

Cheakamus River Project Water Use Plan

Cheakamus River Steelhead Adult Abundance, and Juvenile Habitat Use and Abundance Monitoring

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*Cheakamus River Steelhead Adult Abundance, and Juvenile
Habitat Use and Abundance Monitoring*

Study Period: 2007 – 2008

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September 29, 2008

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Final Report

Report Prepared for BC Hydro

By

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Abstract

The Cheakamus River once supported a large and productive wild winter-run steelhead population and a well-known steelhead fishery. Although the steelhead population is much smaller today, it still attracts considerable angling effort and is likely one of the more productive wild steelhead population in southern BC. A proportion of the Cheakamus River is diverted to the Squamish River for power generation. Recently, rules controlling the timing and extent of the diversion have been modified based on a Water Use Planning (WUP) process. The objectives of this project are to determine if the number of steelhead juveniles and adults in the Cheakamus River are affected by the WUP-flow regime, and more broadly, to determine how flow affects steelhead production in this system. This will be accomplished through long-term monitoring of escapement and the abundance of fry and parr populations in spring and fall. The methodology for estimating steelhead escapement in the Cheakamus River is well-established, but methods for quantifying fry and parr abundance are currently poorly defined. A major emphasis in the first year of this program, and of this report, is to compare alternate methods of estimating juvenile steelhead abundance to structure the sampling program in future years.

Steelhead escapement to the Cheakamus River is estimated by fitting parameters of a run-timing model to count data from repeat snorkel surveys conducted over the adult migration and spawning season. We conducted 14 snorkel surveys between January 23rd and May 8th, 2008. The range of counts across surveys for steelhead, resident rainbow trout, and char were 20-76, 4-23, and 40-136, respectively. Observer efficiency for steelhead, estimated based on the ratio of horizontal visibility to discharge, ranged from 0.16-0.68. Maximum estimates of the number of steelhead and rainbow trout present were 260 and 94, respectively. Most likely estimates of steelhead escapement in 2008 based on the year-independent and pooled-year models were 239 ($\pm 0.95 = 173-305$) and 342 ($\pm 0.95 = 258-425$), respectively. The most likely steelhead escapement based on the year-independent model in 2008 was similar to 2006, and the lowest estimate on record since 2001. The 2008 escapement estimate was over 50% lower than the estimate from 2007.

We conducted backpack and boat electrofishing between September 18th and October 16th, 2007 to evaluate the efficacy of alternate methods of estimating steelhead fry and parr abundance in shallow and deep habitats of the Cheakamus River, respectively. We compared catch rates and length frequency distributions from single pass backpack and boat electrofishing (index sampling) conducted during day and night, and used mark-recapture experiments to quantify capture probability (the proportion of fish captured within a site per sampling event) for the most promising approaches. Backpack electrofishing at night captured a slightly higher fraction of larger steelhead fry compared to sampling during the day, but few parr were captured at either time. The catch from boat electrofishing at night contained a much higher fraction of steelhead parr. Catch rates for steelhead fry and parr based on single-pass backpack electrofishing were at least 3-fold higher at night compared to catch rates during the daytime. Catch rates of steelhead parr based on boat electrofishing at night were similar to catch rates based on backpack electrofishing at night. In contrast, catch rates of steelhead fry based on boat electrofishing were much lower than those based on backpack electrofishing.

The success of mark-recapture experiments, which depends on the number of marks applied on the 1st pass, the proportion recaptured on the second pass, and the proportion of marks found outside of mark-recaptures sites, was variable among gear types and species during fall sampling. Capture probabilities for steelhead fry were higher than for parr when backpack electrofishing, and capture probability based on boat electrofishing was generally very low for both life stages. Most likely estimates of capture probability for steelhead fry averaged 0.39 and 0.08 based on backpack and boat electrofishing, respectively. Estimates of capture probability for steelhead parr averaged 0.04 and 0.06 based on backpack and boat electrofishing, respectively, and were very imprecise in both cases. Trends in estimates of abundance reflected the patterns seen for capture probability. Precise estimates of abundance were obtained for steelhead fry based on backpack electrofishing with densities ranging from 400-900 trout \cdot 100m⁻¹ (coefficient of variation = 0.06). Population size for steelhead fry based on boat electrofishing could only be estimated in five of 11 experiments. Population estimates for steelhead parr could only be obtained in approximately 50% of both backpack and boat electrofishing-based experiments.

The fall sampling session demonstrated that, per unit of effort, nighttime sampling will result in much more precise estimates of abundance since the precision of site-specific population estimates ultimately depends on the number of fish that are caught. Backpack electrofishing experiments yielded precise estimates for steelhead fry but not for parr. Loss of marked fry out of discrete mark-recapture sites was negligible, thus fry populations within sites can be treated as effectively closed. Boat electrofishing in the Cheakamus River only yielded relatively precise estimates of capture probability and abundance for coho salmon fry and was not effective at estimating abundance of either steelhead fry or parr.

We conducted 16 mark-recapture experiments at night at discrete sites in the Cheakamus River using various combinations of backpack electrofishing and snorkeling in the spring of 2008. Steelhead and coho juveniles were caught and marked using backpack electrofishing at eight sites, and by divers using dip nets at the other eight sites. Fish were enumerated, marked, and released back into the sites. At all 16 sites, we conducted two types of recapture events the following evening. We first snorkeled the site and enumerated the number of marked and unmarked fish. One-hour later, we electrofished the site and enumerated the number of marked and unmarked fish. Each mark-recapture experiment was conducted over a 24-hour period. With this design, we were able to determine how estimates of capture probability and population size depended on both the method used to initially capture fish for marking (including how they were marked), as well as the method used during the recapture event.

There was minimal bias in diver estimates of steelhead fork length and precision was very high. Averaged over 178 measurements, divers underestimated fork lengths by only 2.5%. Diver-estimated fork lengths predicted 95% of the variation in measured lengths. Electrofishing was more effective at capturing small steelhead while divers were more efficient at seeing larger steelhead, especially those larger than 140 mm, which were virtually absent from the electrofishing sample. In total, 759 and 301 marks were applied to steelhead fry and parr, respectively. The assumption that populations within mark-recapture sites could be treated as effectively closed over the 24-hour period between marking and recovery was supported by the data as a total of only 6 (0.8%) and

9 (3%) marked steelhead fry and parr were observed in the 25 m sections surveyed upstream and downstream of mark-recapture sites by snorkeling, respectively.

Capture probability estimates for steelhead fry and parr in the spring were very dependent on both the method used to initially capture and mark fish, as well as the recapture method. Capture probabilities for fry based on snorkel marking and recapture (SN-SN, 0.37) or electrofishing marking and recapture (EF-EF, 0.38) were similar and not significantly different. Average capture probabilities for fry based on electrofishing recapture, when fish were first captured and marked by snorkeling (SN-EF, 0.27) or electrofishing (EF-EF, 0.38), were not significantly different. Average capture probability for parr based on snorkeling (SN-SN, 0.76) was significantly higher than the average based on electrofishing (EF-EF, 0.14). Similar to the result seen for fry, there was no significant effect of the marking method on capture probability when recapturing based on electrofishing. Capture probability depended on fish size and the nature of the relationship varied with gear type. In the case of electrofishing, capture probability declined linearly with fork length, while for snorkeling, capture probability was relatively constant between 70 and 150 mm, but dropped to 0 for the smallest size class (40-60 mm). Snorkel-based capture probability was significantly higher for all size classes except the smallest (40-60 mm), where electrofishing-based capture probability was significantly higher.

Population estimates for steelhead fry and parr in the spring were sensitive to both marking and recapture methods. The average of electrofishing-based estimates (EF-EF) of $295 \text{ fry} \cdot 100\text{m}^{-1}$ was significantly higher than the snorkel-based (SN-SN) average of $142 \text{ fry} \cdot 100\text{m}^{-1}$. We suspect that the snorkel-based estimates were biased low because capture probability varied substantially among individuals, likely in relation to their size and concealment behaviour. The average coefficient of variation for fry population estimates based on snorkeling and electrofishing were 0.34 and 0.16, respectively. Population estimates for steelhead parr were similar across most combinations of first capture and recapture methods ($96\text{-}105 \text{ parr} \cdot 100\text{m}^{-1}$) with average coefficients of variation based on snorkeling and electrofishing of 0.10 and 0.55, respectively.

Results from the mark-recapture experiments in the fall and spring indicate that backpack electrofishing is the best method to estimate steelhead fry abundance in the

Cheakamus River. Snorkel-based mark-recapture is the best approach for estimating steelhead parr abundance in the spring. It is likely not feasible to estimate the river-wide abundance of parr in the fall because our sampling showed that electrofishing methods are not adequate, and snorkeling would likely not be effective due to high turbidity at this time. We recommend that electrofishing be used to estimate the river-wide abundance of steelhead fry in fall and spring, and that snorkeling be used to estimate the abundance of parr in the spring. Catch rates and site-specific population estimates for parr captured by backpack electrofishing in fall and spring can be used to index river-wide parr abundance. The spring index can be compared to the more reliable snorkel-based trend over time to test the assumption that parr densities in shallow sites that can be sampled with backpack electrofishing adequately capture river-wide trends in abundance.

Table of Contents

Abstract.....	ii
Table of Contents.....	vii
Acknowledgements.....	viii
1.0 General Introduction.....	1
1.1 References.....	7
2.0 Escapement Surveys.....	8
2.1 Introduction.....	8
2.2 Methods.....	8
2.2.1 Snorkel Surveys and Radio Telemetry.....	8
2.2.2 Steelhead Escapement Model.....	11
2.2.3 Expansion of Resident Rainbow Trout Counts.....	16
2.3 Results.....	16
2.4 Discussion.....	25
2.5 References.....	27
3.0 Fall Juvenile Surveys.....	28
3.1 Introduction.....	28
3.2 Methods.....	29
3.2.1 Index Backpack and Boat Electrofishing.....	29
3.2.2 Backpack and Boat Electrofishing Mark-Recapture Experiments.....	31
3.2.3 Pilot Comparison of Depletion and Mark-Recapture Methodologies.....	36
3.2.4 Enclosed Depletion Backpack Electrofishing.....	39
3.3 Results.....	39
3.3.1 Backpack and Boat Electrofishing Index Sampling.....	39
3.3.2 Mark-Recapture Experiments.....	44
3.3.3 Pilot Comparison of Depletion and Mark-Recapture Methodologies.....	51
3.4 Discussion.....	54
3.5 References.....	57
4.0 Spring Juvenile Surveys.....	59
4.1 Introduction.....	59
4.2 Methods.....	60
4.2.1 Study Site.....	61
4.2.2 Mark-Recapture Methods.....	63
4.2.3 Age Determinations.....	68
4.2.4 Data Analysis.....	68
4.2.5 Electrofishing Shallow Riffle Habitats.....	70
4.3 Results.....	71
4.4 Discussion.....	90
4.5 References.....	94
5.0 Recommendations for Future Sampling and Analysis.....	96
5.1 Adults.....	96
5.2 Juveniles.....	97

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1.0 General Introduction

The Cheakamus River is a productive tributary of the Squamish River that supports populations of steelhead, chinook, coho, pink, and chum salmon, as well as resident populations of rainbow trout, bull trout, and other species. The Cheakamus River has an unregulated mean annual discharge of $65 \text{ m}^3 \cdot \text{sec}^{-1}$ and drains an area of 1032 km^2 of the Coastal Mountain range in southwestern B.C. (Fig. 1.1). It was impounded in 1957 by Daisy Lake Dam and a proportion of the water entering Daisy Lake Reservoir is diverted to the Squamish River for power generation. The Cheakamus River, downstream of Daisy Lake Reservoir, extends 26 km to its confluence with the Squamish River. Only the lower 17.5 kilometers of this river are accessible to anadromous salmon and steelhead. As a result of the diversion, the Cheakamus River downstream of the dam receives only a portion of its natural discharge, and there is much interest in understanding how this change affects fish populations.

The Cheakamus River once supported a large and productive wild winter-run steelhead population and a well-known steelhead fishery. Although the steelhead population is much smaller today, it still attracts considerable angling effort and is likely one of the more productive wild steelhead populations in southern BC (Van Dischoeck 2000). Steelhead juveniles rear for two to four years in the Cheakamus River before migrating to sea as smolts. Steelhead juveniles are potentially more sensitive than other juvenile salmonids in the Cheakamus River to changes in flow because they have a longer period of freshwater residency. All these factors contribute to a strong interest among resource users and fisheries managers in determining whether changes in the flow regime below Daisy Lake Dam are affecting steelhead in the Cheakamus River.

The timing and volume of diversion rates from the Cheakamus River have varied considerably since impoundment. From 1958-1994, diversions were largely driven by power generation. The original water license specified that no more than 45% of the annual runoff flowing into Daisy Lake Reservoir could be diverted, but this requirement was not always met. In 1997, the Department of Fisheries and Oceans issued an instream flow order to BC Hydro, which was subsequently modified to become an instream flow agreement (IFA). The IFA specified that the greatest of $5 \text{ m}^3 \cdot \text{sec}^{-1}$ or 45% of the previous days' inflows to the reservoir be released downstream. In February 2006, the rules of

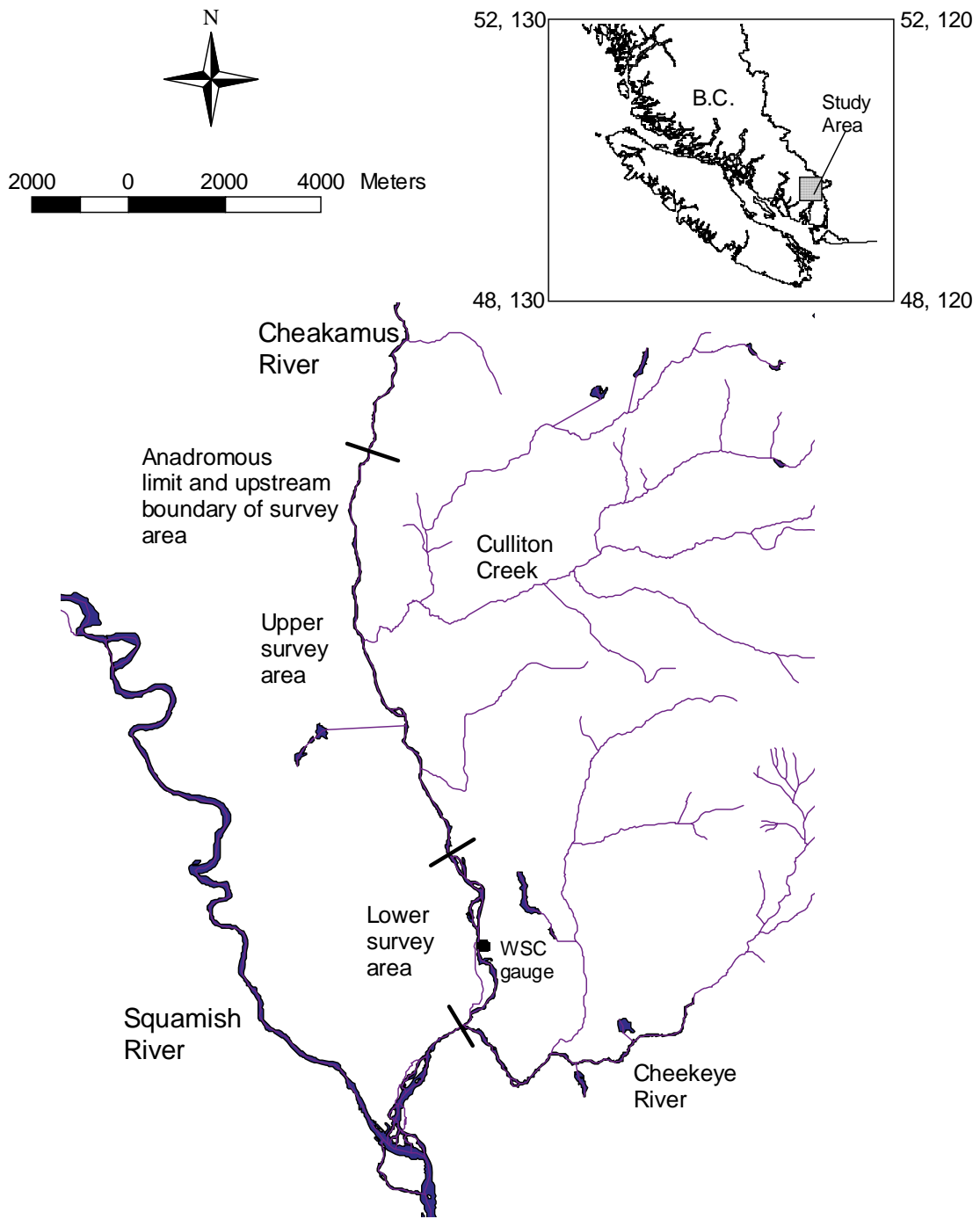


Figure 1.1. Map of the Cheakamus River, BC, showing the location of major tributaries, upper and lower adult steelhead survey areas (separated by the Bailey Bridge), the Water Survey of Canada gauge at Brackendale.

operation were modified based on a Water Use Plan (WUP) and no longer depended on releasing a constant proportion of reservoir inflows. Instead, the WUP-flow regime was based on meeting minimum flows at the dam and further downstream at Brackendale. Flows from the dam must now exceed $3 \text{ m}^3 \cdot \text{sec}^{-1}$ (November 1-March 31st) or $7 \text{ m}^3 \cdot \text{sec}^{-1}$ (April 1st-October 31st), and additional water must be released to maintain minimum flows at Brackendale of $15 \text{ m}^3 \cdot \text{sec}^{-1}$ (November 1st-March 31st), $20 \text{ m}^3 \cdot \text{sec}^{-1}$ (April 1st-June 30th), or $38 \text{ m}^3 \cdot \text{sec}^{-1}$ (July 1st – August 15th or 31st).

As part of the new water license agreement for the Cheakamus River, BC Hydro supports a number of monitoring programs to assess the effects of the new flow regime on fish populations downstream of the dam. This project, which tracks the status of returning steelhead spawners and juvenile steelhead abundance, is one such program. Its central objectives are to determine if the number of adult returns and juvenile abundance are affected by the WUP-flow regime, and more broadly, to determine how flow affects steelhead production in this system. Steelhead escapement to the Cheakamus River has been consistently assessed since 1996 (Korman et al. 2007). As the average age of a returning Cheakamus steelhead is five years, the historical time series of escapement in part reflects the rivers capacity to produce steelhead under pre IFA- and IFA-flow regimes. In the future, this time series can be used to evaluate the WUP-regime as well. The simplest way to determine whether changes in flow have affected steelhead production is to compare escapement over these three time periods. However, as escapement is also determined by parental abundance and marine survival, inferences from this comparison may be weak unless flow effects are very large relative to these other factors. To address this limitation, this project will estimate parr abundance in the spring as an index of overall steelhead productivity during their period of freshwater residency. Each annual estimate of escapement and parr abundance will contribute a single data point to estimate a freshwater stock-recruitment relationship between escapement and parr abundance. The relationship controls for the effects of escapement on juvenile production, and removes any effects associated with changes in marine survival. As data points accumulate, it will be possible to relate outliers from the escapement-to-parr stock-recruitment relationship, which indicate substantially higher or lower juvenile steelhead production per unit escapement, to particular aspects of the flow

regime, such as the frequency and magnitude of high flow events during late fall, or the duration of minimum flow periods during the winter. If the flow regime from Daisy Lake Dam changes in the future, the escapement-to-parr stock-recruitment relationship under the current WUP-flow regime can be compared to a relationship estimated under the new regime.

An escapement-to-parr stock-recruitment relationship is necessary for evaluating population-level effects of flow, but provides little insight into what life stages are most affected or which elements of the flow regime have the biggest effect on juvenile steelhead survival. For example, higher flows during late fall could increase mortality of recently emerged age-0 steelhead, but this mortality may not effect subsequent parr abundance and overall freshwater production because of compensatory survival responses over the winter due to lower densities. To account for such dynamics, it is necessary to quantify the stock-recruitment relationship for multiple life stages. This project will therefore develop relationships between escapement and steelhead fry in the fall, between steelhead fry in the fall and the following spring, and between fry and parr in the spring. The first relationship quantifies incubation success and survival from emergence (summer) into the fall. The second quantifies fry overwintering survival. The third quantifies the annual survival rates for parr. The overall approach of this project is relatively straightforward: 1) quantify escapement, and fry and parr abundance in the fall and spring; 2) use these metrics to determine the survival rate between life stages and define life stage-specific stock-recruitment relationships; and 3) over time, compare these survival rates and stock-recruitment relationships under different flow regimes, and relate residuals to particular flow events.

The methodology for estimating steelhead escapement in the Cheakamus River is well established (Korman et al. 2007), but methods for quantifying fry and parr abundance are currently poorly defined. Initially, downstream trapping of outmigrating steelhead smolts was envisioned as a viable method for quantifying juvenile production. However, because steelheads smolts are difficult to catch in downstream traps in large rivers like the Cheakamus, estimates of run size were, and continue to be, highly uncertain (Melville and McCubbing 2008). Estimating fry and parr abundance by electrofishing-based removal of fish from small areas of high quality habitat that can be

enclosed by block nets has been used by the Ministry of Environment and BC Hydro to estimate juvenile steelhead densities at discrete sites in Cheakamus River. This sampling approach will not meet the objectives of this project for a number of reasons: 1) depletion sampling has been shown to underestimate population size within discrete sites because it overestimates the proportion of fish that are captured, and the extent of this bias increases with river size (Riley et al. 1993, Peterson et al. 2004, Rosenberger and Dunham 2005, Korman et al. in press); 2) enclosing sites with block nets is very time consuming and limits the total number of sites that can be sampled, which in turn greatly increases the extent of extrapolation error when trying to estimate river-wide abundance from site-specific data, and; 3) block nets can only be deployed in a small fraction of the habitat types in the Cheakamus River utilized by steelhead parr. Extrapolation of population estimates from these areas to estimate river-wide abundance would therefore be highly uncertain. Further, as the proportion of a population utilizing high quality habitat changes with density (e.g., Gibson et al. 2008 and references therein), it is unlikely that a non-random sample of high quality habitat will reliably index trends in river-wide abundance. Given these uncertainties and challenges, a major focus in the first year of this project is to establish methods to reliably estimate the river-wide abundance of steelhead fry and parr in the Cheakamus River during both fall and spring.

This report is divided into three main components. Section two summarizes the methods and results from the annual steelhead escapement program. We summarize data collected in the winter and spring of 2008 used to derive the 2008 escapement estimate and compare it to those determined using the same methods since 1996. Section three summarizes methods and results from juvenile steelhead surveys based on backpack and boat electrofishing conducted in the fall of 2007. We compare catch rates, length-frequency distributions, and estimates of capture probability and abundance from the two sampling approaches. Results from this analysis are used to provide recommendations for sampling steelhead fry and parr in the fall, and were also used to guide sampling approaches evaluated in the spring of 2008. Section four summarizes methods and results from juvenile surveys conducted in the spring of 2008, that were based on backpack electrofishing and snorkeling. We conducted paired mark-recapture experiments to compare the efficacy of the two sampling methods for quantifying capture probability

and abundance of steelhead fry and parr at discrete sites and to evaluate critical assumptions of the mark-recapture methodology. Section five provides a set of final recommendations for sampling adult and juvenile components of the Cheakamus River steelhead population based on the findings from Sections two through four. Sections three and four of this report focus on methodologies to reliably determine juvenile steelhead abundance in the Cheakamus River. Future reports will be simpler and focus on the data and analytical methods used to derive annual estimates of steelhead fry and parr abundance, using a format similar to section two.

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2.0 Escapement Surveys

2.1 Introduction

A program to enumerate adult steelhead escapement to the Cheakamus River was initiated by BC Hydro in 1996. Steelhead escapement is estimated by fitting parameters of a run-timing model to count data from repeat snorkel surveys conducted over the adult migration and spawning season (Korman et al. 2007, Korman et al. 2002), and estimating survey life and departure timing by fitting models to radio telemetry data collected between 2001 and 2005. This section of the report provides an estimate of steelhead escapement to the Cheakamus River in 2008. A synthesis of relevant physical information, other supporting information required to generate the 2008 escapement estimate, and counts of resident rainbow trout and char are also provided. The 2008 steelhead escapement estimate is compared to previous estimates from 1996-2007. Note that all steelhead escapement estimates provided in this report are based on the revised escapement model described in Korman et al. (2007). The major advantage of the revised model is that it increases the precision of escapement estimates and avoids the use of arbitrary constraints and overly simplistic assumptions about run timing. This is accomplished by jointly fitting run-timing parameters to count, survey life, and departure data, and by reducing uncertainty in swim-specific observer efficiencies by using a physical model that integrates mark-recapture estimates over multiple years.

2.2 Methods

2.2.1 Snorkel Surveys and Radio Telemetry

The Cheakamus River, downstream of Daisy Lake Reservoir, extends 26 km to its confluence with the Squamish River. Only the lower 17.5 kilometers of this river are accessible to anadromous salmon and steelhead (Fig. 1.1). The area surveyed for returning steelhead was limited to the upper 14.5 km of the anadromous portion of the river that extends from ca. 500 m below the natural barrier to the confluence with the Cheekeye River. Fourteen surveys were conducted between January 23rd and May 8th, 2008. Two additional surveys were attempted on March 5th and May 13th but were not

completed due to an illness of one member of the crew and high discharge, respectively. On each survey, a team of three divers floated the entire study area (14.5 km of river) in 4-6 hours. The survey area is divided into 34 sections averaging 500 m in length (Table 2.1). The number of steelhead (>40 cm), resident rainbow trout (20-40 cm), and char observed in each section was recorded. Horizontal visibility (HV) was estimated by measuring the maximum distance from which a diver could detect a dark object held underwater at 1 m depth. Horizontal visibility was measured in sections 4 and 21 to index conditions in the upper and lower survey areas, respectively (Fig. 1.1, Table 2.1).

A radio telemetry program for steelhead was conducted in 2000, 2001, and 2003-2005. These data were analyzed by Korman et al. (2007) to determine survey life and observer efficiency. Historical radio telemetry data is used in this analysis to determine steelhead escapement in all survey years based on the assumptions that: 1) tagged fish were a representative sample of the total population in years when tagging was conducted; and 2) survey life and observer efficiency data collected in years when radio telemetry data was collected are exchangeable with data from other years.

Mean daily discharge (Q) over the survey period was computed from the Water Survey of Canada (WSC) hourly discharge record for the Cheakamus River at Brackendale (WSC 08GA043, Fig. 1.1). Hourly water temperatures were recorded with an Onset Tidbit temperature logger placed at the North Shore Outdoor School just downstream of the Water Survey of Canada Brackendale gauge (section 28, Table 2.1, Fig. 1.1).

We conducted a single survey for redds and spawners in the Brohm River on May 13th. Three biologists walked the entire anadromous length of the Brohm River (Cheekeye confluence to just upstream of Cat Lake Bridge). Two biologists walked along the banks while one walked and snorkeled in the river to look for redds and spawners that would not be visible to observers on the bank.

Table 2.1. Description of 34 river sections used to define sampling locations in the Cheakamus River steelhead project.

Section ID	Upstream Boundary Description	Survey Area
0	Swimmer put-In to raft put-in	Upper
1	Raft put-n	Upper
2	Large rock/powerlines	Upper
3	Huge Boulder at Start of Pool	Upper
4	End of pool/rock on River Right; Small pool	Upper
5	Suspension Bridge to Sweepers on RL at start of riffle	Upper
6	Sweepers to u/s of Culliton confluence	Upper
7	Pool starting just u/s of Culliton	Upper
8	Long boulder rapid	Upper
9	Big rock on River Right (orange tape)	Upper
10	Above Upper Campground; Logjam on River Right	Upper
11	Below giant gravel dump on River Left	Upper
12	Below split channels	Upper
13	Lunchspot/cableway	Upper
14	First pool above tree-fort (new lunch spot)	Upper
15	First pool below wife wanted (Don's Pool, includes riffle d/s of new wood on RR)	Upper
16	Right corner (orange tape)	Upper
17	End of pool (orange tape)	Upper
18	Boil in pool (orange tape)	Upper
19	Lower Campground (orange tape)	Upper
20	Orange tape on River Left above Bailey Bridge	Upper
21	Bailey Bridge	Lower
22	Riffle above side channel that is now gone	Lower
23	Tenderfoot Confluence	Lower
24	Riffle just below Al's Rock	Lower
25	NVOS pool	Lower
26	NVOS Tailout	Lower
27	Gauge pool (warning sign on RR at start of pool)	Lower
28	RST pool to below longhouse	Lower
29	Top of riffle; Woody pool below longhouse	Lower
30	Start to end of new channel	Lower
31	Start at d/s confluence with new channel. Log sticking out of water on RR	Lower
32	Tree lying along River Left	Lower
33	Start of gravel bar (River Left); Hydro lines above	Lower
34	Frog pond; Ends at Cheekye	Lower

2.2.2 Steelhead Escapement Model

The escapement model consists of three main elements. A simple process model predicts the number of fish present on each day of the run and the departure schedule based on the total escapement and parametric relationships simulating arrival timing and survey life. An observation model simulates the number of marked and unmarked fish observed on each survey based on the number of tags known to be in the survey area, predictions of the number of unmarked fish that are present, and observer efficiency. Process and observation model parameters are estimated by maximizing the value of likelihood function that integrates data on the number of marked and unmarked fish observed on each survey, the fraction of marked fish observed, survey life of marked fish, and departure schedules of marked fish. The latter 3 elements are assessed using external marking combined with a radio telemetry program, which has been undertaken in only five (2000-2005, excluding 2002) of 12 years that the swim surveys have been conducted (1996-2008, excluding 1998). The model can be applied in years with and without marking and telemetry information. We assume that data on observer efficiency, survey life, and departure schedules collected in years with radio telemetry and external marking are exchangeable among all years that surveys have been conducted.

Process Model

The proportion of the total escapement entering the survey area on day ‘ i ’ (PA_i) of the simulated run is predicted by a beta distribution,

$$(1) \quad PA_i = \phi_i^{\tau-1} (1 - \phi_i)^{\beta-1}$$

where, τ and β are parameters of the beta distribution and ϕ_i represents the proportional day of the run for day i , ranging from 0 to 1 on the assumed first (January 1, $i=1$) and last (June 30, $i=181$) day, respectively. τ is the precision of run timing with smaller values representing a low and constant rate of arrival over the duration of the run, and larger values representing a shorter and more concentrated arrival timing. The beta distribution is reparameterized so that β is calculated based on estimates of the day when the peak

arrival rate occurs (μ) and the precision of arrival timing, using the transformation

$$\beta = \frac{\tau - 1}{\frac{\mu}{T}} + 2 - \tau \quad (\text{Gelman et al. 2004, Appendix A}).$$

Survey life, the number of days a fish spends in the survey area, is predicted using a negative logistic relationship,

$$(2) \quad SL_i = \lambda_m \left(1 - \frac{i^{\lambda_s}}{\lambda_h^{\lambda_s} + i^{\lambda_s}} \right)$$

where SL_i is the mean survey life for a fish entering on day i , λ_m is the maximum mean survey life, λ_h is the day at which mean survey life is half the maximum, and λ_s is the slope of the relationship. The mean departure day for a fish arriving on day i is simply $d_i = i + SL_i$.

The proportion of fish that arrive on day i and depart on day j ($PAD_{i,j}$) is predicted from a normal distribution with mean d_i and standard deviation σ_{sl} ,

$$(3) \quad PAD_{i,j} \sim \text{Normal}(j, d_i, \sigma_{sl})$$

PAD values are standardized so that proportions across all departure days for each arrival day sum to 1, that is, all fish must exit the survey area by the assumed last day of the run. As a fish cannot depart before it arrives, $PAD_{i,j} = 0$ for $j < i$. The proportion of fish departing on each day (PD_j) is computed from,

$$(4) \quad PD_j = \sum_i PA_i * PAD_{i,j}$$

Note that departure timing depends on both arrival timing and the survey life relationship that defines PAD . Finally, the number of unmarked fish present in the survey area on each day (U_i) is the product of the total escapement (E) less the number of fish marked per year (R) and the difference between the cumulative arrivals and departures of unmarked fish on that day,

$$(5) \quad U_i = (E - R) \left[\int_1^i PA - \int_1^i PD \right]$$

The difference between the cumulative values of PA and PD on any date represents the proportion of the total run that is present.

Observation Model and Estimating Model Parameters

Escapement, arrival timing, and survey life parameters, and those defining the relationship between observer efficiency (q) and the ratio of horizontal visibility to discharge (HV/Q), are jointly estimated by maximum likelihood. Independent likelihood terms are developed for counts of marked and unmarked fish, survey life, departure schedule, and q - HV/Q data. The log-likelihoods are added together to give an overall likelihood function.

The likelihoods of the number of marked (L_r) and unmarked (L_u) fish observed are assumed to follow a Poisson distribution,

$$(6) \quad r_i \sim \text{Poisson}(q_i R_i)$$

$$(7) \quad u_i \sim \text{Poisson}(q_i U_i)$$

where, R_i is the total number of marked fish present for a survey conducted on day i (determined from telemetry data), r_i is the number of marked fish that are observed by swimmers, U_i is the predicted number of unmarked fish that are present (from eqn. 5), u_i is the number of unmarked fish observed, and q_i is the observer efficiency coefficient. The terms L_r and L_u , as for all that follow represent the sum of log-transformed probabilities across all observations. Note that observer efficiency is a nuisance parameter that does not need to be directly estimated. It is evaluated at its conditional maximum likelihood estimate for each survey using (Korman et al. 2002),

$$(8) \quad q_i = \frac{r_i + u_i}{R_i + U_i}$$

That is, observer efficiency is simply the ratio of the total number of fish observed to the total number present. Values of U_i are not independent across surveys because they are linked through the model structure, thus the number of unmarked fish observed contributes to the estimate of observer efficiency.

Korman et al. (2002 and 2007) found that the ratio of horizontal visibility to discharge on each survey was a reasonable predictor of observer efficiency, calculated as the ratio of tags observed to tags present. Physically-based observer efficiency predictions are required to estimate the number of fish present in years when there is no tagging. In this analysis, we recognize that observer efficiency predictions can also be used in years with tagging information to increase the precision of estimates of the numbers present. Precision of a purely tag-based estimate of observer efficiency will be

very poor when the total number of tags present or the true observer efficiency is very low. In this situation, estimates of observer efficiency from the physically-based model, which incorporates information on observer efficiency from multiple surveys within and across years, will make an important contribution to the estimate of the numbers present. The following logistic model is used to predict observer efficiency based on river conditions in the escapement estimation procedure,

$$(9) \quad qP_i = \frac{\frac{HV}{Q}^{\rho_s}}{\rho_h^{\rho_s} + \frac{HV}{Q}^{\rho_s}}$$

where, qP_i is the physically-based prediction of observer efficiency, HV/Q is the ratio of horizontal visibility to discharge, ρ_h is the HV/Q ratio at which observer efficiency is 0.5, and ρ_s is the slope of the relationship. Two additional likelihoods for the observed number of marked (L_{pr}) and unmarked (L_{pu}) fish can now be computed by replacing the conditional observer efficiencies in eqn.'s 6 and 7 (q_i) with efficiencies predicted by the physical model (eqn. 9).

Parameters of the qP - HV/Q relationship are jointly estimated with other model parameters using data from all surveys when tags were present in all years when telemetry was conducted (n=52 surveys across 5 years). The likelihood of the observed number of marked fish (L_p) on each of these surveys is assumed to follow a Poisson distribution,

$$(10) \quad r_i \sim \text{Poisson}(qP_i R_i)$$

Note that L_{pr} is the sum of likelihoods across surveys in only the year that escapement is being estimated for. L_p is the sum of likelihoods across all surveys when tags were present over all years when telemetry was conducted, excluding observations used in calculating L_{pr} (to avoid double counting).

The likelihood of the survey life data (L_s) was computed assuming normally distributed error,

$$(11) \quad \text{slobs}_i \sim \text{Normal}(i, SL_i, \sigma_{sl})$$

where, slobs_i is the observed survey life for a fish that entered the survey area on day i , and SL_i is the predicted survey life for the same fish based on its observed date of entry

(eqn. 2). Note that σ_{s_i} is a nuisance parameter that is calculated at its conditional maximum likelihood value of $\sqrt{\frac{\sum (slobs_i - SL_i)^2}{n-1}}$, where n ($n=33$) is the number of survey life observations (Walters and Ludwig 1994).

The likelihood of the observed number of fish exiting the lower survey area in a downstream direction (departure schedule - L_d) was computed assuming multinomial error,

$$(12) \quad next_i \sim Multinom(Texit, PD_i)$$

where, $Texit$ is the total number of radio tagged fish for which an exit date could be determined ($n = 104$), $next_i$ is the number of radio tagged fish that departed on day i , and PD_i is the predicted departure proportions for that day (from eqn. 4).

The overall log-likelihood of all the data given a set of model parameters $\theta = E, \mu, \tau, \lambda_m, \lambda_h, \lambda_s, \rho_h, \rho_s$, was determined by summing all component log-likelihoods,

$$(13) \quad L_T(data | \theta) = \frac{L_r + L_{pr}}{2} + \frac{L_u + L_{pu}}{2} + L_p + L_s + L_d$$

When estimating parameters for a particular year, note that the first four terms of the total likelihood are evaluated based only on data collected in that year, while the latter 3 depend on data collected over all years when telemetry was conducted. The denominator of 2 in eqn. 13 accounts for the fact that observations of marked and unmarked fish are double-counted in the overall likelihood because they are evaluated using both conditional MLE values (q from eqn. 8) and physically-based predictions of observer efficiency (qP from eqn. 9). The first term of eqn. 13 does not contribute to the total likelihood in years with no tagging, or for surveys where no tags are present in years when tagging is conducted. In years when tagging data is available, highest likelihoods of the objective function will occur when escapement, arrival, and survey life parameters maximize the survey-specific likelihoods but also predict a survey life relationship and departure schedule that is consistent with observations collected across all telemetry years, and a set of observer efficiencies consistent with predictions from the physically-based model, which again, is dependent on data from all telemetry years.

Two alternate hierarchies can be used to estimate the historical time series of escapement for the Cheakamus River steelhead population ($E_{1996} - E_{2008}$). In the first

case, all model parameters are estimated independently for each year. 8 parameters are separately estimated for each of the 12 years for which count data are available, for a total of 96 parameters. We refer to this model as the year-independent model. In the second case, parameters for survey life – date of entry and qP-HV/Q relationships are assumed to be common to all years, while escapement and arrival timing parameters are not. In this case 36 year-specific (E, μ, τ), and 5 parameters common to all years, were estimated (41 for all 12 survey years). We refer to this model as the pooled-year model. Korman et al. (2007) showed that the common and independent models produce very similar MLEs for escapement, but that uncertainty in these estimates is slightly larger for the year-independent model due to the larger number of parameters. In this report and future ones, we generally focus on escapement estimates from the year-independent model because uncertainty estimates are larger, and likely more realistic than the more constrained pooled-year model. Escapement estimates were computed using the AD model builder software (Otter Research 2004). Asymptotic estimates of the standard deviation for the MLEs were computed using the Delta method.

2.2.3 Expansion of Resident Rainbow Trout Counts

To estimate the total number of rainbow trout present during each survey, we expanded individual rainbow counts using the same survey-specific observer efficiency estimates predicted for steelhead. (i.e., number present or expanded count = raw count/observer efficiency). Observer efficiencies were estimated using the steelhead qP-HV/Q (eqn. 9) relationship, whose parameters were estimated independently from the main model using the historical steelhead mark-recapture data (Model 9 of Table 3 from Korman et al. 2007).

2.3 Results

Discharge between January and early-May, 2008, was for the most part low and steady (Fig. 2.1a). Warm conditions in mid-May, combined with high snowpack at low elevations, led to a relatively early and abrupt increase in discharge, precluding our ability to conduct additional surveys. The water temperature regime, which determines

the onset of spawning and perhaps affects survey life, was similar to other years during the survey period (Fig. 2b).

Counts of steelhead, resident rainbow trout, and char over 14 surveys ranged from 20-76, 4-23, and 40-136, respectively (Table 2.2). Observer efficiency for steelhead, estimated based on the ratio of horizontal visibility at the Bailey Bridge (section 21) to discharge at Brackendale, ranged from 0.16-0.68. As in other years, observer efficiency was high in early February and March and declined initially due to minor increases in turbidity, and then due to higher discharge and turbidity. The number of steelhead and resident rainbow trout present in the survey area, determined by expanding counts by the estimated observer efficiency for steelhead, increased over time (Fig. 2.2). Maximum estimates of the number of steelhead and rainbow trout present were 260 and 94, respectively. We completed 4 surveys under moderately good counting conditions between May 1st and 8th. There was large variation in the estimated number of steelhead present in the survey area over this period, due either to sampling error (see error bars in Fig. 2.2), bias in observer efficiency predictions resulting from changes in the proportion of spawners in upper and lower survey areas (Fig. 1.1), or due to true variation caused by pulses of spawners arriving and departing from the survey area over short periods. Expanded counts of rainbow trout declined by almost 50% between May 1st and 5th, similar to decline for steelhead, but then remained very stable, unlike the situation for steelhead. This latter difference was likely caused by differences in movement dynamics between steelhead and rainbow trout over this period. We observed two spawners and 20 redds during the survey of Brohm River on May 13th.

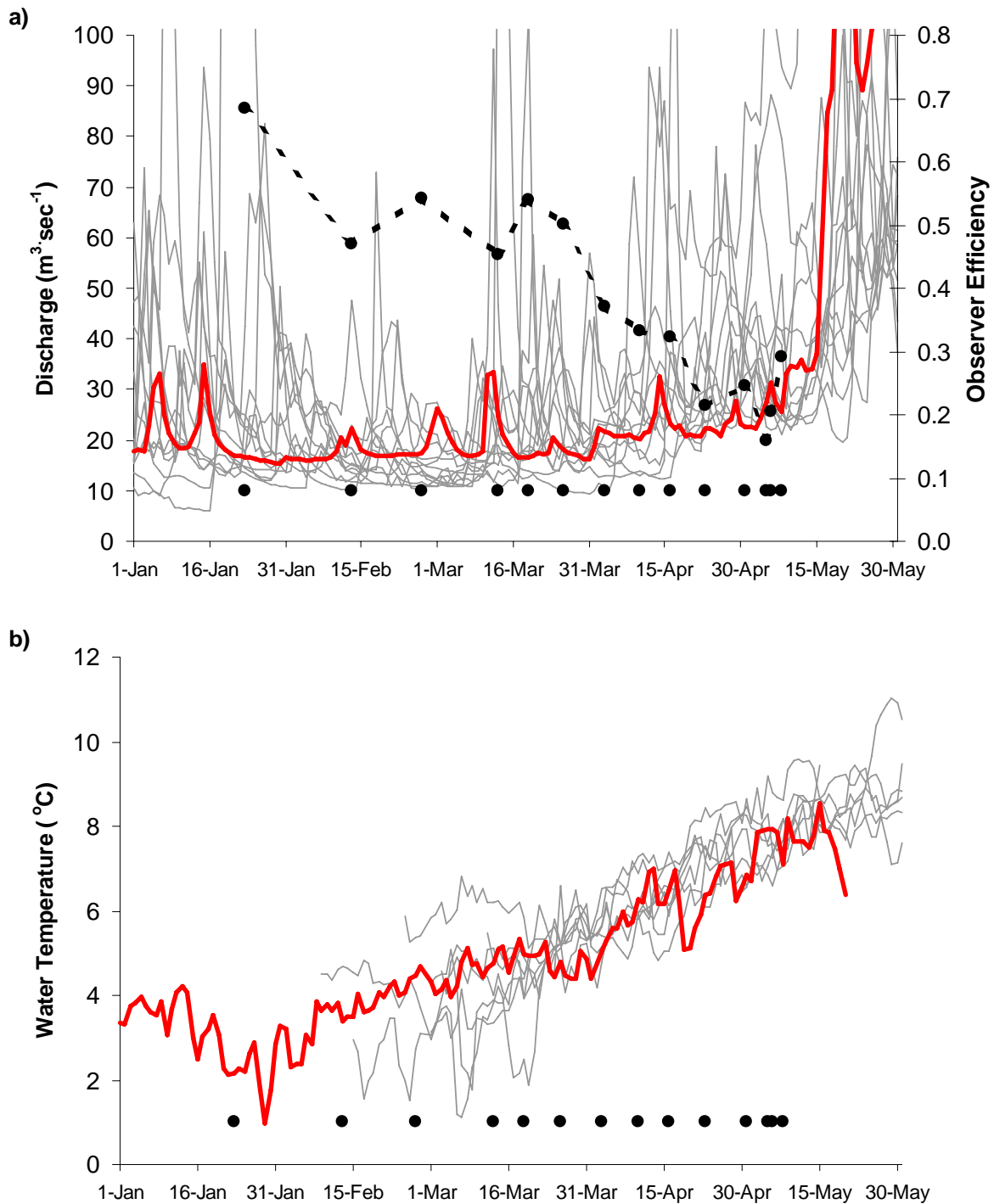


Figure 2.1. Discharge (a) and water temperature (b) between January 1st and May 30th at the Water Survey of Canada Brackendale gauge. The thick solid red lines highlight conditions in 2008 and thin gray lines show discharge from 1996-2007 (a) and water temperature from 2001-2007 (b). Days when swims were conducted are shown by solid black points. The thick dashed black line with points in a) shows predicted observer efficiency during swims based on the ratio of horizontal visibility to discharge. the survey period (Fig. 2.1b).

Most likely estimates of steelhead escapement to the Cheakamus River in 2008 based on the year-independent and pooled-year models were 239 ($\pm 0.95 = 173-305$) and 342 ($\pm 0.95 = 258-425$), respectively. Relative to other years, the year-independent model estimated a relatively constant pattern of arrival (Fig. 2.3a and b). To fit the departure timing data from years when radio telemetry was conducted given this arrival timing, the model predicted a long residence time for fish arriving early relative to other years (Fig. 2.3c). As there is no survey life data to represent fish that arrive early, there was no penalty in estimating such a dynamic. There were considerable deviations between the predicted number of fish present based on the escapement model compared to survey-specific estimates determined by predicted observer efficiency alone (Fig. 2.3d). This discrepancy was also apparent in the comparison of observer efficiency determined based on the ratio of horizontal visibility to discharge relative to efficiency based on the ratio of the observed count to the estimated numbers present (Fig. 2.3f).

Table 2.2. Number of steelhead (SH), resident rainbow trout (RB), and char enumerated over 14 swims conducted in the Cheakamus River, 2008. Also shown is the ratio of horizontal visibility to discharge (HV/Q) and the predicted observer efficiency based on the HV/Q ratio.

Date	HV/Q	Efficiency	SH	RB	Char
23-Jan	0.57	0.68	28	13	118
13-Feb	0.34	0.47	27	12	116
27-Feb	0.41	0.54	47	12	121
13-Mar	0.33	0.45	44	19	95
19-Mar	0.40	0.54	46	18	136
26-Mar	0.37	0.50	42	12	113
3-Apr	0.27	0.37	37	6	79
10-Apr	0.25	0.33	56	12	98
16-Apr	0.24	0.32	66	12	68
23-Apr	0.17	0.21	22	4	40
1-May	0.19	0.25	56	23	42
5-May	0.14	0.16	20	8	44
6-May	0.17	0.21	31	11	63
8-May	0.22	0.29	76	14	79

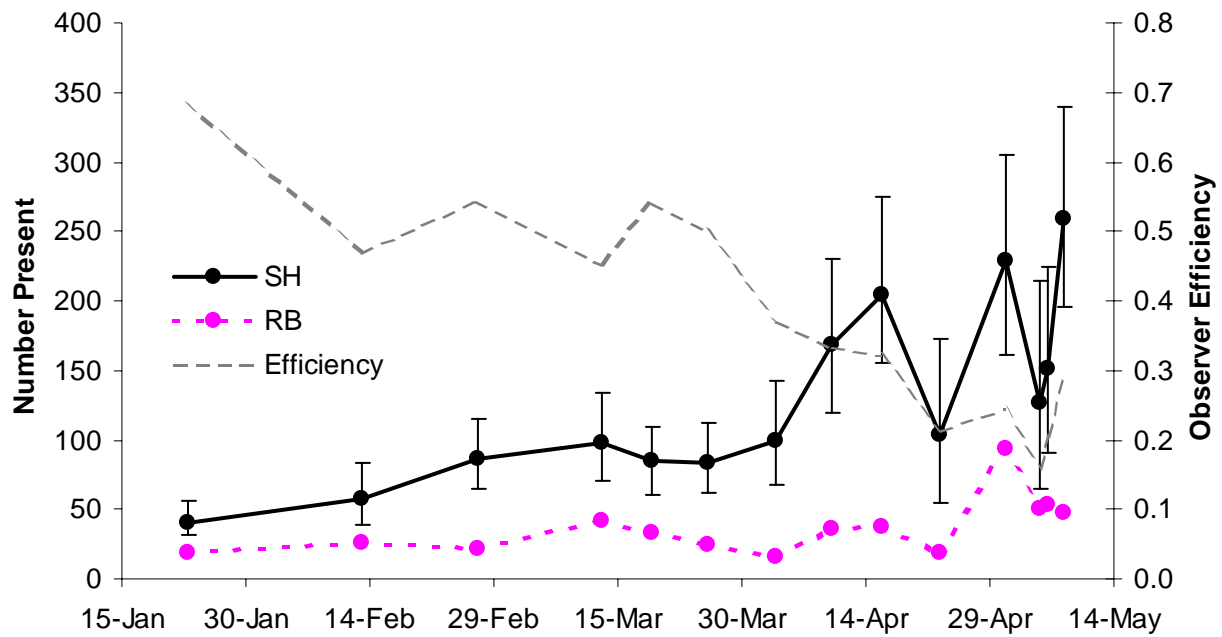


Figure 2.2. Total number of steelhead (solid black line) and rainbow trout (dashed pink line) present in the Cheakamus River survey area on 14 swims conducted in 2008. Numbers present was computed by dividing the total count on each swim by the observer efficiency (dashed gray line) predicted based on the ratio of horizontal visibility to discharge. Error bars denote 95% confidence limits of the number of steelhead present, determined based on the assumption that sampling error follows a Poisson distribution.

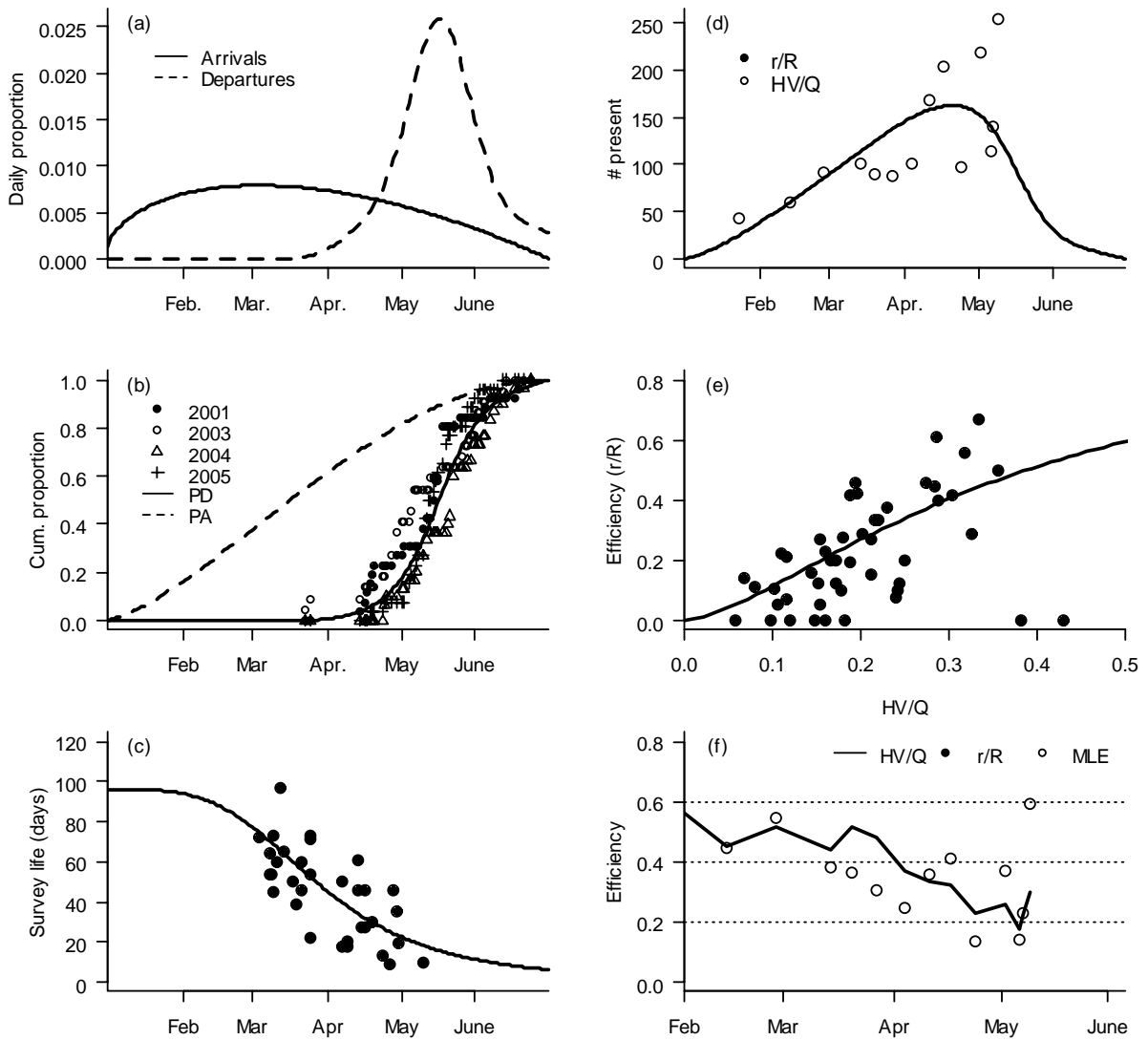


Figure 2.3. Predictions from the year-independent escapement model for 2008. The graphs show: a) the proportion of the run arriving and departing by day; b) the predicted cumulative departure schedule for 2008 (PD), the observed departure schedules from 2001-2005, and the predicted cumulative arrivals (PA); c) the predicted survey life-date of entry relationship (line) and observations (points); d) the predicted numbers present (line) and expanded counts (points) based on the survey-specific recapture rates (r/R) if tagging was conducted, and river conditions (HV/Q); e) predicted observer efficiency (line) based on the ratio of horizontal visibility (HV) to discharge (Q) and estimates of catchability (r/R) from 2000-2005 (points); and f) the seasonal trend in observer efficiency for 2008 based on either the qP -HV/Q relationship (HV/Q), the ratio of the number counted to the maximum likelihood estimates of the numbers present (MLE), and the recapture rate (r/R) if tagging was conducted.

Escapement estimates based on year-independent and pooled-year models across all surveyed years (n=12) were highly correlated ($r^2 = 0.94$) and generally close to each other (Fig. 2.4). The greatest deviation occurred in 2008, where escapement based on the pooled-year model was 43% higher than the one based on the year-independent model. The difference was great enough that this was the only year when the 95% confidence limits of escapement based on the pooled-year model did not overlap the 1:1 line of the two types of escapement estimates. These differences occurred because the year-independent model allows parameters defining the survey life and the qP-HV/Q relationships to vary among years while the pooled-year model does not.

The most likely steelhead escapement based on the year-independent model in 2008 was similar to 2006, and the lowest estimate on record since 2001 (Fig. 2.5). The 2008 escapement estimate was over 50% lower than the estimate from 2007. The ratio of the expanded peak count of rainbow trout and steelhead escapement has been highly variable over time (Fig. 2.5). Since the spill (2006-2008) the ratio has been low, ranging from 0.24-0.39. These recent ratios were considerably lower than those from 2000-2005, which typically ranged from 0.5-1.0.

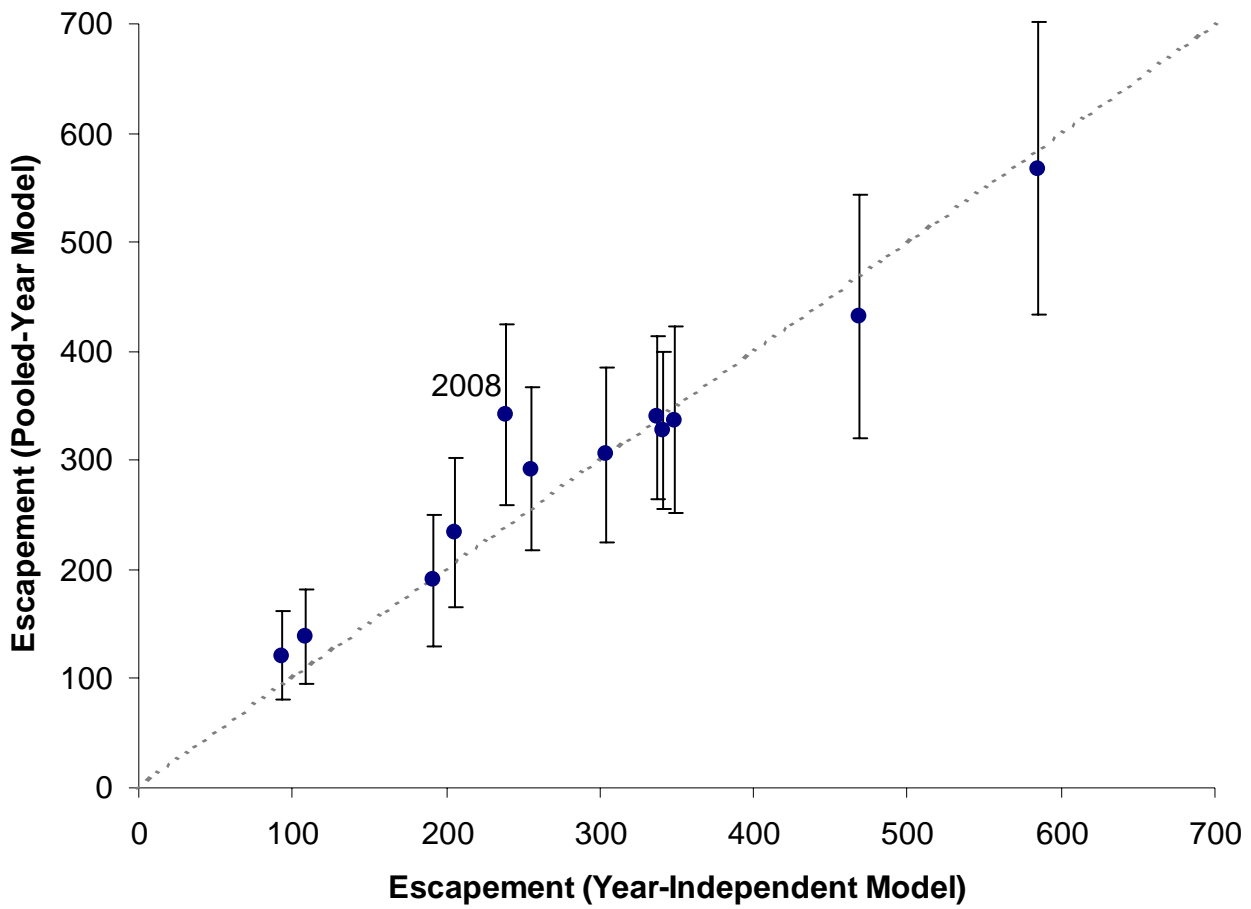


Figure 2.4. Relationship between the most likely estimates of steelhead escapement to the Cheakamus River survey area from 1996-2008 (note no estimate for 1998) based on year-independent and pooled-year models. Error bars denote 95% confidence limits for the pooled model. The dashed line shows the 1:1 relationship.

