Site C Clean Energy Project

Site C Reservoir Tributaries Fish Community and Spawning Monitoring Program (Mon-1b)

Task 2b – Peace River Bull Trout Spawning Assessment – Bull Trout Redd Counts

Construction Year 2 (2016)

Note: This report has been redacted for the protection of Bull Trout (*Salvelinus confluentus)*

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Peace River Bull Trout Spawning Assessment - Bull Trout Redds Counts (Mon-1b, Task 2b)

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Executive Summary

This report summarizes the 2016 Bull Trout redd enumeration program in the upper portion of the Halfway River mainstem and its tributaries. We conducted three rounds of aerial and ground surveys to visually enumerate Bull Trout redds in five main spawning streams; the Chowade River, Cypress Creek, Fiddes Creek, Turnoff Creek, and the upper Halfway River. Redd spatial distributions observed in each river were similar to previous surveys. To estimate Bull Trout redd abundance with associated uncertainty we used a Gaussian area-under-the-curve (GAUC) method with maximum likelihood estimation. This method incorporates the mean and standard error for the number of fish days, observer efficiency and redd survey life. Data were collected for estimating observer efficiency and redd survey life by marking and re-sighting redds during ground and aerial surveys. Ground observer efficiency was calculated as the proportion of marked redds re-sighted. Aerial observer efficiency was calculated by comparing the expanded number of redds in a ground survey reach to the number observed within the same reach during aerial surveys. Observer efficiency varied among streams but was relatively consistent within streams and among surveys (range in ground observer efficiency 0.8 to 0.95; range in aerial observer efficiency 0.27 to 0.79). Redd survey life was estimated through redd age determination with a mean survey life of 13.7 days and a standard error of 1.83. The most likely estimates for the total number of redds was 290 for the Chowade River, 90 for Cypress Creek, 107 for Fiddes Creek, 44 for Turnoff Creek, and 20 for the upper Halfway River. GAUC estimates were within the range of baseline estimates from 2002 to 2012. Redd sizes varied considerably among and within streams (range for all redds: 0.32 to 8.12 m^2). We discuss the implications of redd size variation among streams on juvenile recruitment.

Acknowledgements

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1 Project Background

The Site C Reservoir Tributaries Fish Community and Spawning Monitoring Program objectives are to determine the effects of the Site C Dam on, and mitigation measures for, fish populations that migrate to tributaries of the reservoir and their habitats. A subcomponent of this monitoring program (Task 2b) aims to assess spawning populations of Bull Trout in the Halfway Watershed. Data collected for this task will be used to directly address the following management hypotheses:

H_0: There will be no change in Bull Trout spawner abundance in the Halfway River relative to baseline estimates.

H_1: Bull Trout spawner abundance in the Halfway River will decline by 20 to 30% relative to baseline estimates.

Historic data on the Halfway River meta-population have been collected through various spawner assessment methods, including aerial, ground and snorkel surveys of Bull Trout redds (Diversified Environmental Services and Mainstream Aquatics Ltd. 2009; 2011; 2013). These peak redd counts provide a baseline index of spawner abundances and continued population monitoring pre- and post-construction of Site C Dam is required to test the management hypotheses. Previous baseline data will provide an important contribution to evaluating population status prior to the construction of Site C Dam, however revised methods used in this program aim to provide more accurate estimates of Bull Trout redd abundance and reflect associated uncertainties in these estimates.

2 Introduction

Salmonid breeding population sizes have been estimated through a variety of methods (Hilborn et al. 1999, Rand et al. 2007, Braun et al. 2016) including redd count surveys. Bull Trout (*Salvelinus confluentus*) population sizes have previously been assessed using redd count surveys in key spawning tributaries of the Halfway Watershed (Diversified Environmental Services and Mainstream Aquatics Ltd. 2009; 2011; 2013). Unlike visual surveys that count the number of spawning adults, redd count surveys provide an index of effective population size (i.e. the number of reproducing adults) (Gallagher et al. 2007). Redd counts can also provide the advantage of lower operating costs as the surveys do not rely on larger-scale fish tagging efforts associated with mark-recapture surveys (Gallagher et al. 2007).

The main limitation of visual count surveys is their subjective nature, which relies on the ability of each surveyor to minimize the error associated with their observations. The primary sources of error are: (1) observer efficiency (OE; bias towards over- or under-estimating redd abundance on any survey), (2) not accounting for redd survey life (SL; the length of time a redd can be detected by an observer), (3) poor temporal coverage of surveys (too few surveys or surveys not covering peak spawning), (4) poor spatial coverage (only surveying likely spawning areas or areas convenient to access). If these sources of uncertainty are not accounted for and temporal and spatial coverage is poor, inference is reduced, as is the confidence one can have in resultant population estimates.

Observer efficiency can vary among individual observers, survey days and systems (Grant et al. 2007, Muhlfeld et al. 2006). OE is the ratio of the number of redds observed *versus* the true number of redds present. OE values less than one indicate a bias to underestimating redd abundance by the surveyor (e.g. missed redds because of multiple overlapping redds and/or redds hidden by large woody debris or overhanging vegetation). OE values greater than one suggest overestimation of redds (e.g. counting a 'test' redd rather than an actual redd, mistakenly determining that a scour feature is a redd, or double-counting). Both sources of error are common to any form of visual stock assessment survey methodology but the degree to which each contributes to error in population estimates depends on the unique set of survey conditions such as water clarity, depth, light conditions, habitat complexity and redd density as well as the experience of the observers (Gallagher and Gallagher 2005).

Quantifying the within- and among-site variability in Bull Trout redd survey life (i.e. length of time a redd is visible to an observer) can further reduce the error associated with double counting redds over consecutive surveys. Digging of redds by spawning females scours the substrate, removing periphyton and fine sediments and exposing clean substrate. The visible contrast between scoured and periphyton-covered rocks enables identification of redds. After eggs have been fertilized and buried, periphyton and fine sediments will recolonize and settle on the clean substrate. The amount of time before redds become indistinguishable from the rest of the stream bed can vary. This can be system- and species-specific and is currently unknown for tributaries of the Halfway Watershed. Therefore, accurate estimates of redd survey life are essential to reduce the inaccuracies associated with the amount of time a redd is 'surveyable'.

Adequate temporal coverage of surveys is important for reliable estimates of spawn-timing and redd abundance (Holt and Cox 2008). Estimates based on peak counts fail to account for variability in migration timing and spawning behaviour, and abundance estimates derived from a limited number of surveys are associated with high uncertainty and are often inaccurate (Holt and Cox 2008). Inadequate spatial coverage can also bias estimates low by focusing only on obvious spawning locations or locations that are most accessible.

Area-under-the-curve (AUC) methods can incorporate observer efficiency and survey life when estimating population abundances. This approach is widely used to estimate the number of spawners or redds in a river from visual count data (Hilborn et al. 1999). Estimating observer efficiency and survey life can be challenging or costly, however they are fundamental parameters in the AUC calculation. There are many versions of AUC models that employ a range of run- or spawn-timing models and estimation procedures (Holt and Cox 2008) and whether they incorporate uncertainty. For example, Millar et al. (2012) developed a Gaussian (GAUC) approach that uses a normally distributed timing model with maximum likelihood estimation, and allows for uncertainty in observer efficiency and survey life to be incorporated. This approach outperformed other commonly used AUC approaches such as the Trapezoidal method and was robust to assumptions of a normal timing model when estimating the number of Pink Salmon (Millar et al. 2012).

Since 2002, Bull Trout redds have been enumerated in six tributaries of the Halfway Watershed (Figure 1) (Diversified Environmental Services and Mainstream Aquatics Ltd. 2013). During the most recent three survey years (2008, 2010 and 2012), four of the original six streams have been consistently enumerated (Chowade River, Cypress Creek, the upper Halfway River, and Needham Creek; Table 1) in addition to two streams surveyed in 2010 (Fiddes and Turnoff Creeks). Redd counts during these surveys were conducted using a variety of visual survey methods, including ground, snorkel and aerial surveys. Survey efforts have primarily focused on established Wildlife Habitat Areas (British Columbia Ministry of Environment), but additional reaches, of varying lengths, have been surveyed in some years. While these surveys provide valuable baseline information on the extent of Bull Trout spawning in each tributary and population sizes prior to the construction of Site C Dam, estimates are based on only two surveys per season and did not consider key parameters such as observer efficiency and survey life, which could reduce their accuracy.

Redd counts provide an index of the number of females that successfully deposited eggs. However, in populations where female size varies, redd counts may not accurately represent the number of eggs deposited. For example, larger females produce more eggs (Kindsvater et al. 2016) and build larger redds (Riebe 2014). Accounting for redd size could increase the reliability of redd estimates as an indicator of juvenile recruitment and provide a more direct link to juvenile data being collected under Task 2c (Golder Associates Ltd. 2016). Furthermore, redd size may provide information about the relative number of resident *versus* migratory Bull Trout. This could be achieved by directly linking female length and fecundity to redd size through coordination among Site C monitoring programs that capture, tag and track adult Bull Trout to their spawning grounds.

The objective of this current monitoring program is to standardize data collection methodology and estimate redd abundance to provide accurate information on Bull Trout population status over time while minimizing and quantifying uncertainty. Accurate estimates of Bull Trout redd abundance will be achieved through estimation of uncertainty in observer efficiency and redd survey life using AUC models. In addition, increasing the number of redd surveys over longer time periods will provide more reliable information on spawn timing and redd abundances. Increased accuracy in redd abundance estimates will strengthen statistical power to detect changes in the Halfway River meta-population over time (Maxwell 1999). Finally, accounting for redd size will provide a more direct link to the number of eggs deposited in each tributary. This approach provides an increased ability to track changes in Bull Trout population size over time to inform effective mitigation measures for migratory Bull Trout moving upstream and downstream of the Site C Dam.

3 Methods

3.1 Study Sites

We surveyed five key spawning streams in the Halfway Watershed (Figure 1). The selection of these streams and survey areas was based on previous studies that examined spawning and migration patterns from radio telemetry data (Diversified Environmental Services and Mainstream Aquatics Ltd. 2009; 2011; 2013, and references therein). The

Halfway Watershed joins the Peace River 36 km west of Fort St. John. Spawning streams range in size from 21 river km (Fiddes Creek) to 304 river km (Halfway River) (Table 1). [REDACTED]. Sites were accessed via helicopter from the Fort St. John airport.

Table 1. Summary of stream size characteristics including stream order (stream order is equal to 1 plus the *n*th order of two joining stream segments (Platts 1979)), stream magnitude (equal to the sum all stream segments with magnitude of one (Bridge 2003)), and stream length (total length of the stream mainstem). Data were sourced from BC Ministry of Environments Watershed Dictionary Query (http://a100.gov.bc.ca/pub/fidq/viewWatershedDictionary.do) and are taken from a 1:50 000 scale.

Watershed Code	Name	Order	Magnitude	Length (km)
235	Halfway River	7	3130	303.6
235-430800	Chowade River	5	424	87.1
235-492500	Cypress Creek	5	331	81.7
235-821300	Turnoff Creek	4	47	20.2
235-821600	Fiddes Creek	4	37	21.0

[Figure 1 – REDACTED]

3.2 Visual Surveys

Redd count surveys on the upper Halfway River system (upper Halfway River, Fiddes and Turnoff Creeks), Cypress Creek, and Chowade River were conducted weekly for 3 consecutive weeks. [REDACTED]. Surveys were scheduled to be 7 days apart but were conducted between 5 and 7 days apart due to weather conditions and helicopter availability.

[Table 2 – REDACTED]

Each week, two biologists with previous experience assessing or counting salmonid redds and spawners conducted redd count surveys over a three-day period (one day per system). All surveys used helicopter transport and consisted of both aerial surveys in all known spawning reaches and ground surveys in high-density spawning reaches (e.g. Wildlife Habitat Areas). Survey reaches were based on reconnaissance surveys done to establish the distribution of spawners for Chowade and upper Halfway Rivers, Cypress Creek, Fiddes and Turnoff Creeks and radio telemetry studies (Diversified Environmental Services and Mainstream Aquatics Ltd. 2013 and references therein). Aerial surveys were typically conducted first, followed by ground surveys. All aerial surveys for Chowade, Cypress and the Halfway were conducted flying in an upstream direction, however direction of travel varied for Fiddes and Turnoff, dependent on light and wind conditions. Wind was the primary factor in determining flight direction, height and speed. When safe, the direction flown aimed to minimize glare and maximize visibility. Water clarity was visually assessed to be > 2 m at all sites and for all surveys, although turbidity can reduce visibility at higher discharges.

Redds were identified as areas with disturbed and cleaned substrate, with an obvious crest at the upstream end of the disturbed area, a tailspill area where disturbed substrate gathered, and a distinct depression between the crest and tailspill (Gallagher et al. 2007). Active spawning was observed and confirmed the identification of redds based on the characteristics. The number of redds in a cluster was determined by counting the number of crest-tailspill pairs. While all redd characteristics were visible during ground surveys, patches of disturbed and cleaned substrate were the key characteristics used to identify redds during aerial surveys.

Ground Surveys

Ground survey areas were established using redd distributions from previous years and locations of Wildlife Habitat Areas (Diversified Environmental Services and Mainstream Aquatics Ltd. 2009; 2011; 2013). One continuous ground reach was established at each site except for Turnoff Creek where ground surveys were not conducted due to difficulty finding an appropriate helicopter landing location. The lengths of ground reaches ranged from 1.5 to 5 km in length (Table 3). Crews were dropped off at the upstream boundary of ground survey areas and surveyed downstream to meet the helicopter at the lower boundary. When side channels were present, one observer would split off and follow the side channel while the other continued on the mainstem. When more than two channels were present, observers would double back to count all remaining channels. All redds were counted and geo-referenced using a handheld GPS (Garmin Monterra, Garmin, Schaffhausen, Switzerland) accurate to ± 3m. A subset of redds were also systematically marked to collect data for estimating observer efficiency and survey life (see Section 3.3, Redd Marking). All spawning Bull Trout were also enumerated (Appendix 1).

Aerial Surveys

Aerial surveys were conducted by helicopter flying between 50 and 100 m above ground and at flight speeds ranging from 15 to 40 km hr^{-1}. Aerial survey methods described herein are based on established DFO protocols (Trouton 2004). Teams surveyed the river channel from the side doors of the helicopter while the pilot flew at an angle to ensure adequate visibility. One observer was in the front passenger seat (port side) and transcribed data, while the second observer was in the back-passenger seat (port side) and called out the number of redds as they were observed. Teams used high-quality polarized glasses to reduce glare off the water surface. Aerial surveys were typically conducted at mid-day when the sun was directly overhead and visibility conditions were optimal, but this varied based on weather conditions. Total redd counts within an aerial survey reach were recorded noting redd location with a GPS. If clusters of redds were observed, we recorded the estimated number of redds. Spawning Bull Trout were also enumerated (Appendix 1). Aerial surveys covered the entire length of ground survey reaches, allowing aerial observer efficiency to be estimated through comparison of aerial and ground counts.

The method of comparing aerial and expanded ground counts is robust to the general assumption of ground surveys being more accurate than aerial surveys. Ground surveys are often considered more accurate than aerial surveys because the surveyor has more time to examine the river for redds and can more accurately assess false redds and clusters of redds. While assessments of OE for redd counts from ground surveys are often close to 1 (Gallagher et al. 2007), there could however, be circumstances when aerial surveys are more accurate than ground surveys. For example, it may be easier to observe redds in a wide, fast flowing section of river from the air than on the ground. This is not a problem when comparing the counts between survey types to determine the aerial OE. When the assumption of more accurate ground counts is met, OE values for aerial surveys would be less than 1 (i.e. the number of expanded redds from the ground surveys would be greater than the aerial surveys). When the assumption is not met, OE values for aerial surveys would be greater than 1 (i.e. the number of redds counted during the aerial surveys would be greater than the expanded number of redds from the ground surveys).

Table 2. Summary of redd survey reaches. Distances are in river km.

Stream	Ground Survey Length (km)	Direction Walked	Aerial Survey (km)	Direction Flown
Chowade	5	Downstream	27	Upstream
Cypress	2.5	Downstream	18.5	Upstream
Fiddes	2.0	Downstream	14.8	Variable
Turnoff	-	-	15.0	Variable
Upper Halfway	1.5	Downstream	22.5	Upstream

3.3 Redd Marking

During each ground survey, the first 5 encountered redds were marked by inserting a bristle tag (Figure 2) with a 6- or 12-inch stake into the crest of the redd. Following the first five marks, every fifth redd was marked until a total of 50 redds were marked. A small label containing information on the survey date and redd number was attached to each tag to allow redds to be tracked throughout the spawning period until they were no longer visible, at which point the tag was removed and the redd was no longer enumerated. Red and green bristle tags were selected to enable surveyors to re-observe redds during consecutive surveys but not draw the observer's eyes to the tag before the redd itself was observed (Figure 2A). Colour choice resulted from in-river pre-season trials of red, green, white, and yellow tags (Figure 2B).

Redd characteristics were recorded following the methods of Gallagher et al. (2007). The unique redd identifier (redd tag number) was recorded on a datasheet along with the date, GPS location, age class, and whether the redd was observable (see Section 3.5, Survey Life). In addition, redd dimensions (length and width) were measured to the nearest centimeter.

Length was defined as the distance between the upper crest of disturbed substrate to the end of the tailspill. Width was the distance of disturbed substrate measured perpendicular to the length axis.

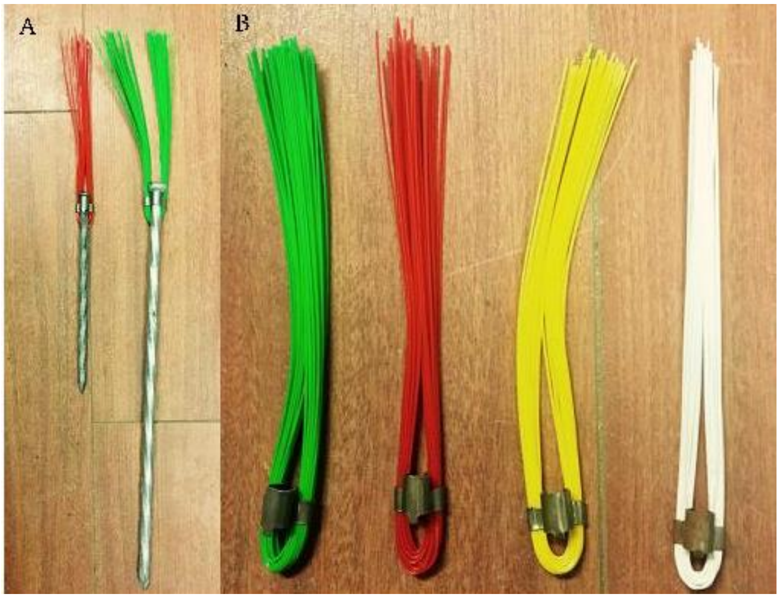

Figure 1. A) Bristle tags and spikes used to mark redds. B) Bristle tag colours tested in the field to determine the most appropriate colour.

3.4 Observer Efficiency

During ground surveys, teams counted the number of marked and unmarked redds. OE was estimated by dividing the number of marked redds observed by the number of marked redds available to be observed. This is similar to the estimation of observer efficiency for visual surveys using mark-recapture methods (Melville et al. 2015). The number of redds observed in the ground survey reach was expanded to a total number of redds by dividing the number of observed redds by the mean ground survey OE. A key assumption was that there was no tag loss; this was assessed by deploying 10 test tags in each system and observing the number of tags each survey to determine the proportion lost over the survey period. All tags remained except in Fiddes Creek where 4 of the 10 tags were lost, which appeared to be due to a high-water event and poor placement of test tags in an area unrepresentative of redd sites. Tags could also be lost due to burial as fish dig on top of marked redds, however the densities of Bull Trout redds are too low for this to be a concern.

Observer efficiency for aerial surveys was estimated by conducting aerial counts over the ground survey reaches. The total ground and aerial redd counts were compared within the ground survey reach. For example, if ground surveys counted 12 redds and the ground OE was 0.75, the estimated total number of redds in the ground reach would equal 16. If 8 redds were observed during the aerial survey over the ground reach, the aerial OE would be calculated as 8/16 = 0.5. For AUC models, we used the mean and standard error of aerial survey OE specific to each tributary to expand aerial counts. This is a novel method for calculating OE for aerial surveys that combines conventional methods for estimating OE.

Redd numbers were insufficient for Cypress Creek and ground surveys were not conducted on Turnoff Creek; thus, surrogate OE values were used from streams with similar characteristics. For example, Chowade and Cypress are similar in width (Table 1) and complexity (observations of the frequency of pools and the amount of large woody debris), therefore the Chowade aerial OE was applied to Cypress, while the Fiddes aerial OE was applied to Turnoff due to their similar characteristics (Table 1).

3.5 Survey Life

Survey life (SL) was estimated by assigning redd age class, and was tracked for marked redds over consecutive surveys. Redd age class was recorded following the methods of Gallagher et al. (2007):

Age-1 = new since last survey but clear;

Age-2 = still measurable but already measured;

Age-3 = no longer measurable but still apparent;

Age-4 = no redd apparent, only a tag (at which point the tag will be removed);

Age-5 = poor conditions; cannot determine if present and measurable or not.

Survey life is the number of days a redd is observable and available to be counted. In the current study, this was determined by the ground surveys but applied to the aerial surveys. We did not attempt to estimate the survey life of redds for aerial surveys. It was calculated as the number of days between when the mark was first applied (to an age-1 redd) and when the redd reached age-4 when it no longer met the characteristics used to identify a redd. Many of the marked redds did not reach age-4 by the last survey. To estimate the survey life for these redds, we used a linear model that related normalized survey day (day 1 is the day the redd was first observed and tagged) to the assigned redd age class. Normalized survey day was related to redd age class. We defined survey life as the predicted normalized survey day at which redds were assessed to be age-4. A random effect of tag id around the intercept and slopes for the effect of redd age on the normalized survey day were used to account for individual redd variation (e.g. tag date, stream). The redd age class model for predicting the normalized survey day was:

$$y_{i,t} = (a + \theta_i) + (b + \mu_i) r_{i,t} + \varepsilon_{i,t} \tag{1}$$

$$\theta \sim N(0, \sigma^2),$$

$$\mu \sim N(0, \sigma^2),$$

$$\varepsilon \sim N(0, \sigma^2)$$

where the y is the normalized survey day for redd i, on survey t ($t =$ 3, 4, or 5), a is the mean intercept and θ is the random variation around the mean intercept, b is the slope for the effect of redd age class on the normalized survey day, μ is the random variation around the mean slope b, and ε is the residual error. Estimates of θ, μ and ε are assumed to be normally distributed with a mean of zero. Using Equation 1, we predicted the mean and standard error of survey life for redds at age-4. Although survey life is likely to vary among streams, sample sizes were insufficient to calculate system-specific redd survey lives. Therefore, all data were combined to estimate a single mean and standard error that was applied to all systems.

3.6 Redd Area, Fish Length, and Fecundity

We measured the length and width (to the nearest 10 cm) of streambed that spawners had disturbed, which was identified as cleaned substrate without periphyton. Redd area was calculated assuming an elliptical shape:

$$A = \pi L W \tag{2}$$

where A is the area of the disturbed streambed, L is the length of the redd measured from the crest to the tailspill, and W is the width of the disturbed stream bottom.

We predicted fork-length from measured redd area using the redd area-fork length relationship defined in Riebe et al. (2014). The authors used individuals from three species of Pacific Salmon (Sockeye, Pink and Chinook Salmon). In their study, redd area was measured at a greater resolution than in our study and therefore better represents actual redd area. The relationship between redd area and fork length was estimated to be:

$$A = 3.3\left(\frac{L}{600}\right)^{2.3} \tag{3}$$

where A is redd area in m^2, L is the female fork length in mm, and 600 is a reference value that was near the average length of individuals in their study. The model was based on 60 observations and was highly significant with a correlation coefficient (r) of 0.89 and a p-value <0.0001.

The redd area equation was transformed to solve for fork length:

$$L = \left(\frac{600^{2.3}\mathrm{A}}{3.3}\right)^{0.434783} \tag{4}$$

Published data on Bull Trout lengths and egg number were used to determine the length-fecundity relationship. Data were extracted from a review of Bull Trout life histories by McPhail and Baxter (1996), which included lengths and egg number for 6 populations (Figure 3). The equation for the regression line used to estimate egg number is:

$$\ln(E) = -8.434 + 2.606\ln(\mathrm{L}) \tag{5}$$

where E is the number of eggs per female and L is the female's fork length in mm.

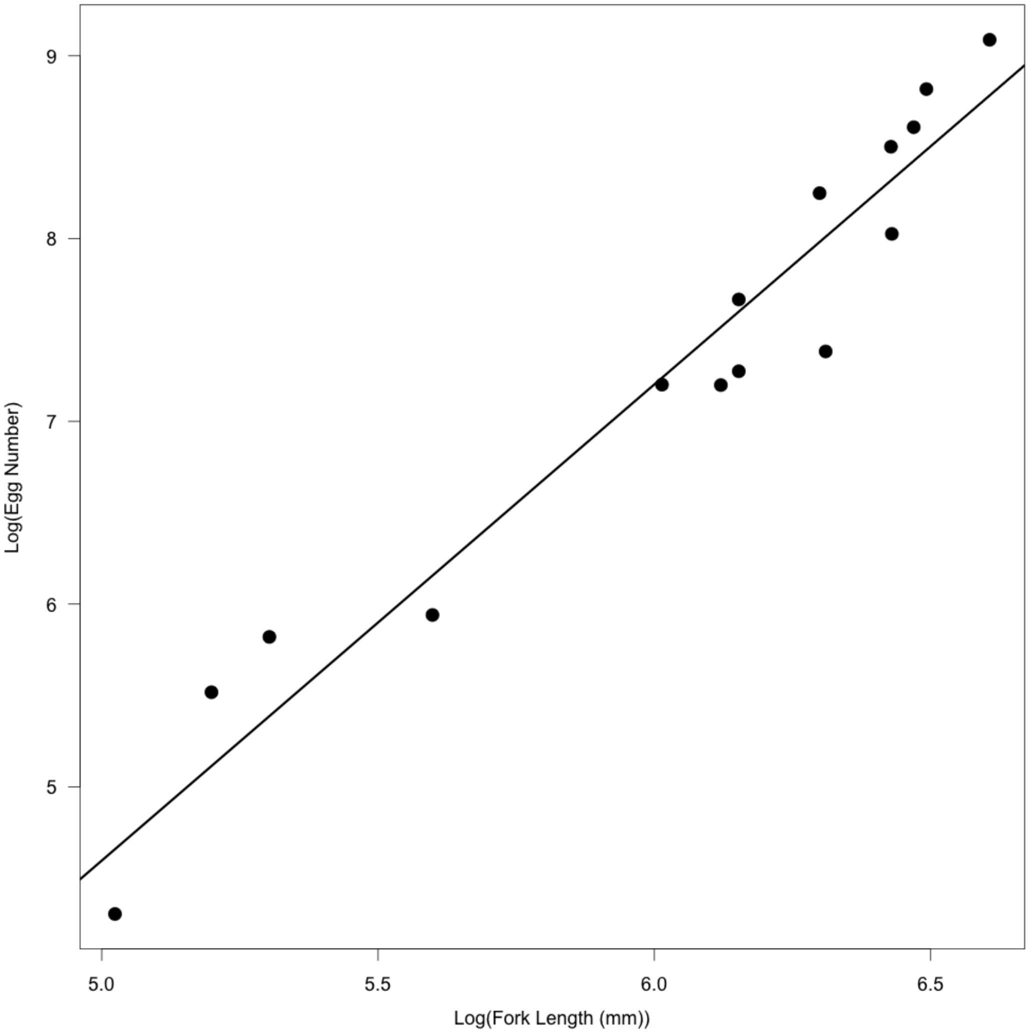

Figure 2. Published data of Bull trout female fork length by egg number. Both axes are on the natural log scale. The model R^2 was 0.94 and the p-value was <0.0001.

3.7 Redd Abundance Estimates

We used a GAUC method for estimating the total number of redds for each system. Visual fish stock assessment data can be modelled as a quasi-Poisson distribution with spawn-timing described by a normal distribution and parameter estimates evaluated using maximum likelihood estimation (described in Millar et al. 2012). Spawn-timing is defined as the timing of new redd establishment throughout the spawning season. An advantage of this GAUC approach over conventional forms of AUC and peak count index used in the baseline surveys is the ability to incorporate variance in OE and SL, fit spawn-timing using maximum likelihood estimation, and estimate the associated uncertainty in abundances.

With abundance modelled as a quasi-Poisson distribution with normally distributed spawn-timing (Millar et al. 2012), the number of observed redds at time t (C_t) is

(6)
$$C_t = a\, exp\left[-\frac{(t-m_s)^2}{2\tau_s^2}\right]$$

where a is the maximum height of the redd count curve, m_s is the time of the peak number of redds, and τ_s^2 is the standard deviation of the arrival timing curve.

Because the normal density function integrates to unity, the exponent term in Equation 6 becomes $\sqrt{2\pi\tau_s}$ and Equation 6 can be simplified to

(7)
$$C_t = a\sqrt{2\pi\tau_s}$$

A final estimate of abundance ($\hat{E}$) is obtained by applying observer efficiency (v) and survey life (l) to the estimated number of observed redds

(8)
$$\hat{E} = \frac{\hat{F}_G}{l * v}$$

$\hat{E}$ in Equation 8 is estimated using maximum likelihood (ML), where $\hat{a}$ and $\hat{\tau}$ are the ML estimates of a and τ_s in Equation 7 ($\hat{C}_t = \hat{a}\sqrt{2\pi\hat{\tau}_s}$).

The GAUC estimation in Equation 6 can be re-expressed as a linear model, allowing the estimation to be performed as a simple log-linear equation with an over-dispersion correction factor. The over-dispersion correction accounts for instances where the variance of the redd observations exceeds the expected value. The log-linear model is computationally simple and can be completed using standard generalized linear modelling. The estimated number of fish-days ($\hat{F}_G$) can be estimated following

(9)
$$\hat{F}_G = \sqrt{\frac{\pi}{-\hat{\beta}_2}}\, exp\left(\beta_0 - \frac{\hat{\beta}_1^2}{4\hat{\beta}_2}\right)$$

where β_0, β_1, β_2 are the regression coefficients of the log-linear model. Uncertainty in observer efficiency and survey life are incorporated into the estimated spawner abundance using the covariance matrix of the modeled parameters (β_0, β_1, β_2) via the delta method (described in Millar et al. 2012).

Mean estimates for abundance and input parameters are presented along with standard error, 2.5% and 97.5% confidence limits and percent relative uncertainty (%RU), which is defined as

(10)
$$\%RU = \left(\frac{|v - v_{CL}|}{v}\right) \cdot 100$$

where v is the mean estimate, v_{CL} is the value of the lower 2.5% confidence limit and the horizontal lines indicate the absolute value.

Zero counts at the beginning and end of spawning were estimated for all streams (Bue et al. 1998). At the beginning of spawning, zero counts were assigned a week before the first survey. The zero count at the end of spawning was assigned a date that was equal to the number of days estimated for the redd survey life after the last new redd was observed (i.e. Survey 4). This ensures that the last redds observed would not be observable (redd age-4) on the zero-count date. The influence of adding zero counts is examined in Appendix 2.

To continue the peak redd count index previously reported (Diversified Environmental Services and Mainstream Aquatics Ltd. 2013), we calculated the peak redd count index following methods described in Diversified Environmental Services and Mainstream Aquatics Ltd. (2013). In the past, redd counts were conducted during two survey weeks. [REDACTED]. Each reach of the river was surveyed by one of three survey types: 1) aerial, 2) ground, and 3) snorkel. The exact dates depended on weather and the number of streams surveyed each year. The peak redd count index was calculated for each stream by adding redds that were observed on the first survey but not on the second survey to the total number of redds counted during the second survey. [REDACTED].

4 Results

4.1 Redd Distributions

In the Chowade River, the highest density of redds occurred in the upper portion of the survey area (Figure 4), specifically within the ground survey area. This area was also occupied with redds earlier in the spawning season compared to lower portions of the survey area. [REDACTED].

In Cypress Creek, the highest densities were observed in two areas, one in aerial reach 1 and the other in aerial reach 2 (Figure 5). Redd counts were low throughout the entire survey area and especially low in the ground survey area. [REDACTED].

[Figure 4 – REDACTED]

[Figure 5 – REDACTED]

Redds were evenly distributed in Fiddes and Turnoff Creeks (Figure 6). [REDACTED]. Ground surveys were not conducted for Turnoff due to poor access. [REDACTED].

[Figure 6 – REDACTED]

4.2 AUC Estimates

Observer Efficiency

Observer efficiencies for ground surveys were calculated from the re-sighting of marked redds. Low numbers of marked redds did not allow for an OE estimate for Cypress Creek and redds were not observed in Turnoff Creek. OE for ground surveys in the other streams were estimated for Surveys 4 and 5. OE was high and consistent among surveys within streams (Table 4). The total number of redds marked during Surveys 3 and 4 varied (N: Chowade = 27, Fiddes = 13, Halfway = 9). The mean OE for Chowade, the upper Halfway and Fiddes ground surveys were high and aerial survey OEs were substantially lower (Table 4). Variation in aerial OEs was low for Chowade and the upper Halfway but relatively high for Fiddes (CV: Chowade = 15%; upper Halfway = 18%; Fiddes = 60%).

Table 3. Summary of ground and aerial counts and calculated observer efficiencies. Ground count OEs for Surveys 4 and 5 are in parentheses. Insufficient redds marked in Cypress Creek and absence of ground surveys in Turnoff Creek prevented efficiency estimates for those streams. Aerial counts are for only the portion of river that ground surveys were conducted in.

Stream	Number of Redds Marked	Mean Ground Observer Efficiency	Survey	Ground Count	Total Redds	Aerial Count	Aerial Observer Efficiency
Chowade	27	0.8 (1.0, 0.67)	3	69	87	29	0.33
			4	75	94	36	0.38
			5	42	53	15	0.28
Fiddes	13	0.92 (1.0, 0.92)	3	9	9.45	1	0.11
			4	15	15.75	7	0.44
			5	14	14.7	4	0.27
Upper Halfway	9	0.95 (1.0, 0.89)	3	16	17.23	11	0.64
			4	16	17.23	14	0.81
			5	13	14	13	0.93

Survey Life

A mean survey life of 13.7 days was estimated using the ages from all marked redds (Figure 7). The standard error in survey life was estimated to be 1.83 days after accounting for the uncertainty in the fixed effect of redd age and the variance in random slopes for redd age and intercepts for marked redds.

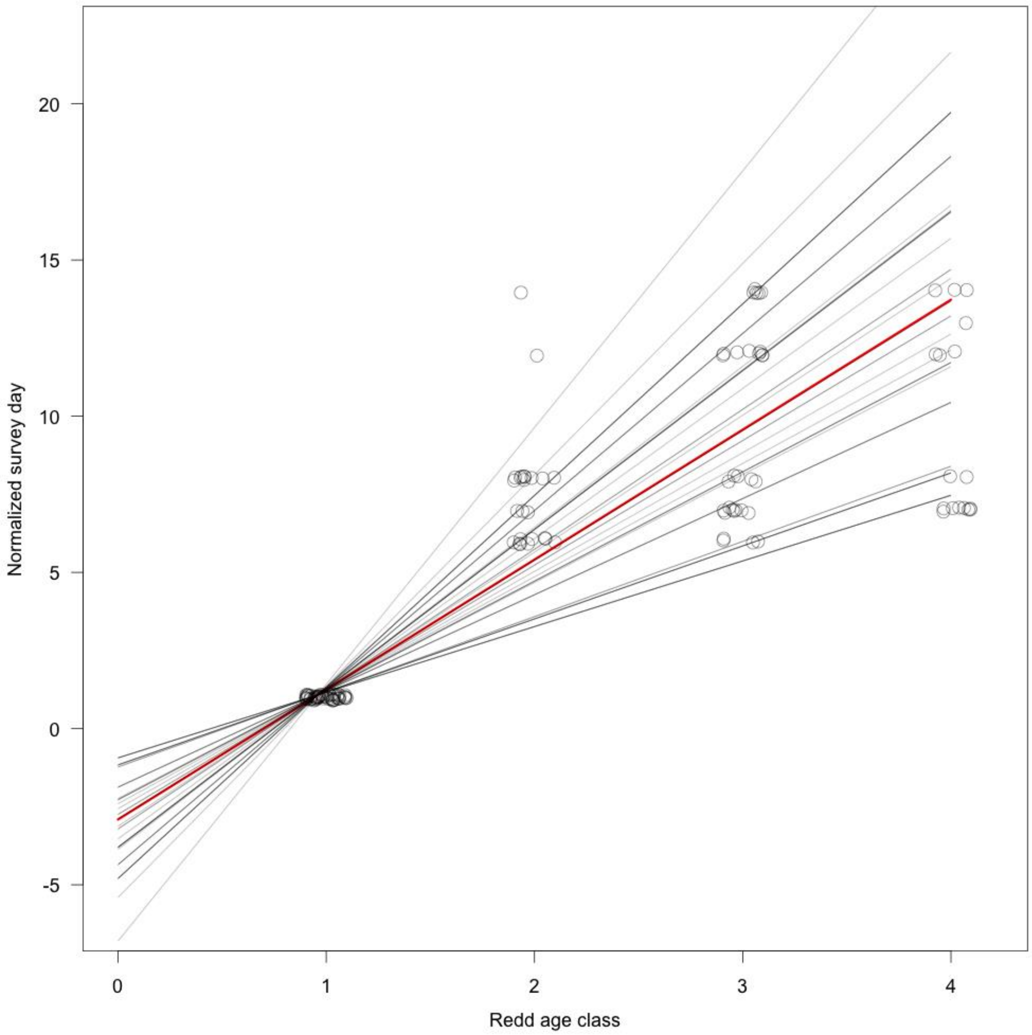

Figure 3. Redd age by normalized survey day. Points are jittered for presentation, and grey lines are random slopes and intercepts. Red line represents the mean fixed effect. Negative normalized survey days correspond to the number of days between the redd being built and the first observation by surveyors. Redd age-0 was not measured during surveys and can only be predicted. A normalized survey day of 1 is when the redd was first observed by surveyors. See Equation 1 for model details.

Redd Abundance Estimates

The maximum likelihood estimates for the number of Bull Trout redds excavated varied 14.5-fold among surveyed streams (Table 5). The redd abundance ranged between 20 and 290 for the upper Halfway and Chowade Rivers, respectively. The percent relative uncertainty (%RU) ranged from 41.7% (Chowade) to 75.7% (Fiddes). The arrival timing model fit the count data well for all streams (Figure 8). For example, the %RU for the fish day parameter ($\hat{F}$) estimated by the GAUC model (see Equation 5) ranged from 11.8% to 40.5% and was $<$ 30% for all streams except the upper Halfway. The poorer fit of the model to the upper Halfway counts is likely due to the broad distribution of counts, as compared to the narrower and higher peak counts observed in the other streams (Figure 8).

Peak count (PC) indices were calculated following Diversified Environmental Services and Mainstream Aquatics Ltd. (2013) methods for comparison between baseline estimates and GAUC estimates. We found a 12-fold difference between the lowest (9 in Turnoff Creek) and highest (108 in the Chowade River) PC estimates of redd abundance among streams. The PC index for the upper Halfway was the only index value within the confidence limits of the GAUC estimate. The direction of the bias between the PC indices and GAUC estimates were consistent, however the magnitude was not. For example, the PC method consistently underestimated redd abundance but ranged from 25% to 435% (Table 4).

Table 4. GAUC estimates for Bull Trout redd abundance. OE and SL means and standard errors are input parameters for the AUC models. The 95% confidence limits are the 2.5 and 97.5% confidence bounds. Standard errors are in parentheses. OE is estimated by comparing the aerial counts observed within the ground reach to the number of redds estimated to be in the ground reach. Survey life is estimated by aging marked redds and predicting average stream life from the redd age model described in equation 1.

Stream	GAUC Abundance	2.5% CL	97.5% CL	%RU	Aerial Observer Efficiency	Survey Life	Peak Count Index
Chowade	290 (62)	169	411	41.7	0.33 (0.029)	13.7 (1.83)	108
Cypress	90 (19)	52	128	42.2	0.33 (0.029)	13.7 (1.83)	33
Fiddes	107 (41)	26	188	75.7	0.273 (0.095)	13.7 (1.83)	20
Turnoff	44 (17)	11	76	75	0.273 (0.095)	13.7 (1.83)	9
Upper Halfway	20 (5)	10	31	50	0.793 (0.084)	13.7 (1.83)	16

[Figure 8 – REDACTED]

Redd Size, Fish Length, and Egg Number

The mean redd area varied 2-fold among streams (Figure 9). The largest redds were observed in the upper Halfway, followed by the Chowade River. The smallest redds were observed in Fiddes Creek (mean redd area: upper Halfway = 1.83 m^2, Chowade = 1.55 m^2, Fiddes = 0.97 m^2). The largest variation in redd area was observed in the Chowade River (CV = 99%). Redd size appeared to be positively correlated with stream size. Predicted mean fork lengths varied 1.3-fold among streams while the predicted number of eggs per female varied over 2-fold (Table 6).

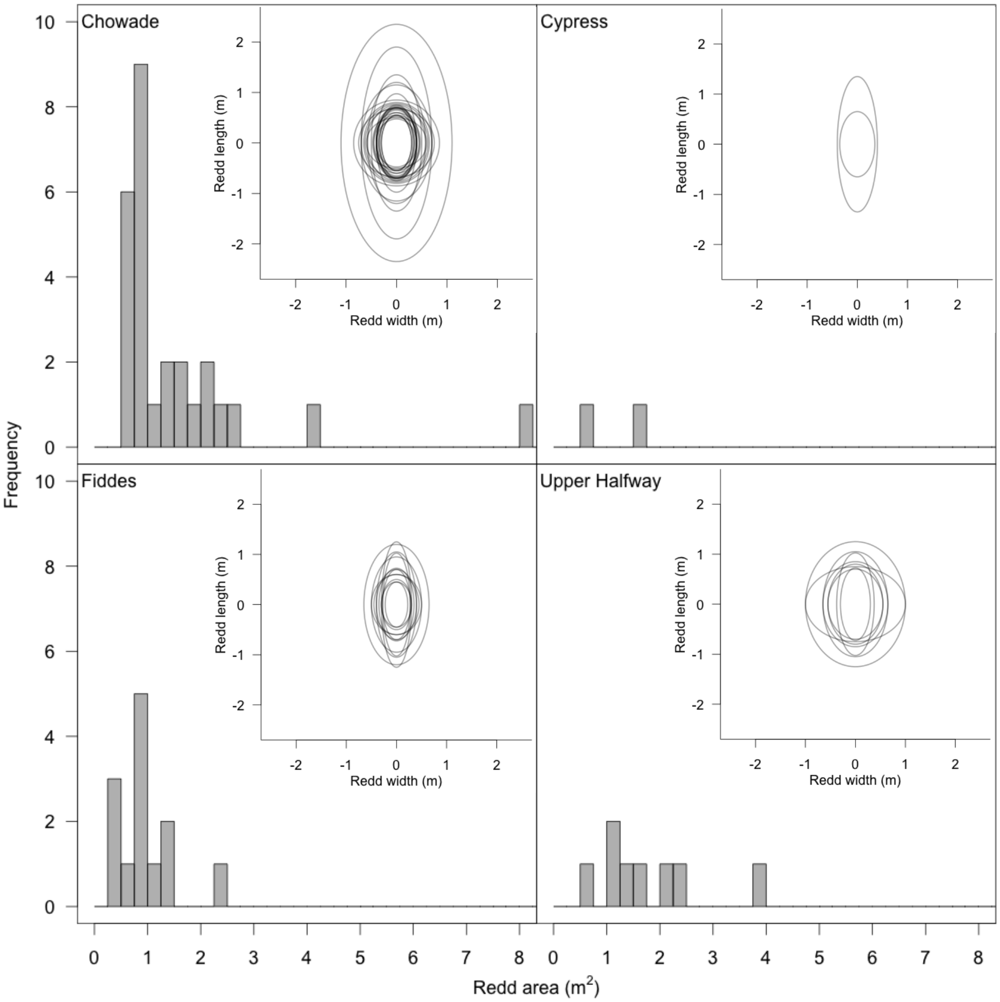

Figure 4. Frequencies of redd area by stream. Insets represent the shape of redds based on lengths and widths and an assumed elliptical shape. The redds are centered at the origin of the inset plots (0,0).

Table 5. Summary of predicted mean fork lengths and egg number from redd area by stream using Equations 2, 3 and 4. Ranges are in parentheses.

Stream	Fork Length (mm)	Egg Number
Chowade	432 (269-888)	1605 (467-10 492)
Cypress	388 (308-450)	1213 (664-1785)
Fiddes	352 (218-527)	941 (270-2694)
Upper Halfway	464 (302-647)	1933 (631-4597)

5 Discussion

As part of a multi-year project, aerial and ground surveys were conducted on five key Bull Trout spawning tributaries in the Halfway Watershed. We used estimates of observer efficiency and survey life in a GAUC model to estimate the mean redd abundance with associated uncertainty for each tributary. A peak count index of redd abundance was calculated for comparison with baseline data. Finally, we measured redd size to provide additional information on potential egg deposition.

Redd Distributions

Redd distributions within streams and across surveys were similar to distributions observed in previous years (Diversified Environmental Services and Mainstream Aquatics Ltd. 2009; 2011; 2013). In Cypress Creek and the upper Halfway River there were distinct spawning areas separated by kilometers of river where no spawning was observed. Areas lacking evidence of spawning activity were often low gradient sections with inappropriate substrate. However, there were also suitable river sections absent of redds. This was most prevalent in Cypress Creek. [REDACTED]. Redd distributions for Chowade River and Fiddes and Turnoff Creeks were more evenly distributed throughout survey areas. [REDACTED]. This area is also separated by a small tributary which may be indicative of different water quality or thermal regimes.

Redd Abundance

Observer efficiency is a key parameter to account for when deriving AUC abundance estimates. We calculated OE for both ground and aerial survey data. Our estimates varied among streams but were relatively consistent among surveys and within streams. The Chowade River had the lowest OEs for both ground and aerial surveys which is reasonable given the complexity of this river and the micro-habitat selection of Bull Trout for spawning. Based on observations in the field, Chowade had the largest number of side channels, large woody debris and pools. This complexity makes it difficult to observe a high proportion of redds from both the ground and air. The upper Halfway River had the highest OEs for both ground and aerial surveys. In spawning reaches, the upper Halfway River is a single low-gradient channel with an open canopy and low complexity (i.e. low volume of large woody debris and undercut banks) making it easier to observe redds. The OE for Fiddes Creek was high for ground surveys but low and variable for aerial surveys. The high ground survey OE is primarily due to its small size which makes it easy to observe redds during stream walks. However, OE for aerial surveys was low and variable, likely due to variable flying conditions (i.e. wind, flight direction and glare). Steep canyons also prevented low altitude flying at times, making it difficult to count.

Observer efficiencies could be biased by redd marking methods. For example, the coloured tags may cause surveyors' eyes to be drawn to a marked redd more often than an unmarked redd. The act of marking a redd could also lead a surveyor to remember where marked redds were in the river and anticipate their location when conducting ground surveys. Both of these biases, however, are unlikely given our experience in 2016. The whisker tags we used to mark redds were often difficult to see and required closer inspection once the redd had been observed to determine their presence. Furthermore, anticipating the location of marked redds is difficult because of the complexity of the rivers, lengths of river surveyed (1.5 to 5.0 km), and the alternating survey crew.

Survey life provides information on the degree of double counting during visual surveys. We estimated a mean SL based on redd age data collected from ground surveys on all streams combined. Two main assumptions are made about the SL estimate: 1) redds within and among streams have the same survey life, and 2) redds are observed on the day they are constructed and the day they become unobservable. The first assumption is likely to be false as there are system-specific factors that would affect SL, such as water temperature, substrate size, nutrient content and discharge regimes. We were unable to test this assumption due to small sample sizes in all streams except the Chowade River, where 55% of all redds were marked. Increasing the number of marked redds is possible in all streams except Cypress Creek, as all redds observed during ground surveys were marked (N = 2). Variation among redds within a stream are also likely. For example, the survey life of clustered redds may be longer than single redds due to the increased and prolonged activity on and near redds from other spawning Bull Trout pairs. The second assumption of redds being observed on the first and last day they are visible is also false. Weekly surveys only provide a coarse estimate of SL because the first time a redd is observed can be up to 7 days after it was established. Likewise, the last day a marked redd is observed may be the same number of days before or after it becomes unobservable. There is equal probability of this assumption being violated on either end of redd observability, which means that this will not affect the mean estimate. However, violating this assumption will likely lead us to underestimate the uncertainty of our SL estimate. To track redd senescence, wildlife cameras could be used to photo-document a small number of redds on each stream throughout their survey life. This would provide detailed information about the fish that construct the redds and when the redds become unobservable. Additional years of redd age data under different conditions would provide further insights into SL estimates and the associated uncertainty.

Peak redd count indices for 2016 were generally within the range of the baseline indices (Table 7). The rank order of streams from highest to lowest abundance followed the order in previous years. The Chowade River has consistently had the highest redd abundance among all streams surveyed (i.e. 3 out of the 3 baseline years with 2 or more streams enumerated). Based on field observations, it is also the most complex habitat (i.e. high amounts of large wood debris, large deep pools, many side channels) of the rivers surveyed, which is positively related to spawner density in salmon populations (Braun and Reynolds 2011). The lowest abundance was estimated for Turnoff Creek followed by the upper Halfway River, which has had the lowest abundance in 3 out of the 4 baseline years with 2 or more streams enumerated.

Table 6. Current and baseline estimates of Bull Trout redd abundance. From 2002 to 2012, peak count estimates are provided and for 2016 GAUC and peak count estimates are presented. Surveys for peak counts varied in the length of stream surveyed and survey method among years within streams. NS denotes no surveys were conducted.

	Peak Counts							GAUC
Stream	**2002**	**2004**	**2007**	**2008**	**2010**	**2012**	**2016**	**2016**
Chowade	104	210	NS	425	864	321	108	290
Cypress	NS	NS	17	120	60	62	33	90
Fiddes	NS	NS	NS	NS	146	59	20	107
Turnoff	NS	NS	NS	NS	56	40	9	44
Upper Halfway	NS	NS	11	23	86	33	16	20
Needham	NS	NS	29	78	103	80	NS	NS

Redd Size, Fish Length and Egg Number

Redd abundance can be a reliable indicator of Bull Trout spawning abundance (Gallagher et al. 2007), however it may not be a good indicator of egg deposition and thus recruitment. We observed substantial variation in redd size (i.e. area) both within and among streams. Redd size is strongly correlated with fish length (Riebe et al. 2014), and because of the strong length-fecundity relationships in salmonids (Kindsvater et al. 2016), redd size should also be correlated with the number of eggs a female deposits. We use these well-established relationships to calculate rough estimates of fecundity for spawning Bull Trout in three tributaries of the Halfway River with adequate redd size data. First, we estimated the mean fork length of Bull Trout using the relationship between fish length and redd area from Riebe et al. (2014). Using this relationship, we estimated the fork lengths of fish that excavated the redds that we measured and calculated the mean fork length for Fiddes (352 mm), Cypress (388 mm), Chowade (432 mm) and upper Halfway (464 mm), which were similar to adult sizes captured during the juvenile sampling program (Golder Associates Ltd. 2016). The mean size for the Chowade River, however, was smaller than the Bull Trout measured from video footage in 2016 (mean = 700 mm, range = 410-930 mm) (Braun et al. 2017) and caught at a fence in 1994 (mean = 622, range = 397-905 mm) (R.L. & L. Environmental Services Ltd. 1995); this suggests our predictions of fish length and thus egg number from redd area are biased low. We then used the fork lengths to estimate the number of eggs per female using a Bull Trout length-fecundity relationship parameterized from data found in McPhail and Baxter (2016) (see Appendix 3 for details). Bull Trout spawning in Fiddes Creek were estimated to have a mean egg number of 950 eggs, females in the Chowade River had a mean egg number estimate of 1604 and females spawning in the upper Halfway River had a mean egg number of 1925 eggs. The smallest redd measured was 0.32 m^2 and was established by a female estimated to be 218 mm in length with 270 eggs. The largest redd measured was 8.12 m^2 and established by a female estimated to be 888 mm in length with a fecundity of over 10 000 eggs. We acknowledge that the values presented here are coarse calculations, however the dramatic variation in fecundity among females could lead to large variation in juvenile recruitment and population dynamics in future years. The error surrounding the unaccounted-for variation in egg number among females within and among streams is likely larger than any error in the number of redds.

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7 Appendix

Appendix 1. Counts of spawning Bull Trout during ground and aerial surveys.

		Number of Bull Trout	
Stream	**Survey**	**Ground**	**Aerial**
Chowade	1	0	80
	2	11	165
	3	31	36
	4	2	7
	5	0	1
Cypress	1	1	0
	2	0	1
	3	0	0
	4	0	2
	5	0	0
Fiddes	1	0	0
	2	0	3
	3	0	1
	4	2	0
	5	0	0
Turnoff	1	0	0
	2	0	0
	3	0	0
	4	0	0
	5	0	0
Upper Halfway	1	0	6
	2	0	6

		Number of Bull Trout	
Stream	Survey	Ground	Aerial
	3	3	0
	4	0	1
	5	0	0

Appendix 2. Sensitivity of GAUC estimates to the addition of zero counts before the first survey and after the last survey. Mean estimates and standard errors are presented.

	Abundance			
Stream	**Zeros at start and end**	**Zero at end**	**Zero at start**	**No zeros**
Chowade	290 (62)	291 (72)	302 (55)	310 (27)
Cypress	90 (19)	90 (23)	98 (16)	98 (9)
Fiddes	107 (41)	110 (42)	107 (42)	113 (39)
Turnoff	44 (17)	44 (17)	44 (17)	44 (15)
Upper Halfway	20 (5)	21 (7)	21 (6)	31 (3)