Columbia River Water Use Plan

Lower Columbia River Fish Management Plan

Lower Columbia River Rainbow Trout Spawning Assessment

Implementation Year 8

Reference: CLBMON-46

Study Period: January to July 2015

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LOWER COLUMBIA RIVER RAINBOW TROUT SPAWNING ASSESSMENT 2015

WLR Monitoring Study

CLBMON-46 (Year 8)

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February 2, 2016 – Final Report

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Cover Photos: Lower Columbia River Rainbow Trout Spawning Assessments (HLK Dam, Rainbow Trout DNA sampling, and aerial view of the Norn's Fan spawning area).

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EXECUTIVE SUMMARY

Each spring in the Lower Columbia River (LCR) below Hugh L. Keenleyside Dam (HLK) and in the Lower Kootenay River (LKR) below Brilliant Dam, thousands of Rainbow Trout (*Oncorhynchus mykiss*) spawn. Since 1992, BC Hydro has stabilized the spring discharge releases from HLK to protect Rainbow Trout redds from dewatering. Prior to the 1992 implementation of the spring operational regime (April 1-June 30) of stable or increasing flows known as the Rainbow Trout Spawning Protection Flows (RTSPF), the discharge from HLK Dam decreased during the March to May period. This resulted in Rainbow Trout redds being dewatered and possible population level effects.

The current Rainbow Trout spawning assessment monitoring program, which commenced in 2008, was implemented to better understand the links between the spring flow regime and the abundance of the Rainbow Trout population and to assess population trends in this ecologically and recreationally important species. In 2015, nine helicopter surveys and sixteen boat surveys were conducted to count redds and spawners, obtain samples for DNA collection of early and peak spawners and to determine the presence and location of shallow redds at risk of dewatering. The regulatory agencies have granted BC hydro permission to dewater up to 1% of the average estimated annual redd abundance annually and only salvage after this level is exceeded. This threshold has not been reached in the past three years. In 2015, there were 52 dewatered redds observed. The Rainbow Trout abundance was estimated at 14,920 fish, which was an increase from 2014 and continued the positive trend in Rainbow Trout abundance that has occurred since 1999. The estimated residence time for fish on the spawning grounds was 14.9 days and there was a slight increasing trend in the spatial distribution of fish throughout the river over the study's duration. The mean redd dewatering rate was 1.2% from 1999-2015. There was a strong positive correlation found between the number of age-1 recruits and the percentage of dewatered redds. This may seem counter-intuitive unless the conditions that lead to higher rates of dewatering are coincident with conditions that may benefit young rainbow trout (e.g., environmental or flow variables such as habitat and river stage associated with higher dewatering rates are more optimal for rearing). The spatial distribution of Rainbow Trout throughout the study area has gradually increased through time with more habitats potentially being used as preferred areas achieve saturation. Rainbow Trout spawning select habitats where velocities range from 0 to 1.4 m/s with peak spawning activity at a velocity of ~0.6 m/s and depth ranges from 1 to 1.5 m with peak habitat suitability curve values at ~1.1 m depth.

The current knowledge relative to the defined management questions of CLBMON-46 is summarized in the table below. To address the two unanswered management questions, well-designed scientific studies are needed to assess the effects of altering the timing and magnitude of the RTSPF.

Objectives	Management Questions	Year 8 (2015) Status
Assess changes in the relative abundance, distribution and spawn timing of Rainbow Trout in the lower Columbia River	1. Does the implementation of RTSPF over the course of the monitoring period lead to an increase in the relative abundance of Rainbow Trout spawning in the LCR downstream of HLK?	The number of Rainbow Trout spawners and redds has increased ~10-fold since 1999; the increase continued in 2015. RTSPF may be responsible for this increase. Further exploration of the relationship between dewatering and age-1 recruits may clarify the role of river stage and discharge in influencing abundance.
	2. Does the implementation of RTSPF over the course of the monitoring period lead to an increase in the spatial distribution of locations (and associated habitat area) that Rainbow Trout use for spawning in the LCR downstream of HLK?	The spatial distribution of Rainbow Trout spawning has increased since 1999. This may be related to an increase in the number of Rainbow Trout spawners, but since the effects of the RTSPF on Rainbow Trout abundance are still unclear, this management question cannot be answered definitively at present (Thorley and Baxter 2011; Appendix C).
	3. Does the implementation of RTSPF over the course of the monitoring period protect the majority of Rainbow Trout redds (as estimated from spawning timing) from being dewatered in the LCR downstream of HLK?	Yes. Over all years of analysed data, the mean stranding rate of redds has been 1.2%, as compared to the estimated 50-75% stranding rate noted in shallow water habitat on Norn's Fan in 1990 and 1991 prior to implementation of RTSPF.

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ABBREVIATIONS

Abbreviations used throughout the report:

Abbreviation	Full Name
2D	Two Dimensional
ALH	Arrow Lakes Hydro unit
ALR	Arrow Lakes Reservoir
AUC	Area-Under-the-Curve
BCH	BC Hydro
BRX	Brilliant Expansion Project
BIR	Birchbank Gauging Station
BRD	Brilliant Dam
HLK	Hugh L. Keenleyside Dam
KHz	Kilohertz Frequency
LCR	Lower Columbia River
LDR	Lower Duncan River
LKR	Lower Kootenay River
MAF	Million Acre Feet
MFLNRO	Ministry of Forest Lands & Natural Resource Operations
PIT	Passive Integrated Transponder
RB	Rainbow Trout
RTSPF	Rainbow Trout Spawning Protection Flows
TOR	Terms of Reference
WLR	Water Licence Requirements
WUP	Water Use Plan

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

1.0 INTRODUCTION

The Rainbow Trout (*Oncorhynchus mykiss*) population in the Lower Columbia River (LCR) between Hugh L. Keenleyside (HLK) dam and the U.S. border and in the Lower Kootenay River (LKR) below Brilliant Dam (BRD) has been studied extensively since the early 1990s. Studies have focused on the assessment of effects of hydro-electric dam operations on various life history parameters, genetics, spawn timing, habitat use, and population trends and dynamics. (Heaton and Hildebrand 1997a, 1997b, Arndt 2000, Taylor 2002, Arndt and Klassen 2004, Ford and Hildebrand 2007, Baxter 2011). A brief summary of the previous studies on the Rainbow Trout in this section of the Columbia River can be found in Irvine et al. (2014).

Prior to 1992, HLK discharge typically decreased from March to May resulting in Rainbow Trout redd dewatering and potential population level effects (Hildebrand and McKenzie 1995, Thorley and Baxter 2011). BC Hydro therefore altered the spring HLK operations to keep river levels stable or increasing from April 1 to June 30 and agreed to consult with the government agencies regarding the timing and rampdown method from the Mountain Whitefish protection flows to Rainbow Trout protection flows at the beginning of April (BC Hydro 2005, Ford et al. 2008). The Rainbow Trout Spawning Protection Flows (RTSPF) have occurred annually since 1992 (BC Hydro 2007) and have been effective at significantly reducing the cumulative elevational drops in the Lower Columbia River (Larratt et al. 2013).

Various programs have monitored Rainbow Trout redds in shallow water areas since 1992 to identify redds at risk of dewatering. From 1999-2012, dewatered redds were excavated as a matter of course after each major flow reduction and the salvaged eggs were transferred to suitable, wetted gravels to minimize egg mortality (Baxter 2010a, 2010b, 2011). Since 2013, the regulatory agencies have granted BC hydro permission to dewater up to 111 redds, or 1% of the estimated annual redd abundance (1999-2011), annually and only salvage after this level is exceeded. Since the redd salvage program concluded in 2012, the number of redds dewatered in the past three years has not exceeded the threshold. The number of dewatered redds was monitored by BC Hydro staff in 2014 and 2015.

The level of redd stranding prior to the implementation of protection flows in 1992 is not well defined due to limited studies quantifying redd dewatering. The only data from pre-RTSPF flows where the stranding was estimated, found stranding rates of 50-75% in shallow water habitat on Norn's Fan in 1990 and 1991 (Hildebrand and McKenzie 1995, Irvine et al. 2014). The mean stranding rate of redd dewatering over all years of protection flow data (1999-2015) was 1.2%.

The primary objective of the present program is to monitor the status of the Rainbow Trout population in order to better understand the link between flow management strategy and population abundance and to propose and monitor testing of other flow strategies (BC Hydro 2007). It is important to consider alternatives to the established format of the RTSPF flow strategy as its implementation requires ~1 million acre-feet of retained storage in Arrow Lakes Reservoir (ALR) that is released in summer. Minimizing the volume of water stored in ALR, delaying the onset of storage and quickly releasing the additional storage could improve vegetation survival and increase littoral productivity and wildlife habitat (BC Hydro 2007).

The spawner assessment program has occurred in various formats each year since 1999. The program annually monitors spawn timing, location and spawner abundance in order to address the primary objective of the program which "*is to continue the collection of annual Rainbow Trout monitoring data to qualitatively and quantitatively assess changes in the relative abundance, distribution and spawn timing of Rainbow Trout in the lower Columbia River*" (BC Hydro 2007 p.3) and to address the specific management questions outlined below.

Long term monitoring of the LCR RB population continues to be of vital importance due to ongoing changes in the river's natural and operationally altered environment. Current questions of relevance to the health and sustainability of the RB population in the LCR include, but are not limited to, the impact of the invasive species such as Northern Pike (*Esox lucius*), the influence of the very prevalent Didymo (*Didymosphenia geminata*) mats that now exist in the river, the influence of increased angling pressure as a result of the Kootenay Lake fisheries collapse, and the effects of thousands of hatchery released White Sturgeon (*Acipenser transmontanus*) as they form a large adult population. While the long term fish indexing study on the LCR provides key data on a number of important parameters including growth rate, body condition, and spatial distribution of Rainbow Trout, Walleye and Mountain Whitefish fish in this section of the river, the low recapture rates may be limiting the program's ability to detect population trends (Ford et al. 2013). In addition, as densities of fish have increased in the river, the netters on an electrofishing boat may reach a saturation point where they cannot net any additional fish despite seeing more fish. The trial georeferenced visual enumeration program that has been in place since 2013 may provide data to test whether saturation of netting is indeed occurring on the Lower Columbia. In this regard, the RB spawning monitoring program is currently a more robust program for determining adult Rainbow Trout trends as the proportion of the population observed is higher.

The following management questions are the focus of the LCR RB spawning assessment program:

1) Does the implementation of RTSPF over the course of the monitoring period lead to an increase in the relative abundance of Rainbow Trout spawning in the LCR downstream of HLK?
2) Does the implementation of RTSPF over the course of the monitoring period lead to an increase in the spatial distribution of locations (and associated habitat area) that Rainbow Trout use for spawning in the LCR downstream of HLK?
3) Does the implementation of RTSPF over the course of the monitoring period protect the majority of Rainbow Trout redds (as estimated from spawning timing) from being dewatered in the LCR downstream of HLK?

The TOR state that these three management questions will be answered by testing three key hypotheses:

H_{01}: The relative abundance of Rainbow Trout spawners or redds in the Columbia River mainstem does not increase between the baseline period (1999 to 2006) and the WUP monitoring period associated with the continued implementation of RTSPF.

H_{02}: The spatial distribution of locations and the associated habitat area that Rainbow Trout spawners use in the Columbia River mainstem does not increase between the baseline period (1999 to 2006) and the WUP monitoring period associated with the continued implementation of the RTSPF.

H_{03}: The proportion of redds dewatered relative to the total redd production for Rainbow Trout spawning in the Columbia River mainstem does not increase between the baseline period (1999 to 2006) and the WUP monitoring period associated with the continued implementation of the RTSPF.

In order to achieve the program's primary objective, the population's response to alternative discharge regimes also needs to be understood since the annual studies on this population have mainly been conducted with the same flow regime in each year. Discussions were begun on this topic in 2012, but have not yet coalesced into study designs (Baxter 2012) to implement an alternate spring flow regime in the future and assess the impacts on the Rainbow Trout population. The experimental approach has been successful at teasing apart mechanisms behind population trends in other systems such as the Colorado (Korman et al. 2011).

2.0 METHODS

2.1 Mainstem Spawner and Redd Surveys

The mainstem portions of the Canadian LCR below HLK and the LKR below BRD (Figure 1) have been surveyed from helicopter approximately once a week during the spawning season since 1999 and the numbers of redds and spawners recorded by location. Prior to commencing helicopter surveys, boat surveys are done to ensure spawning has begun.

The major gravel areas on the LCR and in the LKR are known by name and river kilometre, and all areas are surveyed during the flights. In 2014 and in 2015, the section of river with the lowest density of spawners (from Genelle to the U.S. border) was not surveyed in order to save flight budget. Because of minimal numbers of spawners and redds in this section of river in all years of survey, this section was excluded from all analyses. The helicopter surveys are supplemented by the use of boat surveys, which cover the main spawning areas from Norn's Creek Fan to the lower island at Genelle. The boat surveys allow the identification of redds that are questionable from the air, the noting of redds in less than 1.0 m of water to monitor the risk of dewatering and the confirmation of possible new spawning areas seen from the air (Baxter 2011).

In 2015, nine aerial surveys were completed in a twin engine helicopter and each aerial survey was followed by a boat survey (Table 1). As in previous surveys the spawners and redds were enumerated by two experienced observers situated on the same side of the helicopter with one person responsible for counting redds and the other for counting spawners. Boat surveys without aerial surveys were conducted to assess the onset of spawning and assess shallow water redds on January 30, February 13 and May 19 and for DNA collection to assess the possibility of genetic differences between early and peak spawners on March 17, 20 and April 21 (Table 1). The number of days between helicopter surveys during the 2015 field season ranged from 23 to 6 with 9.5 days on average between surveys. The large gap between the first and second survey were due to helicopter maintenance and the absence of the regular pilot as well as low spawner numbers that did not necessitate a closely placed survey. During the final survey on May 11, 2015, the visibility was noted as poor in all sections so no further helicopter surveys were completed after that date.

Table 1. Helicopter and boat based redd survey, DNA collection and shallow water survey schedule for 2015.

Date	*Survey Type(s)*
January 30	Spawner onset and shallow water boat survey
February 13	Spawner onset and shallow water boat survey
February 24	Twin engine helicopter, Boat survey
March 17	DNA Collection Boat EF (Genelle)
March 19	Twin engine helicopter, Boat survey
March 20	DNA Collection Boat EF (Genelle)
March 27	Twin engine helicopter, Boat survey
March 31	Shallow water boat survey
April 2	Twin engine helicopter, Boat survey
April 11	Twin engine helicopter, Boat survey
April 18	Twin engine helicopter, Boat survey
April 21	DNA Collection boat EF (Norn’s)
April 24	Twin engine helicopter, Boat survey
May 2	Twin engine helicopter, Boat survey
May 11	Twin engine helicopter, Boat survey
May 19	Shallow water boat survey

2.2 Norn’s Creek Spawner and Redd Surveys

Spawner and redd surveys are conducted in Norn’s Creek when time, resources and conditions permit. It is a major spawning tributary and a significant contributor for Rainbow Trout recruitment in the LCR. The surveys were not conducted in 2015 to allow budget to be allocated to DNA analysis for sexing of fish tagged in 2012.

2.3 Redd Dewatering Surveys

Redd dewatering surveys in the past were implemented as part of a separate project, but in conjunction with the boat surveys of CLBMON-46. Although locations of shallow water redds with the potential to dewater have continued to be recorded by CLBMON-46 crews during the boat surveys in 2014 and 2015, the surveys identifying the numbers of redds dewatered have been completed by BC Hydro staff for the past two years. Redd dewatering estimates for 2015 were provided by BC Hydro staff based on one survey at the beginning of April. A standardized survey approach developed in conjunction with regulatory agencies that is utilized by whomever is conducting the dewatering surveys including the collation of data in a database and reduction thresholds at which surveys would be triggered would increase the robustness of the program.

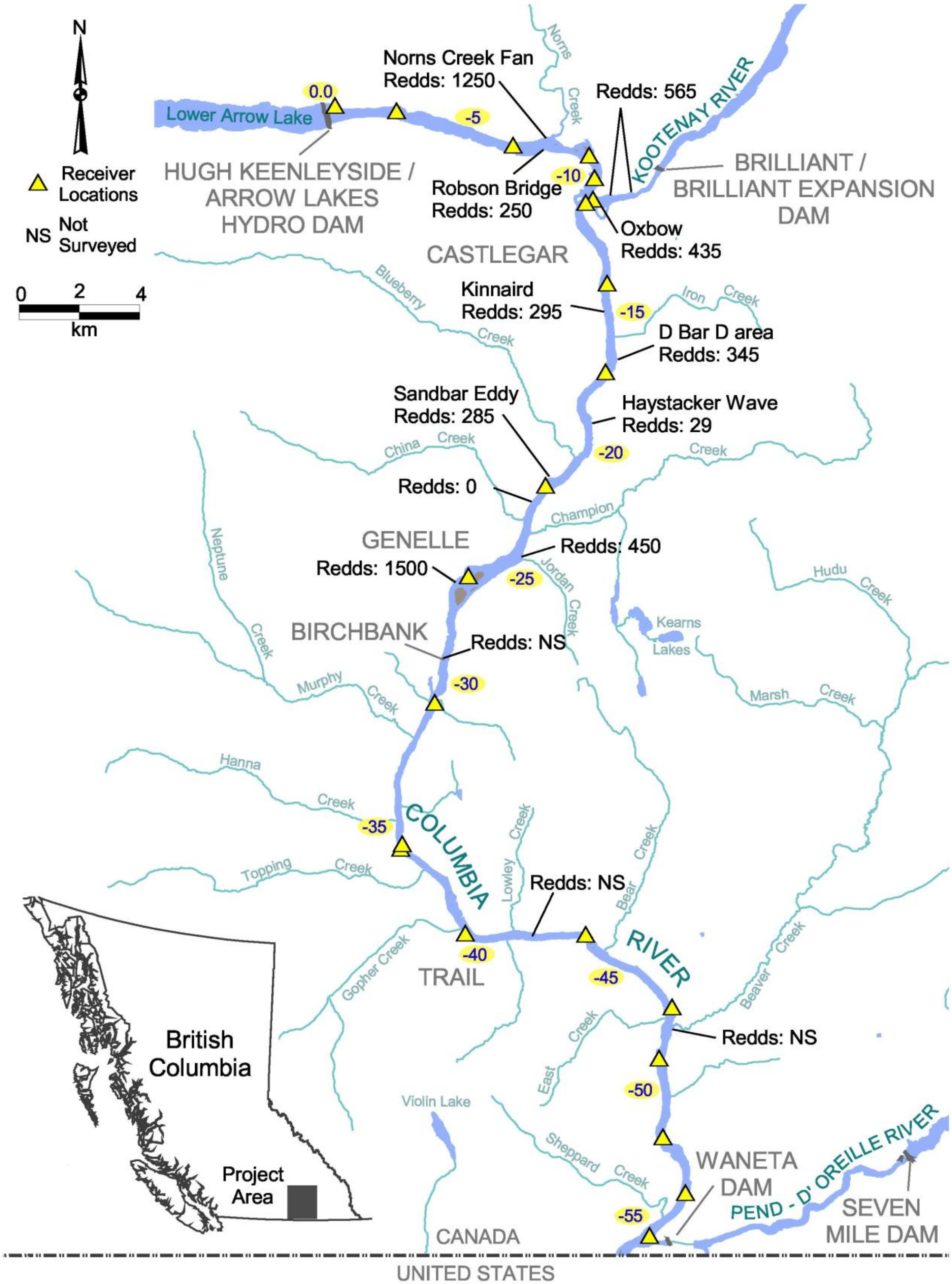

Figure 1. **Study area for the Rainbow Trout spawning assessment program within the Lower Columbia and Lower Kootenay Rivers. The yellow numbers indicate river kilometre downstream of HLK dam and NS refers to areas that were not surveyed.**

2.4 Acoustic Telemetry

To collect information on Rainbow Trout spawn timing and residence time, 16 adult Rainbow Trout were tagged in the fall of 2010 and 20 adults were tagged in 2012 with Vemco V13-1x-A69-1303 69 KHz tags and PIT tags. The biometric and capture data for the fish tagged in 2012 are summarized in Irvine et al. (2013) and the equivalent data for fish tagged in 2010 can be found in Thorley and Baxter (2012). The spawner residence time was modelled this year utilizing the 2011-2014 acoustic data and a Generalised Linear Model – details are described in the section below on estimating spawner and redd abundance.

The tag type and frequency were utilized to make use of the existing array of acoustic receivers maintained by BC Hydro in the LCR mainstem to detect tagged White Sturgeon (*Acipenser transmontanus*) and additional receivers were deployed in Norn's Creek and fan from 2011-2014 to focus detections on this important spawning location (Table 2). The locations of the 28 acoustic receivers are mapped in Figure 1. Because the fish were tagged as spawning adults, the probability of natural or angling mortality occurring in 1-3 years was high. Despite the 4.6 y battery life, the number of tags detected in each year declined significantly with less than half the tags detected in 2014 as in 2013. Therefore, the decision was made to not deploy additional receivers in the Norn's area in 2015. The acoustic receiver data from the BC Hydro maintained array to look at RB movements throughout the system have not yet been provided so these data have not been analyzed. If the data are provided in a timely fashion from BC Hydro, next year's report will include the analysis of these data.

DNA samples (caudal fin clips) were taken at the time of capture in 2012 and were processed in January, 2016 to attempt to sex the tagged fish in order to potentially refine residence time estimates in future analyses and assess if they differ between males and females. The results of the sexing analysis are presented here and will be assessed next year to determine if they can be used to improve the residence time model (Table 3).

Table 2. Vemco VR2W receiver deployment information by year. The receivers deployed in Norn's Creek in 2014 are denoted by NC.

Year	Number of Receivers	Date Deployed	Date Retrieved
2011	3	April 8	May 31
2012	1	February 9	June 2
2013	1	March 4	May 30
2014	1	February 22	May 30
2014	2	March 29(NC)	May 30
2015	0	NA	NA

Table 3. The sex of the twenty Rainbow Trout acoustically tagged in 2012 as determined from caudal fin DNA.

Fish Number	*Sex*
1	F
2	F
3	M
4	F
5	F
6	M
7	M
8	F
9	F
10	M
11	F
12	F
13	M
14	F
15	M
16	M
17	F
18	F
19	M
20	M

Spawner and Redd Abundance and Spawn Timing

2.4.1 Data Preparation

The Rainbow Trout fish and redd aerial count data for the LCR and LKR were collected by Mountain Water Research and databased by G. Pavan. Golder Associates provided the age-1 Rainbow Trout abundance data from the LCR Fish Population Indexing Program (CLBMON-45) database.

The study area was divided into three sections: the LCR above the LKR, the LKR and the LCR below the LKR. Redd and spawner counts upstream of Norns Creek Fan and downstream of Genelle were excluded from the section totals because they constitute less than 0.1% of the total count and were not surveyed every year. The redd and spawner counts for the right bank (looking downstream) above Robson Bridge were also excluded as they appear to be primarily driven by viewing conditions (and constitute less than 2.5% of the total). A decline in the redd count of more than one third of the previous maximum count for a particular section was inferred to be caused by poor viewing conditions (turbidity) and the affected spawner and redd section counts were excluded from any subsequent analyses.

2.4.2 Data Analysis

In order to estimate spawner and redd abundance as well as spawn timing of Rainbow Trout in the LCR throughout the spawning period over all years with applicable data, hierarchical Bayesian Area-Under-the-Curve (AUC) models were fitted to the aerial spawner and redd counts combined. For the purposes of the analyses the abundance was estimated for each of the three sections (the LKR below BRD, the LCR above the LKR, and the LCR below the LKR).

The spawner residence time informing the AUC model was extracted from acoustic detection data collected from 2011-2014 using a Generalised Linear Model. An acoustically tagged fish was considered to be resident on a particular day between March 7th and May 31st if it was detected by the Norns Creek receiver at location 1 for at least three hours (with at least three detections in each hour) between 8:00 and 12:00 (which corresponds to the general timing of the surveys). This is an update on the previous usage of spawner residence timing extracted from Lower Duncan River data (Thorley et al. 2010). The key assumption of the residence time model was that the residual variation in spawner residence time is log-normally distributed.

Key assumptions of the AUC model included:

- Spawner and redd arrival and departure times are normally distributed.
- Spawner abundance varies by river section.
- Spawner abundance varies randomly by year and section within year.
- Spawner observer efficiency is between 0.9 and 1.1 (where values greater than 1 indicate overcounting)
- Peak spawn timing varies randomly by year.
- Spawning duration varies by river section.
- Mean spawner residence time is as determined by the Acoustic Detection model which had a prior distribution based on a peak residence time of 11 days and a standard deviation of 3.1 days.
- Redd observer efficiency is between 0.9 and 1.1, (where values greater than 1 indicate overcounting)
- The number of redds per spawner is a fixed constant.
- The residual variations in the spawner and redd counts are described by separate overdispersed Poisson distributions.

The models' variables, parameters, distributions and assumptions are fully described in the online appendix and in Appendix C in this document. The online analytic memo can be found at: http://www.poissonconsulting.ca/f/1611032936.

2.5 Spatial Distribution of Spawners

The proportions of spawners at each site were used to calculate the Shannon Index, an information-theoretic measure of the diversity in the abundance distribution of a resource (Krebs 1999). In the current context, the Shannon Index takes into account both the number of spawning sites and how the spawning activity is distributed among these, with a higher index indicating a greater spatial distribution of spawning. A higher index value indicates spawners more equally spread amongst more sites.

The Shannon Index (H) is given by:

$$H = -\sum p_i log(p_i)$$

Where, p_i is the proportion of the spawning activity at the i^{th} location.

2.6 Fry Emergence Timing

The expected annual emergence timing was calculated from the estimated spawn timing and the surface water temperature at Norn's Creek Fan under the assumption that Rainbow Trout embryos require 480 accumulated thermal units (ATUs) to reach the emergence stage. Water temperature data have been collected at the gauging station on Norn's Creek Fan since 1999 and consistently throughout the year since 2000 though in some years there are missing data. In 2009, temperature loggers were buried in the gravels at depths of 0.15 m and 0.30 m from May to August at the Norn's Creek Fan site. Comparison of these two hyporheic temperatures with the surface water temperature suggested that surface water temperatures approximate the ATUs experienced by the developing embryos.

2.7 Stock-Recruitment Relationship

There are three main sources of data for Rainbow Trout stock recruitment in the LCR: the spawner counts, the redd counts (e.g., Irvine et al. 2013) and the boat electrofishing captures (Ford et al. 2012). All three data types have historically been sampled over the LCR from HLK dam to the U.S. Border and in the ~1.8 km of the lower Kootenay River below Brilliant Dam. Previous genetic work shows that the fish in the Kootenay and the Columbia interbreed readily so they are considered the same population for the purposes of assessment (Taylor 2002).

In order to examine the relationship between spawners and recruits, the indexing program's mark-recapture-based estimates of age-1 Rainbow Trout abundance (Ford et al. 2012) were plotted against the previous year's AUC-based spawner abundance estimates and the relationship was assessed using a Beverton-Holt stock-recruitment model.

Key assumptions of the stock-recruitment model include:

- The prior probability distribution for the maximum number of recruits per spawner (R0) is normally distributed with a mean of 90 and a SD of 50.
- The residual variation in the number of age-1 recruits is log-normally distributed.
- The prior probability distribution mean of 90 for R0 was based on an average of 2,900 eggs per female spawner, a 50:50 sex ratio, 50% egg survival, 50% post-emergence fall survival, 50% overwintering survival and 50% summer survival (Allen and Sanger 1960, Hildebrand and McKenzie 1995, Thorley 2009).

Models were fitted to the data using R version 3.2.2 (R Core Team 2015) and JAGS 3.4.0 (Plummer and Northcott 2013) which interfaced with each other via jaggernaut 2.3.1 (Thorley 2013). For additional information on hierarchical Bayesian modelling in the BUGS language, of which JAGS uses a dialect, the reader is referred to Kery and Schaub (Kéry and Schaub 2011).

2.8 General Analytic Approach

Unless indicated otherwise, the models used prior distributions that were vague in the sense that they did not affect the posterior distributions (Kery and Schaub 2011). The posterior distributions were estimated from a minimum of 1,000 Markov Chain Monte Carlo (MCMC) samples thinned from the second halves of three chains. Model convergence was confirmed by ensuring that Rhat was less than 1.1 for each of the parameters in the model (Kery and Schaub 2011).

The posterior distributions of the fixed parameters are summarised in terms of a point estimate (mean), lower and upper 95% credible limits (2.5th and 97.5th percentiles), the standard deviation (SD), percent relative error (half the 95% credible interval as a percent of the point estimate) and significance (Kery and Schaub 2011). Variable selection was achieved by dropping insignificant fixed variables and uninformative random variables. A fixed variable was considered to be insignificant if its significance was 0.05, while a random variable was considered to be uninformative if its percent relative error was 80%. The Deviance Information Criterion (DIC) was not used because of its questionable validity when applied to hierarchical models (Kery and Schaub 2011).

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

3.0 RESULTS

3.1 Mainstem LCR and LKR Spawner and Redd Abundance and Spawn Timing

The spawner and redd counts from the eight aerial surveys conducted in 2015 were analyzed together to produce abundance estimates by year and annual spawn timing estimates (Figure 3). The estimated abundance of Rainbow Trout for 2015 was 14,920 fish (95% CI 9,090 – 27,050). This is an increase of 1,260 fish from the 2014 estimate of abundance and an increase of 3,260 from the 2013 estimate. The visual trend is that the estimates are becoming more uncertain, however, the percent relative error is well within the range over all sampled years in the 2013-2015 period with the 2015 having a 60% relative error (range 58-76%). The perceived increase in uncertainty is in part due to the fact that the error is scaled to the absolute abundance levels. The upward trend in spawner numbers continued this year with some slowing in the increase (i.e., the difference between 2015 and 2014 is less than that between 2014 and 2013) (Figure 2).

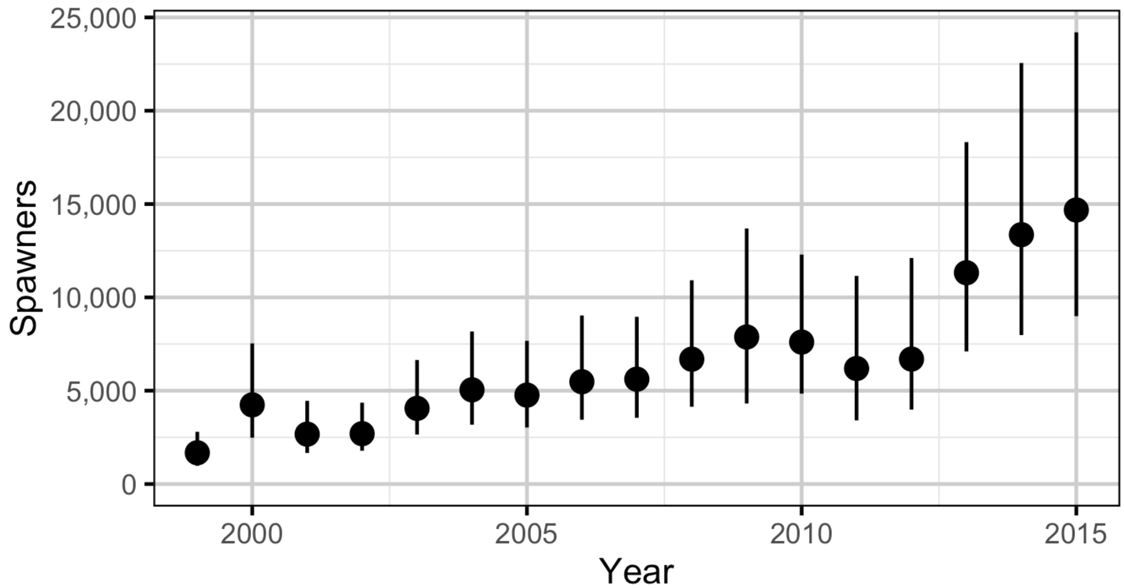

Figure 2. **Annual estimates of abundance of Rainbow Trout spawners in the LCR below HLK dam and the LKR below Brilliant Dam from 1999-2015 with 95% credible intervals.**

The spawn timing for three stages of spawning within the spawning period were estimated with 95% credibility intervals for each period (start, peak, end) from spawner and redd surveys for 2015. The start of spawning was estimated to be on March 2 (95% CI Feb 25 - March 8), the peak spawning had an estimated mean date of May 2 (95% CI April 26 – May 9), and the end of spawning had an estimated mean date of June 19 (95% CI June 8 – June 29) (Figure 3). The spawner and redd counts for 2015 are mapped in Appendix A. The spawner and redd counts for the study area's three sections, their AUC estimates and viewing conditions are plotted in Appendix B.

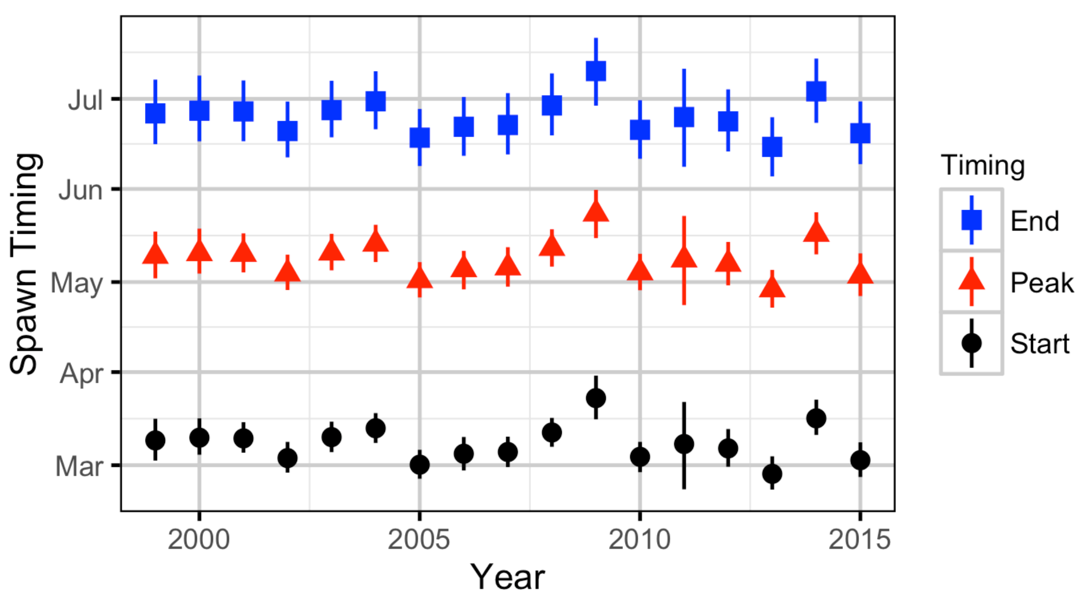

Figure 3. **Annual estimates of peak, start and end of spawn timing of Rainbow Trout in the LCR below HLK dam and the LKR below Brilliant Dam from 1999-2015 with 95% credible intervals plotted for each timing category.**

3.2 Spatial Distribution of Spawners

The percent of peak spawner count by river kilometre shows relatively similar distributions among years with the exception of a spike in the percentage of fish in the river section of the Columbia above the Kootenay confluence in 2012 (Figure 4).

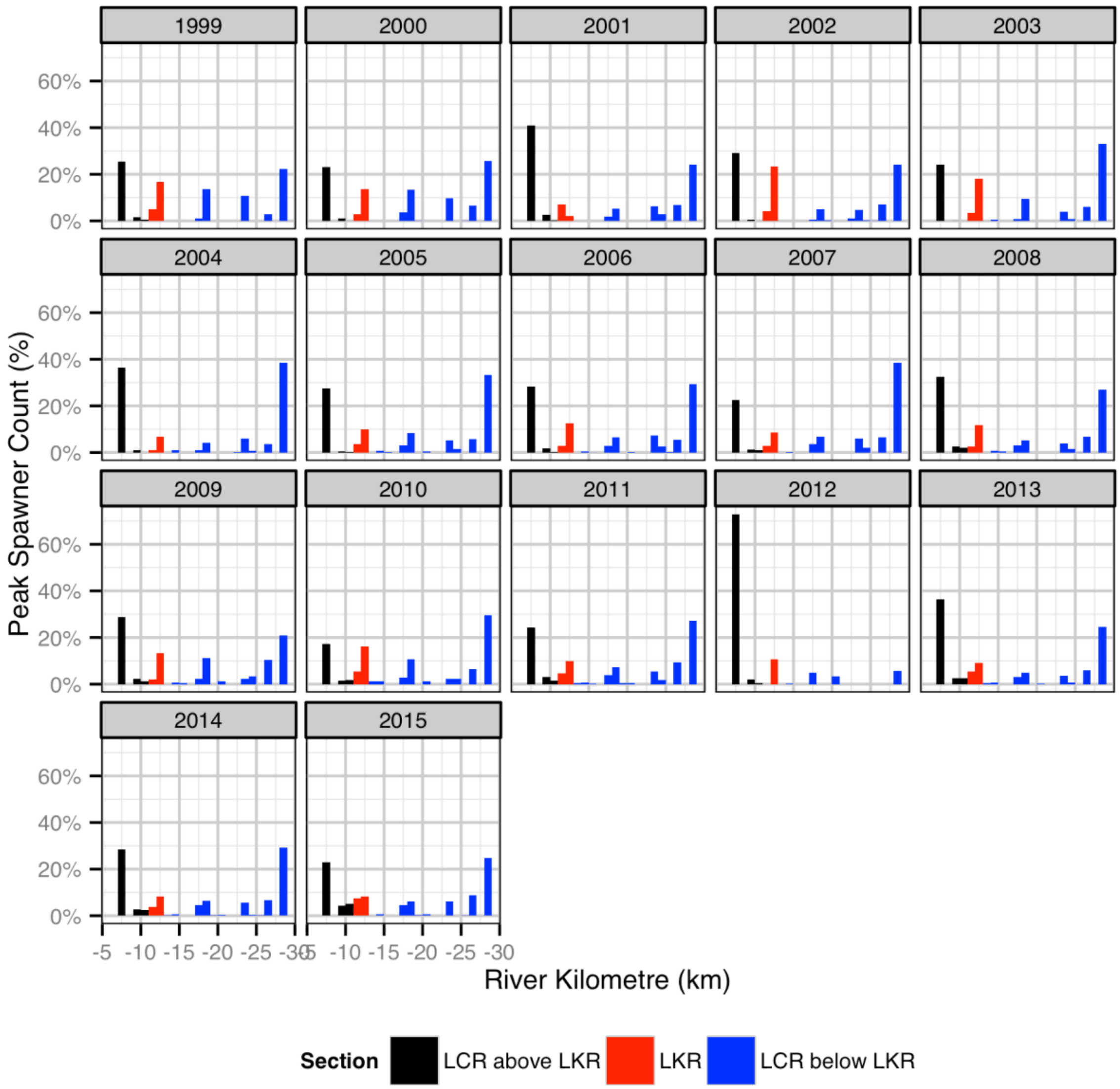

Figure 4. **Percent of peak spawner counts by river kilometre and year and coded by river section with the mainstem Columbia above the Kootenay confluence in black, the Kootenay River in red and the Columbia below the Kootenay confluence in blue.**

A higher Shannon index value indicates a greater spatial distribution of the spawning Rainbow Trout throughout the sites in the river. The trend through time has been for a gradual increase in the spatial distribution of the spawners from 1999 – 2015 with the most dispersed distribution in 2015. It should be noted that the positive trend is subtle and there is not a large change in the spatial distribution from start to finish of the time series (Figure 5).

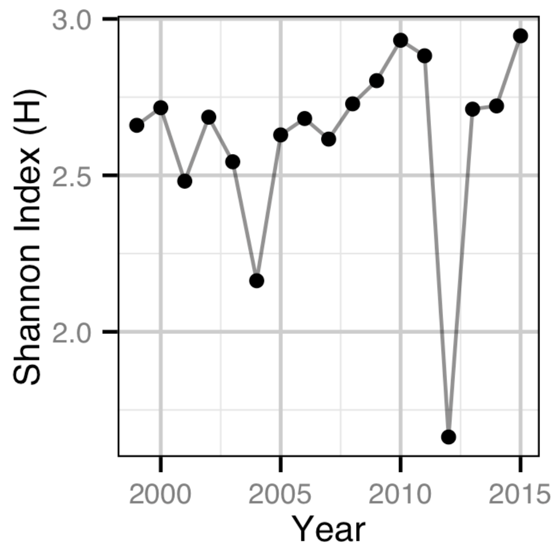

Figure 5. Shannon index values for the spatial distribution of Rainbow Trout spawners by year.

3.3 Redd Dewatering

During 2015 no redds were salvaged. Redds were surveyed by BC Hydro staff in a single survey at the start of April to determine the number and percentage that were in shallow water habitat and either dewatered or at risk of dewatering if a reduction event should happen. The biologists at MFLNRO and DFO decided not to excavate and salvage redds until 1% of the mean annual redd abundance from 1999-2011 (i.e., 111 redd threshold) was reached. In total, 52 redds were reported to have been dewatered in the 2015 spawn year which was estimated to be 0.05 % of the total redds (Table 4). When the annual dewatering rate for each year was averaged over the fifteen years for which there were data, the mean percentage of dewatered redds was 1.2% and ranged from near zero to 3.8% (Figure 6).

Table 4. Dewatered redd abundance from 2013-2015.

Year	Number of Dewatered Redds	Observer
2013	97	MWR
2014	77	BCH
2015	52	BCH

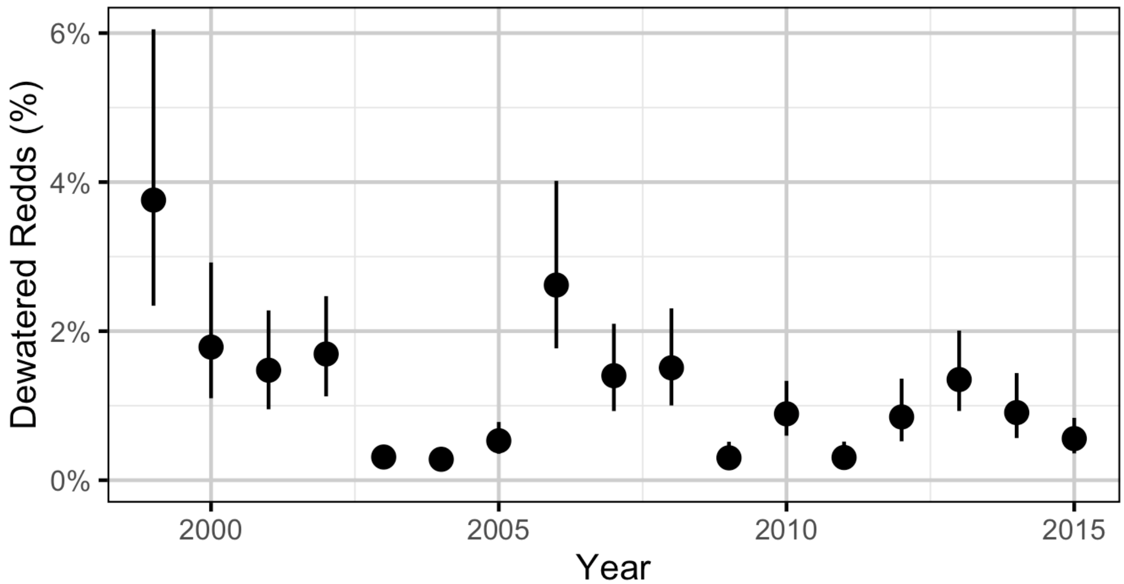

Figure 6. **Percentage of redds dewatered in the Lower Columbia River below Hugh L. Keenleyside Dam and the Kootenay River below Brilliant Dam by year from 1999 to 2015. The bars represent 95% credible intervals.**

3.4 Fry Emergence Timing

The fry emergence timing estimates use the results of the spawn timing model (Section 3.1) and water temperatures. To provide a representative water temperature, the metric used in the model averaged the daily temperatures recorded at Norn's Creek Fan with those recorded at Birchbank gauge for the calculation of the ATUs. When only a single water temperature gauge was operational, the single source value was used to have as continuous a data source as possible. The averaged water temperatures were plotted with the mean and the range of temperatures throughout the spawning and emergence periods to describe trends (Figure 7). The water temperature reaches 5°C in mid-April on average, a temperature associated with the advent of spawning in other systems (Thorley et al. 2012). On average, the water temperature reaches 17°C by the end of July and in some years this temperature is reached as early as the first week of July. This is a temperature associated with increased embryonic mortality (Humpesch 1985) (Figure 7).

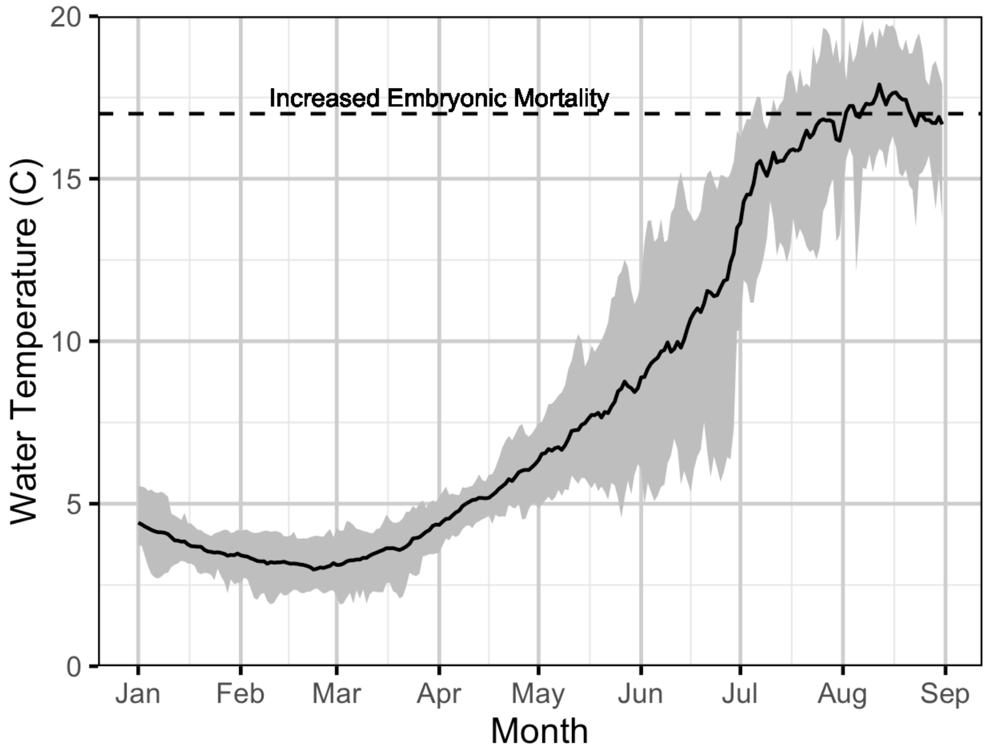

Figure 7. **Mean daily surface water temperature at Norn's Creek Fan from January to September for the years 2000 to 2015 with the range of spawning and emergence dates demarcated. The black line indicates the average temperature, while the grey band indicates the range.**

When predicting emergence timing, a similar approach was used as for determining the spawning timing where three periods of spawning (start, peak, and end) were delineated and estimates and 95% credibility intervals were derived for each period. The mean estimate of peak fry emergence for the 2015 spawn year was June 16 (95% CI June 13 – June 20) (Figure 8). The mean estimate for the start of fry emergence was unable to be estimated due to missing temperature data. The end period of fry emergence was estimated at July 19 (95% CI July 10 – July 28). It is important to note that the last fry may not emerge until mid-August as the upper 95% credibility interval for 2009 was August 18^{th} and for 2011 was August 12^{th} (Figure 8, Irvine et al. 2014).

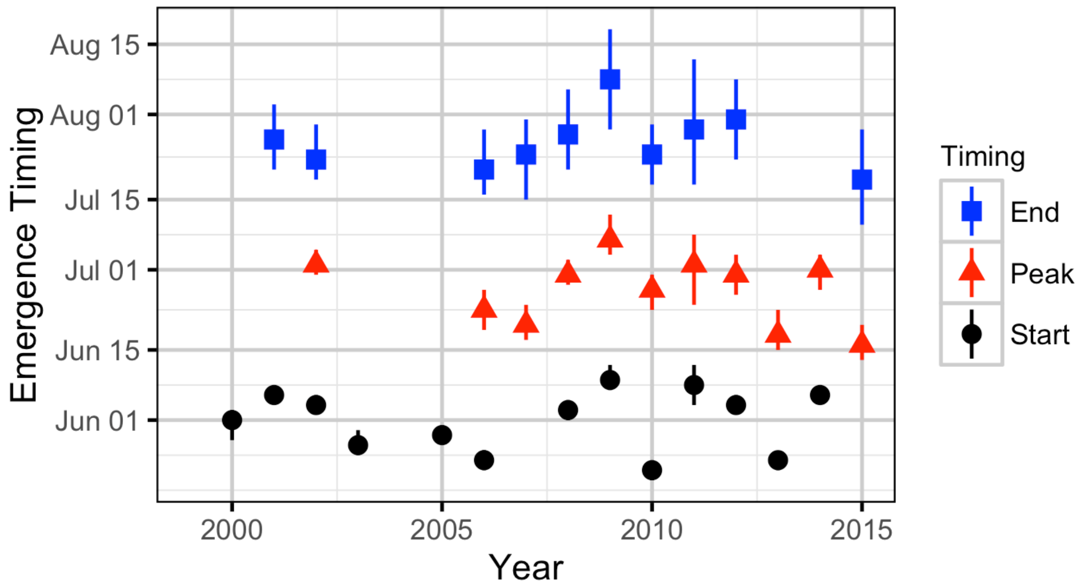

Figure 8. **Annual estimates of the timing of emergence of Rainbow Trout fry from 2000 to 2015 in the Lower Columbia River below Hugh L. Keenleyside dam and the Lower Kootenay River below Brilliant Dam. The bars indicate the 95% credibility intervals for each estimated timing point. The estimates are derived from the spawner and redd counts and surface water temperature at Norn's Creek Fan.**

3.5 Stock-Recruitment Relationship

The Beverton-Holt stock recruitment model fitted to age-1 RB abundance vs. spawner abundance showed no clear patterns of density dependent or independent stock-recruitment dynamics with a scattering of data over the range of possibilities (Figure 9). There were no data pertaining to the slope of the line through the origin at low densities of spawners, so the slope of the initial portion of the curve was informed based on the known biology of the species including information on the number of eggs, survival of eggs and survival of 1 year old fish.

The abundance of age-1 Rainbow Trout at the index sites in the Lower Columbia River and Lower Kootenay River as estimated by the indexing program (Ford et al. 2013) is highest in the 2000, 2001, 2006 and 2010 spawn years. There is a strong correlation between the patterns in age-1 RB abundance by spawn year and the number of dewatered redds (Figure 6).

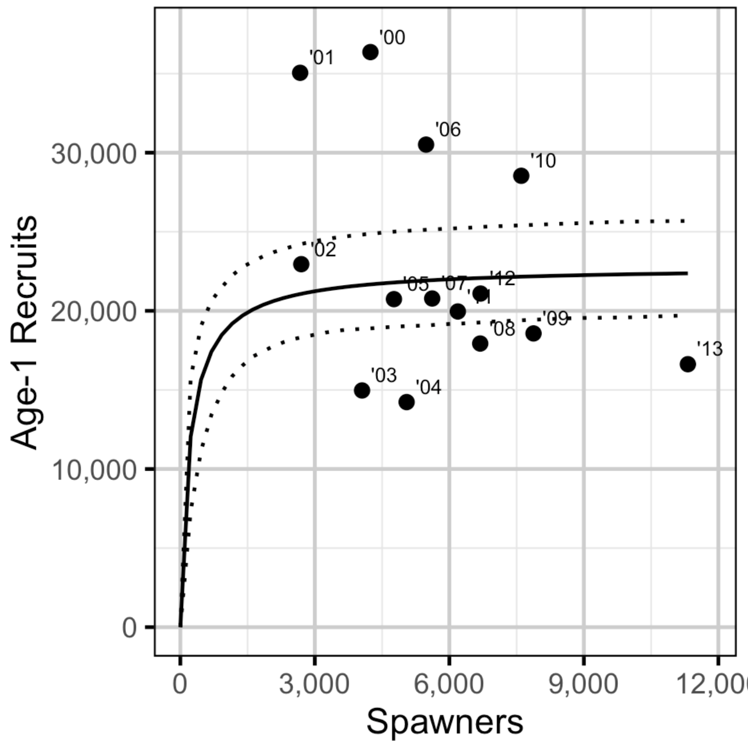

Figure 9. **Beverton-Holt stock recruitment curve including prior information for estimating the starting slope of the curve for Rainbow Trout in the Lower Columbia River below Hugh L. Keenleyside Dam and the Kootenay River below Brilliant Dam for the spawn years from 1999 to 2013.**

The last two strong peak abundance levels in Age-1 fish are 4 years apart (2006, 2010) with another peak in 2000 and 2001. The abundance of Age-1 recruits has been relatively steady around the 20,000 point since 2002 with high points in the time series between 30,000 - 40,000 (Figure 10). The trend in the age-1 recruits is highly correlated with the trend in the dewatered redd percentages (Figure 6 and Figure 11) with high values of dewatered redds associated with the spawn years with high levels of age-1 recruits (Figures 6 and 10).

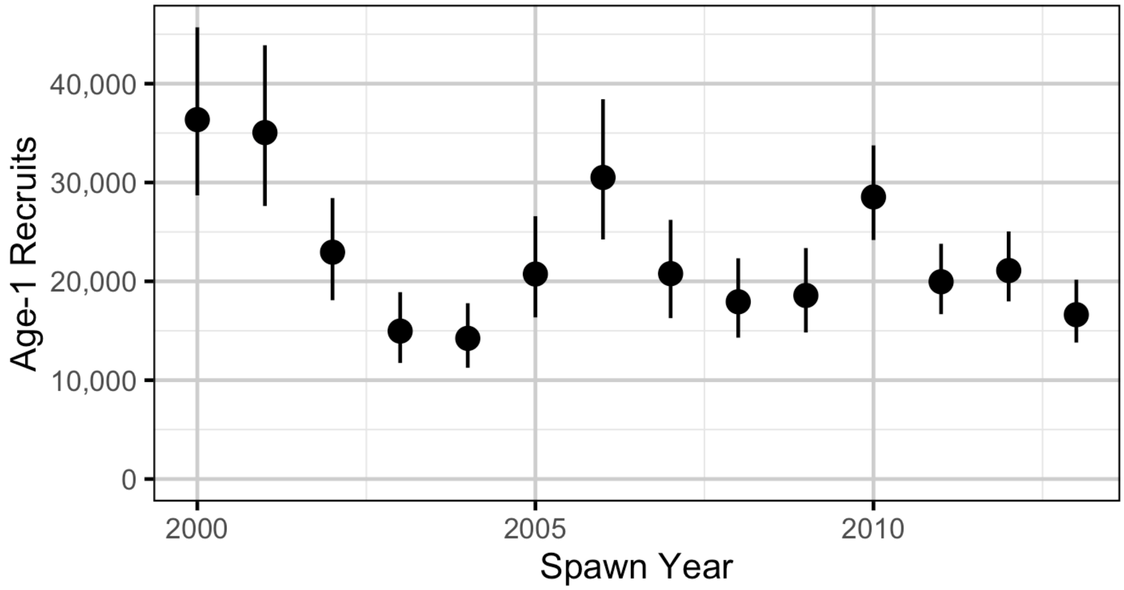

Figure 10. **Number of age-1 Rainbow Trout vs. the spawn year for the Lower Columbia River below Hugh L. Keenleyside Dam and the Kootenay River below Brilliant Dam from 1999 to 2013. The vertical and horizontal bars represent 95% credible intervals.**

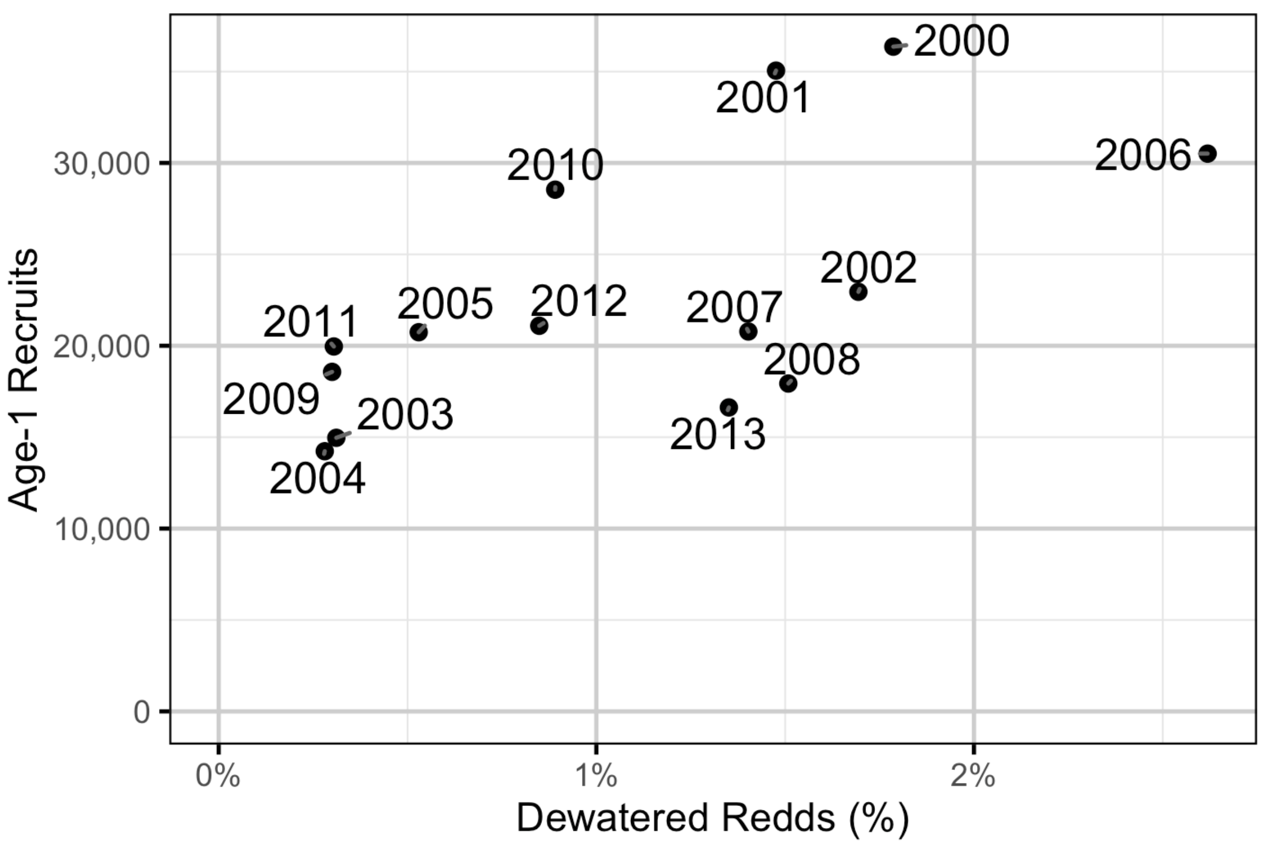

Figure 11. **Correlation between the number of age-1 Rainbow Trout and the the percentage of dewatered redds by year for the Lower Columbia River below Hugh L. Keenleyside Dam and the Kootenay River below Brilliant Dam from 2000 to 2013.**

4.0 DISCUSSION

4.1 Management Question 1

The first management question asks whether RTSPF are linked to an increase in the number of spawners. The AUC-based estimates showed ~15,000 spawners in 2015 in comparison to ~1600 in 1999 which is an almost 10-fold increase of RB in the Lower Columbia and Lower Kootenay Rivers since the study program commenced. However, it is unknown whether this increase is due to the RTSPF, as a number of environmental and biological factors have also changed including the opening of 26 km of Blueberry Creek for Rainbow Trout spawners (Arndt and Klassen 2004), and the fertilization programs in Kootenay Lake and Arrow Lakes Reservoir. It is also likely that some of the spawning population in the study area is coming up from the United States portion of the Columbia River so some of the increase may be due to management strategies undertaken in the U.S. Nonetheless it is an impressive increase in Rainbow Trout abundance.

The accuracy and magnitude of the abundance estimates depend on the extent to which the assumptions of the model are met. Spawner residence time was estimated by modelling acoustic receiver data from 2012-2014, which derived an average residence time of 14.9 days (the range was from 2 - 46 days). The redd residence time was able to be estimated by the model this year and was substantially longer than previous years' assumed timing of 35 days. The mean estimated redd residence time was 71 days (95% CI 44-113). If the assumed observer efficiencies of 0.9 to 1.1 for spawners and redds are too high an underestimate will result, and the opposite will occur if they are too low.

It is also important to be aware that the AUC-based estimates exclude fish spawning in tributaries (other than the Lower Kootenay River below Brilliant Dam), at deep-water sites, downstream of Genelle including below the US Border and upstream of Norn's Creek fan. The current state of knowledge with regard to the numbers of fish spawning in tributaries, deep-water sites and in the US is summarized in Thorley and Baxter (2011, 2012). In brief, tributaries to the LCR may provide habitat for over 3,000 spawners, fish are likely spawning unrecorded in the deeper parts of the Lower Columbia and Lower Kootenay Rivers (based on deep water observations on an exceptionally clear viewing day in 2010) and Rainbow Trout in the U.S. spawning locations may contribute to the LCR Canadian population. As part of their early 1990s Lower Columbia River fisheries inventory Hildebrand et al. (1995) radio-tagged 34 Rainbow Trout, 15 (44%) of which moved downstream into the U.S. and acoustically tagged fish have been observed to undertake 50 km spawning migrations.

4.2 Management Question 2

The second management question concerns the spatial distribution and associated habitat area of spawning Rainbow Trout within the study area. As discussed by Thorley & Baxter (2011) the spawner and redd count data indicate that the spatial distribution and habitat area of spawning have increased slightly over the last decade. In addition, this year's analysis of the spatial distribution of the redds and spawners with the Shannon Index indicated that the spatial distribution has been very gradually increasing from 1999 – 2015. One possible explanation is that as spawner abundance has increased, particular areas have become saturated and as a result fish have begun to utilize additional locations. This could mean a differential survival rate depending upon spawning location given that some habitat will be less optimal than other habitat.

Field crews have noted over the years of monitoring that the locations available for spawning Rainbow Trout vary considerably with the river stage and the discharge levels provided from HLK and BRD. Rainbow Trout spawning in the LCR and LKR select habitats where velocities range from 0 to 1.4 m/s with peak spawning activity at a velocity of ~0.6 m/s and depth ranges from 1 to 1.5 m with peak habitat suitability curve values at ~1.1 m (Thorley and Baxter 2012). Therefore, although there are some spawning areas that are used every year, there are locations and habitats that are used sporadically depending on their suitability. In 2012, which was a very high water year, the percentage of fish observed above the Kootenay confluence was higher which may have been habitat or food related as much of the low lying forest was inundated that spring. As Rainbow Trout move into additional habitats within the LCR and LKR or spawn in increasing densities in existing habitats, they may be using areas that are less optimal or at risk of operational effects on flow or water temperature.

One of the most interesting and strongest results from this year's analysis was the strong positive correlation between the number of age-1 Rainbow Trout recruits with the percentage of dewatered redds. The positive correlation between dewatering and subsequent age-1 recruitment suggests that the conditions which result in more redd dewatering are correlated with substantially higher survival in the remaining redds. One possible explanation is that the discharge and river stage conditions that result in more redds in shallower water, thus leading to the higher dewatering percentage, cause less redd disturbance due at higher discharges later in the incubation period. To test this hypothesis we propose to model the velocities experienced by redds in each year or to model discharge during peak spawning as a surrogate for river stage to understand the mechanisms behind this correlation. A full model would require a substrate layer and access to the outputs of the River2D model if it were sufficiently detailed in its scope and scale. A less robust model could be fitted to the discharge data alone under the assumption that discharge is linearly correlated with depth and depth is linearly correlated with velocity.

There may be different mechanisms operating to affect Rainbow Trout survival from egg to age-1 in the different river systems due to the operational choices enacted at BRD and HLK in the summer months. The discharge from HLK dam increases or stays flat throughout the summer months, while the discharge from BRD decreases over 1000 m^3/s from mid-late June until early August. Within the LKR, where approximately 15% of the Rainbow Trout population spawns, the range of emergence timing predicted from the modeling indicates that some redds with developing eggs may be dewatered or reach lethal water temperatures before the end of their development window. In this system dewatering and minimal flows leading to inhospitable water temperatures may limit recruitment. However, in the LCR where the majority of the spawners develop their redds, a mechanism where increased flows may cause water velocities to increase over the redds could limit recruitment. Rainbow Trout fry are most susceptible to being washed away by high flows in the 30-70 days after absorbing the yolk sac (Fausch et al. 2001). Flow regime was predictive of whether

Rainbow Trout could survive after being introduced into rivers. Trout are most successful when the flow regime of the river into which they are introduced matches the flow regime in which they evolved (Fausch et al. 2001). When HLK increases summer flows in a year when protection flow levels were low, this may result in a flow regime that differs substantively from the flow regime within which the population evolved. The Rainbow Trout would have used the available inundated habitat to spawn lower down in the river's contour due to the stage of the river. Increases in flow would then substantively increase the velocities and potentially lead to increased susceptibility to wash out by high flows in the first 30-70 days after absorbing their yolks as has been found in other studies (e.g., Nehring and Anderson 1993). Conversely, when the benched cobble habitat higher up the river's bathymetric contours is utilised by the fish, the dewatering percentage for the year would be higher, but the velocities encountered by the emergent fry would be lower with less mortality and therefore greater recruitment. This type of interaction between velocity, accessible habitat and flow regime could explain the counter intuitive link between the number of age-1 recruits and dewatering percentage and may be key to maximizing the recruitment of Rainbow Trout in the LCR.

4.3 Management Question 3

The third and final management question asks whether RTSPF protect the majority of redds from dewatering. This management question can be answered positively with the current flow regime. In 2015, 52 Rainbow Trout redds were estimated to have dewatered during the spawning season. Using the redd dewatering estimates from the hierarchical model, the calculations suggest that the mean dewatering rate is 1.2% with the current flow regime. There are no good, continuous data on the level of redd dewatering prior to the protection flows, but in a study done in 1990-1991 approximately 50-75% of the redds observed during field surveys were exposed by ensuing flow reductions (Hildebrand and McKenzie 1995).

Each year the vast majority of dewatering occurs during the early spawning period (beginning of January to the end of March). Fish were sampled from early and late spawners in the LCR study area to determine whether the early spawners are genetically unique from the peak spawners. DNA collection was conducted by Mountain Water Research on March 17 and 20th at Genelle for early spawners and on April 21 at Norn's Creek Fan for peak timing spawners with help from BCH and AMEC staff. The draft report on the genetics analysis was provided just prior to report finalization and it was found that there is no significant genetic difference between the two groups negating the idea of 'genetic isolation by timing' (Taylor, E.B. 2016).

4.4 Recommendations

The primary purpose of the program is '*to better understand the link between flow management strategy and population abundance'* (BC Hydro 2007). Specifically, the next obvious direction for this study program is to understand what mechanisms may be driving the strong relationship determined in this year's analysis between age-1 recruit abundance and percentage of dewatered redds. It is proposed that BC hydro provide the CLBMON-46 study team with the existing River 2D and transect data (depth and velocity over Rainbow Trout redds). This will allow advanced exploration of the data and modelling to occur in order to explore the possibility that increasing velocity from flow changes out of HLK during the summer months when fry emerge may be reducing recruitment.

Further research is also recommended to assess if different mechanisms are driving recruitment in the Lower Kootenay River and the Lower Columbia River. Recommended research in the LKR would include: 1) obtaining accurate and precise stage data from a levellogger/barologger combination to determine what drops actually dewater usable and utilised habitat, and 2) reliable water temperature data for the LKR during the incubation period to refine the timing of when habitats need to remain watered in order to protect fry.

5.0 CONCLUSIONS

To date, the program has conclusively answered the last of the three management questions. The first two management questions have been partially answered by the documenting of the increasing trends in RB abundance and spatial distribution (Table 5). However, these increases cannot be attributed solely to the RTSPF without further research. The primary objective of the program is to better understand the link between flow management strategy and LCR RB population abundance and it remains unanswered at this point. The strong data and extensive time series in place at this point in the program will allow the testing of specific questions and the monitoring and testing of alternative flow strategies. The study’s results and the above recommendations have pointed out where and what type of additional research appears to be needed at this time to advance the understanding of the primary objective.

Table 5. Status of Objectives, Management Questions and Hypotheses after Year 8

Objectives	Management Questions	Year 8 (2015) Status
Assess changes in the relative abundance, distribution and spawn timing of Rainbow Trout in the lower Columbia River	1. Does the implementation of RTSPF over the course of the monitoring period lead to an increase in the relative abundance of Rainbow Trout spawning in the LCR downstream of HLK?	The number of Rainbow Trout spawners and redds has increased ~10-fold since 1999; the increase continued in 2015. RTSPF may be responsible for this increase. Further exploration of the relationship between dewatering and age-1 recruits may clarify the role of river stage and discharge in influencing abundance.
	2. Does the implementation of RTSPF over the course of the monitoring period lead to an increase in the spatial distribution of locations (and associated habitat area) that Rainbow Trout use for spawning in the LCR downstream of HLK?	The spatial distribution of Rainbow Trout spawning has increased since 1999. This may be related to an increase in the number of Rainbow Trout spawners, but since the effects of the RTSPF on Rainbow Trout abundance are still unclear, this management question cannot be answered definitively at present (Thorley and Baxter 2011; Appendix C).

	3. Does the implementation of RTSPF over the course of the monitoring period protect the majority of Rainbow Trout redds (as estimated from spawning timing) from being dewatered in the LCR downstream of HLK?	Yes. Over all years of analysed data, the mean stranding rate of redds has been 1.2%, as compared to the estimated 50-75% stranding rate noted in shallow water habitat on Norn's Fan in 1990 and 1991 prior to implementation of RTSPF.

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APPENDIX A

2015 Spawner and Redd Count Maps

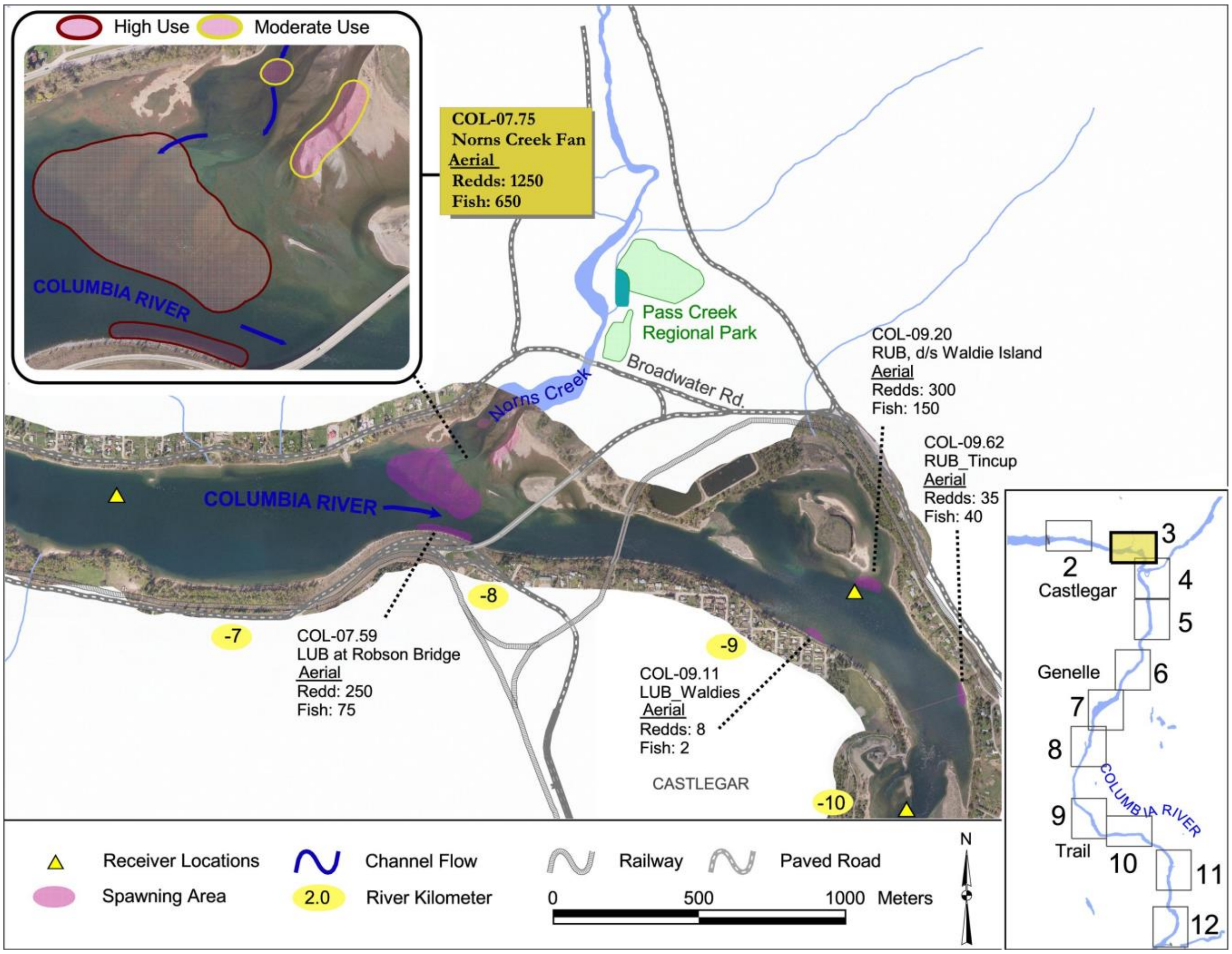

Figure A1. **Peak spawner and redd counts in Norn's Fan Area in 2015.**

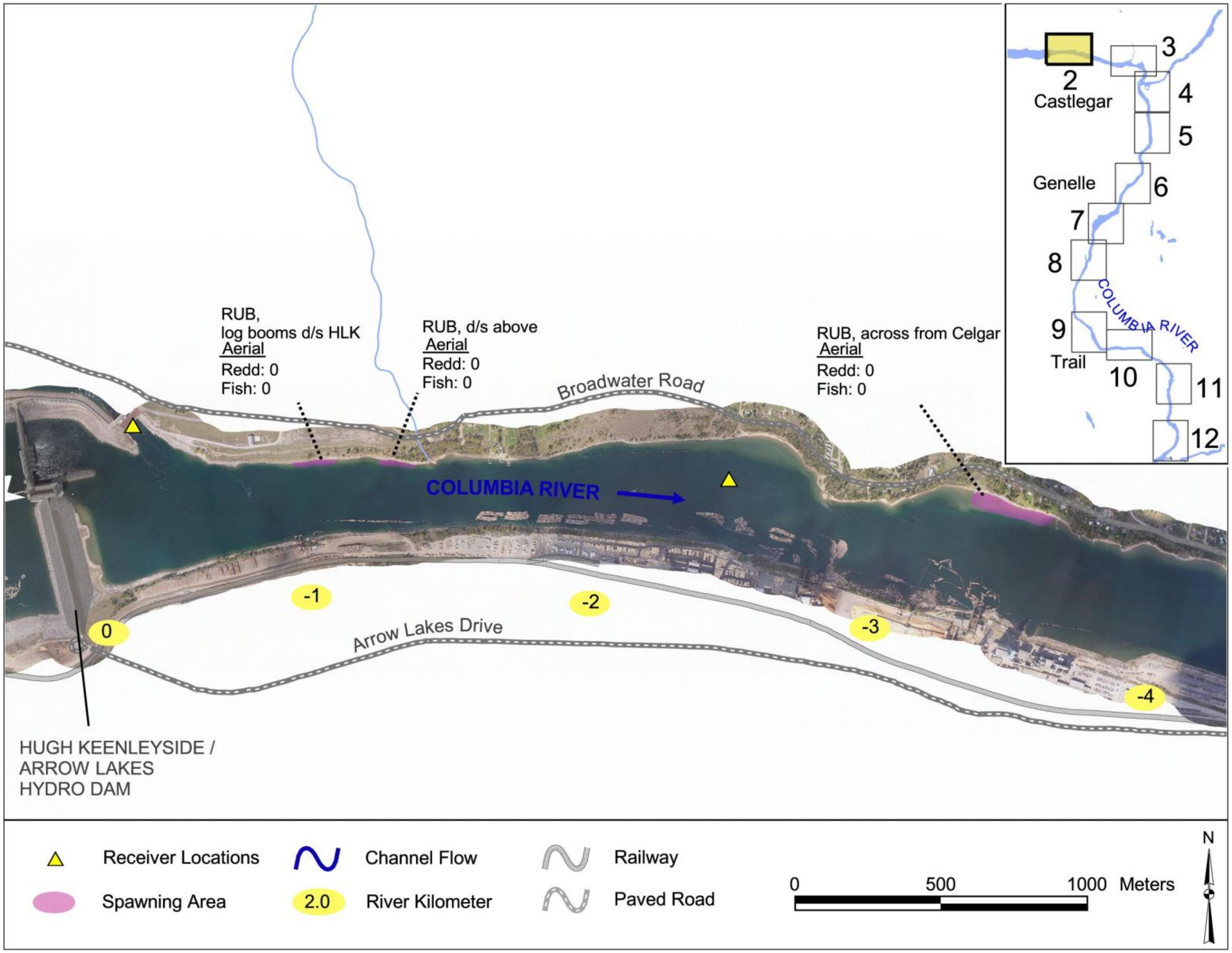

Figure A2. **Peak spawner and redd counts by location in the HLK Dam area in 2015.**

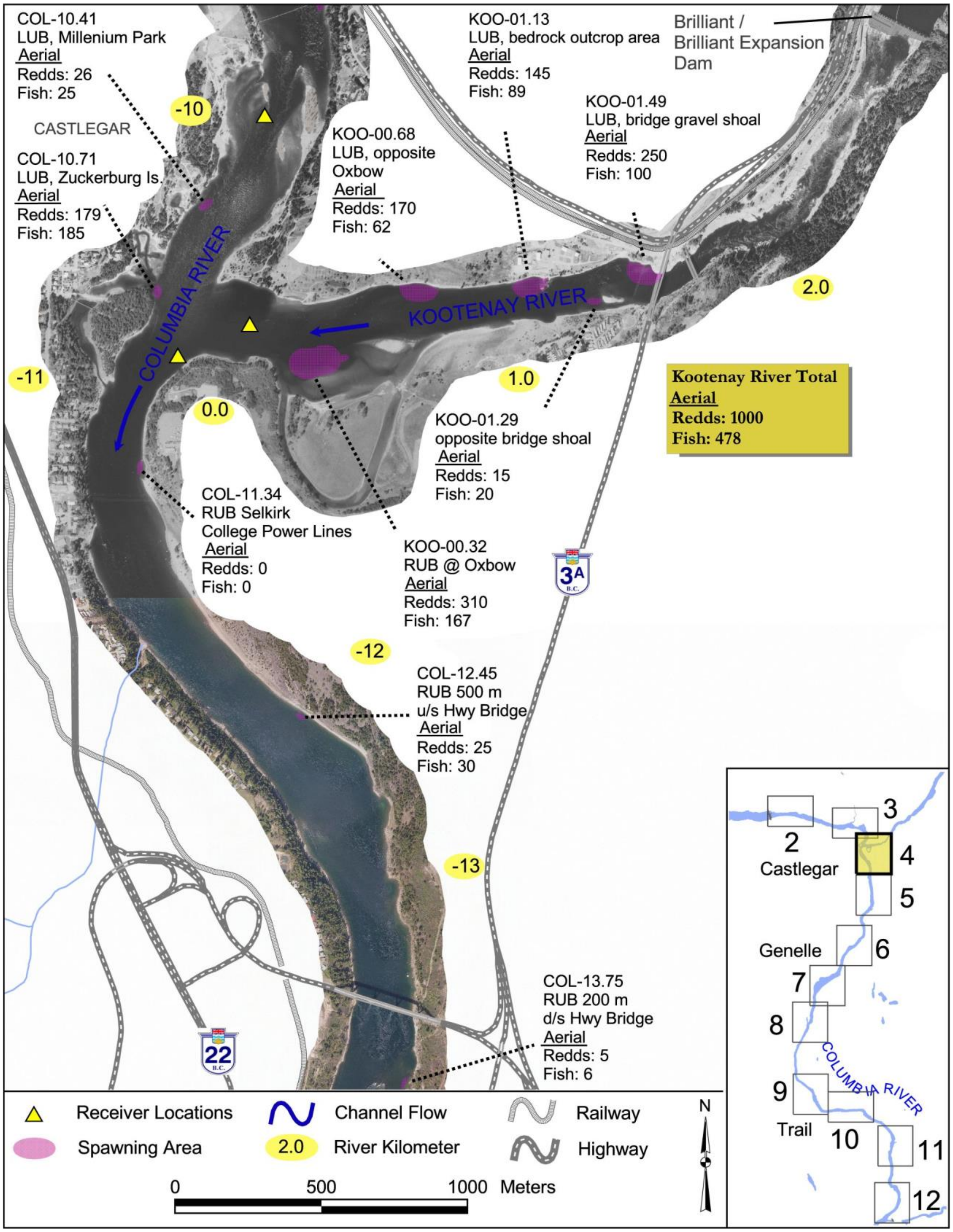

Figure A3. **Peak spawner and redd counts by location in the Kootenay-Columbia confluence area in 2015.**

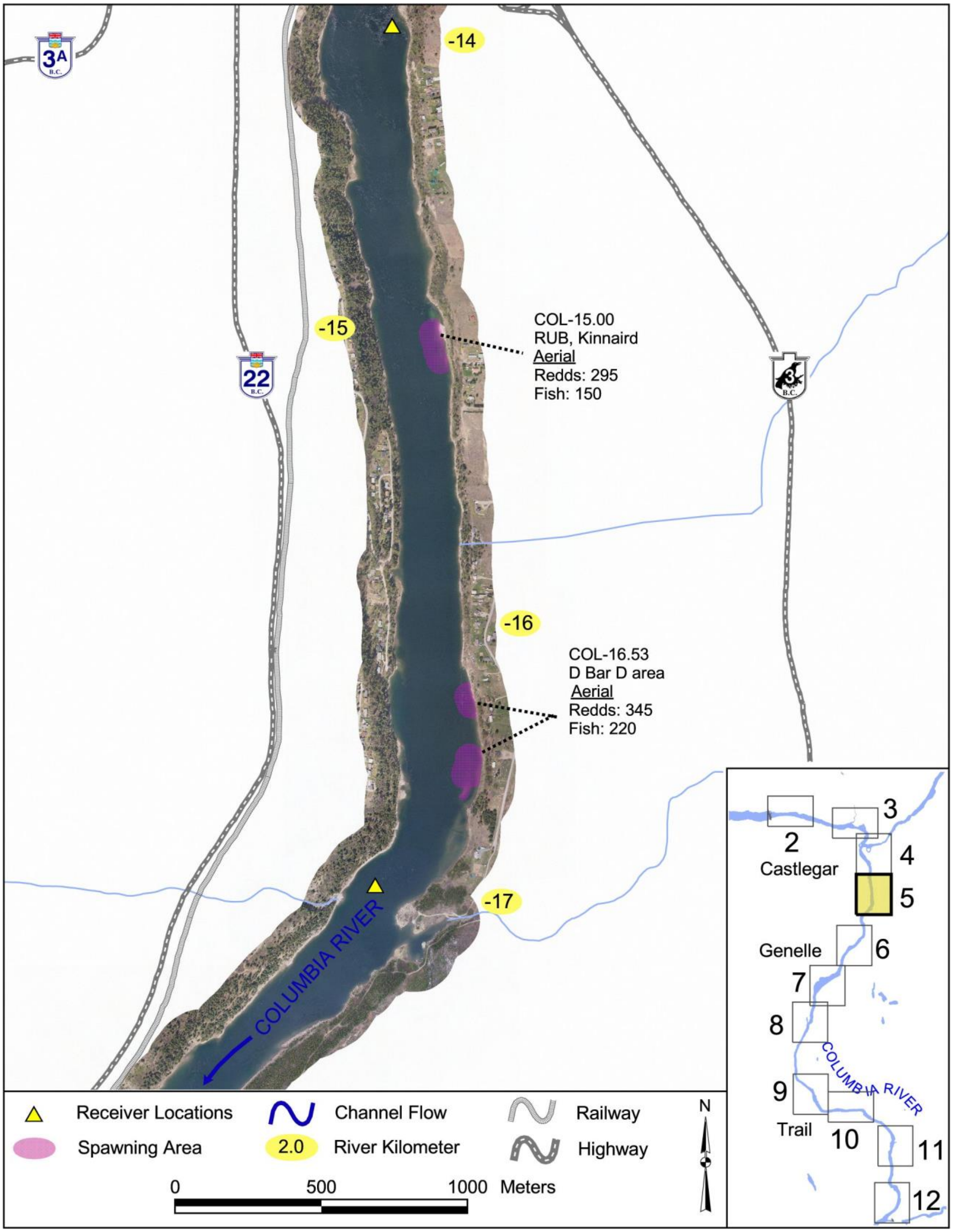

Figure A4. **Peak spawner and redd counts by location in the D-Bar-D area in 2015.**

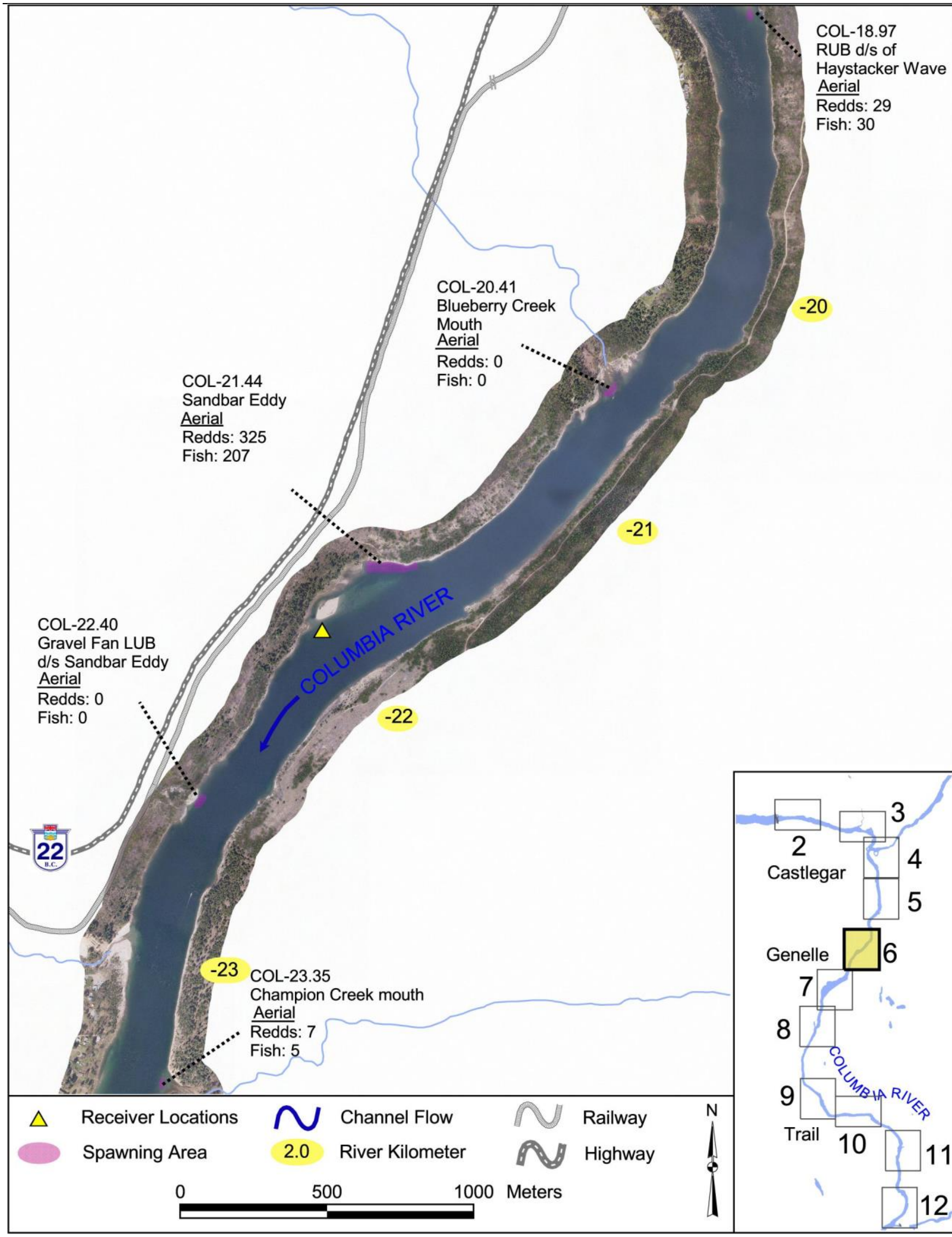

Figure A5. **Peak spawner and redd counts by location in the Sandbar Eddy area in 2015.**

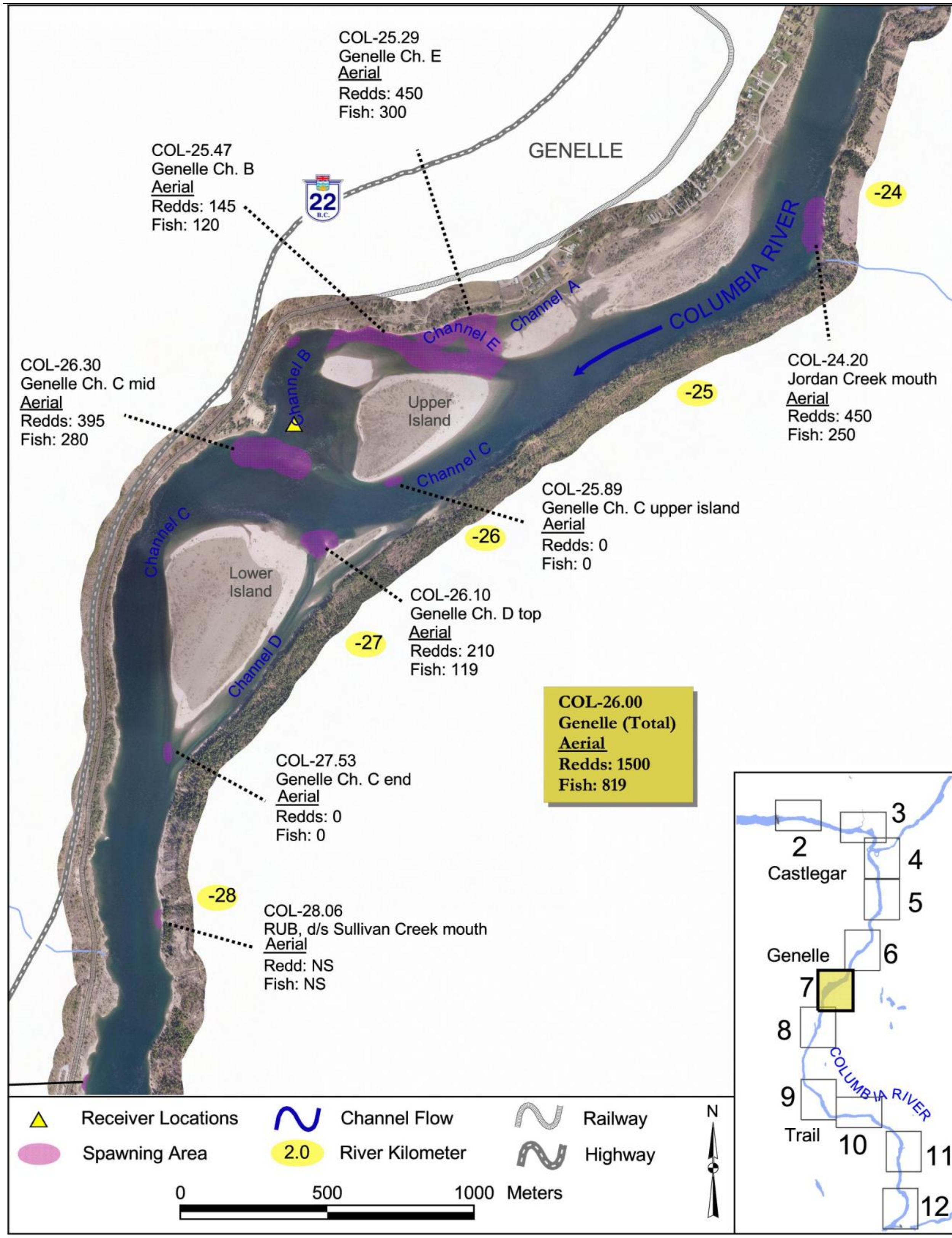

Figure A6. Peak spawner and redd counts by location in the Genelle area in 2015.

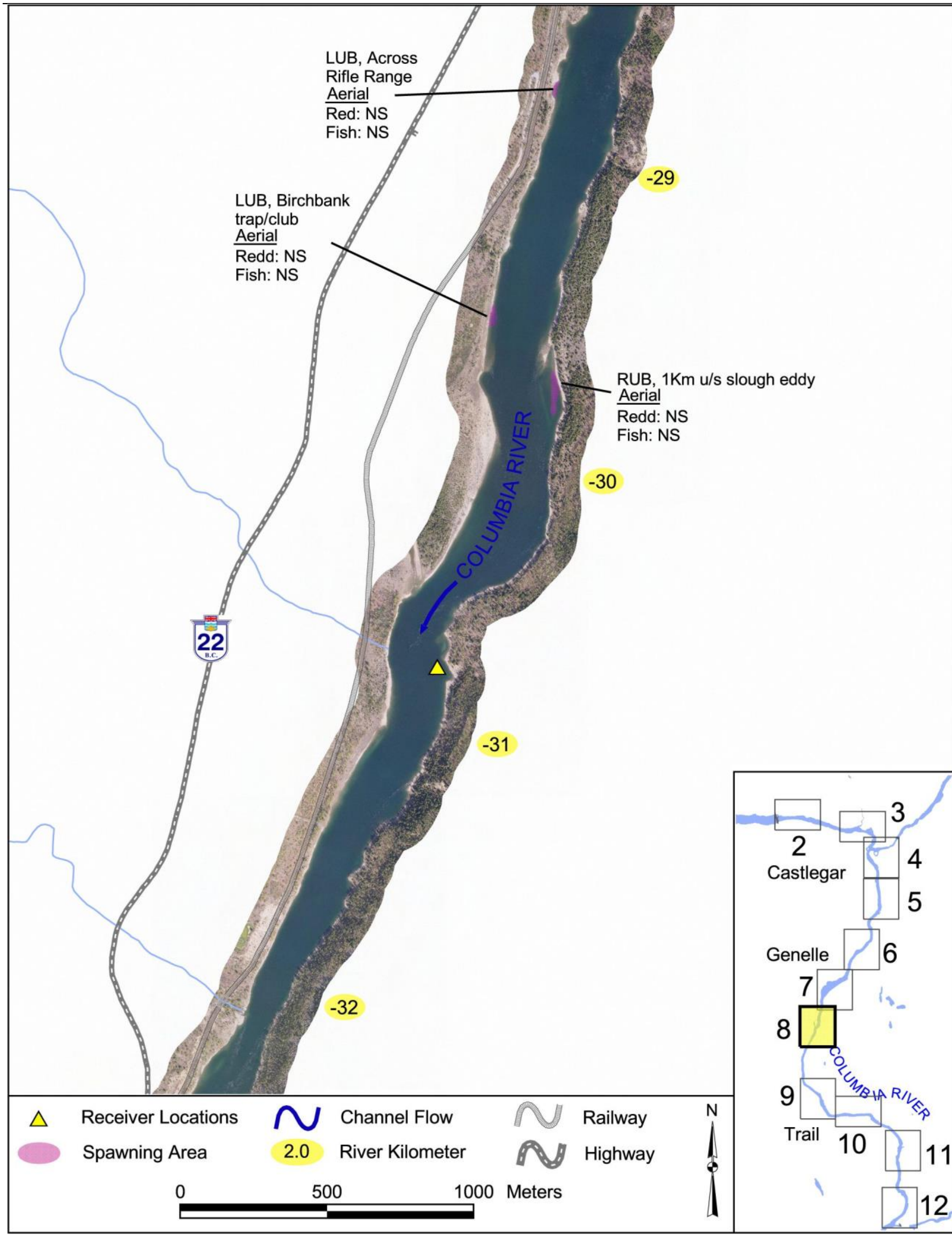

Figure A7. **Peak spawner and redd counts by location in the Birchbank area in 2015.**

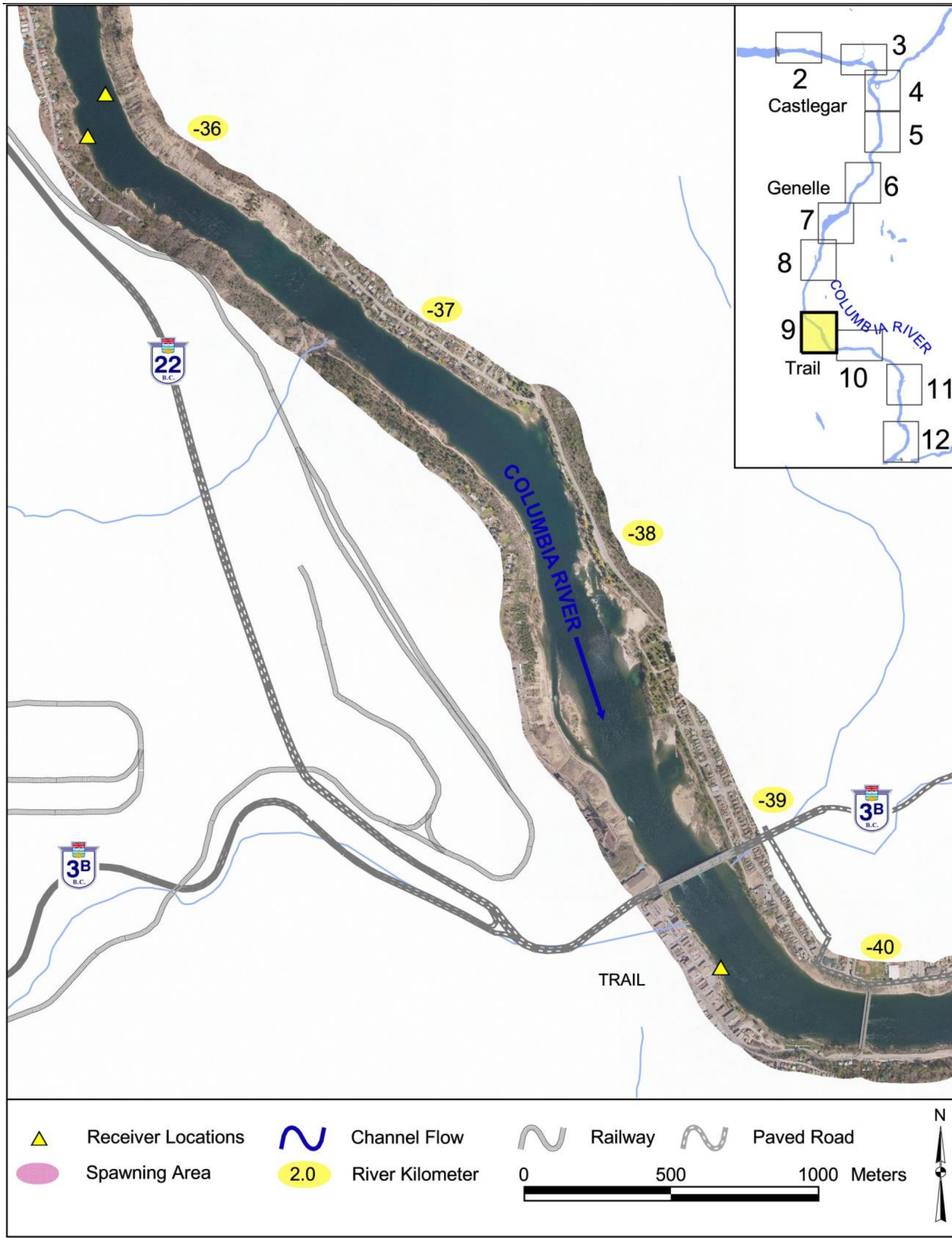

Figure A8. **Peak spawner and redd counts by location in the Trail area in 2015.**

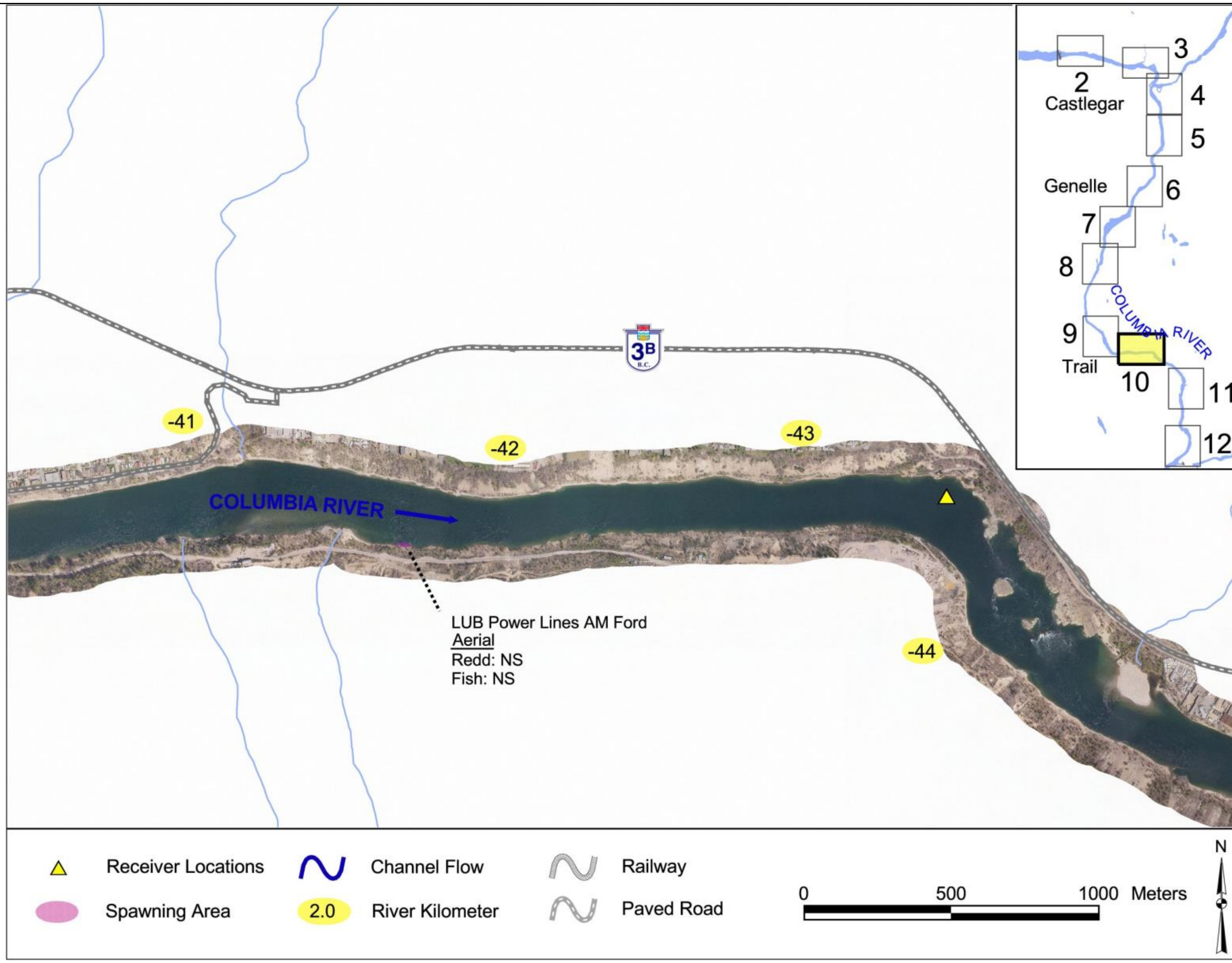

Figure A9. **Peak spawner and redd counts by location in the Trail AM Ford area in 2015.**

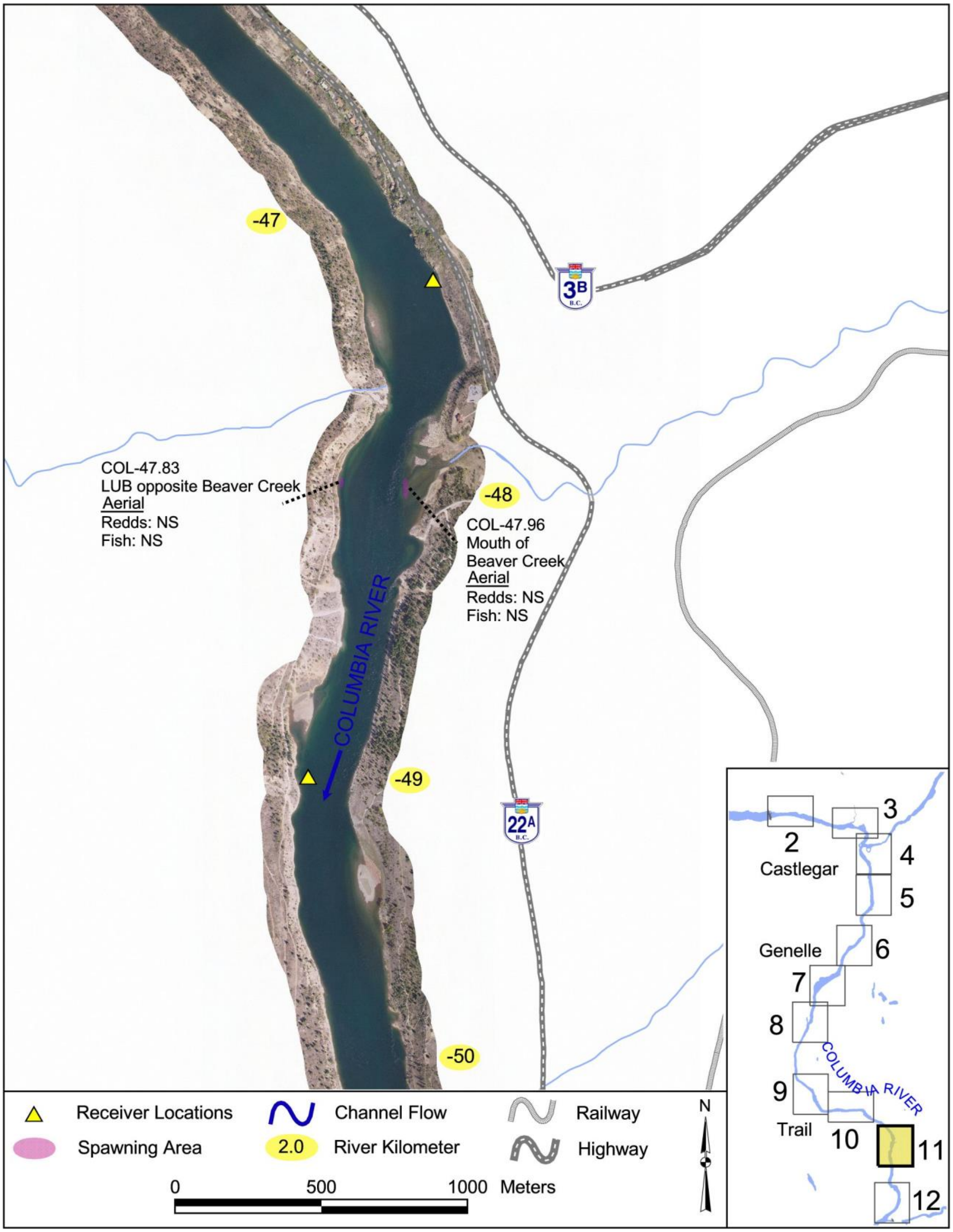

Figure A10. Peak spawner and redd counts by location in the Beaver Creek area in 2015.

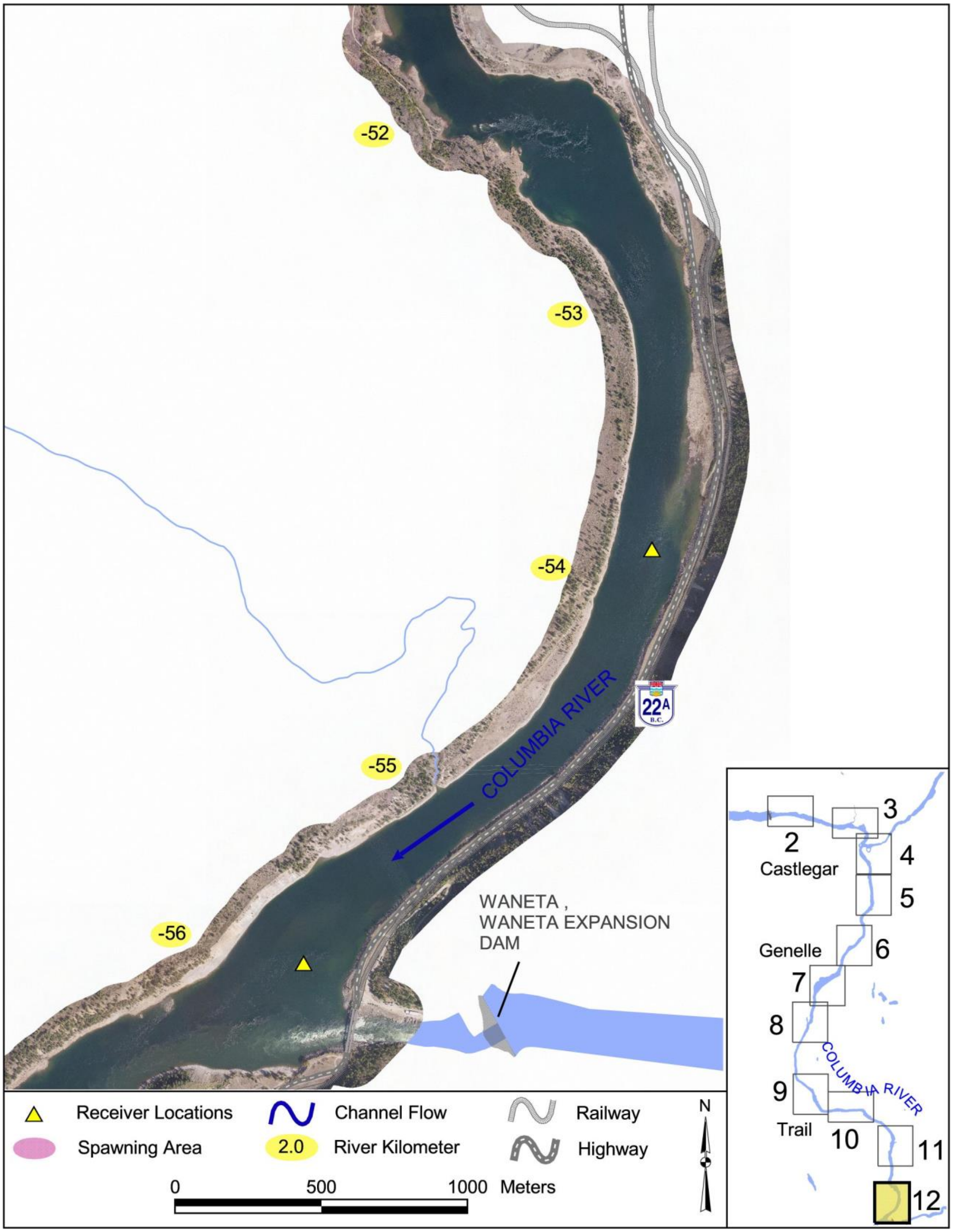

Figure A11. Peak spawner and redd counts by location in the Waneta Dam area in 2015.

APPENDIX B

2015 Spawner and Redd Counts with AUC Estimates and Viewing Conditions

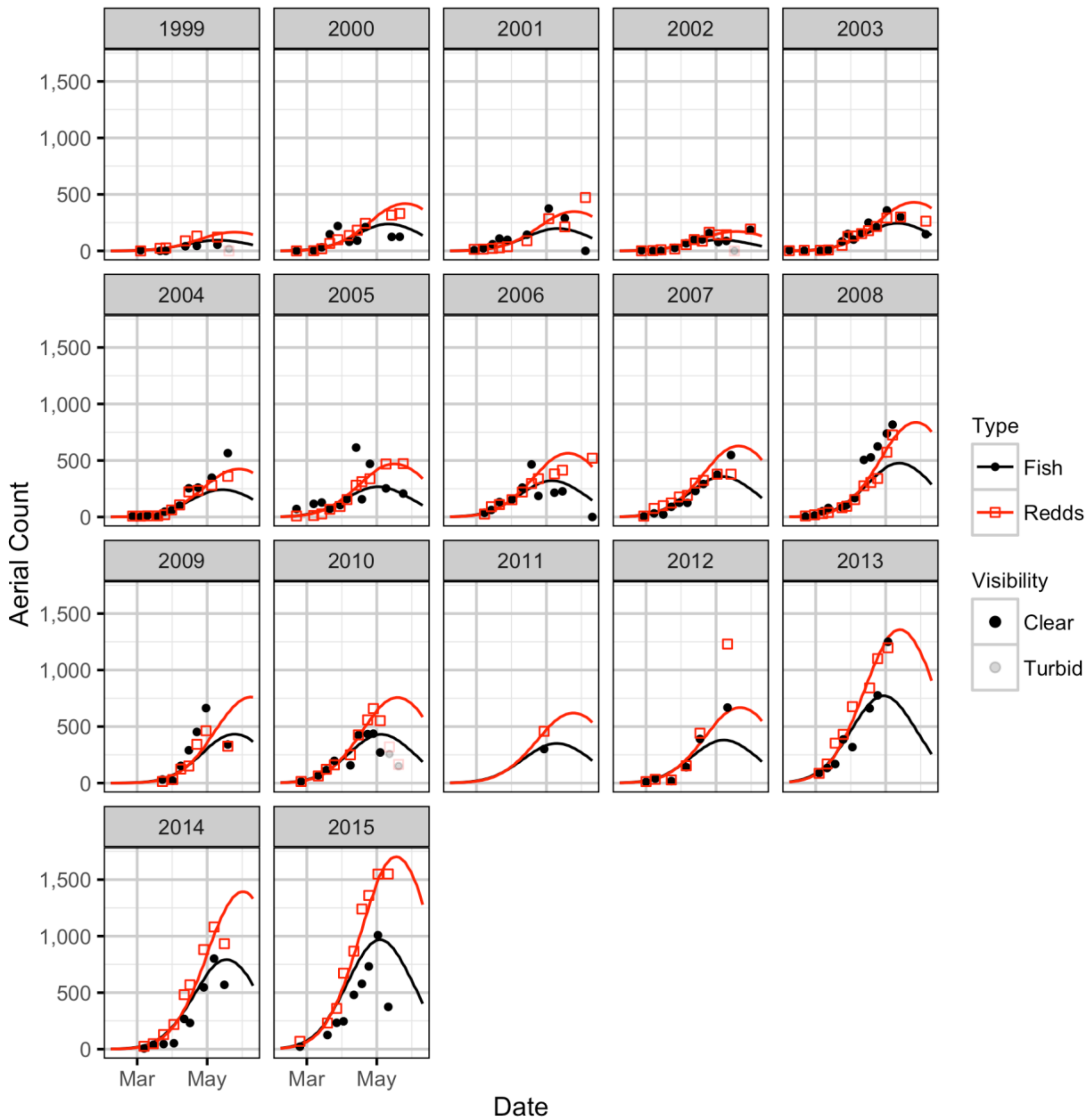

Figure B1. **The spawner and redd counts for the Lower Columbia River above the Kootenay River with the AUC-based estimates of the expected counts 1999-2015.**

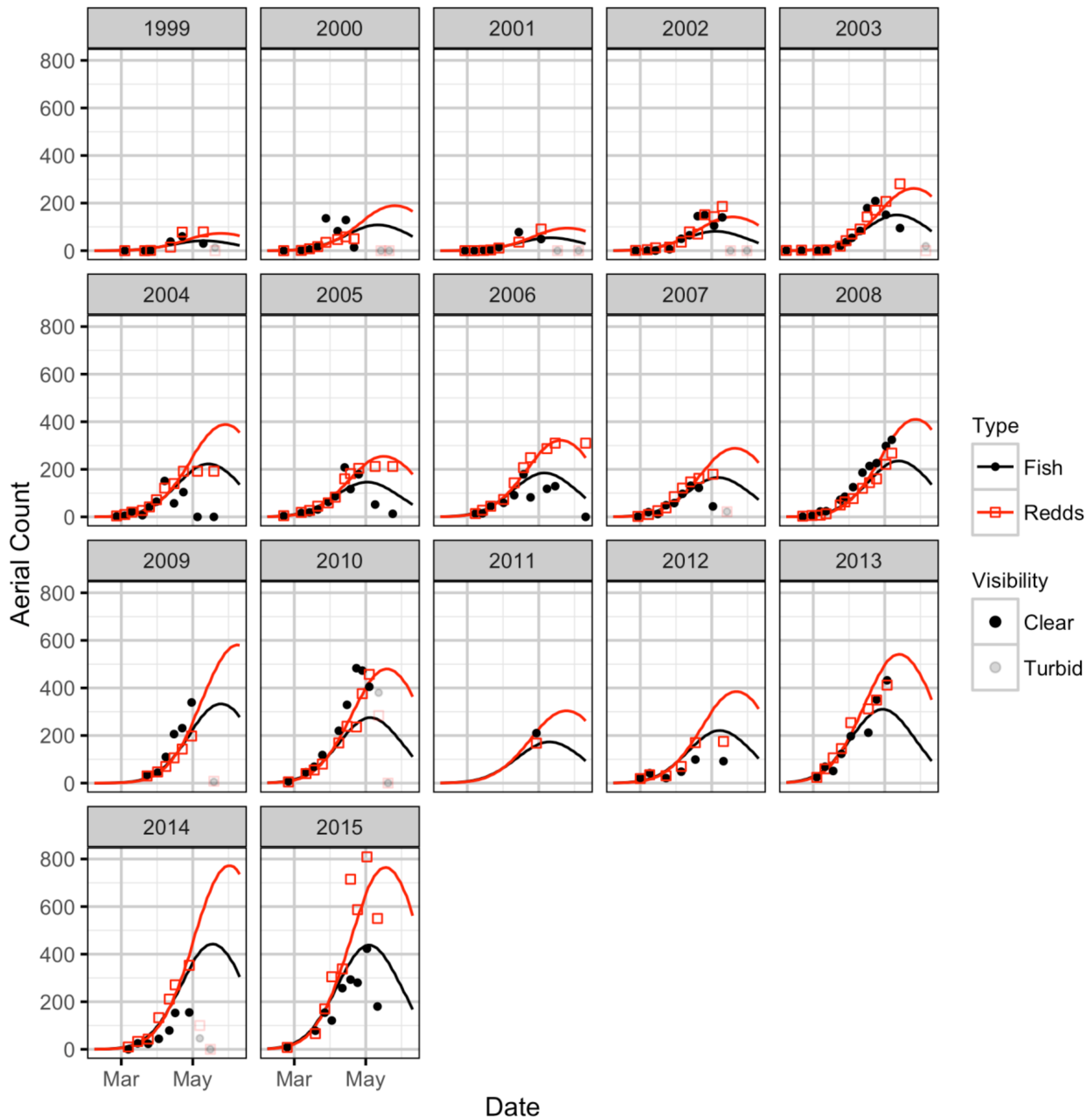

Figure B2. **The spawner and redd counts for the Kootenay River below Brilliant Dam with the AUC-based estimates of the expected counts 1999-2015.**

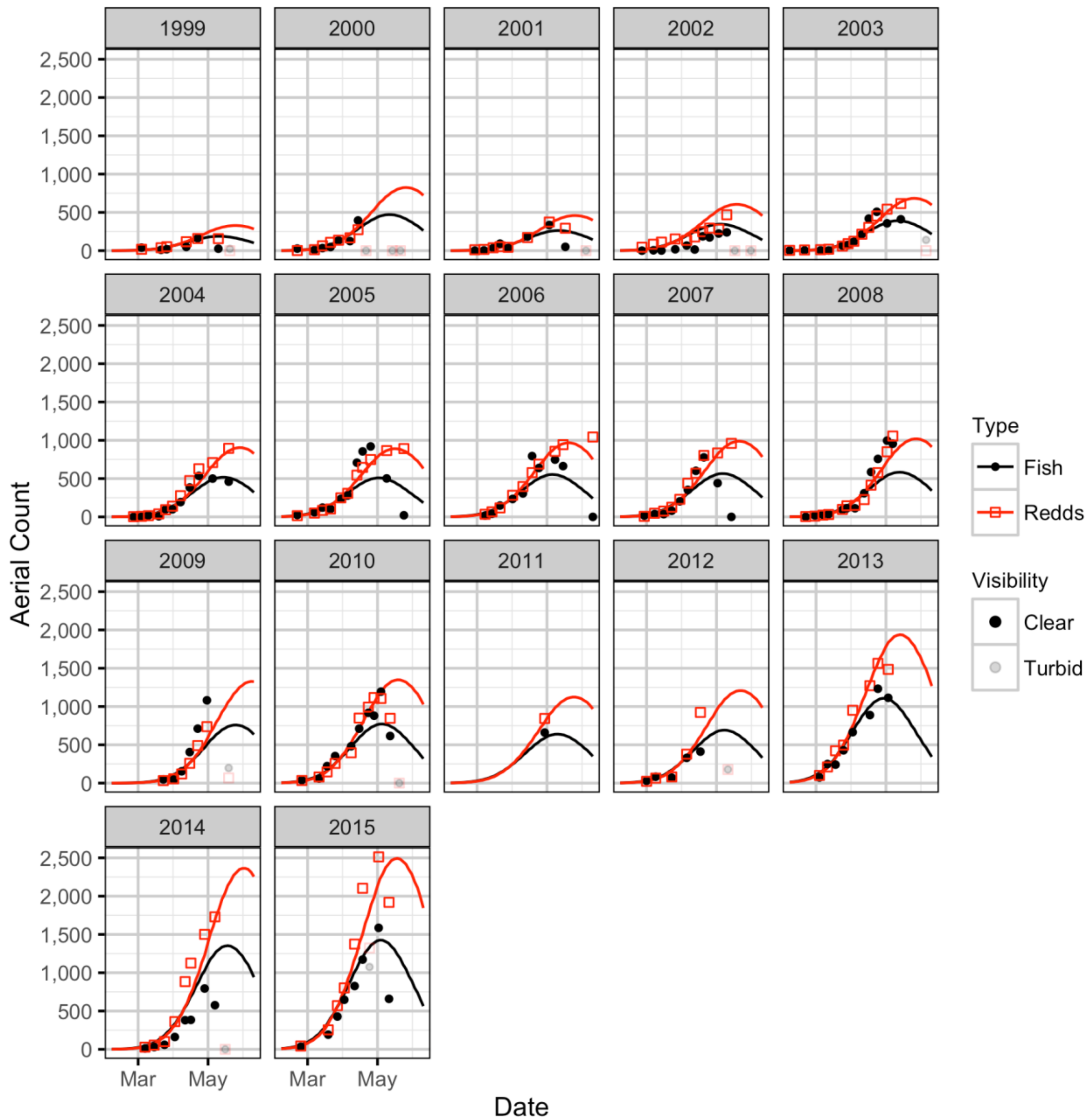

Figure B3. **The spawner and redd counts for the Lower Columbia River below the Kootenay River with the AUC-based estimates of the expected counts 1999-2015.**

APPENDIX C

2015 Model Code and Parameter Estimates

Model Code

The JAGS model code, which uses a series of naming conventions, is presented below.

Acoustic Detections

Variable/Parameter	Description
`bResidenceTime`	Intercept of `log(eResidenceTime)`
`eResidenceTime[i]`	Expected residence time of `i`th spawner
`ResidenceTime[i]`	Observed residence time of `i`th spawner
`sResidenceTime`	SD of residual variation about `log(eResidenceTime)`

Acoustic Detections Model

```
model {
  bResidenceTime ~ dnorm(0, 5^-2)
  sResidenceTime ~ dunif(0, 5)

  for(i in 1:length(ResidenceTime)){
    log(eResidenceTime[i]) <- bResidenceTime
    ResidenceTime[i] ~ dlnorm(log(eResidenceTime[i]), sResidenceTime^-2)
  }
}
```

Area-Under-The-Curve

Variable/Parameter	Description
`bRdObsEfficiency`	Redd observer efficiency
`bRdResidence`	Redd residence time
`bReddPerSpawner`	Number of redds per spawner
`bSpAbundance`	Intercept of `log(eSpAbundance)`
`bSpAbundanceSite[i]`	Effect of `i`th site on `log(eSpAbundance)`
`bSpAbundanceSiteYear[i, j]`	Effect of `i`th site within `j`th year on `log(eSpAbundance)`
`bSpAbundanceYear[i]`	Effect of `i`th year on `log(eSpAbundance)`
`bSpArrivalPeak`	Intercept of `eSpArrivalPeak`
`bSpArrivalPeakYear[i]`	Effect of `i`th year on `eSpArrivalPeak`
`bSpArrivalWidthSite[i]`	Effect of `i`th site on `log(eSpArrivalWidth)`
`bSpObsEfficiency`	Spawner observer efficiency
`bSpResidence`	Spawner residence time
`Dayte[i]`	Day of the year on `i`th count
`eFishDispersion`	Overdispersion of `Fish`
`eRdAbundance[i]`	Expected redd abundance on `i`th count
`eReddDispersion`	Overdispersion of `Redds`
`eSpAbundance[i]`	Expected spawner abundance on `i`th count
`eSpArrivalPeak[i]`	Expected peak of spawner arrival timing on `i`th count
`eSpArrivalWidth[i]`	Expected SD of spawner arrival timing on `i`th count
`Fish[i]`	Observed number of fish on `i`th count
`Redds[i]`	Observed number of redds on `i`th count
`sFishDispersion`	SD of overdispersion for `Fish`

Variable/Parameter	Description
`Site[i]`	Site of `i`th count
`sReddDispersion`	SD of overdispersion for `Redds`
`sSpAbundanceSiteYear`	SD of effect of site within year on `log(eSpAbundance)`
`sSpAbundanceYear`	SD of effect of year on `log(eSpAbundance)`
`sSpArrivalPeakYear`	SD of effect of year on `eSpArrivalPeak`
`sSpArrivalWidth`	Intercept of `log(eSpArrivalWidth)`
`Year[i]`	Year of `i`th count

Area-Under-The-Curve Model

```
model {
 bSpAbundance ~ dnorm(5, 5^-2)

 bSpArrivalPeak ~ dnorm(0, 14^-2)
 sSpArrivalWidth ~ dunif(log(14), log(42))
 bSpResidence ~ dnorm(11, 3.07^-2) T(6.31, 18.16)

 bSpObsEfficiency ~ dunif(0.9, 1.1)

 bSpAbundanceSite[1] <- 0
 for (i in 2:nSite) {
  bSpAbundanceSite[i] ~ dnorm(0, 2^-2)
 }

 sSpAbundanceYear ~ dunif(0, 2)
 for (i in 1:nYear) {
  bSpAbundanceYear[i] ~ dnorm(0, sSpAbundanceYear^-2)
 }

 sSpAbundanceSiteYear ~ dunif(0, 2)
 for (i in 1:nSite) {
  for (j in 1:nYear) {
   bSpAbundanceSiteYear[i, j] ~ dnorm(0, sSpAbundanceSiteYear^-2)
  }
 }

 sSpArrivalPeakYear ~ dunif(0, 28)
 for (i in 1:nYear) {
  bSpArrivalPeakYear[i] ~ dnorm(0, sSpArrivalPeakYear^-2)
 }

 bSpArrivalWidthSite[1] <- 0
 for(i in 2:nSite){
  bSpArrivalWidthSite[i] ~ dnorm(0, 1^-2)
 }
```

```
bReddPerSpawner ~ dunif(0, 4)

bRdResidence ~ dnorm(100, 50^-2)

bRdObsEfficiency ~ dunif(0.9, 1.1)

sFishDispersion ~ dunif(0, 2)
sReddDispersion ~ dunif(0, 2)

for (i in 1:length(Fish)) {
  log(eSpAbundance[i]) <- bSpAbundance +
                    bSpAbundanceSite[Site[i]] +
                    bSpAbundanceYear[Year[i]] +
                    bSpAbundanceSiteYear[Site[i], Year[i]]

  eSpArrivalPeak[i] <- bSpArrivalPeak + bSpArrivalPeakYear[Year[i]]
  log(eSpArrivalWidth[i]) <- sSpArrivalWidth + bSpArrivalWidthSite[Site[i]]

  eSpFracArrived[i] <- pnorm(
                   Dayte[i],
                   (eSpArrivalPeak[i] - bSpResidence/2),
                   eSpArrivalWidth[i]^-2
                  )
  eSpFracDeparted[i] <- pnorm(
                    Dayte[i],
                    (eSpArrivalPeak[i] + bSpResidence/2),
                    eSpArrivalWidth[i]^-2
                   )
  eFish[i] <- (eSpFracArrived[i] - eSpFracDeparted[i])
          * eSpAbundance[i]
          * bSpObsEfficiency

  eFishDispersion[i] ~ dgamma(1/sFishDispersion^2, 1/sFishDispersion^2)
  Fish[i] ~ dpois(eFish[i] * eFishDispersion[i])

  eRdAbundance[i] <- eSpAbundance[i] * bReddPerSpawner

  eRdFracArrived[i] <- pnorm(
                   Dayte[i],
                   (eSpArrivalPeak[i] - bSpResidence/2),
                   eSpArrivalWidth[i]^-2
                  )
  eRdFracDeparted[i] <- pnorm(
                    Dayte[i],
```

```
                     (eSpArrivalPeak[i] + bRdResidence/2),
                     eSpArrivalWidth[i]^-2
                    )
   eRedds[i] <- (eRdFracArrived[i] - eRdFracDeparted[i])
             * eRdAbundance[i]
             * bRdObsEfficiency

   eReddDispersion[i] ~ dgamma(1/sReddDispersion^2, 1/sReddDispersion^2)
   Redds[i] ~ dpois(eRedds[i] * eReddDispersion[i])
  }
}
```

Stock-Recruitment

Variable/Parameter	Description
`eRecruits[i]`	Expected number of recruits in `i`th year
`k`	Maximum number of recruits
`R0`	Maximum number of recruits per spawner
`Recruits[i]`	Observed number of age-1 fish in `(i+1)`th year
`sRecruits`	SD of residual variation about `log(eRecruits)`
`Stock[i]`	Observed number of spawners in `i`th year

Stock-Recruitment Model

```
model{
  R0 ~ dnorm(90, 50^-2) T(0, )
  k ~  dnorm(2*10^4, (2*10^3)^-2) T(0, )
  sRecruits ~ dunif(0, 5)

  for(i in 1:length(Stock)){
    eRecruits[i] <- R0 * Stock[i] / (1 + Stock[i] * (R0 - 1) / k)
    Recruits[i] ~ dlnorm(log(eRecruits[i]), sRecruits^-2)
  }
}
```

Parameter Estimates

Acoustic Detections

Parameter	Estimate	Lower	Upper	SD	Error	Significance
bResidenceTime	2.3470	1.7590	2.9030	0.2780	24	7e-04
sResidenceTime	1.0405	0.6988	1.5356	0.2195	40	7e-04

Convergence	Iterations
1	1000

Area-Under-The-Curve

Parameter	Estimate	Lower	Upper	SD	Error	Significance
bRdObsEfficiency	0.99730	0.90400	1.09410	0.05690	10	0.0010
bRdResidence	71.87000	44.49000	113.11000	17.59000	48	0.0010
bReddPerSpawner	0.63590	0.42610	0.83010	0.09910	32	0.0010
bSpAbundance	7.45000	6.91300	8.04700	0.31000	8	0.0010
bSpAbundanceSite[2]	-0.67150	-0.83720	-0.49900	0.08870	25	0.0010
bSpAbundanceSite[3]	0.52780	0.35500	0.70260	0.08660	33	0.0010
bSpArrivalPeak	33.97000	27.86000	40.52000	3.23000	19	0.0010
bSpArrivalWidthSite[2]	-0.04635	-0.08676	-0.00465	0.02043	89	0.0278
bSpArrivalWidthSite[3]	-0.02989	-0.06695	0.00435	0.01839	120	0.0913
bSpObsEfficiency	1.00030	0.90390	1.09580	0.05810	10	0.0010
bSpResidence	13.85600	7.96400	17.87400	2.74200	36	0.0010
sFishDispersion	0.75840	0.70250	0.81990	0.02910	8	0.0010
sReddDispersion	0.29987	0.27228	0.32855	0.01450	9	0.0010
sSpAbundanceSiteYear	0.21150	0.15280	0.28940	0.03540	32	0.0010
sSpAbundanceYear	0.65390	0.44220	0.96770	0.14040	40	0.0010
sSpArrivalPeakYear	7.33700	4.64500	11.31300	1.74000	45	0.0010
sSpArrivalWidth	3.32230	3.25760	3.38410	0.03360	2	0.0010

Convergence	Iterations
1.05	4e+05

Stock-Recruitment

Parameter	Estimate	Lower	Upper	SD	Error	Significance
k	20955.0000	17681.0000	23953.0000	1.61e+03	15	0.001
Ro	108.9000	41.8000	192.5000	4.08e+01	69	0.001
sRecruits	0.3436	0.2291	0.5437	8.17e-02	46	0.001

Convergence	Iterations
1.04	10000