Columbia River Water Use Plan

WLR Monitoring Study No. CLBMON-46 (Year 6)
Lower Columbia River Rainbow Trout Spawning Assessment
Study Period: January to July 2013

Robyn L. Irvine[1], Jeremy T.A. Baxter[2] and Joseph L. Thorley[1]

Prepared for:
BC Hydro
Castlegar, BC

Final Report

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WLR Monitoring Study

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Cover Photos: Left top – A pair of Rainbow Trout spawners constructing a redd in the Lower Kootenay River (photo credit Dave DeRosa). Left bottom – Biologist Joseph Thorley during a Rainbow Trout snorkel survey of Norns Creek (photo credit Dave DeRosa). Rainbow Trout eggs in a dewatered redd from the Lower Columbia River (photo credit Jeremy Baxter).

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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 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 substantial numbers of 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.

With six years of monitoring and analysis completed under the current program, the state of knowledge of baseline responses of the Rainbow Trout population has been much improved and the current knowledge relative to the defined management questions of CLBMON-46 is summarized in the table below and addressed in detail in this report. The remaining uncertainties now require a more experimental and adaptive approach going forward with the program to assess what the effects are of altering the timing and magnitude of the RTSPF. The Rainbow Trout in the LCR and LKR are an important ecological and recreational resource for the region. In order to manage this population optimally, the remaining management questions should be answered with well-designed scientific studies.

Management Question	Status
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 dam?	The number of Rainbow Trout spawners and redds has increased since 1999. RTSPF may be responsible for the increase. Experimental flow manipulations are needed to clarify the role of the hydrograph in influencing the Rainbow Trout abundance.
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 dam?	The density of redds and the occurrence of superimposition in known spawning locations has increased over time. Although the main spawning areas are consistent from year to year, the other locations utilised by spawning fish within the study area each year vary with the discharge and stage levels provided by HLK and BRD. There has been a slight increase in the amount of habitat used by Rainbow Trout over the time span of the monitoring of this population.
Does the implementation of RTSPFs 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 dam?	Yes. Over all years of analysed data since 1993, the mean stranding rate of redds has been 0.75%. Previous to RTSPF implementation, approximately 50% of the 30 redds that were visible on 21 April, 1990 were dewatered and in the 1991 spawning season, 75% of the redds able to be observed were estimated to be exposed by decreasing flows in June. The 1990-91 surveys were focused on the Norns' Creek Fan location.

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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) is of substantial ecological and recreational importance. Each spring, thousands of fish spawn in the mainstem of the two rivers as well as in the major tributaries of the Columbia (Heaton and Hildebrand 1997a, 1997b, Arndt 2000, Arndt and Klassen 2004, Ford and Hildebrand 2007, Baxter 2011). The Rainbow Trout spawning in these various areas constitute a single genetic population (Taylor 2002) and are managed accordingly.

This population of Rainbow Trout (RB) has been the focus of several study programs since the early 1990s. Since 1992 BC Hydro has monitored RB redds in shallow water areas to identify those at risk of dewatering. From 1999-2012, if a flow reduction resulted in dewatering, the redds were excavated and the salvaged eggs were transferred to more suitable gravels (2010a, 2010b, 2011). In 2013, the Department of Fisheries and Oceans (DFO) and the Ministry of Forests, Lands, Natural Resources and Operations (MFLNRO) granted BC Hydro permission to dewater up to 1% of the previous year's redd estimate without salvaging the dewatered redds. As less than 124 redds were dewatered in 2013 no salvage was required. Commencing in 1999, various forms of the spawner assessment program have occurred in each year. 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. The LCR and LKR RB have also been studied annually since 2001 with the Large River Indexing program (Ford et al. 2012). The goal of the indexing program with respect to RB is to understand the effect of the flow regime on the abundance, growth rate, survival rate, body condition, and spatial distribution of sub-adult and adult RB. The combined study programs are working to understand the biology, life history and population trends of the Rainbow Trout in the LCR and to assess the effects of operational regimes on these fish.

Prior to 1992, the discharge from HLK typically decreased during the March to May period (Figure 1). This hydrograph resulted in substantial numbers of Rainbow Trout redds being dewatered with potential effects on the abundance of the adult population (Hildebrand and McKenzie 1995, Thorley and Baxter 2011). BC Hydro therefore altered the spring operational regime 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 Mountain Whitefish protection flows in March to Rainbow Trout protection flows in April (BC Hydro 2005, Ford et al. 2008). This operational regime is known as the Rainbow Trout Spawning Protection Flows (RTSPF) and has been implemented every year since 1992 (BC Hydro 2007).

The constant or increasing river levels from April to June for the RTSPF require approximately 1 million acre feet (MAF) of retained storage in Arrow Lakes Reservoir (ALR) which is then released in summer. This represents a significant trade off for other operational soft constraints (BC Hydro

2005). 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). Consequently, 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 alternative flow strategies (BC Hydro 2007).

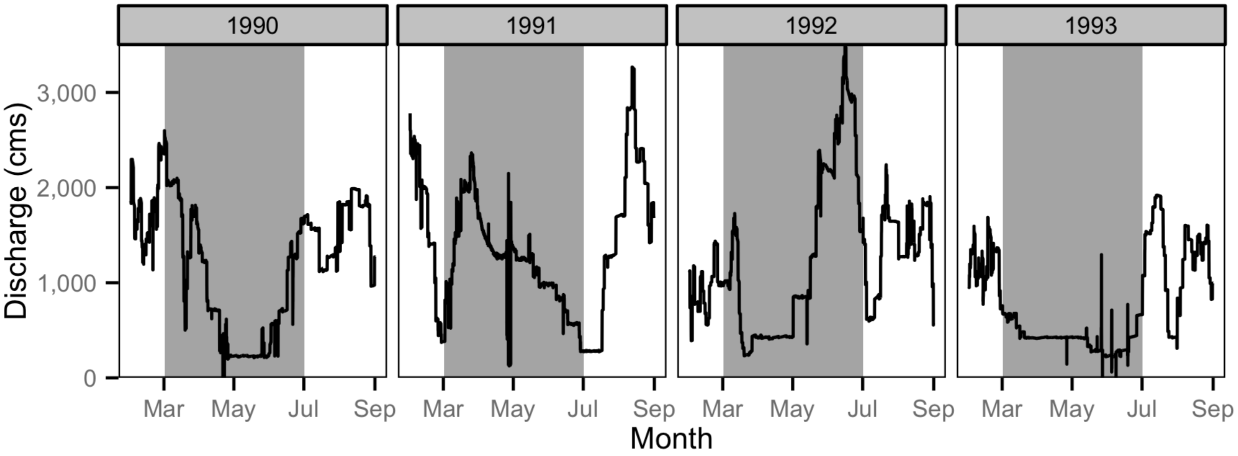

Figure 1. Mean hourly discharge at HLK, February to June, 1990 to 1993. Rainbow Trout spawning usually occurs from February to July though it can commence as early as January.

The following key 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 Terms of Reference 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 are ongoing (Baxter 2012) to implement an alternate spring flow regime commencing in 2015 for assessing its impact on the Rainbow Trout population. This experimental approach has been successful at teasing apart mechanisms behind population trends in other systems such as the Colorado (Korman et al. 2011).

Another complementary approach, which may be possible upon completion of the River 2D model for the LCR and LKR as part of CLBMON-47 (BC Hydro 2007b), is to combine Habitat Suitability Curves (Rosenfeld 2003) with a substrate map, the 2D model output (Hatten et al. 2009) and a stock-recruitment curve (Rose *et al.* 2001). The combination of these three data streams could produce a Habitat Suitability Stock-Recruitment (HSSR) model.

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 2) 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. The major gravel areas on the LCR and in the LKR are known by name and river kilometer, and all areas are surveyed during the flights. 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 marking of redds in less than 1.0 m of water to monitor the risk of dewatering and to delineate redds that may require redd salvaging, and to confirm possible new spawning areas seen from the air (Baxter 2011).

In 2013, eight aerial surveys were completed in a single engine helicopter and each aerial survey was followed by a boat survey (Table 1). Boat surveys without aerial surveys were conducted to assess the shallow redds and the number of redds dewatered on February 12, February 16, April 11 and May 10 (Table 1). The number of days between helicopter surveys during the 2013 field season ranged from 7 to 15 with the mean time between surveys of 7.5 days; the one larger time gap between April 2 and April 17 was due to helicopter maintenance issues followed by severe weather. Following the May 3 survey, the visibility in the Kootenay River and Norns' Creek became very limited due to high turbidity so no further helicopter surveys were completed after that date.

Table 1. Helicopter and boat based redd survey schedule for 2013.

Date	Survey Type(s)
February 12	Redd Dewatering Boat Survey
February 16	Redd Dewatering Boat Survey
March 4	Single engine helicopter, Boat survey
March 11	Single engine helicopter, Boat survey
March 18	Single engine helicopter, Boat survey
March 25	Single engine helicopter, Boat survey
April 2	Single engine helicopter, Boat survey
April 11	Shallow Water Redd Boat Survey
April 17	Single engine helicopter, Boat survey
April 24	Single engine helicopter, Boat survey
May 3	Single engine helicopter, Boat survey
May 10	Shallow Water Redd Boat Survey
May 30	Norns Fan Vemco Receiver Download & Removal

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. Previous years' surveys from 1999-2010 were conducted between 30 and 50m above ground level. In 2011, only one survey could be completed as helicopter safety regulations were in flux and it was done at 30-50m above ground. In 2012, most of the surveys were conducted at 150m above ground except for one on March 23, 2012 done in a twin-engine helicopter at the 30-50m above ground level. The 2013 surveys were completed at 150m above ground level as per the current helicopter safety regulations.

2.2 Redd Dewatering Surveys

Redd dewatering surveys were implemented as part of a separate project, but in conjunction with the boat surveys of the current program. A detailed redd survey was conducted weekly and on the days prior to any flow reductions, so that the locations of shallow water redds having the potential to dewater could be determined. The day of the flow reductions, a complete boat and ground survey of all the key spawning areas was conducted and all of the dewatered redds were enumerated to verify the total redd loss caused by HLK and BRD operations.

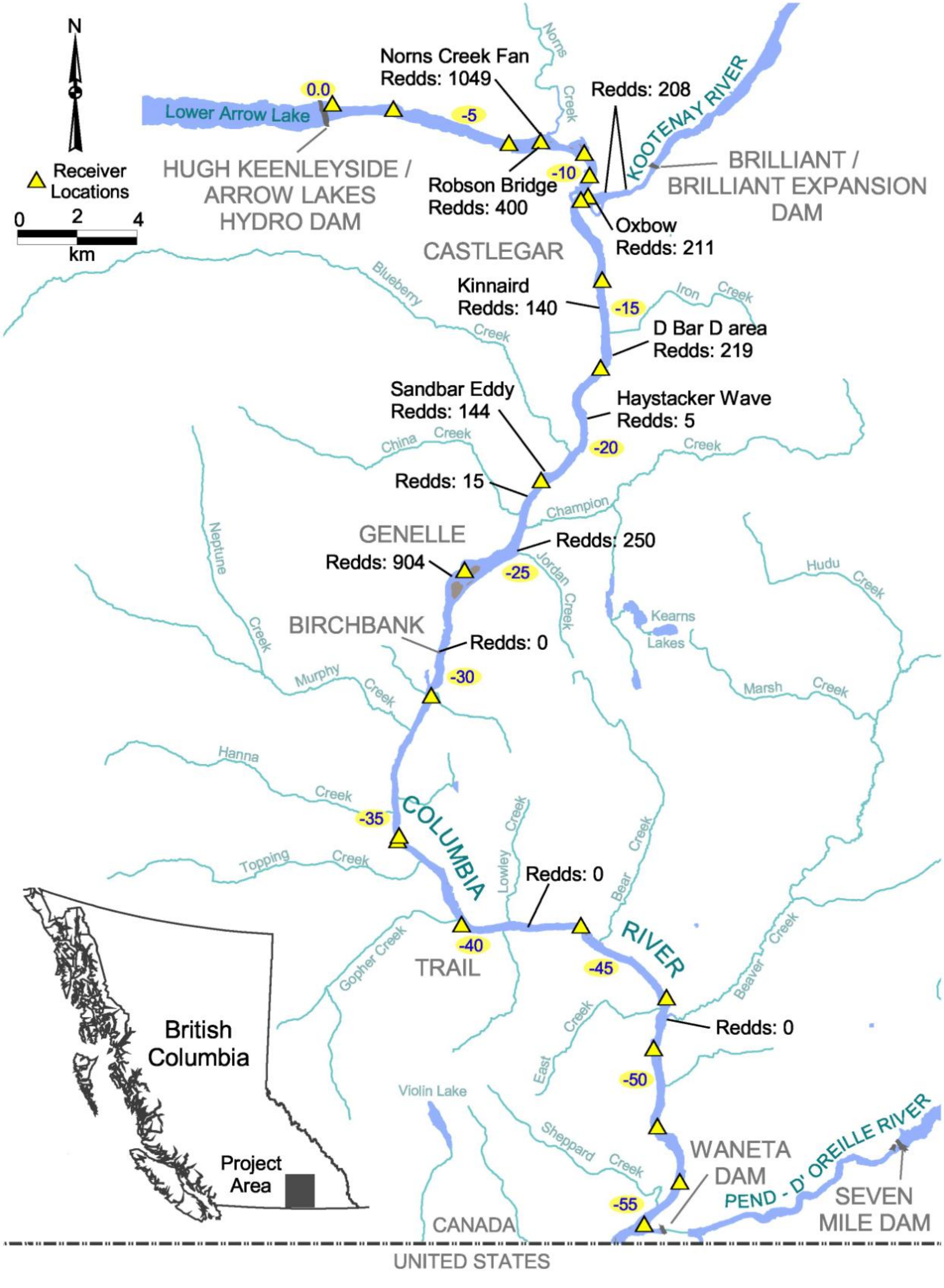

Figure 2. Study area for the Rainbow Trout spawning assessment program within the Lower Columbia and Lower Kootenay Rivers. The yellow circled numbers indicate the river kilometre downstream of HLK dam, and the yellow triangles indicate acoustic receiver locations.

2.3 Spawner and Redd Abundance and Spawn Timing

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 spawner and redd count of data. For the purposes of the analyses the study area was divided into three sections and the abundance estimated for each section. The sections were: the Lower Columbia River above the confluence with the Lower Kootenay River, the Lower Kootenay River below Brilliant dam and the LCR below the confluence with the LKR. The models' variables, parameters, distributions and assumptions are fully described in Appendix B.

Key assumptions of the model include:

- Spawner (or redd) arrival and departure are normally distributed.
- The duration of spawning is constant across years.
- The timing of spawning is affected by the standardized day of the year when the mean weekly water temperature at Norn's Creek Fan first reaches or exceeds 5°C. The day of the year is standardized by subtracting the mean of the days of the year (when the temperature reached or exceed 5°C) and dividing by the standard deviation.
- The redd model does not distinguish between test redds and egg-bearing redds.
- The total number of spawners (or redds) varies by section as a fixed effect and year and section within year as random effects.
- The residence time is between 7 and 14 days for spawners and 15 and 28 days for redds. For redds this time range is based on mark recapture information from the Lardeau on how long the redds remain distinguishable. The observer efficiency was assumed to vary between 0.9 and 1.1 for spawners and was fixed at 1.0 for redds. Values greater than 1.0 correspond to overcounting.
- Simultaneous declines in both spawners and redds are thought to be caused by poor viewing conditions (turbidity) and the affected spawner and redd counts are excluded from the analyses.
- The residual variation in the spawner (or redd) counts is described by an overdispersed Poisson distribution (Poisson-gamma distribution).

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 in the summer and fall of 2012. The sixteen Rainbow Trout acoustically tagged in 2010 were boat electrofished for capture and then had Vemco V13-1x-A69-1303 69 KHz tags inserted internally by Golder Associates Ltd. as part of the Lower Columbia River Fish Population Indexing program (Ford et al. 2011). The twenty fish tagged in 2012 were captured through angling to reduce capture stress and were tagged by a Mountain Water Research/Poisson Consulting Ltd. field crew. The same tag type and frequency of tag were utilized to continue to make use of the existing array of 25 acoustic receivers maintained by BC Hydro in the mainstem of the LCR to detect acoustically tagged White Sturgeon (*Acipenser transmontanus*). The locations of the 28 acoustic receivers are mapped in Figure 2.

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. All fish with an acoustic tag inserted in their body cavity also had a Passive Integrated Transponder (PIT) tag inserted on the left side of the dorsal fin to provide permanent identification after the battery on the Vemco tags expires. In order to minimize interference with White Sturgeon during their spawning season, the Rainbow Trout tags turn off after May 31 of each year and then turn back on to a regular pulse rate at the end of September. The battery of each tag is estimated to last 1701 days (4.6 years).

Vemco VR2W receivers have been deployed in the Norn's Creek Fan area since 2011 to detect the tagged fish at this key spawning location (Table 2). In the 2013 field season the VR2W receiver was located adjacent to Norn's Fan where previous range testing had shown the best reception to occur for a single receiver (Irvine et al. 2013).

Table 2. Vemco VR2W receiver deployment information by year.

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

2.5 *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 suggests that surface water temperatures approximate the ATUs experienced by the developing embryos.

2.6 *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 are 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 against the previous year's AUC-based redd abundance estimates and the patterns were assessed.

3.0 RESULTS

3.1 Spawner and Redd Abundance and Spawn Timing

The spawner and redd counts from the eight aerial surveys conducted in 2013 were each modeled to produce abundance estimates by year (Figure 3 and 5) and annual spawn timing estimates (Figure 4 and 6). The abundance of Rainbow Trout as predicted by spawner surveys for 2013 was 18,219 fish (95% CI 10,267 -33,678). This is almost a doubling of 2012's estimate of spawner abundance and 9.8 times higher than the low abundance estimate from 1999 of 1,852 fish (Figure 3). The modeled abundance of Rainbow Trout based on the redd surveys for 2013 was 12,475 fish (95%CI 9,310-17,233). This number of redds was up ~3,500 from the 2012 estimate and is 6.2 times higher than the low value from 1999 (Figure 5).

The peak spawn timing as predicted from spawner surveys for 2013 had an estimated mean date of April 27 (95% CI March 7 – June 17) (Figure 4). The peak spawn timing as predicted from redd surveys had an estimated date of April 29 (95% CI March 4 – June 25) (Figure 6). The surface water temperature at Norn's Creek Fan was not a significant predictor of the timing of spawning at the 5% level (the p-value was 0.35 for spawners and 0.28 for redds). The spawner and redd counts for 2013 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 C.

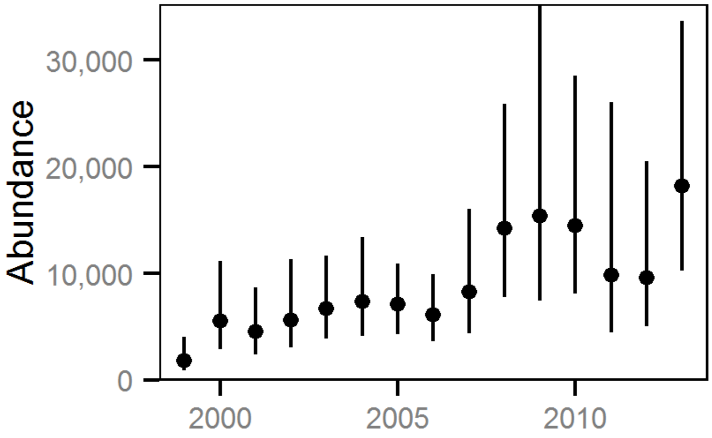

Figure 3. Annual estimates of abundance of Rainbow Trout spawners in the LCR below HLK dam and the LKR below Brilliant Dam from 1999-2013 with 95% credible intervals. The estimates are derived from spawner counts.

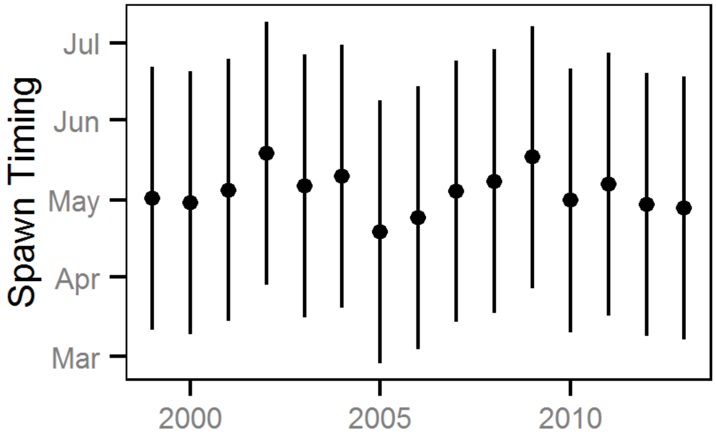

Figure 4. Annual estimates of spawn timing of Rainbow Trout spawners in the LCR below HLK dam and the LKR below Brilliant Dam from 1999-2013 with 95% credible intervals. The estimates are derived from spawner counts.

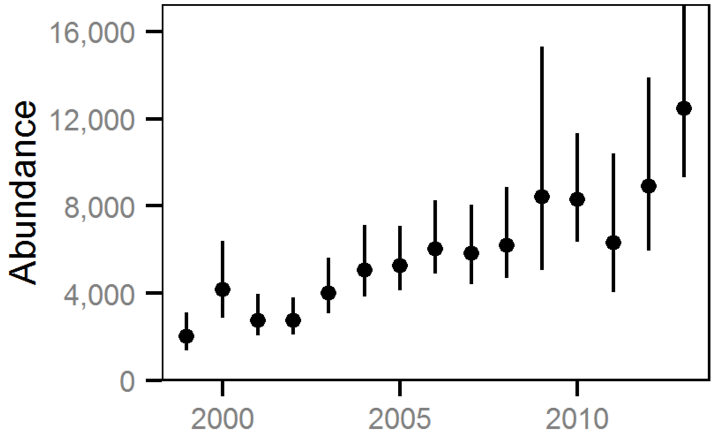

Figure 5. Annual estimates of abundance of Rainbow Trout redds in the LCR below HLK dam and the LKR below Brilliant Dam from 1999-2013 with 95% credible intervals. The estimates are derived from the redd counts.

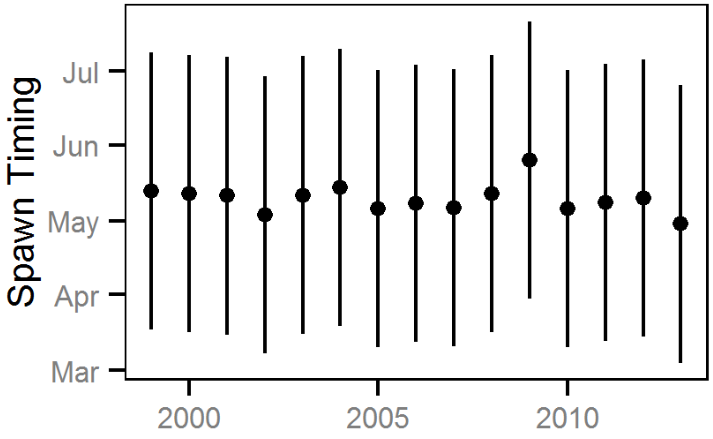

Figure 6. Annual estimates of Rainbow Trout spawn timing in the LCR below HLK dam and the LKR below Brilliant Dam from 1999-2013 with 95% credible intervals. The estimates are derived from redd counts.

The slope of the correlation between the annual spawner and redd abundance estimates was 0.63 and the correlation coefficient 0.95 (Figure 7). A slope of 1 between the two estimates would mean that each female is constructing two redds (assuming a sex ratio of 1:1) so the slope of 0.63 suggests that each female is estimated to be building 1.26 redds, based on the current modeling assumptions. This number of redds per spawner could be skewed by either model or observer error in either the spawner abundance model, the redd abundance model or in both.

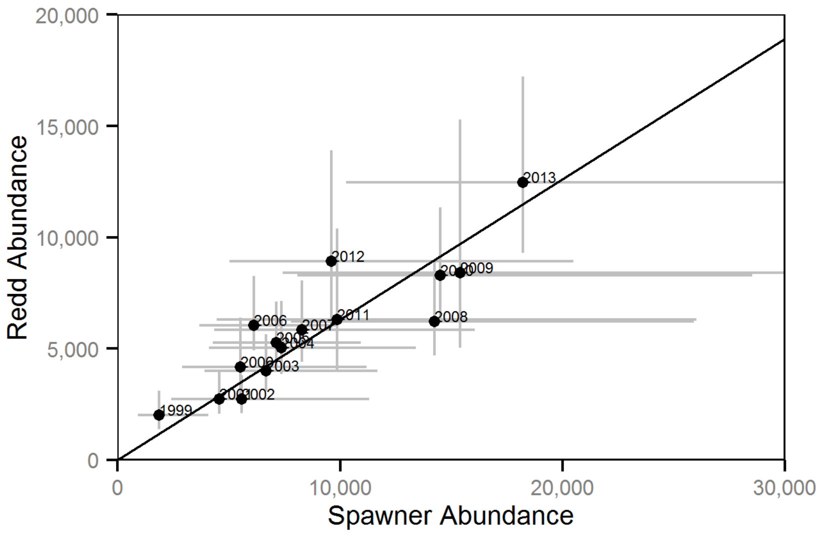

Figure 7. Redd abundance estimates versus annual spawner abundance for the Lower Columbia River below Hugh L. Keenleyside Dam and the Kootenay River below Brilliant Dam from 1999 to 2013. The bars represent 95% credible intervals.

3.2 Redd Dewatering

During 2013 no redds were salvaged, but redds were surveyed to determine the number and percentage that were dewatered. The biologists at MFLNRO and DFO decided not to excavate and salvage redds until 1% of the previous year's redd estimate was reached; this value equates to approximately 120 redds. In total, 97 redds were dewatered in the 2013 spawn year which was estimated to be 0.78% when the number of redds was divided into the model's estimate of total redds for the year. When the annual dewatering rate for each year was averaged over the fifteen years for which there were data, the mean percentage of redds that dewatered was 0.75% and ranged from near zero to 2% (Figure 8).

The redd dewatering plot does not show the timing of the events during a field season but the field crew notes the timing and location along the river during surveys. In the 2013 season, some redds dewatered during the downramping from Mountain Whitefish protection flows to RTSPF; these redds were mainly associated with early spawning fish. On February 12, when HLK flows dropped from 67 to 40 kcfs, 26 redds dewatered and on February 16, 23 redds were dewatered when HLK flows dropped from 40 to 28 kcfs at HLK. The other dewatering events occurred on March 4 when 3 redds were exposed with the drop from 31 to 26 kcfs at HLK and on April 2 when 45 redds dewatered during HLK reductions from 34 to 24 kcfs.

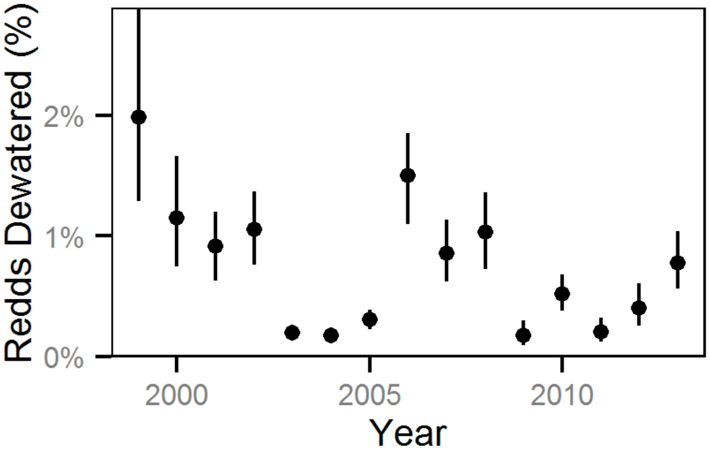

Figure 8. Percentage of redds dewatered in the Lower Columbia River below Hugh L. Keenleyside Dam and the Kootenay River below Brilliant Dam by year from 1999 to 2013. The bars represent 95% credible intervals.

3.3 Acoustic Telemetry

Of the 16 Rainbow Trout acoustically tagged in 2010, six were detected by the receivers on Norn's Creek Fan in 2011, three in 2012 and one in 2013 (Figure 9). Of the 20 fish tagged in the summer and fall of 2012, 12 were detected in 2013 (Figure 9). For the purposes of displaying photoperiod, day was considered to be the period between 06:00 and 18:00 hours. It was assumed that the period of time the fish was detected by the receiver was representative of the residence time on the spawning beds. The calculated residence times did not require the fish to be detected in consecutive days but instead represent the total of number of days during which fish were detected at least once during the spawning period. When residence was defined as detection once per 24h period, the average residence time in 2013 was 13.1 days. When residence was defined by a detection during daylight hours in a 24h period, the average residence time in 2013 was 11.8 days

(Figure 10). Over all years, the average residence time was 14.5 days when fish were detected once in a 24h period and 12.3 days when they were detected only during daylight (Figure 10). The 2011 detections differ slightly from 2012 and 2013 detections since three receivers were in place in 2011 and only one receiver in 2012 and 2013. Range testing of the single receiver detected acoustic tags as far west of the fan as 100 m upstream of the old Robson boat launch and downstream to approximately 50 m up from the Robson highway bridge on the right bank to a maximum range of 350 m (Irvine et al. 2013).

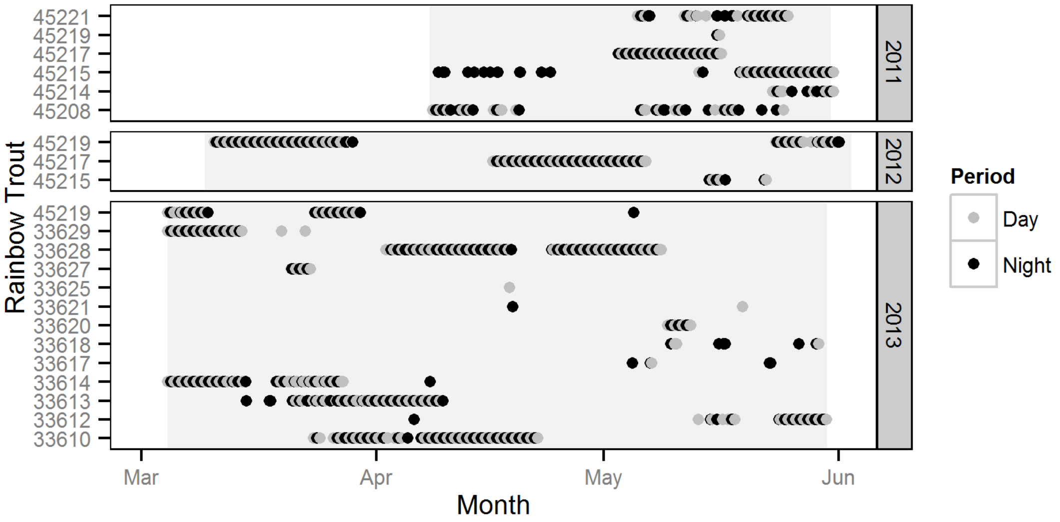

Figure 9. Norn's Creek Fan Rainbow Trout acoustic tag detections. The period of receiver deployment is indicated by the grey area. The Rainbow Trout numbers correspond to acoustic tag codes.

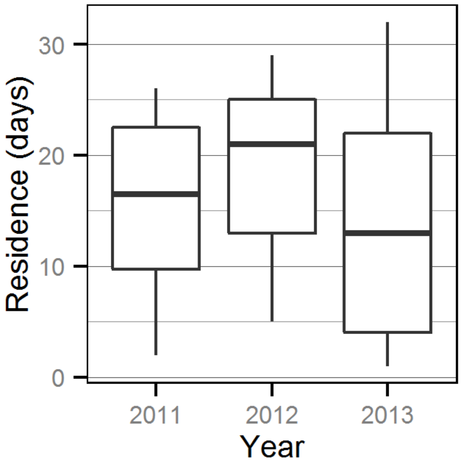

Figure 10. Norn's Creek Fan Rainbow Trout residence times by year where residence is considered any detection within a 24h period.

As well as the acoustically tagged Rainbow Trout, the receiver on Norn's Creek Fan also detected 24 White Sturgeon in 2012 and 32 White Sturgeon in 2013.

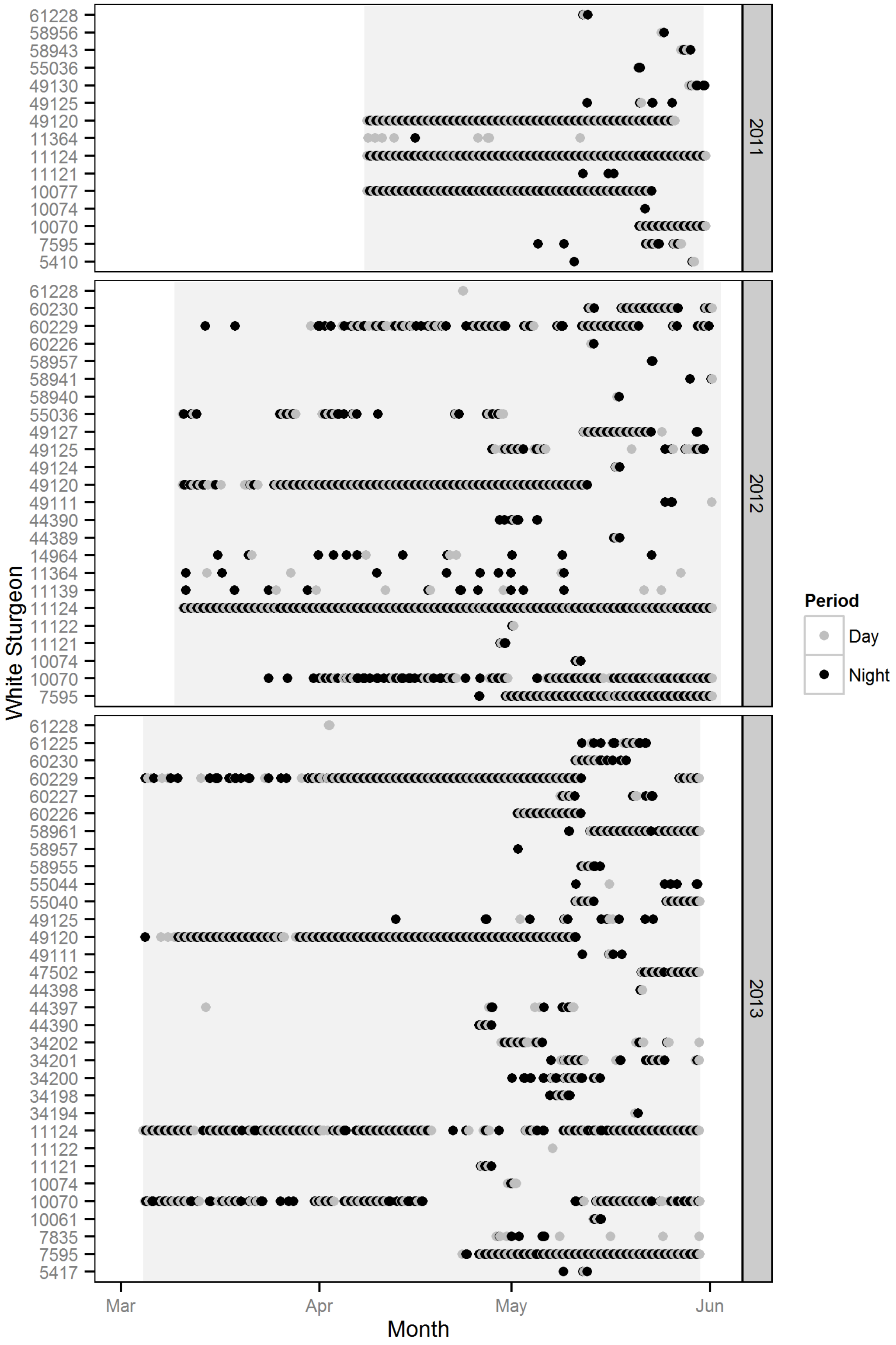

Figure 11. Norn's Creek Fan White Sturgeon acoustic tag detections. The period of receiver deployment is indicated by the grey area. The White Sturgeon numbers correspond to acoustic tag codes.

Thirteen of the White Sturgeon detected by the acoustic receiver on the fan were recorded in all three years (Figure 11). Six of the fish recorded in 2012 and ten of the fish detected in 2013 were present in the area for a substantial span of time during the Rainbow Trout spawning period (Figure 11).

3.4 Fry Emergence Timing

The fry emergence timing estimates use the results of the spawn timing model (Section 3.1) and water temperatures recorded at Norn's Creek Fan for the calculation of the ATUs. There is general agreement between the water temperature at Birchbank and Norn's with the biggest differences seen in June when Birchbank temperatures tend to be higher on average (Irvine et al. 2013). The Norn's temperature data was used since there are data for the study's entire duration and Birchbank water temperature data only commenced in 2005. Norn's water temperature data were plotted with mean and range of temperatures throughout the spawning and emergence periods to describe trends and the earliest predicted date for spawning and emergence (from both redd and fish data) and the latest predicted date are plotted on the temperature plot as well (Figure 12). The water temperature reaches 5°C in mid-April at Norn's Creek Fan, a temperature associated with the advent of spawning in other systems (Thorley et al. 2012) and reaches 17°C in early July, a temperature associated with increased embryonic mortality (Humpesch 1985) (Figure 12).

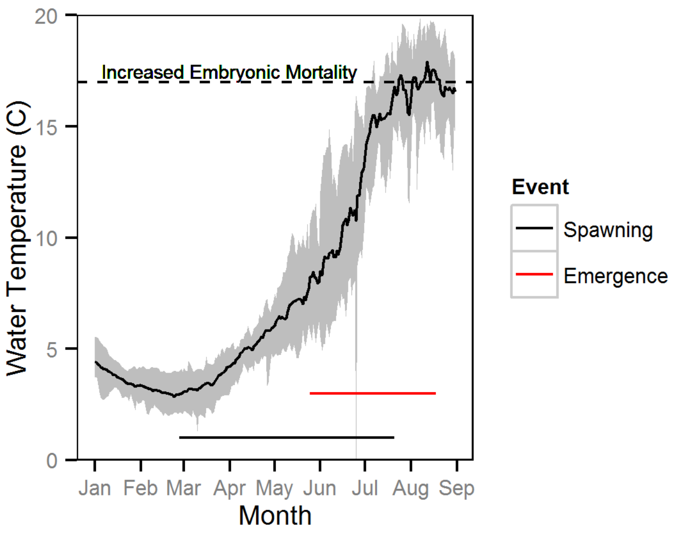

Figure 12. Mean daily surface water temperature at Norn's Creek Fan from January to September for the years 2000 to 2013 with the range of spawning and emergence dates demarcated. The black line indicates the average temperature, while the grey band indicates the range.

When predicting emergence timing, the earliest estimate is derived from calculating the ATUs from the lower bound of the lower 95% credible interval estimate for spawn timing, the peak estimate by using the peak estimate for spawn timing as the start point for the ATU calculation and the latest estimate by using the upper bound of the upper 95% credible interval estimate for spawn timing. The peak date of fry emergence for the 2013 spawn year as predicted from the timing of the peak estimate of spawner counts was June 20; for the 2012 spawn year the estimated peak emergence time was June 27 (Figure 13). The earliest predicted peak emergence date over all years of study was June 15 in 2005 and the latest predicted peak emergence date was July 9 in 2009. The peak date of emergence for the 2013 spawn year as predicted from the redd counts was June 21; for the 2012 spawn year the estimated peak was July 2 (Figure 14). The latest predicted spawning date from the redd data was July 12 in the spawn year of 2009 and the earliest date was June 21 from the 2013 spawn year (Figure 14). Missing temperature data in some years did not allow estimates of peak emergence timing and/or bounds for emergence of 95% of the fry (Figure 13, Figure 14). It is important to note that based on the redd count data, the latest emergence of fry from the redds may be as late as August 18 (2009) and based on the spawner count data, the latest emergence of fry from the redds may be as late as August 7 (2002) (Figure 13, Figure 14).

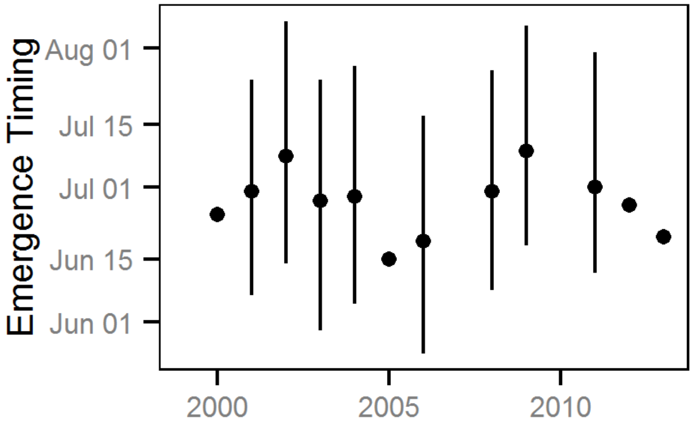

Figure 13. Annual estimates of the timing of emergence of Rainbow Trout fry from 2000 to 2013 in the Lower Columbia River below Hugh L. Keenleyside dam and the Lower Kootenay River below Brilliant Dam from 1999-2013. The bars indicate the upper and lower bounds for dates of emergence of 95% of the fry. The estimates are derived from the spawner counts and surface water temperature at Norn's Creek Fan.

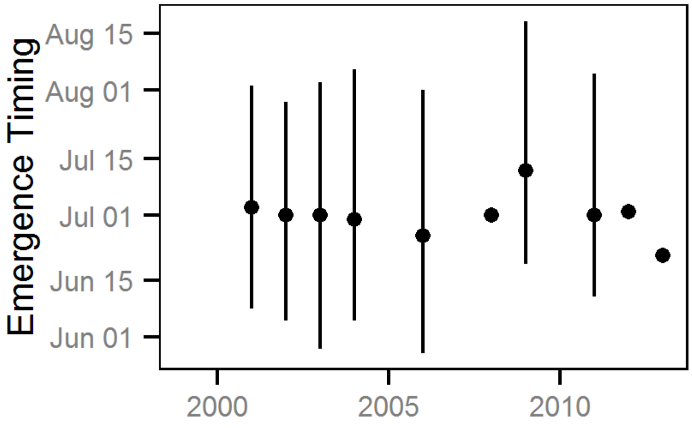

Figure 14. Annual estimates of the timing of emergence of Rainbow Trout fry from 2001 to 2013 in the Lower Columbia River below Hugh L. Keenleyside dam and the Lower Kootenay River below Brilliant Dam. The bars indicate the upper and lower bounds for emergence of 95% of the fry. The estimates are derived from the redd counts and the surface water temperature at Norn's Creek Fan.

3.5 Stock-Recruitment Relationship

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. 2011) has three peak years of age-1 abundance for the 2001, 2006 and 2010 spawn years (Figure 15.). The roughly quadrupled number of redds over the 11 years where there are data for all three indices (1999-2010) does not mirror numbers of age-1 recruits (Figure 15.). The best recruitment year for age-1 RB to date was in 2001 with the 2000 spawn year, the 2010 spawn year and 2006 spawn year in second, third and fourth places respectively.

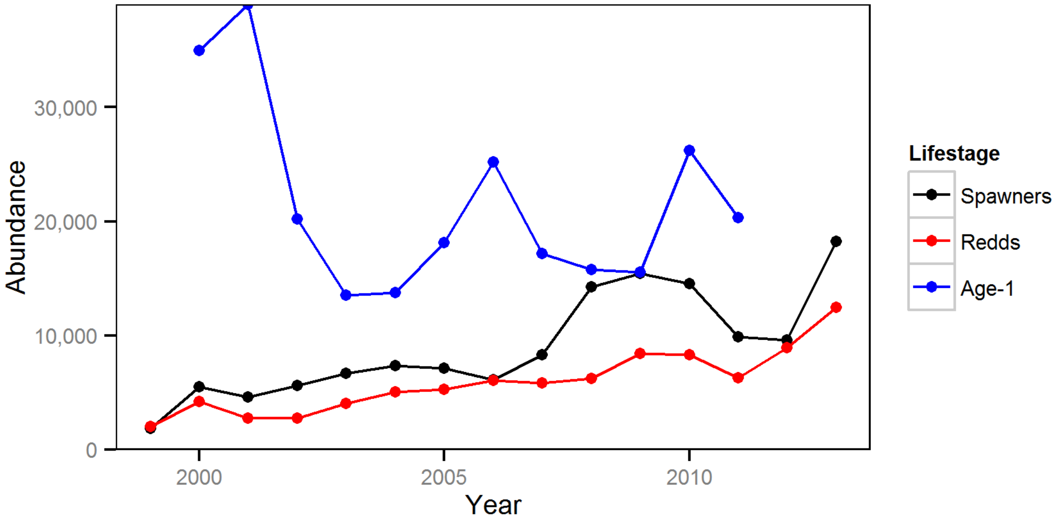

Figure 15. Spawner, redd and subsequent age-1 Rainbow Trout abundance estimates by spawn year for the Lower Columbia River below Hugh L Keenleyside Dam and the Kootenay River below Brilliant Dam from 1999 to 2013.

The plots of age-1 RB abundance vs. spawner abundance and age-1 RB vs. redd abundance in the study area do not show clear patterns of either completely density independent or completely density dependent stock-recruitment dynamics (Figure 15, Figure 16, Figure 17). The last two peak abundance levels in Age-1 fish are 4 years apart (Figure 15). Interestingly, the two highest juvenile abundances resulted from the 2000 and 2001 spawn years (Figure 16, Figure 17) which were marked by the lowest redd and spawner abundances. The relationship between age-1 RB and spawners suggests that recruitment of age-1 RB is unaffected as long as a minimum of approximately 5,000 spawners are present in the system and it may be unaffected below 5000 fish, but other than 1999 and 2001, the abundance has not fallen below that level (Figure 16).

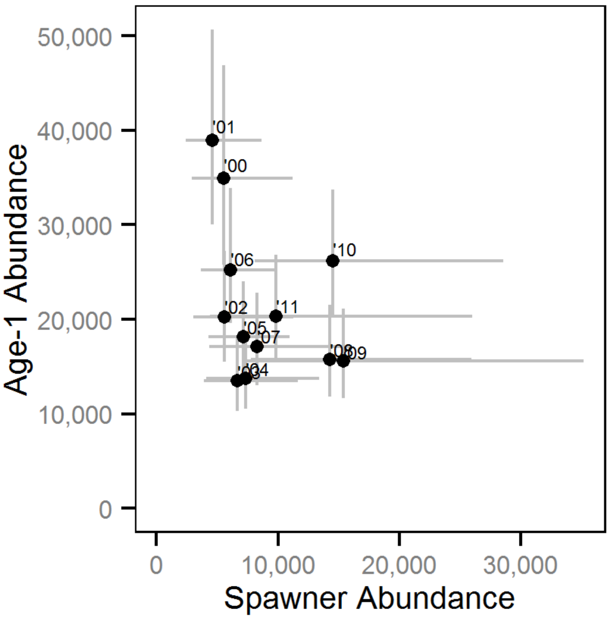

Figure 16. Number of age-1 Rainbow Trout vs. number of spawners the previous year for the Lower Columbia River below Hugh L. Keenleyside Dam and the Kootenay River below Brilliant Dam from 1999 to 2013. The vertical and horizontal bars represent 95% credible intervals. Numbers indicate spawn years.

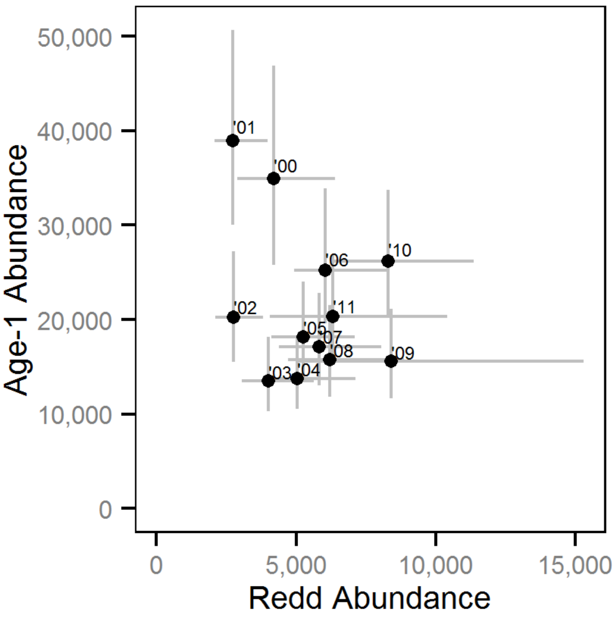

Figure 17. Number of age-1 Rainbow Trout vs. number of redds the previous year for the Lower Columbia River below Hugh L. Keenleyside Dam and the Kootenay River below Brilliant Dam from 1999 to 2013. The vertical and horizontal bars represent 95% credible intervals. Numbers indicate spawn years.

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 support a six to nine fold increase of RB spawners and redds in the Lower Columbia and Lower Kootenay Rivers since the study program commenced in 1999. 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.

The accuracy and magnitude of the redd and spawner abundance estimates depend on the extent to which the assumptions of the model are met. Spawner residence time was described by a uniform distribution from 7 to 14 days and redd residence time was assumed to be described by a uniform distribution from 15 to 28 days. If this assumed residence time is too high, it will result in an underestimate of the spawner and redd abundance and if it is too low, it will result in an overestimate. It is a similar situation for the assumed observer efficiencies. If they are too high an underestimate will result and the opposite if they are too low. Furthermore, interpretation of the spawner residence time at Norn’s Creek Fan is complicated by the fact that fish may spend time at multiple spawning locations throughout the study area which would make the acoustic-tag based residence time estimates too low; furthermore, the detection area may have included deeper holding water in the mainstem LCR which would make the residence time estimates too high. Redds have been observed in depths up to 9m (Thorley and Baxter 2011) so the deeper holding areas may or may not contain redds.

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 and downstream of the US Border. The current state of knowledge with regard to the numbers of fish spawning at these three different types of habitat 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 US and acoustically tagged fish have been observed to undertake 50 km spawning migrations. The twenty acoustically tagged fish from the 2012 study year should contribute to our knowledge of adult fish movements once we are able to obtain the receiver data from BC Hydro, which unfortunately was not available for inclusion in this report.

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. As RTSPF have been implemented since 1992 it is unclear why they would be responsible for this increase. 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. It has been noted by field crews 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 the 2013 spawn year, the spawning season commenced early and reached high numbers and stayed there for a protracted period of time. The density of redds in known, annually used spawning locations was higher than in previous years and significant superimposition was probable.

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. The range of emergence timing predicted from the modeling indicates that some redds with developing eggs may be dewatered at the end of their development window. The discharge from HLK dam increases or stays flat throughout the summer months, but the discharge from BRD decreases over 1000 m^3/s from mid-late June until early August (Figure 18). It is unknown whether all Rainbow fry have emerged by that time and the latest emergence dates predicted from the model over all years are August 18 (from redd data) and August 7 (from spawner data). This may put Rainbow Trout redds in the LKR at risk of dewatering. Approximately 15% of the spawning Rainbow Trout in the study area use the LKR.

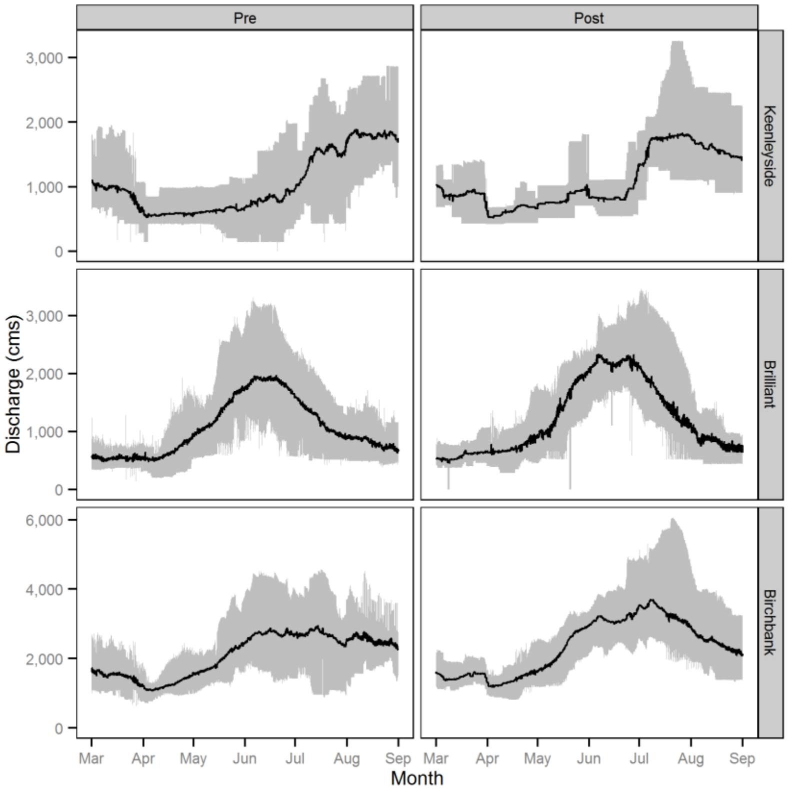

Figure 18. Discharge from HLK dam (Keenleyside), Brilliant Dam and at the Birchbank gauge from 1993-2013. The pre-Brilliant expansion period is from 1993-2006 and the Post period from 2007-2013. The black line is the average discharge, and the grey band indicates the range.

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. As a result of the salvage operations commenced in 1999, it is possible to estimate the percent of total egg deposition dewatered on an annual basis and over all years. In 2013, Rainbow Trout commenced spawning earlier than average and as a result there were 49 redds dewatered in early February on two occasions when HLK flows decreased from 67 to 40 and 40 to 28 kcfs. The majority of the remaining dewatering for the year occurred in early April when HLK flows dropped from 34 to 24 kcfs. When flows are dropped prior to the onset of spawning, the amount of shallow spawning habitat is reduced and less redd dewatering occurs. Using the redd abundance estimates from the hierarchical Bayesian AUC model, the calculations suggest that the mean dewatering rate is 0.75% with the current flow regime and was 0.78% with the earlier spawning observed in 2013. This protects the majority of the redds from dewatering and is a substantive improvement on the previous dewatering of high numbers of redds in 1990 and 1991 where between 50-75% of the redds observed at the time of the field surveys were exposed by ensuing flow reductions (Hildebrand and McKenzie 1995). As noted in the Hildebrand and McKenzie report and as seen in this year's pattern of redd dewatering, 'the persistent occurrence of some early spawning activity on the fan and at Genelle (i.e., before water levels decline), however, will likely require annual salvage operations to preserve eggs in these redds' (Hildebrand and McKenzie 1995, p.ii).

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, p.2). In order to experimentally test the effect, if any, of the RTSPF on trout abundance in the study area to address the first management question, it is proposed that alternative flow scenarios be tested (Baxter 2012). The proposed study plan which will be discussed at the interim review stage of the WLR programs in 2015 is to maintain 35 kcfs until mid-April or until a large number of redds have been constructed and then drop flows to 15 or 20 kcfs to dewater approximately 25% of Rainbow Trout redds within the study area. Results from the current analysis suggest that 50% of the redds could be dewatered without a population effect, but to be conservative while still potentially observing an effect, 25% was selected.

It is further proposed that any selected alternative flow scenario be implemented for three years occurring in alternate years (i.e., three redd dewatering events over 6 years) to ensure the observation of any effect in the abundance estimates from this study program or in recruitment to the Large River Indexing program. Alternate year sampling is suggested to conservatively assess any effect on the Rainbow Trout population without causing sustained population decline and due to the incursion of Northern Pike (*Esox lucius*) into the Lower Columbia River. Alternate year experimentation will allow the effects of the two variables (flow manipulation and invasive species) to be separated with analyses.

The first analysis of the stock-recruitment relationship between spawners and age-1 fish was conducted by Thorley (2009) and found that the compensatory model was supported more highly than the density independent model for the Rainbow Trout population in the study area. It suggested that the number of eggs being deposited was in excess of the threshold above which a proportion of the eggs might be dewatered with little to no consequences for the abundance of the adult population. The compensatory model is also suggested by the fact that a reduction in the number of spawners may have little to no effect on recruitment based on the highest recruitment years occurring in the years with the lowest spawner abundance in 2000 and 2001. The proposed alternate flow regime that would dewater 25% of the RB redds should generate data to help confirm or deny the compensatory model.

A stock-recruitment curve can be used to model the relationship between the number of eggs surviving to emergence and the number of individuals at a subsequent life-stage (Rose et al. 2001). Due to density-dependent competition such curves typically involve a minimum egg threshold above which there is little to no benefit to the adult population. In order to generate such a curve two time series are required: the number of spawners, which provides a proxy for number of eggs deposited, and the number of individuals at a subsequent life-stage. The current program has been monitoring the number of spawners since 1999 while the indexing program has been monitoring the number of age-1 fish since 2001. The indexing data has the advantage of a long time series of data, but is not particularly effective at capturing large numbers of the age-1 Rainbow Trout. In order to see the effect of flow manipulation more directly and more immediately on the abundance and habitat use of fry, it is recommended that in future years of this study program, it be expanded to include a fry habitat use and abundance estimation study similar to those done on the Lower Duncan River or the Lardeau River (Thorley et al. 2012) commencing with a pilot program to determine its feasibility in the LCR and LKR. Ideally, the fry program would commence in 2014 so that there were two years of data prior to any flow manipulations if the pilot proved successful. The allocated budget for next year's Rainbow Trout spawning survey is likely inadequate to run a pilot program. There are many nearby successful examples of large river studies (e.g., (Thorley et al. 2012) that have linked flow manipulations and habitat use with salmonid fry through snorkel survey work, GIS and modelling, but it is unknown at this time whether a study of this type on the Columbia would be successful.

A complementary approach to assessing the link between the spring discharge regime and recruitment to the adult population of Rainbow Trout is to combine Habitat Suitability Curves (HSCs) with substrate maps, the output of a two-dimensional hydrodynamic model and a stock recruitment relationship to produce a HSSR model as suggested in Thorley and Baxter (2012). A two-dimensional depth-velocity model is slated for completion on the LCR above the LKR and the LKR and if reliable, it could describe the depths and velocities throughout a section of river which, if combined with a substrate map and HSCs, could be used to predict the amount of habitat and the distribution of spawning (Hatten et al. 2009). The HSCs were completed for this population in 2012 (Thorley and Baxter 2012) and it is recommended that this approach be explored if the 2D model output is accurate enough and can be made available to the study team.

Further research is recommended for the Lower Kootenay River due to the drop in discharge from BRD during the incubation period for Rainbow Trout in the spawning location where 15% of the spawning population chooses to make their redds. Research would include: 1) obtaining accurate and precise stage data from a levellogger/barologger combination to determine what drops actually dewater usable and utilised habitat, 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, and 3) monitoring of egg stages and egg mortality or fry emergence during the summer months would address this data gap.

Habitats within the study area that experience sudden changes in water temperature or water warm enough to cause embryonic mortality prior to emergence may be sub-optimal habitat for the survival of Rainbow Trout from egg to age-1. Water temperatures measured on Norn's Creek Fan in 1990-1993 showed rapid decreases of 3-5°C with increases in discharge from HLK dam in the spring-summer period and temperatures exceeding 20°C in the July-August period (Hildebrand and Mckenzie 1995). In more recent years of study, the water temperatures at Norn's Creek Fan show low variability through the early spawning months from January to April and much more variability in May, June and July with potentially lethal temperatures for emerging fry occurring in July and August. By the summer months, water temperatures range between ~17°C and ~19°C. The percentage of rainbow fry that die due to high water temperatures varies with pH, water hardness and the genetic makeup of the population (Kwain 1975, Jobling 1981, Robison et al. 2001). Water temperatures from 15°C to 26.5°C are reported in the literature for mortality of Rainbow Trout with the wide range partly due to reporting of LC_{50} values for some studies and 100% mortality of the test population for other studies, and partly due to the effects of different genetic strains and acclimation regimes (Kwain 1975, Jobling 1981, Humpesch 1985, Robison et al. 2001). Higher water temperatures could exacerbate oxygen limitations by lowering dissolved oxygen levels in the water column while at the same time increasing embryos' oxygen demands through increased metabolic rate.

The model did not show any statistically significant effect of water temperature on redd or spawn timing. The date when 5°C is attained in the spring has been predictive of the onset of spawn timing in other systems (Thorley et al. 2012) and on average, the water temperatures recorded at Norn's Fan reach 5°C in mid-April (Figure 12), yet still no statistically significant result. This is perhaps not surprising given that the water temperature data is quite consistent without much variability from year to year to test for its effect during the assessed period. It is recommended to obtain more accurate water temperature data at key spawning sites over the next several years of the program to continue to obtain data to test whether there is an effect and whether operational changes cause any rapid alterations in water temperature for the eggs during their incubation and emergence periods.

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 3). However, these increases cannot be attributed 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. The proposed experimental manipulations in the spring hydrograph commencing in 2015 are a potentially exciting step towards improving the answers to these management questions (Baxter 2012) and a final decision on whether this experimental approach is taken will be confirmed after the interim review of the WLR studies on the LCR.

Table 3. Status of Objectives, Management Questions and Hypotheses after Year 6

Objectives	**Management Questions**	**Year 6 (2013) 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 since 1999. RTSPF may or not be responsible for this increase. Proposed experimental flow manipulations may clarify the role of the hydrograph in influencing the Rainbow Trout 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 number of locations and the spatial distribution of Rainbow Trout spawning have increased since 1996. This may be related to an increase in the number of Rainbow Trout spawners (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 0.75%, as compared to the estimated 50-75% stranding rate noted in 1990 and 1991 prior to implementation of RTSPF.

ABBREVIATIONS

Table 4. 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
BRX	Brilliant Expansion Project
BIR	Birchbank Gauging Station
BRD	Brilliant Dam
HLK	Hugh L. Keenleyside Dam
HSSR	Habitat Suitability Stock Recruitment
HSC	Habitat Suitability Curve
KHz	Kilohertz Frequency
LCR	Lower Columbia River
LDR	Lower Duncan River
LKR	Lower Kootenay River
MAF	Million Acre Feet
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

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APPENDIX A

2013 Spawner and Redd Count Maps

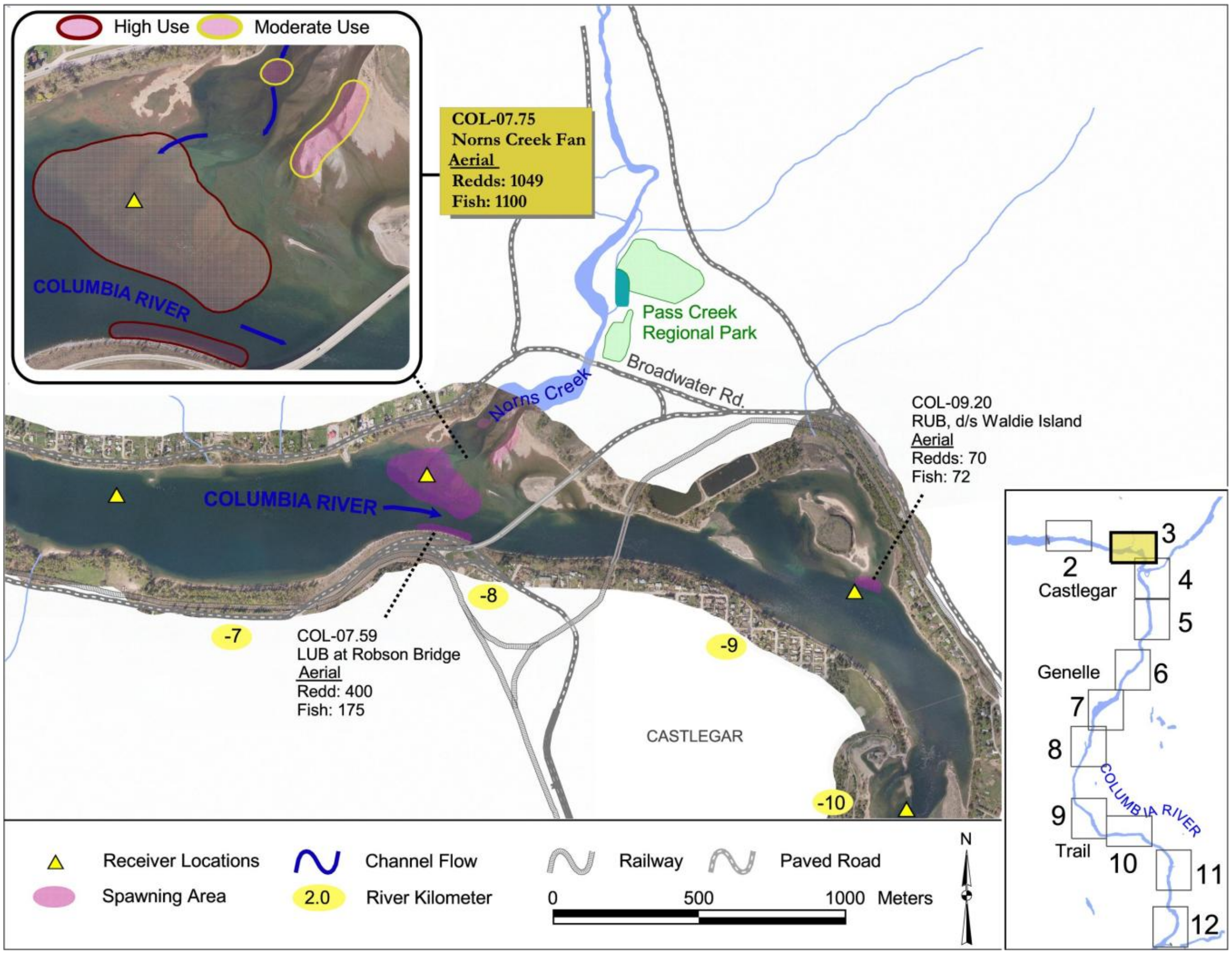


Figure A1. Spawner and redd counts in Norn's Fan Area in 2013.

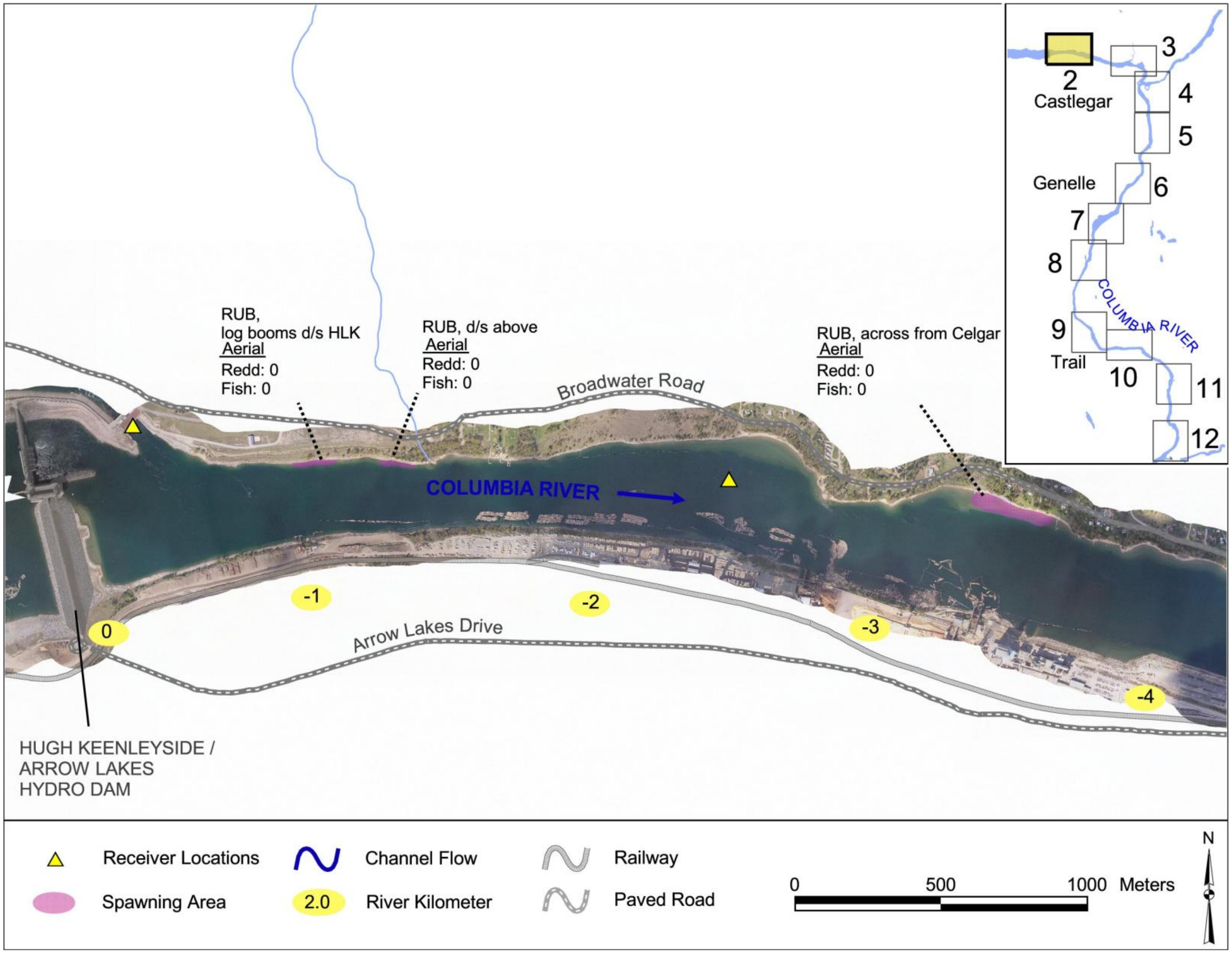


Figure A2. Spawner and redd counts by location in the HLK Dam area in 2013.

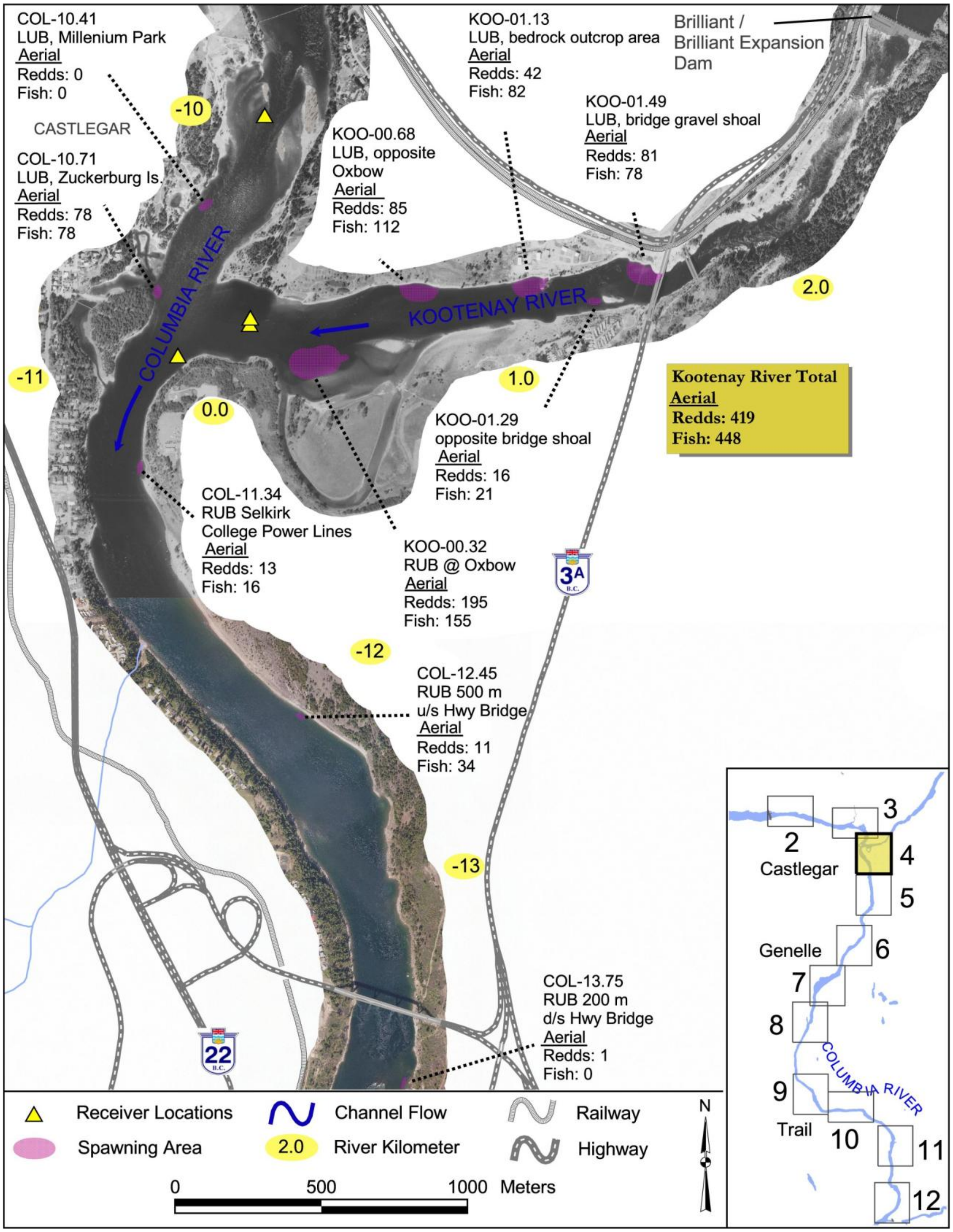


Figure A3. **Spawner and redd counts by location in the Kootenay-Columbia confluence area in 2013.**

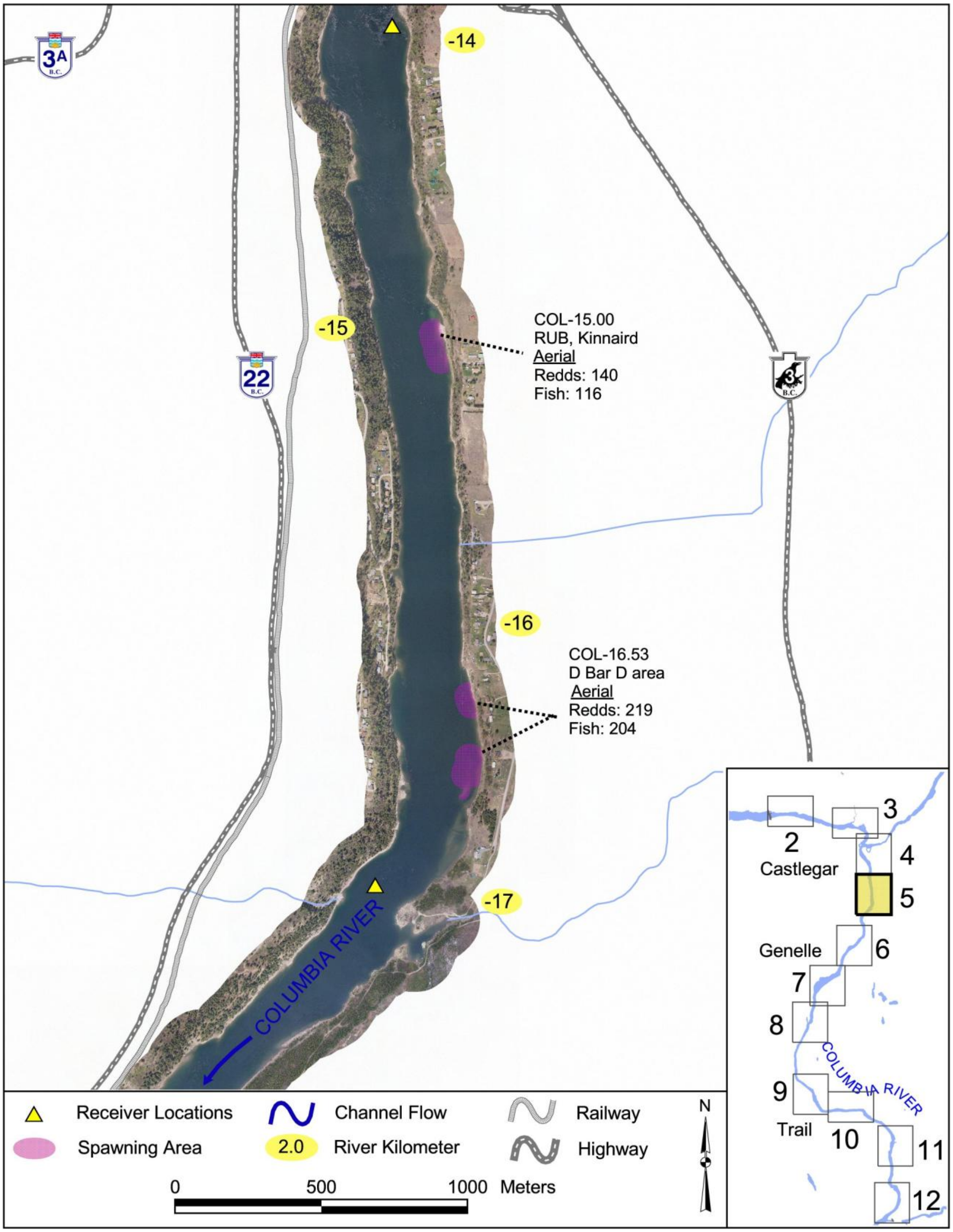


Figure A4. Spawner and redd counts by location in the D-Bar-D area in 2013.

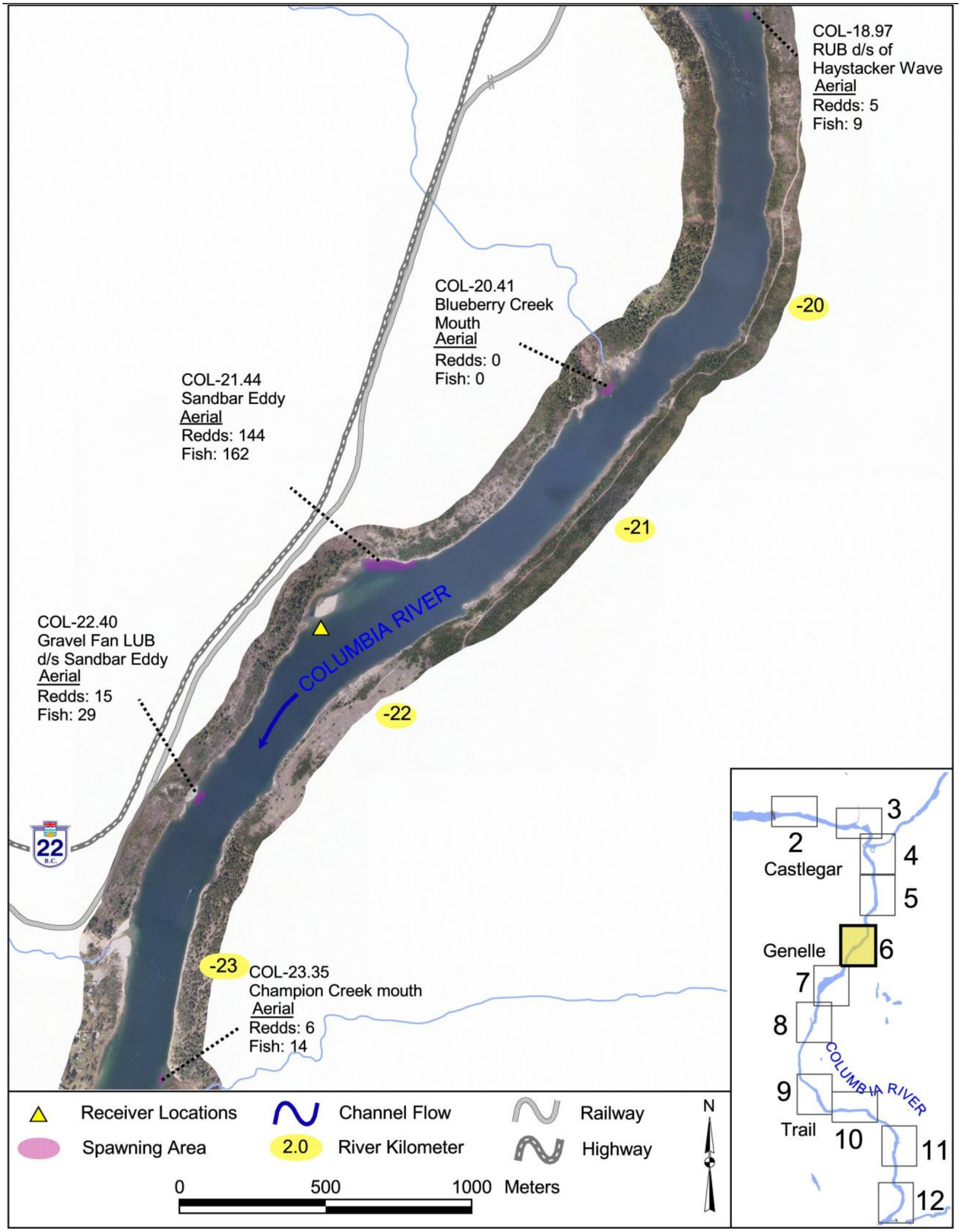


Figure A5. Spawner and redd counts by location in the Sandbar Eddy area in 2013.

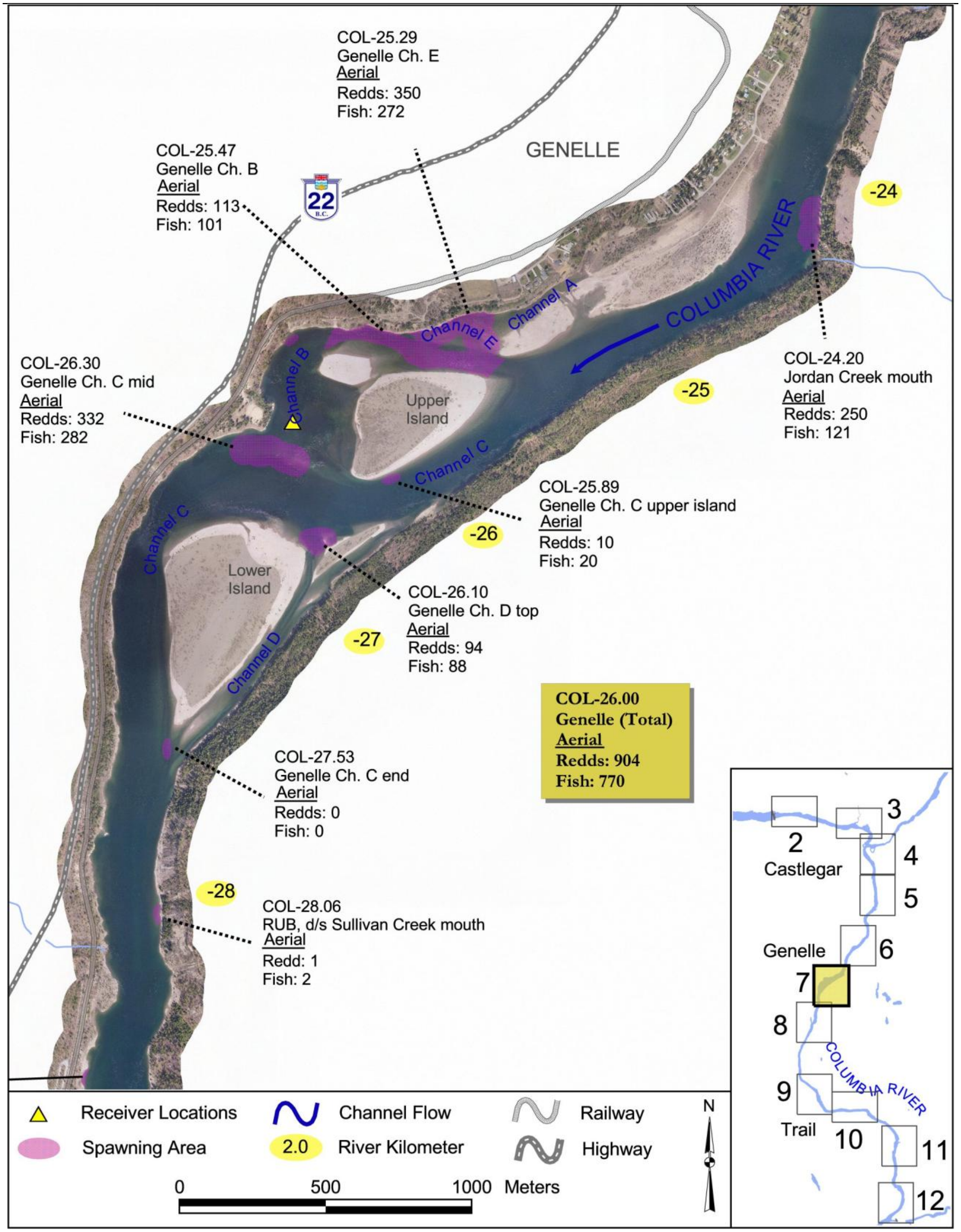


Figure A6. Spawner and redd counts by location in the Genelle area in 2013.

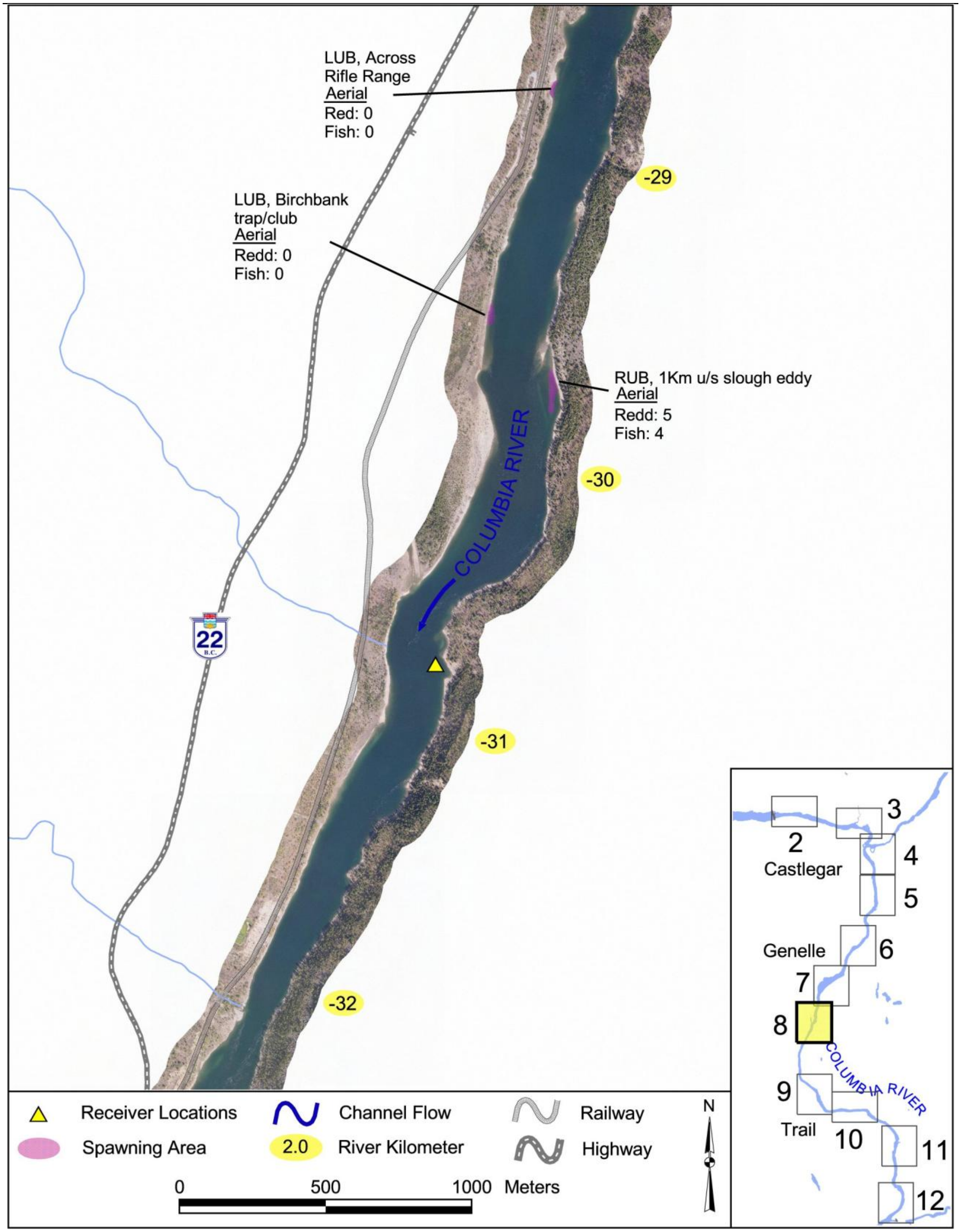


Figure A7. Spawner and redd counts by location in the Birchbank area in 2013.

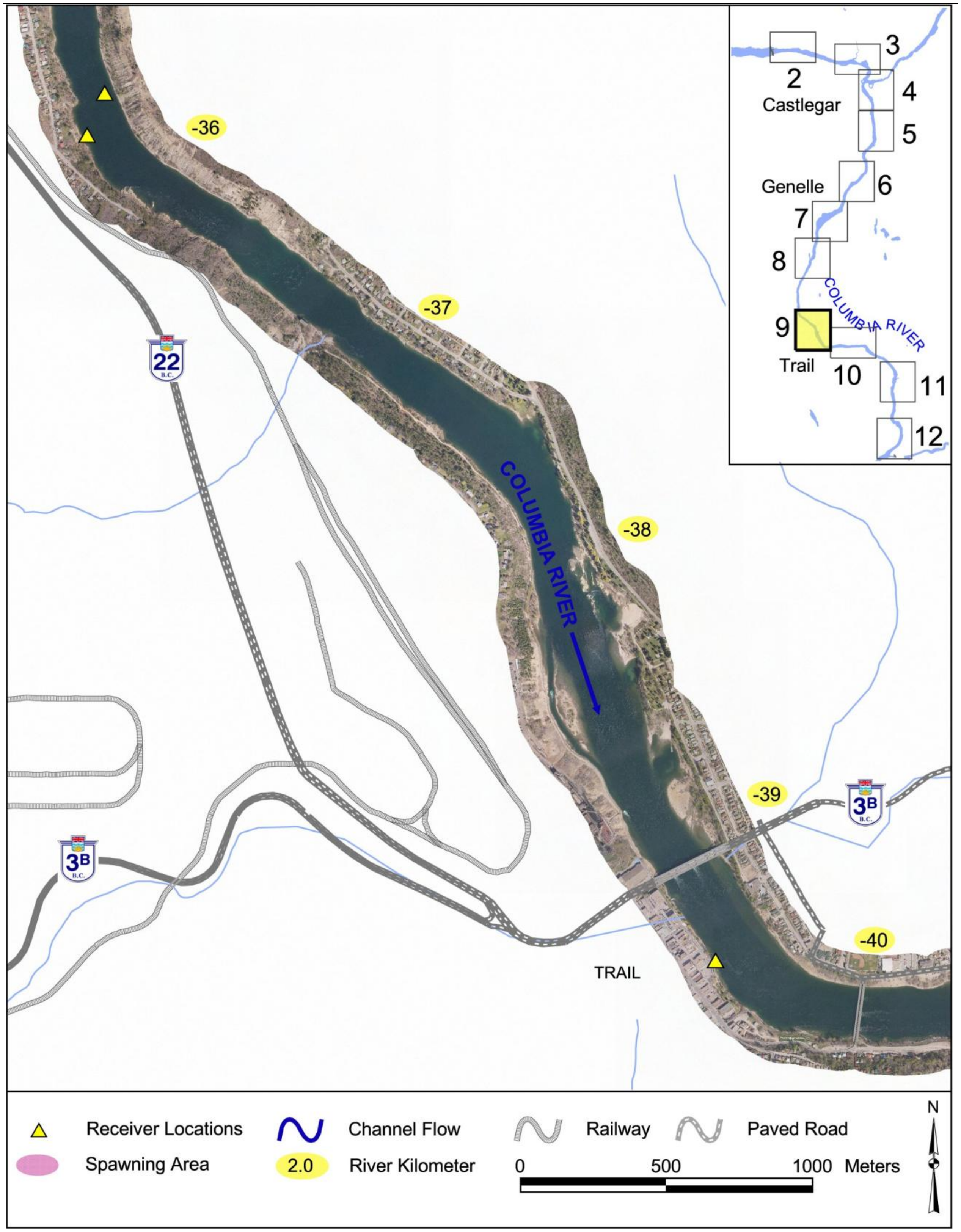


Figure A8. **Spawner and redd counts by location in the Trail area in 2013.**

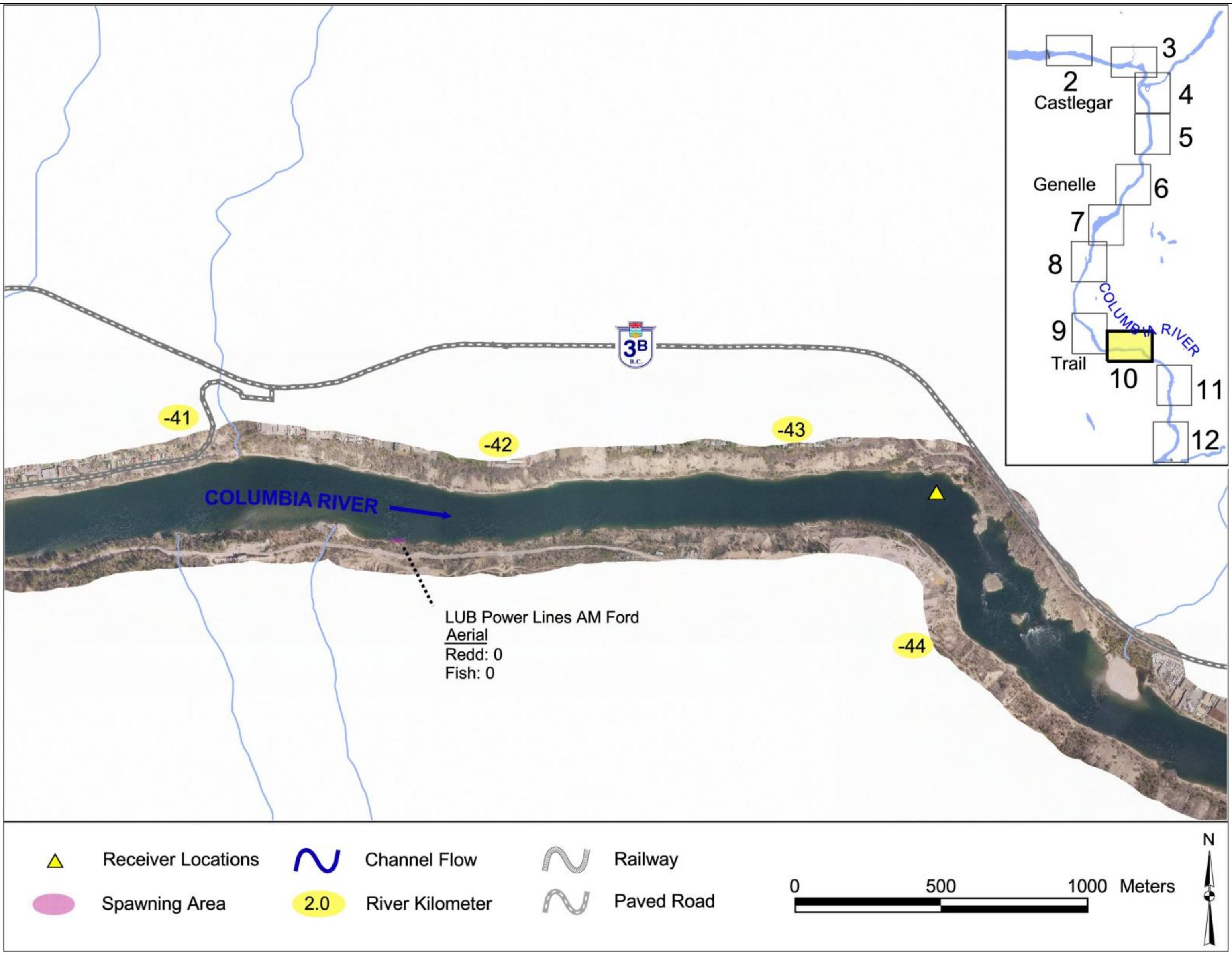


Figure A9. **Spawner and redd counts by location in the Trail AM Ford area in 2013.**

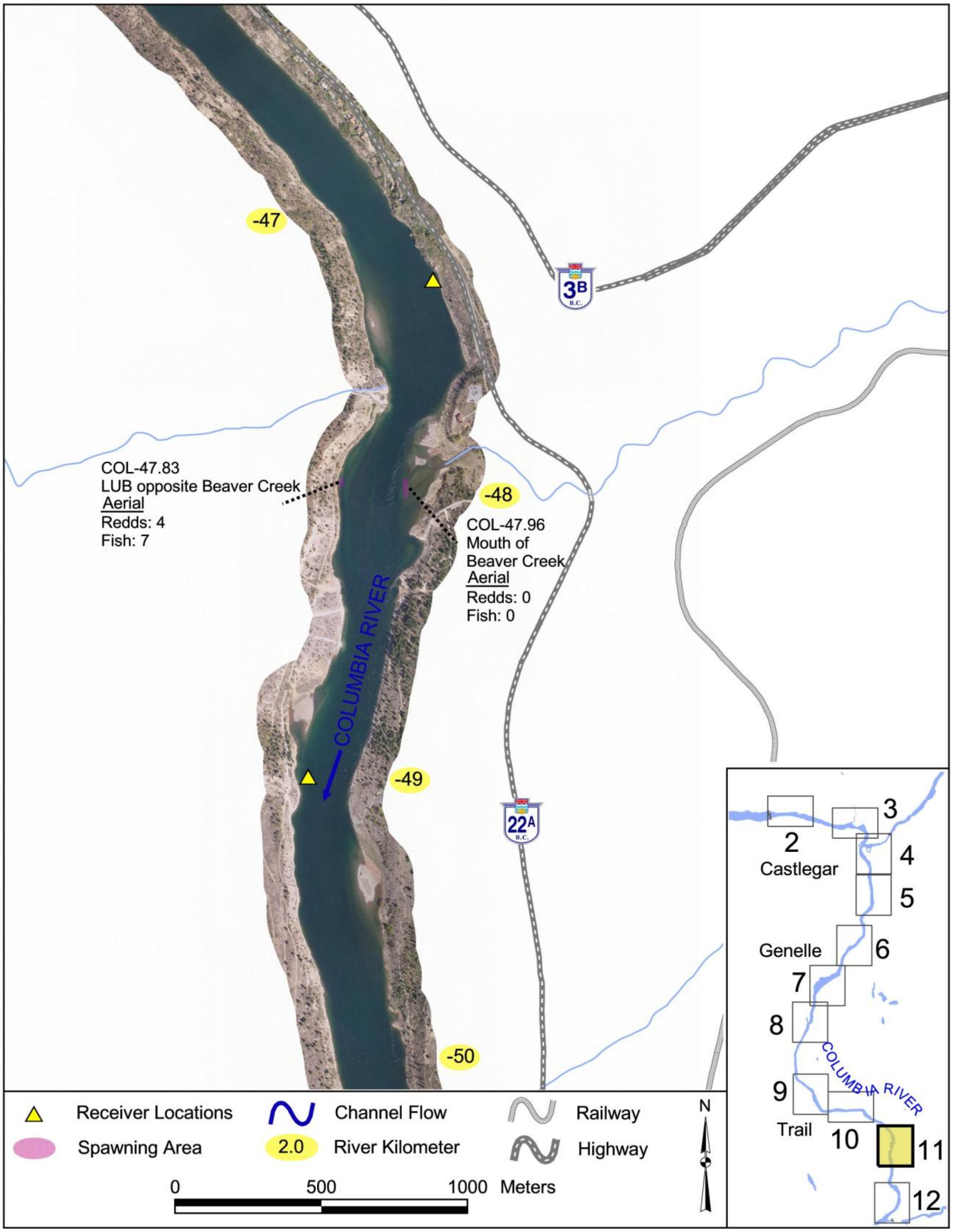


Figure A10. Spawner and redd counts by location in the Beaver Creek area in 2013.

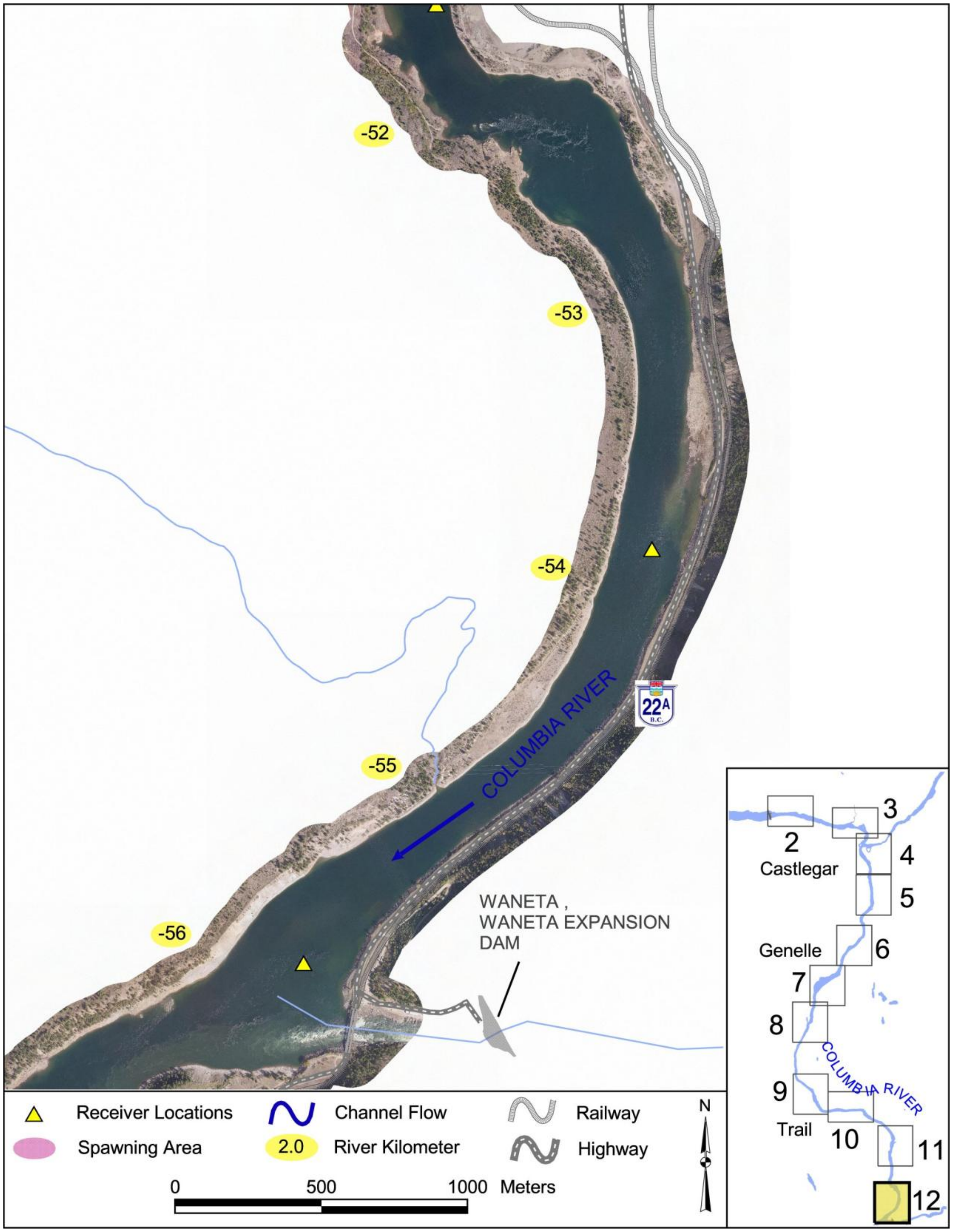
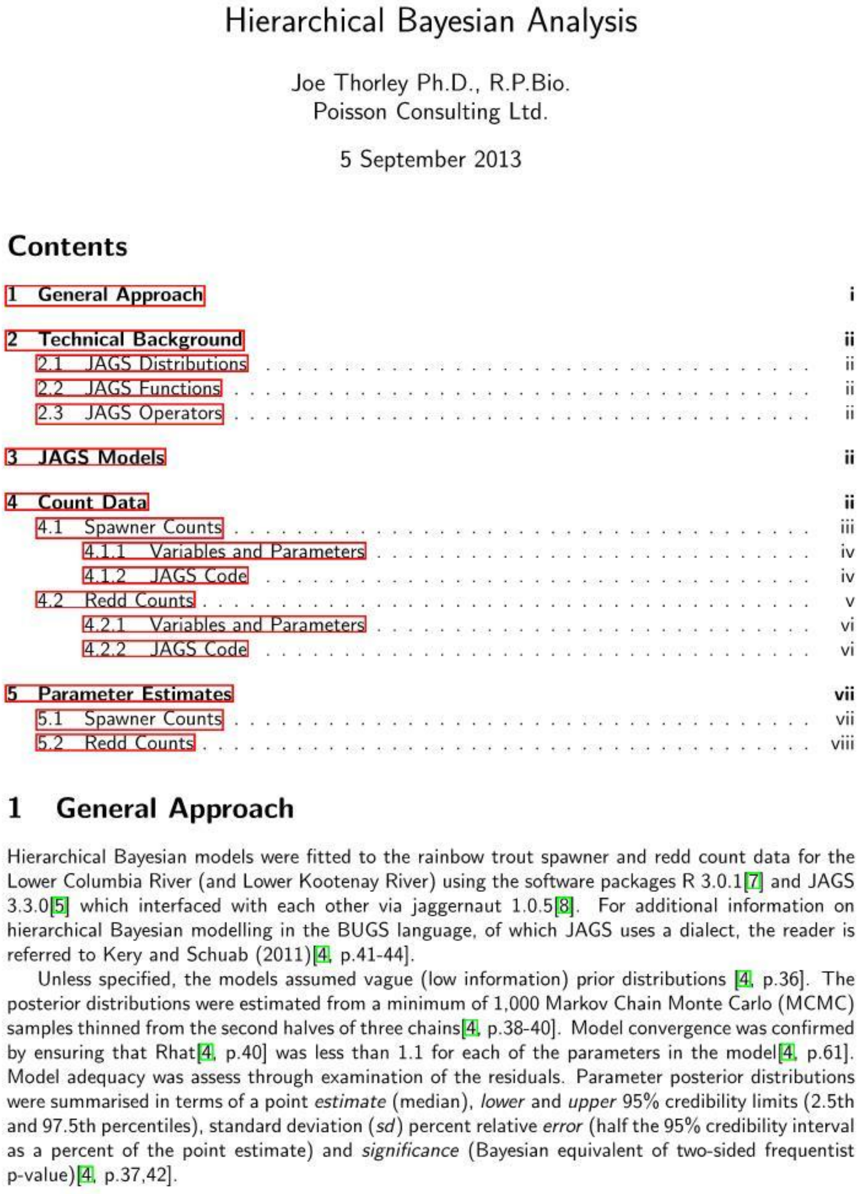


Figure A11. Spawner and redd counts by location in the Waneta Dam area in 2013.

APPENDIX B

2013 Bayesian Analyses Descriptions



Hierarchical Bayesian Analysis

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Poisson Consulting Ltd.

5 September 2013

Contents

1 General Approach

Hierarchical Bayesian models were fitted to the rainbow trout spawner and redd count data for the Lower Columbia River (and Lower Kootenay River) using the software packages R 3.0.1[7] and JAGS 3.3.0[5] which interfaced with each other via jaggernaut 1.0.5[8]. For additional information on hierarchical Bayesian modelling in the BUGS language, of which JAGS uses a dialect, the reader is referred to Kery and Schuab (2011)[4, p.41-44].

Unless specified, the models assumed vague (low information) prior distributions [4, p.36]. 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[4, p.38-40]. Model convergence was confirmed by ensuring that Rhat[4, p.40] was less than 1.1 for each of the parameters in the model[4, p.61]. Model adequacy was assess through examination of the residuals. Parameter posterior distributions were summarised in terms of a point *estimate* (median), *lower* and *upper* 95% credibility limits (2.5th and 97.5th percentiles), standard deviation (*sd*) percent relative *error* (half the 95% credibility interval as a percent of the point estimate) and *significance* (Bayesian equivalent of two-sided frequentist p-value)[4, p.37,42].

The results were displayed graphically by plotting the modeled relationship between the particular variable(s) and the response (with 95% credibility intervals) while the remaining variables were held constant. Unless stated otherwise, continuous and discrete fixed variables were held constant at their mean and first level values respectively while random variables were held constant at their typical values (expected values of the underlying hyperdistributions) [4, p.77-82]. Where informative the influence of particular variables was expressed in terms of the effect size (i.e., percent change in the response variable) with 95% credibility intervals[2]. Plots were produced using the ggplot2 R package [9].

2 Technical Background

JAGS distributions, functions and operators are defined in the following three tables. For additional information on the JAGS dialect of the BUGS language see the JAGS User Manual[5].

2.1 JAGS Distributions

JAGS Distribution	Description
dgamma(shape, rate)	Gamma distribution
dnorm(mu, sd^-2)	Normal distribution
dpois(lambda)	Poisson distribution
dunif(a, b)	Uniform distribution

2.2 JAGS Functions

JAGS Function	Description
log(x)	Log of x
phi(x)	Standard normal cumulative distribution function

2.3 JAGS Operators

JAGS Operator	Description
<-	Deterministic relationship
~	Stochastic relationship
1:n	Vector of integers from 1 to n
a[1:n]	Subset of first n values in a
for (i in 1:n) {...}	Repeat ... for 1 to n times incrementing i each time
x^y	Power where x is raised to the power of y

3 JAGS Models

The following sections provide the key assumptions, variable and parameter definitions and JAGS model code for the analyses. By convention variables are named using camel case, i.e., `ObsVar`, and the number of levels of a discrete variable `ObsFac` is referenced by `nObsFac`.

4 Count Data

The spawner and redd abundance data were estimated from the spawner and redd count data using a hierarchical Bayesian Area-Under-the-Curve (AUC) model[3, 6, 1]. For the purpose of the analysis the study are was divded into three sections: the Lower Columbia River above the confluence with the Lower Kootenay River, the Lower Kootenay River below Brilliant Dam, and the Lower Columbia River below the confluence with the Lower Kootenay River. Simulataneous declines in spawners and redds were considered to be due to poor viewing conditions and the respective spawner and redd counts were excluded from the analyses.

4.1 Spawner Counts

Spawner abundance was estimated from the spawner count data for the Lower Columbia River using a hierarchical Bayesian Area-Under-the-Curve (AUC) model.

Key assumptions of the spawner AUC model include:

- Spawner arrival timing is normally distributed.
- The duration of spawning is constant across years.
- Peak spawning is affected by the standardized day of the year when the seven day moving average water temperature at Norns Creek Fan first reaches or exceed 5°C.
- The total number of spawners varies between sections.
- The total number of spawners varies randomly with year and section within year.
- The spawner residence time is betweeen 7 and 14 days.
- The observer efficiency varies between 0.9 and 1.1.
- The residual variation in the spawner counts is described by an overdispersed Poisson distribution (Poisson-gamma distribution).

4.1.1 Variables and Parameters

Variable/Parameter	Description
bAbundance[sc, yr]	Abundance at the scth section in the yrth year
bAbundanceSection[sc]	Intercept for abundance in the scth section
bAbundanceSectionYear[sc, yr]	Effect of the scth section within the yrth year on abundance
bAbundanceYear[yr]	Effect of the yrth year on abundance
bObserverEfficiency	Observer efficiency as a proportion
bPeakTiming	Mean timing of peak spawning
bPeakTimingTemperature	Effect standardised temperature day of the year on peak timing
bPeakTimingYear[yr]	Effect of the yrth year on peak spawn timing
bResidenceTime	Individual residence time in days
bRho	Overdispersion parameter
bTemperature	Mean of the standardised temperature day of the year
Count[i]	The ith spawner count
Dayte[i]	Day of the year of the ith spawner count
dError[i]	Expected overdispersion in the ith spawner count
eAbundance[i]	Expected abundance for the ith spawner count
eCount[i]	Expected ith spawner count
ePeakTiming[i]	Expected timing of peak spawning for the ith spawner count
nrow	Number of spawner counts
sAbundanceSectionYear	SD of the effect of section within year on abundance
sAbundanceYear	SD of the effect of year on abundance
Section[i]	The section of the ith spawner count
sPeakTimingYear	SD of the effect of year on peak spawn timing
sSpawnDuration	SD of the duration of spawning
sTemperature	SD of the standardised temperature day of the year
Temperature	Standardised temperature day of the year
Year[i]	The year of the ith spawner count

4.1.2 JAGS Code

```
model {
  sSpawnDuration ~ dunif(0, 42)

  sPeakTimingYear ~ dunif(0, 42)
  bPeakTiming ~ dnorm(130, 35)

  bResidenceTime ~ dunif(7,14)
  bObserverEfficiency ~ dunif(0.9,1.1)
  bRho ~ dgamma(0.1, 0.1)

  sAbundanceYear ~ dunif(0, 5)
  sAbundanceSectionYear ~ dunif (0, 5)

  sTemperature ~ dunif(0, 2)
  bTemperature ~ dnorm(0, 1)
  bPeakTimingTemperature ~ dnorm (0, 35)

  for (yr in 1:nYear) {
    bPeakTimingYear[yr] ~ dnorm (0, sPeakTimingYear^-2)
```

```
    bAbundanceYear[yr] ~ dnorm (0, sAbundanceYear^-2)
  }
  for (sc in 1:nSection) {
    bAbundanceSection[sc] ~ dunif(0, 10)
    for (yr in 1:nYear) {
      bAbundanceSectionYear[sc, yr] ~ dnorm (0, sAbundanceSectionYear^-2)
      log(bAbundance[sc, yr]) <- bAbundanceSection[sc] + bAbundanceYear[yr]
        + bAbundanceSectionYear[sc, yr]
    }
  }

  for (i in 1:nrow) {
    Temperature[i] ~ dnorm(bTemperature, sTemperature^-2)
    ePeakTiming[i] <- bPeakTiming + bPeakTimingTemperature * Temperature[i]
      + bPeakTimingYear[Year[i]]
    eAbundance[i] <- (phi((Dayte[i] - ePeakTiming[i])/sSpawnDuration)
      - phi((Dayte[i] - ePeakTiming[i] - bResidenceTime)/sSpawnDuration))
      * bAbundance[Section[i], Year[i]]
    dError[i] ~ dgamma(bRho, bRho)
    eCount[i] <- eAbundance[i] * bObserverEfficiency
    Count[i] ~ dpois (eCount[i] * dError[i])
  }
}
```

4.2 Redd Counts

Redd abundance was estimated from the redd count data for the Lower Columbia River using a hierarchical Bayesian Area-Under-the-Curve (AUC) model.

Key assumptions of the redd AUC model include:

- Redd arrival timing is normally distributed.
- The duration of spawning is constant across years.
- Peak spawning is affected by the standardized day of the year when the seven day moving average water temperature at Norns Creek Fan first reaches or exceed 5°C.
- The total number of redds varies between sections.
- The total number of redds varies randomly with year and section within year.
- The redd residence time is betweeen 15 and 28 days.
- The observer efficiency is 1.0.
- The residual variation in the redd counts is described by an overdispersed Poisson distribution (Poisson-gamma distribution).

4.2.1 Variables and Parameters

Variable/Parameter	Description
bAbundance[sc, yr]	Abundance at the scth section in the yrth year
bAbundanceSection[sc]	Intercept for abundance in the scth section
bAbundanceSectionYear[sc, yr]	Effect of the scth section within the yrth year on abundance
bAbundanceYear[yr]	Effect of the yrth year on abundance
bObserverEfficiency	Observer efficiency as a proportion
bPeakTiming	Mean timing of peak spawning
bPeakTimingTemperature	Effect standardised temperature day of the year on peak timing
bPeakTimingYear[yr]	Effect of the yrth year on peak spawn timing
bResidenceTime	Individual residence time in days
bRho	Overdispersion parameter
bTemperature	Mean of the standardised temperature day of the year
Count[i]	The ith redd count
Dayte[i]	Day of the year of the ith redd count
dError[i]	Expected overdispersion in the ith redd count
eAbundance[i]	Expected abundance for the ith redd count
eCount[i]	Expected ith redd count
ePeakTiming[i]	Expected timing of peak spawning for the ith redd count
nrow	Number of redd counts
sAbundanceSectionYear	SD of the effect of section within year on abundance
sAbundanceYear	SD of the effect of year on abundance
Section[i]	The section of the ith redd count
sPeakTimingYear	SD of the effect of year on peak spawn timing
sSpawnDuration	SD of the duration of spawning
sTemperature	SD of the standardised temperature day of the year
Temperature	Standardised temperature day of the year
Year[i]	The year of the ith redd count

4.2.2 JAGS Code

```
model {
  sSpawnDuration ~ dunif(0, 42)

  sPeakTimingYear ~ dunif(0, 42)
  bPeakTiming ~ dnorm(130, 35)

  bResidenceTime ~ dunif(15,28)
  bObserverEfficiency <- 1
  bRho ~ dgamma(0.1, 0.1)

  sAbundanceYear ~ dunif(0, 5)
  sAbundanceSectionYear ~ dunif (0, 5)

  sTemperature ~ dunif(0, 2)
  bTemperature ~ dnorm(0, 1)
  bPeakTimingTemperature ~ dnorm (0, 35)

  for (yr in 1:nYear) {
    bPeakTimingYear[yr] ~ dnorm (0, sPeakTimingYear^-2)
```

```
    bAbundanceYear[yr] ~ dnorm (0, sAbundanceYear^-2)
  }
  for (sc in 1:nSection) {
    bAbundanceSection[sc] ~ dunif(0, 10)
    for (yr in 1:nYear) {
      bAbundanceSectionYear[sc, yr] ~ dnorm (0, sAbundanceSectionYear^-2)
      log(bAbundance[sc, yr]) <- bAbundanceSection[sc] + bAbundanceYear[yr]
        + bAbundanceSectionYear[sc, yr]
    }
  }

  for (i in 1:nrow) {
    Temperature[i] ~ dnorm(bTemperature, sTemperature^-2)
    ePeakTiming[i] <- bPeakTiming + bPeakTimingTemperature * Temperature[i]
      + bPeakTimingYear[Year[i]]
    eAbundance[i] <- (phi((Dayte[i] - ePeakTiming[i])/sSpawnDuration)
      - phi((Dayte[i] - ePeakTiming[i] - bResidenceTime)/sSpawnDuration))
      * bAbundance[Section[i], Year[i]]
    dError[i] ~ dgamma(bRho, bRho)
    eCount[i] <- eAbundance[i] * bObserverEfficiency
    Count[i] ~ dpois (eCount[i] * dError[i])
  }
}
```

5 Parameter Estimates

5.1 Spawner Counts

Parameter	estimate	lower	upper	sd	error	significance
bAbundanceSection[1]	7.92	7.42	8.44	0.27	6	0
bAbundanceSection[2]	7.12	6.6	7.68	0.271	8	0
bAbundanceSection[3]	8.21	7.68	8.73	0.268	6	0
bObserverEfficiency	0.994	0.907	1.09	0.0554	9	0
bPeakTiming	130	130	130	0.167	0	0
bPeakTimingTemperature	-0.00969	-0.351	0.311	0.167	3.42e+03	0.95
bResidenceTime	9.18	7.07	13.5	1.85	35	0
bRho	1.97	1.65	2.34	0.182	18	0
bTemperature	0.09	-0.00901	0.186	0.0505	108	0.0812
sAbundanceSectionYear	0.138	0.00822	0.299	0.0824	105	0
sAbundanceYear	0.665	0.407	1.13	0.181	54	0
sPeakTimingYear	11.3	6.61	18.9	3.26	54	0
sSpawnDuration	26	23.9	28.2	1.09	8	0
sTemperature	1	0.937	1.08	0.0371	7	0

5.2 Redd Counts

Parameter	estimate	lower	upper	sd	error	significance
bAbundanceSection[1]	7.41	7.07	7.77	0.172	5	0
bAbundanceSection[2]	6.66	6.33	6.99	0.175	5	0
bAbundanceSection[3]	7.92	7.6	8.26	0.167	4	0
bObserverEfficiency	1	1	1	0	0	0
bPeakTiming	130	130	130	0.171	0	0
bPeakTimingTemperature	0.00551	-0.327	0.33	0.172	5.96e+03	0.967
bResidenceTime	24.9	18.6	27.9	2.61	19	0
bRho	12	9.88	14.7	1.27	20	0
bTemperature	0.0852	-0.0155	0.18	0.0515	115	0.0896
sAbundanceSectionYear	0.248	0.178	0.359	0.0474	36	0
sAbundanceYear	0.562	0.349	0.899	0.138	49	0
sPeakTimingYear	7.01	4.26	12.1	2.01	56	0
sSpawnDuration	28.9	28	30	0.517	3	0
sTemperature	1	0.937	1.08	0.0361	7	0

References

[1] Milo D. Adkison and Zhenming Su. A comparison of salmon escapement estimates using a hierarchical bayesian approach versus separate maximum likelihood estimation of each year's return. *Canadian Journal of Fisheries and Aquatic Sciences*, 58(8):1663–1671, 2001.

[2] Michael J Bradford, Josh Korman, and Paul S Higgins. Using confidence intervals to estimate the response of salmon populations (oncorhynchus spp.) to experimental habitat alterations. *Canadian Journal of Fisheries and Aquatic Sciences*, 62(12):2716–2726, 2005.

[3] Ray Hilborn, Brian G Bue, and Samuel Sharr. Estimating spawning escapements from periodic counts: a comparison of methods. *Canadian Journal of Fisheries and Aquatic Sciences*, 56(5):888–896, 1999.

[4] Marc Kery and Michael Schaub. *Bayesian population analysis using WinBUGS : a hierarchical perspective*. Academic Press, Boston, 2011.

[5] M. Plummer. JAGS version 3.3.0 user manual, October 2012.

[6] Zhenming Su, Milo D. Adkison, and Benjamin W. Van Alen. A hierarchical bayesian model for estimating historical salmon escapement and escapement timing. *Canadian Journal of Fisheries and Aquatic Sciences*, 58(8):1648–1662, 2001.

[7] R Core Team. R: A language and environment for statistical computing, 2013.

[8] J. L. Thorley. jaggernaut: An r package to facilitate bayesian analyses using JAGS (just another gibbs sampler), 2013.

[9] Hadley Wickham. *ggplot2 elegant graphics for data analysis*. Springer, Dordrecht; New York, 2009.

APPENDIX C

2013 Spawner and Redd Counts with AUC Estimates and Viewing Conditions

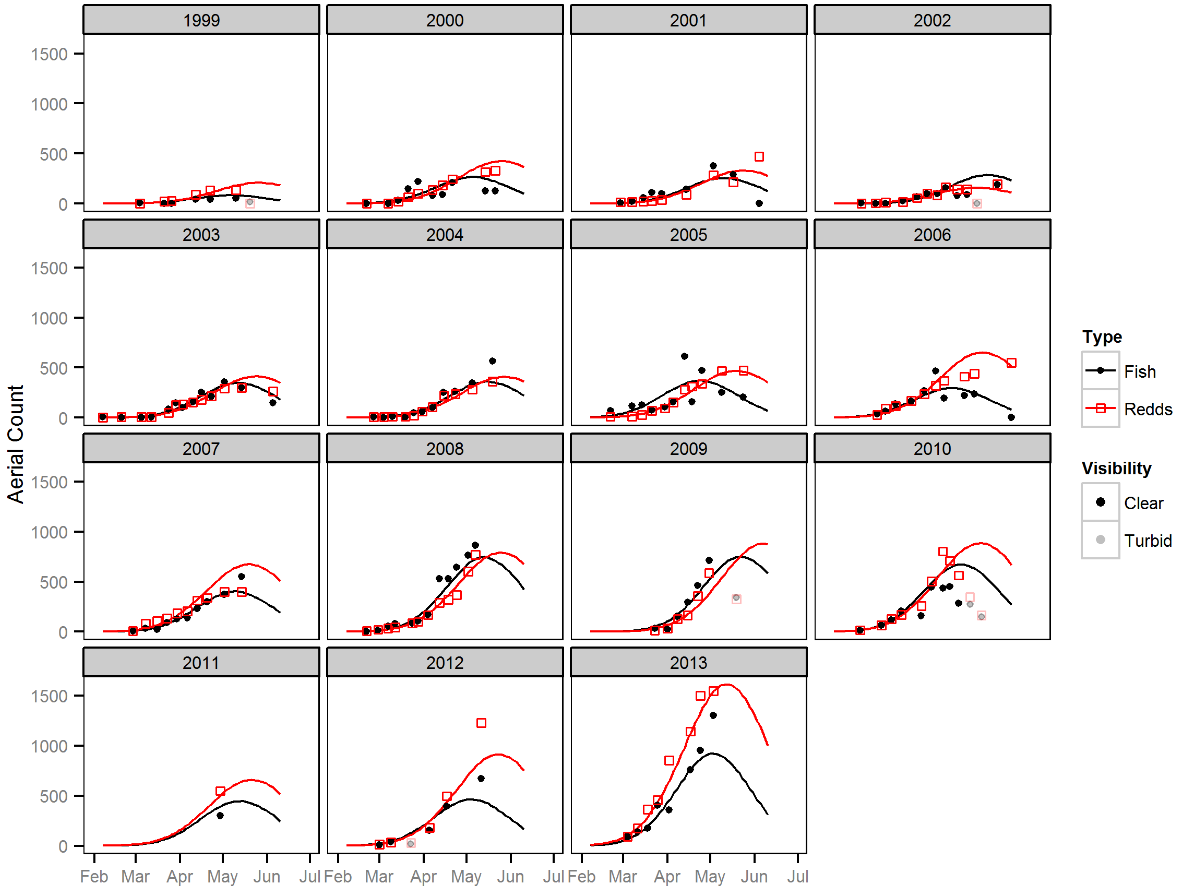

Figure C1. The spawner and redd counts for the Lower Columbia River above the Kootenay River with the AUC-based estimates of the expected counts.

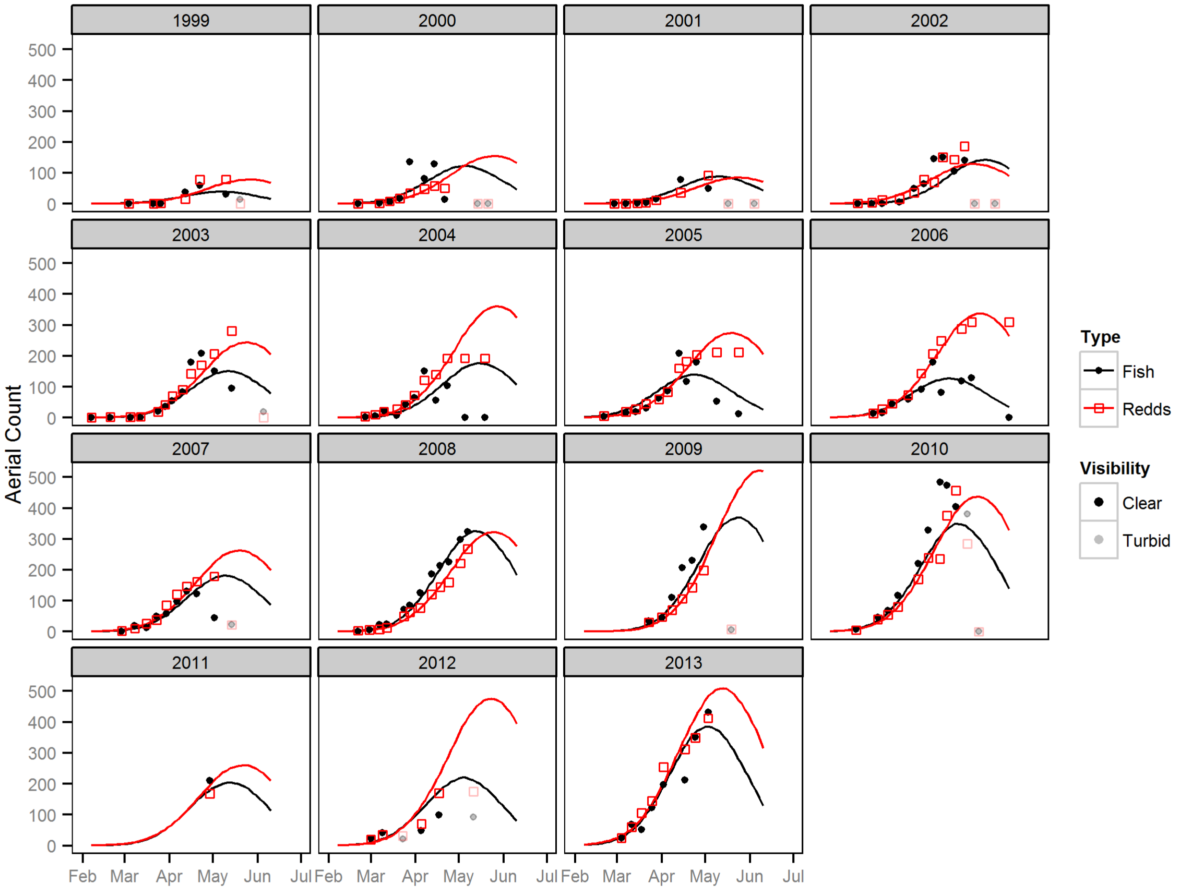

Figure C2. The spawner and redd counts for the Kootenay River below Brilliant Dam with the AUC-based estimates of the expected counts.

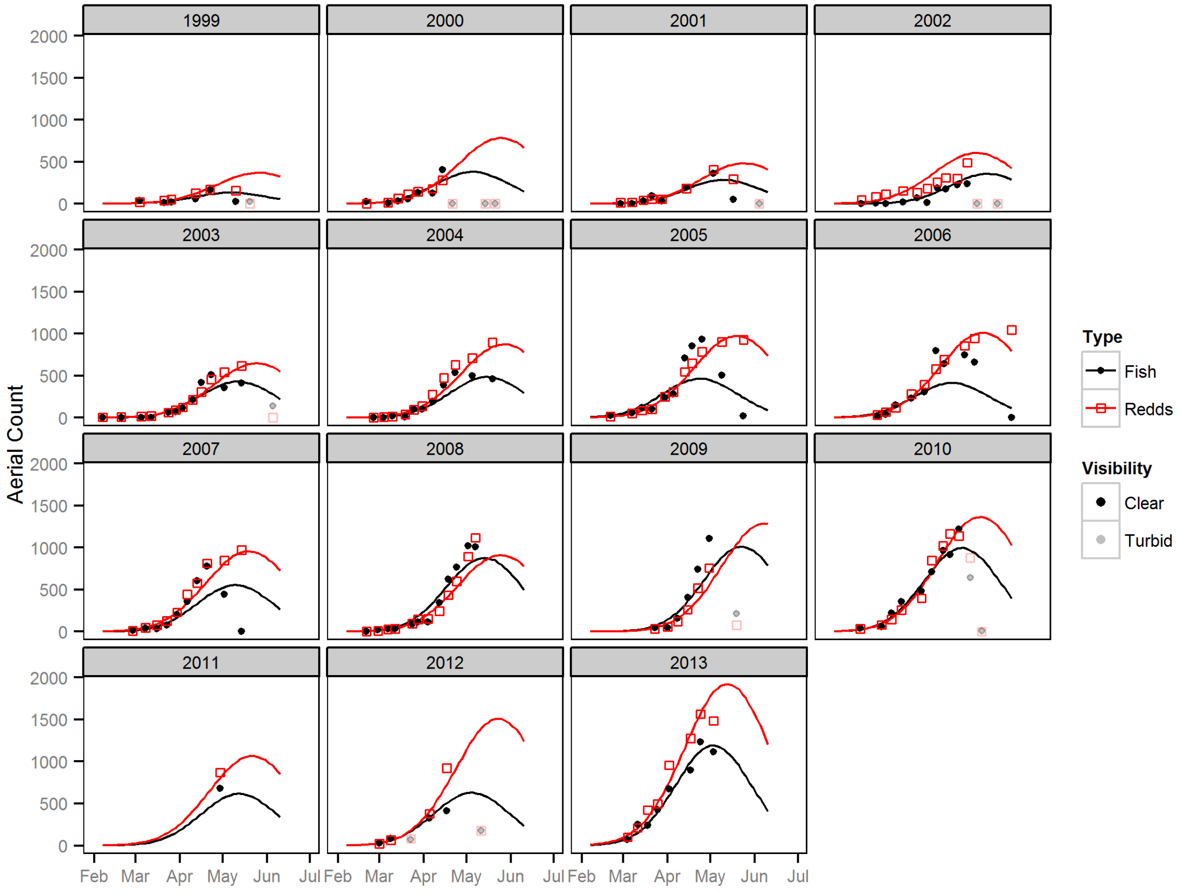

Figure C3. The spawner and redd counts for the Lower Columbia River below the Kootenay River with the AUC-based estimates of the expected counts.