dace densities assuming a 0.15/generation probability of catastrophe and a 50 adult quasi-extinction threshold were approximately 13 ha for the Single population and Linked Meta-population simulations and 4.6 ha and 3.2 ha for the Rescue and Independent Meta-population scenarios respectively. The previous Redside Dace RPA calculated an MAPV of 1.7 ha which was based on a smaller MVP and an API estimated using the Minns (2003) allometry (Vélez-Espino and Koops 2008).

Element 15: Assess the probability that the potential recovery target(s) can be achieved under the current rates of population dynamics, and how that probability would vary with different mortality (especially lower) and productivity (especially higher) parameters.

An initial population growth rate of 0.89 was assumed. Under this scenario population recovery would not be possible without efforts to improve Redside Dace survival or production. The effects of three recovery efforts to improve survival: a 75% increase to YOY survival; a 75% increase to adult (age 2 to 4) survival; and a 25% increase to survival of all age classes were simulated. These recovery efforts result in positive population growth with λ values of 1.08, 1.06, and 1.10 respectively. Stochastic simulations provide estimates of the probability of recovery over time, where recovery is defined as reaching MVP abundances, and allow for the estimation of the time required to reach a 95% probability of recovery. Recovery times can be estimated for all MVP and catastrophe scenarios from the parameters values in Appendix 3. Estimates of recovery times were made for simulations with a probability of catastrophe of 0.15/generation and a quasi-extinction threshold of 50 adults (Table 9). The quickest recoveries occurred after improving survival of all age-classes with recovery times ranging from 48.1 to 73.1 years. These values were the result of fairly modest average population growth rate values for a species of this size (Randall and Minns 2000). Maximum population growth rate was estimated conservatively, using the lower prediction interval of an allometry (Randall and Minns 2000), giving a value of 1.91. While population growth would not be expected to consistently be this high as densities increase, rates greater than 1.19 could be expected, leading to more rapid recovery times.

Element 19: Estimate the reduction in mortality rate expected by each of the mitigation measures or alternatives in element 16 and the increase in productivity or survivorship associated with each measure in element 17.

No clear links have been identified between mitigation measures and Redside Dace mortality rates or productivity. Therefore, it is difficult to provide guidance about the effect of mitigation measures on mortality rates or productivity.

Element 20: Project expected population trajectory (and uncertainties) over a scientifically reasonable time frame and to the time of reaching recovery targets, given mortality rates and productivities associated with the specific measures identified for exploration in element 19. Include those that provide as high a probability of survivorship and recovery as possible for biologically realistic parameter values.

Without a direct link between mitigation measures and Redside Dace mortality rates or productivity, this information this information cannot be provided.

Element 21: Recommend parameter values for population productivity and starting mortality rates and, where necessary, specialized features of population models that would be required to allow exploration of additional scenarios as part of the assessment of economic, social, and cultural impacts in support of the listing process.

The parameter values presented in Table 1 are based on the best available data for this population and should be used for any future population modelling.

Element 22: Evaluate maximum human-induced mortality and habitat destruction that the species can sustain without jeopardizing its survival or recovery.

The assessment of allowable harm requires knowledge of population growth rate for Redside Dace in Canada. Due to the lack of standardized population monitoring data across the species range, population growth rates of Redside Dace are largely unknown, though COSEWIC assessment criterion (and empirical field observations) indicate evidence for population decline. If current population growth rate is 0.89, there is no scope for allowable harm, as any human-induced mortality or habitat destruction would jeopardize survival or recovery. However, allowable harm analysis was conducted assuming average population growth rates of 1.19, 1.47 and 1.91, to illustrate allowable harm under different projections of population growth, as expected following the implementation of recovery measures.

Redside Dace populations were most sensitive to perturbations of pre-adult survival and fecundity, which is consistent with previous modelling on the sensitivity of fish populations to vital rate perturbations (van der Lee and Koops 2016). As a result, human-induced harm to pre-adult stages and during spawning should be minimized. If a population was growing with a λ of 1.19, reducing YOY or juvenile survival by ≥ 39.7% or fecundity by 38.7% would jeopardize population recovery. If all age classes were affected by human-induced harm a reduction in survival of ≥15.4% would jeopardize recovery. If the population were growing at a slower rate allowable harm would be less.

Figure 12 allows for an estimation of risk associated with various levels of chronic harm (deaths per 100 individuals per year) to various life stages assuming a mean population growth rate of 1.19. As the level of harm increases the risk of observing population decline increased following a sigmoid relationship. It is important to note that the results presented in Figure 12 are specific to the unharmed population growth rate (λ = 1.19) and that the amount of risk of population decline for a given level of harm will increase with lower average λs.

Transient harm may be applied without jeopardizing survival or recovery, but only if the population is not in decline. A one-time removal of ~37.5% of the total population will result in a ~5% decline in population growth rate if the population is growing at λ = 1.19. The population would have a population decline, on average, if greater than ~85% of the population were removed. A lower average population growth rate would increase the impact of transient harm.

UNCERTAINTIES

Data related to Redside Dace life history and population dynamics were limited. Foremost, there was a lack of standardized information on Redside Dace population trends. As a result, all calculations where population growth rate was required (e.g., allowable harm, recovery times, etc.) were based on assumed population trends. More information relating to population trajectories at multiple sites, which would require long time series of population abundance, would help refine estimates of λ for use in estimation of allowable harm/recovery effort and expected recovery times/impacts of mitigation effort. There was also little empirical data related to important vital rates such as survival and fecundity. A single empirical estimate of adult mortality was available and may violate the assumptions of catch-curve analysis. As well, there were no empirical data about the survival of younger age classes. Instead an allometric relationship was used to estimate juvenile and YOY survival and it was assumed that adult mortality was constant. It is unknown how these assumptions might differ from extant Redside Dace populations in southern Ontario, and important to note that estimates of population growth rate were sensitive to perturbations of pre-adult survival rates. The fecundity values used in the analysis were based on a relationship developed from only a few (*n* = 13) observations of

Redside Dace fecundity. More data related to individual fecundity are required for greater confidence in these estimates.

Inter-annual variability in vital rates is also largely unknown. The variation in fecundity incorporated in stochastic simulations was based on half the residual standard error of the fecundity relationship, which was chosen to reflect a reasonable amount of variation. However, the residual standard error reflects the amount of variation among individual females which, although halved, may represent an overestimate of population-level inter-annual variability. As well, variability in survival rate was entirely unknown. A constant relationship between instantaneous mortality and its variation was assumed (Bradford 1992) through the use of a coefficient of variation of 0.2 applied to age-1+ mortality rates (Mertz and Meyers 1995). It is unknown how well this assumption approximates variation in Redside Dace mortality. The amount of variation incorporated into stochastic simulations can have a large impact on estimates of MVP (Vélez-Espino and Koops 2012). Increases in the standard deviation of fecundity tend to result in lower MVP estimates while increases in the standard deviation of survival can result in much larger MVP estimates (Vélez-Espino and Koops 2012). These assumptions should be considered when applying abundance targets based on MVP values with future estimates adjusted as more information on vital rate variability becomes available.

Finally, the frequency, spatial configuration, and impact of catastrophic events for Redside Dace are unknown and were assumed in this analysis. Simulations were conducted with two different frequencies (0.10 and 0.15/generation) and four impact scenarios depending on meta-population structure. The choice of catastrophe frequency and scenario had a large impact on MVP and recovery time estimates. Independent and Rescue scenarios, characterized by one or more sub-populations experiencing catastrophes independently, were more resilient relative to linked (simultaneous) catastrophes affecting on all sub-populations. These population structures, however, are contingent on the spatial structure allowing for the isolation of catastrophes and the existence of rescue sub-population(s). Typically, meta-populations experienced lower MVPs and quicker recovery times compared to single population scenarios. As little information exists on the extent of meta-population structure or synchrony of catastrophic events research that identifies the magnitude, frequency of these factors would greatly reduce uncertainty in estimates of MVP size, and is recommendation for the conservation of Redside Dace.

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APPENDIX 1

Table A1.1. Estimates of the stage-specific minimum viable population (MVP) for Redside Dace for two probabilities of extinction (P[ext.]).Values are provided for various catastrophe scenarios: the single population model; a meta-population model with linked catastrophes; a meta-population with one rescue sub-population; and a meta-population model with independent catastrophes. Within the catastrophe scenarios estimates were provided for simulation with quasi-extinction thresholds of 2 or 50 adults and probabilities of catastrophe of 0.10 and 0.15/generation

Catastrophe Scenario	**Catastrophe Rate**	**Extinction Threshold**	**Stage**	**MVP**	
				***P[ext.]* = 5%**	***P[ext.]* = 1%**
Single population	0.10	2	YOY	24,269	206,032
			Juvenile	393	3,339
			Adult	95	806
	0.15	2	YOY	75,111	872,917
			Juvenile	1,217	14,149
			Adult	294	3,413
	0.10	50	YOY	831,386	5,124,691
			Juvenile	13,475	83,063
			Adult	3,251	20,039
	0.15	50	YOY	1,992,413	18,142,236
			Juvenile	32,294	294,058
			Adult	7,791	70,943
Meta-population: Linked	0.10	2	YOY	30,071	195,469
			Juvenile	487	3,168
			Adult	118	764
	0.15	2	YOY	75,601	848,141
			Juvenile	1,225	13,747
			Adult	296	3,317
	0.10	50	YOY	663,602	6,258,536
			Juvenile	10,756	101,441
			Adult	2,595	24,473
	0.15	50	YOY	2,156,758	19,099,783
			Juvenile	34,958	309,578
			Adult	8,434	74,687
Meta-population: Rescue	0.10	2	YOY	19,373	92,523
			Juvenile	314	1,500
			Adult	76	362
	0.15	2	YOY	38,563	235,691
			Juvenile	625	3,820
			Adult	151	922
	0.10	50	YOY	443,376	2,763,555
			Juvenile	7,186	44,793
			Adult	1,734	10,807
	0.15	50	YOY	1,036,993	6,681,718
			Juvenile	16,808	108,300
			Adult	4,055	26,128

Catastrophe Scenario	Catastrophe Rate	Extinction Threshold	Stage	MVP	
				P[ext.] = 5%	*P[ext.]* = 1%
Meta-population: Independent	0.10	2	YOY	14,855	65,830
			Juvenile	241	1,067
			Adult	58	257
	0.15	2	YOY	26,992	169,888
			Juvenile	438	2,754
			Adult	106	664
	0.10	50	YOY	348,993	1,875,519
			Juvenile	5,657	30,399
			Adult	1,365	7,334
	0.15	50	YOY	566,769	4,660,889
			Juvenile	9,186	75,546
			Adult	2,216	18,226

APPENDIX 2

Table A2.1. Stage-specific minimum area for population viability (MAPV) estimates (ha) for Redside Dace for two probabilities of extinction (P[ext.]). MAPV was estimated using three estimates of area per individual (API): using an allometry from the literature (Minns 2003), using a low (5th percentile) estimate from Redside Dace observations, and using the median estimate from Redside Dace observations. Values are provided for various catastrophe scenarios: the single population model; a meta-population model with linked catastrophes; a meta-population with one rescue sub-population; and a meta-population model with independent catastrophes. Within the catastrophe scenarios estimates were provided for simulation with quasi-extinction thresholds of 2 or 50 adults and probabilities of catastrophe of 0.10 and 0.15/generation

				MAPV					
				Minns API		**Minimum API**		**Median API**	
Catastrophe Scenario	**Catastrophe Rate**	**Extinction Threshold**	**Stage**	***P[ext.]*** **= 5%**	***P[ext.]*** **= 1%**	***P[ext.]*** **= 5%**	***P[ext.]*** **= 1%**	***P[ext.]*** **= 5%**	***P[ext.]*** **= 1%**
Single Population	0.10	2	YOY	0.003	0.025	0.005	0.045	0.019	0.157
			Juvenile	0.003	0.025	0.005	0.045	0.019	0.157
			Adult	0.003	0.029	0.006	0.053	0.022	0.185
			Total	0.009	0.078	0.017	0.143	0.059	0.499
	0.15	2	YOY	0.009	0.104	0.016	0.19	0.057	0.667
			Juvenile	0.009	0.104	0.016	0.19	0.057	0.666
			Adult	0.011	0.122	0.019	0.224	0.067	0.784
			Total	0.028	0.331	0.052	0.604	0.182	2.116
	0.10	50	YOY	0.099	0.611	0.181	1.117	0.635	3.913
			Juvenile	0.099	0.611	0.181	1.116	0.634	3.909
			Adult	0.117	0.719	0.213	1.313	0.746	4.6
			Total	0.315	1.941	0.575	3.546	2.015	12.422
	0.15	50	YOY	0.238	2.164	0.434	3.955	1.521	13.852
			Juvenile	0.237	2.162	0.434	3.95	1.52	13.837
			Adult	0.279	2.544	0.511	4.649	1.788	16.285
			Total	0.755	6.871	1.379	12.555	4.829	43.975
Meta-Population: Linked	0.10	2	YOY	0.004	0.023	0.007	0.043	0.023	0.149
			Juvenile	0.004	0.023	0.007	0.043	0.023	0.149
			Adult	0.004	0.027	0.008	0.05	0.027	0.175
			Total	0.011	0.074	0.021	0.135	0.073	0.474
			YOY	0.009	0.101	0.016	0.185	0.058	0.648

Catastrophe Scenario	Catastrophe Rate	Extinction Threshold	Stage	MAPV					
				Minns API		**Minimum API**		**Median API**	
				***P[ext.]* = 5%**	***P[ext.]* = 1%**	***P[ext.]* = 5%**	***P[ext.]* = 1%**	***P[ext.]* = 5%**	***P[ext.]* = 1%**
	0.15	2	Juvenile	0.009	0.101	0.016	0.185	0.058	0.647
			Adult	0.011	0.119	0.019	0.217	0.068	0.761
			Total	0.029	0.321	0.052	0.587	0.183	2.056
	0.10	50	YOY	0.079	0.747	0.145	1.364	0.507	4.779
			Juvenile	0.079	0.746	0.144	1.363	0.506	4.773
			Adult	0.093	0.878	0.17	1.604	0.596	5.618
			Total	0.251	2.37	0.459	4.331	1.608	15.17
	0.15	50	YOY	0.257	2.279	0.47	4.164	1.647	14.583
			Juvenile	0.257	2.276	0.47	4.159	1.645	14.567
			Adult	0.302	2.679	0.553	4.895	1.936	17.145
			Total	0.817	7.233	1.493	13.217	5.228	46.296
Meta-population: Rescue	0.10	2	YOY	0.002	0.011	0.004	0.02	0.015	0.071
			Juvenile	0.002	0.011	0.004	0.02	0.015	0.071
			Adult	0.003	0.013	0.005	0.024	0.017	0.083
			Total	0.007	0.035	0.013	0.064	0.047	0.224
	0.15	2	YOY	0.005	0.028	0.008	0.051	0.029	0.18
			Juvenile	0.005	0.028	0.008	0.051	0.029	0.18
			Adult	0.005	0.033	0.01	0.06	0.035	0.212
			Total	0.015	0.089	0.027	0.163	0.093	0.571
	0.10	50	YOY	0.053	0.33	0.097	0.602	0.339	2.11
			Juvenile	0.053	0.329	0.097	0.602	0.338	2.108
			Adult	0.062	0.388	0.114	0.708	0.398	2.481
			Total	0.168	1.047	0.307	1.912	1.075	6.699
	0.15	50	YOY	0.124	0.797	0.226	1.457	0.792	5.102
			Juvenile	0.124	0.796	0.226	1.455	0.791	5.096
			Adult	0.145	0.937	0.266	1.712	0.931	5.998
			Total	0.393	2.53	0.718	4.624	2.514	16.196
	0.10	2	YOY	0.002	0.008	0.003	0.014	0.011	0.05
			Juvenile	0.002	0.008	0.003	0.014	0.011	0.05

Catastrophe Scenario	**Catastrophe Rate**	**Extinction Threshold**	**Stage**	**MAPV**					
				Minns API		**Minimum API**		**Median API**	
				***P[ext.]* = 5%**	***P[ext.]* = 1%**	***P[ext.]* = 5%**	***P[ext.]* = 1%**	***P[ext.]* = 5%**	***P[ext.]* = 1%**
Meta-population: Independent			Adult	0.002	0.009	0.004	0.017	0.013	0.059
			Total	0.006	0.025	0.01	0.046	0.036	0.16
	0.15	2	YOY	0.003	0.02	0.006	0.037	0.021	0.13
			Juvenile	0.003	0.02	0.006	0.037	0.021	0.13
			Adult	0.004	0.024	0.007	0.044	0.024	0.152
			Total	0.01	0.064	0.019	0.118	0.065	0.412
	0.10	50	YOY	0.042	0.224	0.076	0.409	0.266	1.432
			Juvenile	0.042	0.223	0.076	0.408	0.266	1.43
			Adult	0.049	0.263	0.089	0.481	0.313	1.684
			Total	0.132	0.71	0.242	1.298	0.846	4.546
	0.15	50	YOY	0.068	0.556	0.124	1.016	0.433	3.559
			Juvenile	0.068	0.555	0.123	1.015	0.432	3.555
			Adult	0.079	0.654	0.145	1.194	0.509	4.184
			Total	0.215	1.765	0.392	3.225	1.374	11.297

APPENDIX 3

Table A3.1. Parameter values for the recovery probability relationships ($P[rec.] = \frac{1}{1+e^{-(a_{rec}+b_{rec}\,log(year))}}$*) used to estimate time to recover (Table 9). Three recovery strategies are explored: increasing YOY survival by 75%; increasing adult survival by 75%; and increasing survival of all age classes by 25%. Values are provided for various catastrophe scenarios: the single population model; a meta-population model with linked catastrophes; a meta-population with one rescue sub-population; and a meta-population model with independent catastrophes. Within the catastrophe scenarios relationships were fit for simulation with quasi-extinction thresholds of 2 or 50 adults and probabilities of catastrophe of 0.10 and 0.15/generation. NAs indicate that the recovery target (MVP) was smaller than the initial population size.*

Catastrophe Scenario	**Catastrophe Rate**	**Extinction Threshold**	**Strategy**	**Recovery probability**			
				***P[ext.]* = 5%**		***P[ext.]* = 1%**	
				a_{rec}	b_{rec}	a_{rec}	b_{rec}
Single population	0.10	2	YOY	NA	NA	-1.672	1.413
			Adult	NA	NA	-0.824	1.059
			All	NA	NA	-0.882	1.397
	0.15	2	YOY	NA	NA	-6.742	2.437
			Adult	NA	NA	-6.193	2.171
			All	NA	NA	-6.809	2.708
	0.10	50	YOY	-6.597	2.410	-11.629	3.335
			Adult	-6.049	2.144	-10.869	3.008
			All	-6.643	2.673	-12.054	3.699
	0.15	50	YOY	-9.163	2.893	-14.511	3.816
			Adult	-8.496	2.594	-13.752	3.495
			All	-9.368	3.201	-15.193	4.254
Meta-population: Linked	0.10	2	YOY	NA	NA	-1.416	1.334
			Adult	NA	NA	-0.604	1.010
			All	NA	NA	-0.610	1.332
	0.15	2	YOY	NA	NA	-6.602	2.387
			Adult	NA	NA	-6.209	2.173
			All	NA	NA	-6.666	2.665
	0.10	50	YOY	-5.821	2.235	-11.894	3.343
			Adult	-5.462	2.031	-11.250	3.063
			All	-5.815	2.494	-12.620	3.792
	0.15	50	YOY	-9.273	2.889	-14.490	3.784
			Adult	-8.714	2.626	-13.783	3.492
			All	-9.639	3.243	-15.298	4.250
Meta-population: Rescue	0.10	2	YOY	NA	NA	NA	NA
			Adult	NA	NA	NA	NA
			All	NA	NA	NA	NA
	0.15	2	YOY	NA	NA	-2.404	1.689
			Adult	NA	NA	-1.725	1.371
			All	NA	NA	-1.757	1.706
	0.10	50	YOY	-4.807	2.168	-10.924	3.355
			Adult	-4.468	1.957	-10.267	3.058
			All	-4.557	2.333	-11.261	3.716

Catastrophe Scenario	Catastrophe Rate	Extinction Threshold	Strategy	Recovery probability			
				P[ext.] **= 5%**		***P[ext.]*** **= 1%**	
				a_{rec}	b_{rec}	a_{rec}	b_{rec}
	0.15	50	YOY	-7.844	2.773	-13.364	3.789
			Adult	-7.392	2.532	-12.520	3.443
			All	-7.948	3.062	-13.868	4.200
Meta-population: Independent	0.10	2	YOY	NA	NA	NA	NA
			Adult	NA	NA	NA	NA
			All	NA	NA	NA	NA
	0.15	2	YOY	NA	NA	NA	NA
			Adult	NA	NA	NA	NA
			All	NA	NA	NA	NA
	0.10	50	YOY	-4.021	2.093	-10.417	3.393
			Adult	-3.785	1.908	-9.448	2.997
			All	-3.703	2.236	-10.345	3.627
	0.15	50	YOY	-6.016	2.517	-13.183	3.890
			Adult	-5.566	2.257	-12.054	3.437
			All	-5.735	2.668	-13.352	4.208