Predicting Entrainment of Bow River Sportfish Populations into the Carseland Bow River Headworks and Western Headworks Canals

Final Report

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May 17, 2024

Executive Summary

The Bow River supports a world-renowned recreational trout fishery. On average, about 6% and 12% of Bow River flows have been diverted into the Western Headworks Canal (WHC) and the Carseland-Bow River Headworks Canal (CBRHC), respectively, over the April-to-October irrigation period between 2001 and 2023. Annual fish salvage efforts undertaken at the end of the irrigation season indicate that thousands of sportfish from the Bow River can be entrained into these canals. Post et al. (2006) conducted a detailed study of sportfish entrainment in CBRHC in 2003 and estimated that about 4,000 Rainbow Trout (*Oncorhynchus mykiss*), 600 Brown Trout (*Salmo trutta*), and 94,000 Mountain Whitefish (*Prosopium williamsoni*) were entrained over the irrigation season. Given the potential magnitude of entrainment and impacts on Bow River sportfish populations, further evaluation of entrainment is warranted.

The objectives of this report are to use more than 20 years of historical data on fish salvage (2000 – 2023), and sportfish abundance in the Bow River, to estimate annual entrainment of sportfish (Rainbow Trout, Brown Trout, and Mountain Whitefish) into CBRHC and WHC, and to estimate the proportion of the populations that are entrained. The statistical relationships between flow in the Bow River or flow in the canals and proportional entrainment are evaluated to assess whether more accurate estimates of annual entrainment can be predicted, and to identify key variables determining proportional entrainment. This report also provides recommendations for future entrainment studies to reduce uncertainties of the magnitude of entrainment and proportional entrainment.

A Hierarchical Bayesian model (HBM) was developed to estimate entrainment and proportional entrainment from fish salvage data and Bow River abundance estimates. As in previous work (Post et al. 2006), the model assumes that the ratio of entrainment over the irrigation season into CBRHC estimated in 2003 (E), to the fish salvage (S) in 2003 (E/S ratio), would be the same in other years. To estimate entrainment statistics in WHC, the model further assumes that the WHC E/S ratio is the same as estimated in CBRHC in 2003. The Bayesian model accounts for some of the uncertainty in the E/S ratio, uncertainty in Bow River abundance estimates, and sampling uncertainty in the fish salvage data.

The proportion of the Bow River Rainbow Trout population entrained in CBRHC averaged 8.4% between 2001 and 2023. Proportional entrainment for Rainbow Trout varied from a low of about 4% in 2003 to a high of about 25% in 2021. The full size distribution of Rainbow

Trout sampled in the Bow River was present in the fish salvage in CBRHC. There was a positive relationship between average flow in CBRHC during the irrigation season and proportional entrainment. The model indicated that proportional entrainment was lower (about 5%) at average flows of 15-20 m^3/s, and increased rapidly as average flows over the season increased from 25 m^3/s (about 10%) to 35 m^3/s (about 30%). Average annual entrainment of Rainbow Trout between 2001 and 2023 was 18,000 fish/year.

Proportional entrainment of Brown Trout in CBRHC averaged 2.1% between 2001 and 2023 and annual entrainment averaged about 1,200 fish/year over this period. Larger Brown Trout present in Bow River samples were under-represented in the salvage, indicating that smaller juvenile Brown Trout are more vulnerable to entrainment. Flows in the Bow River or CBRHC were not useful predictors of proportional entrainment for Brown Trout.

Proportional entrainment of Mountain Whitefish in CBRHC was very high. The mean of proportional entrainment was 36% and there was extensive interannual variability in proportional entrainment between 2001 and 2023, with low values less than 5% and high values of almost 80%. The average annual entrainment was about 76,500 fish/year. As for Brown Trout, smaller juvenile Mountain Whitefish were over-represented in the salvage relative to the size distribution in Bow River samples. Flow statistics in the Bow River or CBRHC were not useful predictors of proportional entrainment for Mountain Whitefish. Proportional entrainment estimates for Mountain Whitefish are considerably less certain and potentially biased owing to greater uncertainty in the abundance estimates in the Bow River due to low capture probabilities relative to Rainbow Trout and Brown Trout. However, given the large number of Mountain Whitefish that are salvaged in most years, total entrainment is likely high.

The estimate of the number of Rainbow Trout and Brown Trout entrained into WHC (2000-2023) was considerably lower than for CBRHC. Proportional entrainment of Rainbow Trout into WHC averaged 0.7%, which was less than one-tenth of the proportional entrainment in CBRHC (8.4%). The proportion of Brown Trout entrained in WHC was 0.4%, which was about one-quarter of the proportional entrainment estimate at CBRHC (2.1%). The proportion of the Mountain Whitefish population entrained into WHC averaged 3.1%, again less than one-tenth of the proportion entrained in CBRHC (36%). Annual entrainment to the WHC averaged about 1,900 fish/year for Rainbow Trout, 360 fish/year for Brown Trout, and 16,000 fish/year for Mountain Whitefish. Lower entrainment in WHC compared to CBRHC is not surprising given that WHC diverted about 5% of Bow River flows over the irrigation season (average canal flow of 7.9 m^3/s), compared to 12% at CBRHC (average canal flow of 19.6 m^3/s) over the 2000-2023 study period. Entrainment estimates for WHC should be considered very preliminary as entrainment has never been directly estimated in this system.

The models of entrainment used in this report assume that entrainment-to-salvage ratios don’t vary across years and are the same in CBRHC and WHC. Uncertainty in the model predictions owing to these assumptions could be substantially reduced by additional field studies like Post et al. (2006) to quantify total seasonal entrainment in future years. Based on a preliminary analysis, a whole-river tagging approach for estimating entrainment and proportional entrainment in CBRHC appears feasible. This would be a significant effort, requiring a two-week passive integrated transponder (PIT) tagging effort in the Bow River in spring prior to, or concurrent with, the start of diversions for the irrigation season, and investment in a PIT tag antenna system in CBRHC to detect fish that are entrained. Based on the estimates of proportional entrainment for Rainbow Trout presented here, the whole-river approach should provide reasonably precise estimates of proportional entrainment (coefficient of variation < 0.3) assuming the efficiency of the PIT antenna system in the canal is greater than 0.1 and proportional entrainment is 10-15%.

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The datasets used in this report are derived from two decades of field effort to rescue fish from the Carseland-Bow River Headworks and Western Headworks canals, and to estimate abundance of sportfish in the Bow River. I am grateful to the many biologists and technicians who have been involved in these efforts. Mike Bryski and Paul Christensen defined the scope and work elements of this project and provided guidance throughout the project. Mike Bryski, compiled the fish rescue data and Paul Christensen and Sara Bumstead compiled the Bow River fish population and abundance estimates. Lauren Makowecki provided hydrology data. Mike Bryski, Paul Christensen, Kenton Neufeld, Lauren Makowecki, and Andrew Paul provided helpful comments and ideas throughout this project, and reviewed early drafts of the analyses and report.

1.0 Introduction

The Bow River between Bearspaw Dam and the Carseland Weir supports a world-renowned recreational trout fishery and salmonid range extends downstream nearly to the Bassano Dam (Figure 1). Water from the Bow River is diverted into the Western Headworks Canal (WHC) and the Carseland-Bow River Headworks Canal (CBRHC), primarily to supply the irrigation for the agriculture industry in the Western Irrigation District (WID) and Bow River Irrigation District (BRID), respectively. Annual fish rescue efforts (hereafter referred to as salvage) undertaken at the end of the April-October irrigation season indicate that thousands of sportfish from the Bow River can be entrained into these canals. Post et al. (2006) conducted a detailed study of sportfish entrainment in CBRHC in 2003 and estimated that about 4,000 Rainbow Trout (*Oncorhynchus mykiss*), 600 Brown Trout (*Salmo trutta*), and 94,000 Mountain Whitefish (*Prosopium williamsoni*) were entrained over the course of the irrigation season. They calculated the ratio of total entrainment over the season to the number of fish salvaged at the end of the season for 2003 to expand fish salvage from other years. Post et al (2006) used the expansion method to estimate annual entrainments as high as about 30,000 Rainbow Trout in 2001 and 2002, and as high as about 5,000 Brown Trout in 2002.

The magnitude of entrainment and impacts of such losses on Bow River sportfish populations is potentially large, thus further evaluation of entrainment is warranted. The impact of entrainment to these populations will largely depend on the proportion of the population entrained. A long-term mark-recapture electrofishing program on the Bow River conducted by Alberta Environment and Protected Areas provides data to estimate population abundances in the fall for each year a survey is conducted (Askey et al. 2007, Cahill et al. 2018, Korman 2023). The proportion of a population entrained (hereafter referred to as proportional entrainment) can be determined by dividing annual estimates of entrainment by annual estimates of abundance in the Bow River.

The objectives of this report are to use more than 20 years of historical data on fish salvage and sportfish abundance in the Bow River to estimate annual entrainment of sportfish (Rainbow Trout, Brown Trout, and Mountain Whitefish) into CBRH and WH canals, and to estimate the proportion of the populations that are entrained. The statistical relationships between flow in the Bow River or flow in the canals and proportional entrainment are evaluated to see if more accurate estimates of annual entrainment can be determined, and to identify key variables that influence proportional entrainment. The analysis focuses on entrainment of Rainbow Trout and Brown Trout because these are the most sought-after sportfish in the Bow River and because their abundance in the Bow River is better quantified than Mountain Whitefish. Annual entrainment and proportional entrainment loss for both CBRH and WH canals are estimated. This report also provides recommendations for future studies to reduce uncertainties in estimates of entrainment and proportional entrainment.

This report contains five sections and a large appendix. Section 1 provides background and context. Section 2 describes the data and the model used to estimate annual entrainment and proportional entrainment. The same model is applied to all three sportfish species in both canals. Estimates of proportional entrainment depend on abundance estimates in the Bow River. The model that provides these estimates for Rainbow Trout and Brown Trout has been previously described (Korman 2023), but the application of the model to Mountain Whitefish has not. Simplifications of the model for Mountain Whitefish were required owing to limitations in the data (many fewer marked Mountain Whitefish are recaptured compared to Rainbow Trout and Brown Trout). A description of the simplified model and abundance estimates for Mountain Whitefish are provided in an appendix (Section A1). The entrainment results presented in this report depend on the critical assumption that the ratio of entrained to rescued fish observed in 2003 estimated by Post et al. (2006) in the CBRHC applies to other years in both the CBRHC and WHC. Results for CBRHC are presented in the main body of the report (Section 3), while those for WHC are provided in an appendix. Results for WHC are less certain as the entrainment to salvage ratio has never been estimated in WHC (Section A2). Key results and interpretations of the modelling are summarized in Section 4. In the future, more reliable estimates of entrainment and proportional entrainment could be obtained by field studies in both CBRHC and WHC. Alternative designs and details for these entrainment studies are provided in Section 5.

2.0 Methods

2.1 Data

The study area for the analysis is the Bow River between Bearspaw Dam and Bassano Dam and includes intake locations for the WHC and CBRHC (Figure 1). Water from the Bow

River is diverted into these canals during the irrigation season, which typically runs from mid-April to mid-October (Post et al. 2006, Figure 2, Figure A2.1), although the diversion period is periodically extended when additional winter storage is required. Bow River stream flow and canal diversions are variable in each year, depending on water supply and demand. Flow values used in this report were calculated using mean daily flows in the canals or in the Bow River immediately upstream of the entrance to the canals. Flow in WHC was based on a station in the canal near the headgates (05BM015). The mean daily flow time series for CBRHC was based on an amalgamation of data from two gauges in the canal (05AC004 for 2001 and 05BM021 for 2002-2023). Flow in the Bow River just upstream of WHC was based on the sum of mean daily Bow River flows near Calgary (05BH004) and in the Elbow River below the Glenmore Dam (05BJ001). Flows in the Bow River just upstream of CBRHC were based on the sum of flows in CBRHC and at the Bow River weir located just downstream of the canal headworks headgates (05BM002).

In this report the terms ‘fish rescue’ and ‘fish salvage’ are used interchangeably; both terms refer to the capture of live fish stranded in canals and release back in the Bow River. Data on the number of fish salvaged in the CBRH and WH canals are available from 2001-2023 and 2000-2023, respectively (Table 1). Only data from sites consistently sampled in all years were used (standardized sites). Fish salvage ordinarily occurs within one or two days of closure of headgates. As canals drain, fish congregate near the headgates and other structures where pools of water persist. Standardized sites are isolated with block nets and crews use backpack electrofishers and seines to capture fish. Multiple passes are conducted until fish are depleted from sites. All salvaged fish are identified and counted. All sport fish salvaged from standardized sites are counted and measured with the exception of Mountain Whitefish. All Mountain Whitefish longer than 200mm fork length (FL) are measured. Mountain Whitefish shorter than 200 mm FL are often very numerous so a sub-sample of 50 fish are measured. Fish are released alive back to the Bow River following capture and processing.

A comparison of the length frequency distributions in the canals indicates that the full range of sizes of Rainbow Trout sampled in the Bow River from electrofishing are rescued in CBRHC (Figure 3a). In contrast, salvage is dominated by smaller Brown Trout and Mountain

Whitefish in both canals, and smaller Rainbow Trout in WHC, compared to the Bow River samples (Figure 3b and 3c, Figure A2.2).

Proportional entrainment can only be computed in years when both fish salvage and Bow River electrofishing surveys were conducted. Annual boat electrofishing surveys of the Bow River have been conducted in most years between 1999 and 2021. Typically, both banks of multiple one kilometre (km)-long sites are sampled. The majority of survey years employed a mark-recapture approach where each site was sampled on multiple occasions (over consecutive days) within the sampling trip for each year. Fish are captured, enumerated, measured, and tagged on consecutive days for a total of typically four or five passes (i.e., capture events) of effort. On each pass, unmarked fish are caught, marked and released, and some fish marked on previous passes are recaptured. Annual estimates of sportfish abundance from these surveys were calculated using a hierarchical Bayesian closed population model that was recently developed (Korman 2023). The use of these estimates in the proportional entrainment modelling is described in Section 2.2.

Proportional entrainment was predicted based on a range of covariates that depended on Bow River and canal hydrology, fish ecology, and operation of diversion infrastructure. The hypothesis that flow in the Bow River and the diversion canals influences the magnitude of fish entrainment is based on the fundamental assumptions that more fish will move into canals when canal flow is higher, or when flow in the Bow River is low enough to limit available habitat and encourage fish to search for suitable habitat in other locations. Thus, proportional entrainment is expected to increase with increasing flow in the canals over the entire operating period (hypothesis CQ_4-10, Table 2), and decrease with increasing flows in the Bow River (hypothesis BQ_4-10). Based on the same logic, proportional entrainment is expected to increase with the ratio of canal flows to Bow River flows (hypothesis CBQ_4-10). In addition, proportional entrainment is expected to increase with the number of days the canals are operated each year as this provides more time for entrainment to occur (hypothesis DoD, days of diversion). Hypotheses of proportional entrainment were further refined by averaging daily flows over periods of low and high entrainment risk, as defined by species-specific seasonal patterns of entrainment estimated by Post et al (2006) in 2003, and based on seasonal timing of spawning and pre-and post-winter movements. Results from Post et al. (2006) indicate that the majority of

Rainbow Trout are entrained between June and August (hypotheses BQ_6-8 or CQ_6-8), perhaps due to increased post-spawning movement. In contrast, the majority of Brown Trout and Mountain Whitefish are entrained later in the year in August and September (hypotheses BQ_8-10 or CQ_8-10), perhaps because juvenile fish are beginning to move to over-wintering habitats.

The distribution of annual covariate values over the study period, and the relationships between covariates, are shown in Figures 4 and A2.3 for CBRH and WHC canals, respectively. As expected, covariates that have overlap in the period when they are calculated were correlated. For example, there is a positive correlation between the average flow between April and October and the average flow between June and August because they share about three months of daily flow values. There was also a strong correlation between the ratio of canal (C) to Bow (B) River flows and the components used to calculate the ratio. These correlations were high but not perfect. Thus, one might expect to see differences in fits of models predicting proportional entrainment based on different covariates, but multiple covariates cannot be included in the same proportional entrainment models because their effects would be challenging or impossible to separate. We therefore only considered proportional entrainment models with single covariates. The models were compared using a variety of statistical measures described below.

2.2 Model Description

We begin with a description of the equations used to calculate point estimates of entrainment and proportional entrainment and then describe a Bayesian model to estimate these quantities and their uncertainty, and to test hypotheses for flow and other covariates described above using the model. For brevity, we only describe the model use for Rainbow Trout in the CBRH canal here. The same methodology and model are applied to data for Brown Trout and Mountain Whitefish in CBRHC, and to data for all three species in the WH canal.

Calculating Entrainment from Fish Rescue

Point estimates of annual entrainment into CBRCH are calculated by expanding the annual salvage based on the ratio of the 2003 entrainment estimate over the entire irrigation season from Post et al. (2006) to the at the end of the season fish salvage in that year:

1)
$$E[iyr] = S[iyr] \cdot \frac{E[2003]}{S[2003]}$$

where *E* is entrainment into a canal in year *iyr* or 2003, and *S* is the salvage in the canal for *iyr* or 2003. For Rainbow Trout, the *E[2003]/S[2003]* ratio was 78.3. This means the rescue for each year is expanded by a factor of about 80 to estimate total entrainment over the entire irrigation season. A key assumption in this approach is that the *E/S* ratio does not vary across years, thus a direct estimate of *E/S* in 2003 can be used to expand the salvage to calculate total entrainment in other years. This 'point estimate' of entrainment does not consider any uncertainty in the salvage expansion factor (salvage expansion factor = 78.3 = 3996/51 from Table 3 of Post et al. 2006). Salvage expansion factors for Brown Trout and Mountain Whitefish were 4.5 (664/147) and 39.9 (93,850/2352). The application of these expansion factors to WH canal fish salvage data requires an additional assumption that these species-specific expansion factors are the same for CBRH and WH canals.

Calculating the Proportion of the Bow River Population that is Entrained

The proportion of a sportfish population that is entrained into CBRHC (proportional entrainment) is simply the ratio of entrainment in the canal to abundance in the Bow River,

$$p[iyr] = \frac{E[iyr]}{N[iyr]} \tag{2}$$

where *p[iyr]* is the proportion of the population entrained (*E*) in year *iyr* and *N[iyr]* is the abundance in the Bow River. Annual abundance estimates in the Bow River, expressed as fish/km of stream length sampled, were derived from a closed population model (Korman 2023). These density estimates were then converted to river-wide abundance estimates used in equation 2 by multiplying the density estimates by 169 km, the estimated length of the Bow River that Rainbow Trout, Brown Trout, and Mountain Whitefish populations consistently inhabit (Post et al. (2006). Note that the point estimate of *p[iyr]* is simply the ratio of the point estimates of *E* and *N* and is calculated using the above equations for each year with both salvage data and estimates of abundance in the Bow River. These simple year-specific point estimates of *p[iyr]* are included in the results for comparative purposes to the Bayesian hierarchical model, described in the next section. As details of the abundance model required to estimate *N[iyr]* for Mountain Whitefish were not described in Korman (2023), they are included as an appendix to this report (Section A1).

Bayesian Hierarchical Model to Estimate Entrainment and the Proportion of the Population Entrained

A hierarchical Bayesian model (HBM) is used to estimate the annual entrainment and proportion of a sportfish population entrained each year, and to quantify uncertainty in these estimates. The model uses estimates of the annual proportion entrained as a leading parameter to predict the observed salvages (Figure 5). Predicted salvage is derived by re-arranging the equation for the point estimate of entrainment (equation 1),

3) $$S[iyr] = E[iyr] \cdot \frac{S[2003]}{E[2003]}$$

In other words, salvage in a year is simply the entrainment in that year reduced by the *S/E* 2003 ratio (1/78.3 = 0.0128 for Rainbow Trout, that is, salvage is about 1/78.3 (1.28%) of entrainment).

Combining equations 2) and 3) predicts salvage as function of the Bow River population estimate and the proportion that is entrained,

4) $$S[iyr] = p[iyr] \cdot N[iyr] \cdot \frac{S[2003]}{E[2003]}$$

Note than *E[iyr]* in equation 3) has been replaced by *p[iyr]·N[iyr]* in equation 4. The model is now structured to predict *p[iyr]* (proportional entrainment) for each year, which combined with estimates of abundance, leads to predictions of salvage. Salvage predictions are then compared to the actual observed salvages to estimate the proportional entrainments. This is done using a mixed effects model implemented in a Bayesian framework.

We first predict the proportion of the population entrained based on random year effects,

5a) $$logit(p[iyr]) = \beta 0[iyr]$$

5b) $$\beta 0[iyr] \sim normal(\mu, \sigma)$$

The model estimates $\beta 0$'s, which are year-specific entrainment proportions (*p[iyr]*) in logit space). Annual logit-transformed entrainment proportions are assumed to arise from a common hyper-distribution with estimated mean μ and standard deviation σ. The mean represents the average entrainment proportion across years (in logit space), and the standard deviation represents the extent of interannual variation in the entrainment proportions (process error). These terms, called hyper-parameters, are of considerable management interest because they describe the across year average extent of the population-level impact on Bow River sportfish populations. The first term quantifies the interannual average proportion entrained, and the second term quantifies the magnitude of unexplained interannual variation.

The entrainment proportion component of the model is easily extended to account for covariate effects. For example, we might expect that the annual proportion of the population that is entrained will increase with the average flow in the CBRHC when it is operating,

$$logit(p[iyr]) = \beta 0[iyr] + \beta 1 \cdot \boldsymbol{X}[\boldsymbol{iyr}]. \tag{6}$$

Here $\beta 1$ is the coefficient predicting the effect of covariate ***X*** (e.g., average of CBRHC daily flows from April-October, bold denotes data) on the entrainment proportion. Equation 6 is called a 'linear mixed effects intercept-only model' because there is a random effect on the intercept ($\beta 0$) but also a fixed covariate ($\beta 1$) effect (random + fixed = mixed). We standardize covariate values for each year by subtracting the across-year mean value and dividing by the across-year standard deviation. Thus, when the covariate value in a year is the same as the across-year mean, the standardized value is 0. Thus, $\beta 0$ represents the proportional entrainment at the average covariate condition (because $\beta 1 \cdot 0=0$). $\beta 1$ represents the additive effect of the covariate when its value is one standard deviation from the mean. Owing to the standardization, the magnitude of β1 estimates provides a direct measure of the importance of different covariates for predicting interannual variation in entrainment proportions.

To account for uncertainty in the abundance of a sportfish population in the Bow River we use the following prior distribution for annual abundance estimates,

$$N[iyr] \sim \exp\big(normal(\boldsymbol{mulgN}[\boldsymbol{iyr}], \boldsymbol{sdlgN}[\boldsymbol{iyr}])\big) \cdot \boldsymbol{ReachLength} \tag{7}$$

where *N[iyr]* is the population size vulnerable to entrainment and ***mulgN*** and ***sdlgN*** are estimates of the mean and standard deviation of the log of annual Bow River population estimates per river km (from the closed population model), and ***ReachLength*** is the assumed length of river used by the population (169 km). Note that ***mulgN*** and ***sdlgN*** are not estimated in the entrainment model. Instead, year-specific values for ***mulgN*** and ***sdlgN*** come from the closed population model for the Bow River (Korman 2023) and are treated as data in the entrainment model (hence bolded in equation 7). Equation 7 represents a generally informative prior distribution for annual abundance values. A simplified version of the Bow River abundance model was required for Mountain Whitefish due to the limited number of recaptures. Entrainment predictions for Mountain Whitefish should be considered more uncertain than for Rainbow Trout or Brown Trout due to the more restrictive assumptions in the Mountain Whitefish population model (see Section A1).

The model can now predict salvage (*pSal*) via equation 4,

8) $$pSal[iyr] = p[iyr] \cdot N[iyr] \cdot \frac{\boldsymbol{S}[\mathbf{2003}]}{\boldsymbol{E}[\mathbf{2003}]}$$

but with *p* predicted by equations 5 (null model) or 6 (covariate model) and *N* predicted by equation 7. Annual entrainment, a variable of policy interest is calculated as,

9) $$E[iyr]= p[iyr]\cdot N[iyr].$$

The entrainment estimates account for uncertainty in both *p* and *N*, and because *p* is constrained to be less than one by the logit transformation (equation 5a or 6), entrainment logically can never exceed population abundance.

Finally, the predicted salvages from equation 8) are compared to observations via the data likelihood,

10) $$\log(\boldsymbol{osal}[\boldsymbol{iyr}]) \sim normal\ (\log\ (pSal[iyr]), \boldsymbol{sdobs})$$

where *log(**osal**)* is the observed salvage in log space, *pSal* is the predicted salvage from equation 8, and ***sdobs*** is the standard deviation in observed salvage estimates. This is the observation error in the S*[2003]/E[2003]* ratio described above. The likelihood assumes that errors in predictions of the log of observed salvage are normally distributed. This is a logical likelihood as a normal distribution (i.e., not log transformed) can return a negative number even if its mean is positive.

Our approach for estimating ***sdobs*** includes the effect of uncertainty in *E[2003]* estimated in Post et al. (2006, Coefficient of Variation (CV)=0.33), but it does not include the variability in *S* for a given level of *E*. For example, if the majority of entrainment happens early in the season, (e.g., June), then we might expect *S*, which is sampled at the end of the season, to be lower compared to a year with the same total entrainment but with most occurring later in the season and therefore closer the time of fish rescue. In the latter case we might expect the salvage expansion factor to be lower because a higher proportion of entrained fish would be present in section of the canal where salvage occurs. Our methodology to calculate entrainment hangs on the 'gorilla' assumption that ratio of entrainment to salvage is constant across years, and that the uncertainty of this ratio (***sdobs***) is dominated by the uncertainty in the entrainment estimate in 2003. It is likely this approach underestimates the true-interannual variation in the *S/E* ratio.

Separation of Process and Observation Error

Hierarchical Bayesian models, which can be structured as linear mixed effects models such as the one described above, can separate process and observation error. In this application the process error is the amount of unexplained interannual variation in the proportion of the population that is entrained (σ in equation 5b). When fixed effects like average canal flow are included in the model, the process error should decline relative to the null model (equation 5a) which does not include covariate effects. This occurs because the variance of random effects doesn't have to be as large since some of the interannual variation in the proportion entrained can be explained by the fixed effect. Thus, the utility of different covariates can be compared based on the extent of the reduction in unexplained variation in the proportion entrained relative to a null model.

The observation error in the model is the uncertainty in the observed salvage with respect to how well it represents entrainment (***sdobs*** from equation 9). If we assumed there was no uncertainty in the salvage expansion ratio, the model would attempt to explain all the unexplained variation in the entrainment proportions across years by increasing the process error (σ from equation 5b). But since we admit that the S/E ratio is not perfect in the data likelihood (equation 9), σ doesn't need to be as large because the model recognizes that some of the lack of fit between observed and predicted salvage is due to uncertainty in the S/E ratio. Logically, the model predicts that our ability to estimate the true extent of interannual variation in entrainment proportions depends on the precision of annual estimates of entrainment. Our analysis hinges on two key assumptions: 1) the 'gorilla' assumption that the entrainment-to-salvage ratio in 2003 is the same in other years; and 2) all the uncertainty in the 2003 *E/S* ratio is due to uncertainty in entrainment.

We do not estimate observation error in our model (***sdobs*** in equation 9). Instead, we fix it at a value of 0.33. This value was determined through bootstrapping and data provided in Post et al. (2006). Using Rainbow Trout as an example, a random sample of entrainment was derived by sampling from a normal distribution with a mean of log(1683) and a standard deviation of ***sdobs***. The value 1683 was set to the estimate of entrainment in 2003 for Rainbow Trout >=150 mm (see Table 2 Post et al., 2006). The value of ***sdobs*** was then adjusted so that the 95% confidence interval of the random values was the same as the 95% confidence interval reported in Post et al. (2006, Table 2). This was repeated for Brown Trout and Mountain Whitefish. As this simulation was done in log space, the relative variation in the transformed samples is equal to the standard deviation used in the simulation (***sdobs***). As a result, the value of ***sdobs*** does not need to be adjusted as the mean predicted salvage changes across years (equation 10).

Model Fitting and Model Comparisons

Only years with both salvage and population estimates and covariate values can be included in the model. This translated to 14 years of observations between 2001 and 2023 for CBRHC, and to 15 years of data from 2000-2023 for WHC. Using CBRHC as an example, the model calculates 14 annual proportional entrainment values (*p[iyr]*). With no covariates, this requires 14 estimates of the intercept ($\beta0$), as well as the mean and standard deviation of the hyper-distribution from which they are drawn, for a total of 16 parameters. If modelling a single covariate effect, a fixed effect must also be estimated for a total of 17 parameters. The model also estimates 14 Bow River abundances, however these estimates are constrained by informative prior distributions with fixed means and standard deviations for each year (equation 7). As there are only 14 salvage observations and 17 parameters (excluding the N's which are highly constrained by their priors), the model should almost perfectly predict the observed salvages. As will be shown, the correlation (r^2) is just slightly smaller than one. This occurs because HBMs maximize the joint probability from the data likelihood (equation 9) and the prior distributions (equation's 5b and 7). In the case of equation 5b, the sum of probabilities from the prior increase as σ decreases. This results in a small constraint on the range of $\beta0$ estimates across years, which causes a slight reduction in fit. Increasing the assumed observation error (***sdobs*** in equation 9) will lead to lower process error (σ). This would occur because the data likelihood will have less influence on the Bayesian probability that is being maximized because the year-specific salvage observations are considered less certain. Given that the model is likely underestimating the true observation error of the salvage, it is likely overestimating the extent of unexplained interannual variation in the entrainment proportion.

Posterior distributions of model parameters were estimated using WinBUGS (Spiegelhalter et al. 1999) called from the R2WinBUGS (Sturtz et al. 2005) library from R (R Development Core Team 2009). We used an uninformative gamma distribution as the prior for the standard deviation terms of the hyper-distribution (shape and rate parameters = 0.001), and uninformative zero-centered normal distributions (precision = $1/\sigma^2 = 0.001$, which is a standard deviation of 32) for all other parameters. Posterior distributions were computed by taking every 10th sample from a total of 50,000 simulations from each of three chains, after excluding the first 25,000 to remove the effects of initial values. This approach was sufficient to achieve convergence for all model parameters, as evaluated using the Gelman-Rubin convergence diagnostic (Gelman et. al., 2004).

The null model (no covariate effect) and the 12 covariate models were compared using a variety of statistics. The correlation between the log of predicted and observed salvages is used to evaluate model fit. As covariates were standardized, the magnitude of the mean of the posterior distribution for the fixed covariate effect ($\beta 1$) reflects its relative importance to the prediction of proportional entrainment, and the coefficient of variation in the posterior distribution represents the uncertainty in the effect. Covariates with the largest effect sizes (in negative or positive directions) which are more precisely defined (lower CV's) are better predictors of proportional entrainment because they result in larger decreases in the magnitude of the unexplained variation (σ in eqn 5b). We also compare the predictive ability of models using the Deviance Information Criteria (DIC), which is a hierarchical modelling generalization of the Akaike Information Criteria (AIC, Spiegelhalter et al. 2002). These information theoretic approaches quantify the trade-off between model fit and complexity. Complex models, which include more parameters, will fit the data better, or at least as well, compared to simpler models with fewer parameters. However, more complex models are less precise. DIC quantifies the trade-off between fit and precision and identifies the model with the best balance which will therefore have the best predictive ability. Hierarchal Bayesian models constrain parameter estimates via hyper distributions (e.g., equation 5b) and priors (e.g., equation 7) and the DIC approach quantifies the effect of these constraints by calculating the number of effective parameters (pD), which is needed to calculate DIC (just as the number of parameters estimated is needed in the AIC calculation). Models with lower DIC values are considered to have better predictive ability than models with higher DIC values. Models within two DIC units of the model with the lowest DIC are considered to be strongly supported.

3.0 Results

Estimates of entrainment proportions from the HBM based on the null model for Rainbow Trout (no covariate effects, equation 5a) showed considerable interannual variation (Figure 6). The means of annual HBM estimates were generally similar to the point estimates. However, in years when the population estimates were uncertain (e.g., 2019) the posterior distribution of proportional entrainment had a long right tail because the model can admit much lower population abundances. The mean of the hyper-distribution from which estimates of annual entrainment proportions are drawn was 8.4% which is similar to the mean of the point estimates of 10%. Note how the annual entrainment proportions are slightly shrunken towards the mean of the hyper-distribution. The HBM-based proportions are slightly higher than the point estimates when below the mean, and slightly less than the point estimates when above the mean. The extent of this statistical 'shrinkage' depends on the amount of information in each year's entrainment proportion. This depends in part on the uncertainty in the annual population estimates. The model logically predicts that entrainment proportions are more uncertain in years when there is more uncertainty in abundance estimates in the Bow River. The mean of the hyper-distribution from which annual entrainment proportions is well determined (dark band in Figure 6). However, the unexplained process error is considerable (lighter band in Figure 6) because it has to account for the extensive inter-annual variability in entrainment proportion estimates. Covariate models attempt to explain some of the inter-annual variation with more useful models explaining more of this variation.

We compared the null model (no covariate effects on entrainment proportion) with 12 different covariate models that predict proportional entrainment (equation 6, Table 3). Estimates of covariate effects were consistent with hypotheses about the effects of flow on the proportion of the Bow River Rainbow Trout population that is entrained. Entrainment proportion declined with increases in average flow in the Bow River (negative $\beta1\_mu$ in Table 3a), however the fixed effects were poorly defined (CV=0.8-1.7). Owing to high uncertainty in the fixed effect, the unexplained interannual variation in the proportion entrained from these Bow River flow models were similar to the null model. In contrast, there was a strong positive effect of average flow in CBRHC on entrainment proportions (β1_mu =0.75, β1_cv=0.24 for CQ_4-10), resulting in a very substantive reduction in unexplained variation (σ=0.22 vs 0.78 for null model). The CQ flow – entrainment proportion relationship was non-linear and showed an accelerating effect of flow with increasing flows (Figure 7). For example, there is a greater increase in proportional entrainment as flows increase from 30-35 m^3/s compared to a flow increase from 15-20 m^3/s. There was a 100% probability that there was a positive association between average CBRHC flows between April and October, and average flows between June and August, on proportional entrainment (prob(β1>0)=1). These models had the lowest DIC scores of all the 12 considered. As expected, the entrainment proportion increased with the ratio of CBRHC flow to Bow River flow (CBQ), but the effect was smaller than estimates for the CQ flow models, and considerably more uncertain. The number of days that CBRHC was operated (in total, before June, or after September 15) were poor predictors of proportional entrainment as seen by the very large CV's of the effect sizes and high levels of unexplained variation. Note that all models fit the observed salvage data very well ($r^2>0.95$) because there are almost twice as many parameters (31) than annual observations (14). However, the number of effective parameters (pD in Table 3) is considerably less than the number estimated (31) because of the strong effect of the priors on Bow River abundance estimates, and the constraining effect of the hyper distribution on the intercepts of the proportion of the population entrained. The low value of σ for the most predictive model (CQ_4-10) reduces the penalty from the hyper distribution by constraining unexplained variation in proportional entrainment with only a minimal impact on fit (as indexed by r^2), and so has the lowest DIC.

The April-October average CBRHC flow covariate model is examined in more detail to better describe how the HBM works (Figure 7). The simple point estimates of annual entrainment proportions shown in the plot, that are not calculated from the HBM, also show a positive association with flow over much of the observed range. Thus, the estimated relationship in the HBM is supported by the annual point estimates and is not an artefact of statistical shrinkage from the HBM. All the annual proportional entrainment estimates from the HBM are shrunken towards the discharge-dependent mean (solid line). However, the extent of shrinkage is generally modest with the exception of 2021 and 2023. The greater shrinkage towards the mean in these cases reduces the magnitude of the estimated non-flow dependent (i.e., unexplained) interannual variation in entrainment proportions (σ from equation 5b). This increases the probability returned from the hyper distribution of β0 estimates.

Entrainment based on the April-October CQ– proportional entrainment model averaged ~ 18,000 Rainbow Trout per year between 2001 and 2023 (Figure 8 top). The simulated abundances from the entrainment model generally closely followed the abundance estimates from the closed population model (Figure 8, bottom). We expect some differences in the abundance statistics between these two cases. The entrainment model can adjust abundances (*N[iyr]* in equation 7) to some extent to minimize unexplained variation in proportional entrainment (reduce value of σ in eqn 5b) and increase fit to the salvage data. However, the adjustment to abundance estimates is limited owing to the informative prior distribution for abundance estimates as defined by the closed population model results. To better understand this, consider the abundance estimate in 2023 when the relative uncertainty in the estimate was higher. The entrainment model will return a higher joint probability if it simulates a lower abundance in 2023 to decrease the HBM estimate of proportional entrainment. This provides a better fit to the CQ – proportional entrainment relationship (Figure 7) and hence requires a lower estimate of unexplained variation (σ in Table 3b). These dynamics lead to modest differences between proportional entrainment estimates from the null model and covariate models with strong effects (Figure 9). In some years with higher flows the covariate model predicts greater proportional entrainment compared to the null model, with the opposite occurring in some years with low flows (e.g., 2012). Overall, the annual estimates of proportional entrainment are similar among null and covariate models.

Estimates of proportional entrainment for Brown Trout at CBRHC (Figure 10) were substantially lower compared to Rainbow Trout. The average proportional entrainment for Brown Trout (mean for the hyper distribution) was 2.1%, compared to 8.4% for Rainbow Trout. The mean for point estimates (dashed line) was considerably higher than the mean for the hyper distribution because of the strong influence of 2012 on the mean of the point estimates. The 2012 proportional entrainment estimate from the Bayesian model shrunk towards the mean compared to the point estimate for 2012 and had high uncertainty. Proportional entrainment was about10-fold higher in 2012 compared to the average. This occurred because salvage was the second-highest on record (Table 1) while abundance in the Bow River was the lowest on record (see Figure 12, lower panel).

While it is possible that entrainment of Brown Trout was unusually high in 2012, as suggested by the unusually large number of Brown Trout salvaged in the canal, it is also possible that the population in the Bow River was underestimated. Unlike all other years of population sampling on the Bow River, the four sites sampled in 2012 were all below the Carseland Weir (weir at river km 349, sites in 2012 located at river km 350, 357, 359.5, 367). In 2001, when many sites between Bearspaw and Bassano dams were sampled, densities of Brown Trout were lower downstream of river km 80 compared to upstream locations, and there was evidence for lower densities downstream of the Carseland Weir (see Figure 2 from Askey et al. 2007). Spatial patterns in Brown Trout densities in later work (Korman 2023) confirm the pattern of lower densities at sites just upstream of the Carseland Weir compared to locations further upstream. Thus, it is possible that the very high proportional entrainment estimate for 2012 was at least in part an artefact of a negative bias in abundance in the Bow River due to the unique location of sample sites.

There was very little support for any of the covariate models for Brown Trout (Table 3b). The coefficient of variation for fixed effects was typically large (>0.5). All models had similar DIC values and there was a limited reduction in unexplained variation relative to the null model. The results support the use of the null model to estimate Brown Trout entrainment and suggest that reductions in flow in CBRHC are unlikely to reduce Brown Trout entrainment.

The best of the weakly predictive models for Brown Trout estimated a decrease in proportional entrainment with increasing flows in CBRHC (Figure 11). Examination of the relationship shows high uncertainty in the effect size, with the unexpected direction of response (higher flows in canal leading to lower proportional entrainment) largely driven by the 2012 outlier, which happened to be a year with relatively low flows in the canal and high flows in the Bow River (hence the negative effect of CQ and positive effect of BQ (Table 3b). There does not appear to be a relationship between discharge and the point estimates of proportional entrainment when the estimate from 2012 is ignored. Entrainment of Brown Trout at CBRHC appears highly size selective as shown by the much higher proportion of small fish in the salvage than in the

Bow River electrofishing samples (Figure 3b). This could potentially impact a covariate-entrainment relationship.

Average entrainment of Brown Trout was about 1,200 fish/year, which was approximately 15 times lower than entrainment of Rainbow Trout (Figure 12, top panel). There was a strong correspondence between population estimates from the closed population model (Korman 2023) and those simulated from the null entrainment model (Figure 12, lower panel).

Proportional entrainment of Mountain Whitefish in CBRHC was very high and averaged 36% across years (Figure 13). The average annual entrainment based on the null model was about 76,500 fish, and the average of annual Bow River abundance estimates was about 300,000 fish (Figure 14). The average annual salvage for Mountain Whitefish was more than 5-fold higher than the average salvages for Rainbow Trout and Brown Trout (Table 1), and the 2003 entrainment to salvage ratio for Mountain Whitefish (*E/S*=39.9) was about half the value for Rainbow Trout (79.9) but considerably higher than the ratio for Brown Trout (4.5). There was very large interannual variability in proportional entrainment across years with low values less than 5% and high values of almost 80% (Figure 14). This variability was driven by high variation in Bow River abundance estimates (see bottom panel of Figure 14) and high variation in the annual salvage of Mountain Whitefish (Table 1). Similar to Brown Trout, covariates were not useful predictors of proportional entrainment for Mountain Whitefish (Table 3c). Entrainment of Mountain Whitefish at CBRHC was highly size selective as shown by the much higher proportion of small fish in the salvage than in the Bow River electrofishing samples (Figure 3c).

4.0 Discussion

This study provides annual estimates of Bow River sportfish entrainment and the proportion of the populations that are entrained in CBRH and WH canals (appendix A2 for the latter). Estimates for entrainment for CBRHC are considered more reliable than for WHC as a direct estimate of entrainment is only available for CBRHC. Proportional entrainment for Mountain Whitefish in both systems are considered highly uncertain because of uncertainty in abundance in the Bow River due to low capture probability. Annual entrainment of Rainbow

Trout in the CBRH canal between 2001 and 2023 averaged about 18,000 fish/year, while entrainment of Brown Trout was about 15-fold lower at 1,200 fish/year. Given abundance estimates in the Bow River, the average proportion of Rainbow and Brown Trout population entrained in the CBRH canal was about 8 % and 2.5%, respectively. These estimates indicate the Bow River Rainbow Trout population is more vulnerable to entrainment than Brown Trout. The full size-range of Rainbow Trout captured in the Bow River are entrained into CBRHC, while Brown Trout entrainment is dominated by much smaller fish (largely age-1). Thus, a higher proportion of the young Brown Trout entrained into CBRHC would have died of natural mortality in the Bow River (if not entrained) before recruiting to sizes where they could spawn or enter the recreational fishery. The effect of entrainment of Brown Trout on the abundance of future spawners in the Bow River and the fishery is likely substantially less than the effects on Rainbow Trout owing to both the substantively lower proportional entrainment rate and differences in the ages that are entrained.

Proportional entrainment of Rainbow Trout in CBRH canal was positively related to average flow in the canal over both the entire entrainment period (April-October) and during the highest risk period in June through August (Post et al. 2006). Average canal flows were substantively better predictors of proportional entrainment for Rainbow Trout compared to Bow River flows or the ratio of Canal-to-Bow River flows. The canal flow-based April-October model predicted substantive increases in proportional entrainment between moderate and high average flows. For example, proportional entrainment increased from about 3% to 10% when average flows in the canal increased from 15-25 m^3/s, compared to an increase from about 10% to almost 30% when average flows increased from 25-35 m^3/s. This non-linear relationship suggests that for the same volume of water diverted from the Bow River over an irrigation season, it would be better to have lower and consistent flows in CBRHC than more variable flows with higher peaks. However, this flow regime could lead to greater reductions in flow in the Bow River as higher canal diversions would occur during periods of lower flow in the Bow River. The resulting lower flows in the Bow River could have impacts on fish in the Bow River. Interestingly, the proportion of flow from the Bow River diverted into CBRHC was a much weaker predictor of proportional entrainment than just CBRHC flows. This suggests that effects of diversion on hydrodynamics near the entrance point of the canal could be having important effects on entrainment. Further study on the velocity gradient in the entrainment field using a twodimensional hydrodynamic model could provide insights about effects of CBRHC flows on entrainment risk.

The estimate of the number of Rainbow Trout and Brown Trout salvaged from WHC was considerably lower than in CBRHC. Assuming similar salvage-to-entrainment ratios in the two systems leads to the prediction that proportional entrainment in WHC was much lower than in CBRHC. Covariates were not useful predictors of proportional entrainment for Brown Trout and Mountain Whitefish in CBRHC or for all three sportfish species in WHC. This result is likely caused by a combination of factors including: 1) greater uncertainty in abundance estimates in the Bow River for Brown Trout and especially Mountain Whitefish; 2) greater uncertainty in the entrainment-to-salvage ration for WHC; and 3) higher sampling error in the expanded estimates of entrainment in WHC for Rainbow and Brown Trout compared to CBRHC due to lower salvage numbers. Estimates of entrainment for WHC should be considered very preliminary.

The entrainment and proportional entrainment estimates provided in this report are highly dependent on the species-specific entrainment-to-salvage ratios estimated in 2003 in CBRHC. The model assumes these ratios don’t vary across years and are the same in CBRHC and WHC. Uncertainty in the model predictions owing to these assumptions could be substantially reduced by additional field studies to quantify entrainment and proportional entrainment in future years. An evaluation of alternrate entrainment study designs is provided in the following section of this report.

5.0 Entrainment Study Design

Estimates of entrainment and proportional entrainment of sportfish in CBRH and WH canals presented in this report depend on some critical and uncertain assumptions. First, the model assumes that the species-specific entrainment-to-salvage ratios estimated in 2003 in CBRHC from Post et al. (2006) would be similar in other years. Entrainment results for WHC are based on the additional assumption that the entrainment-to-salvage ratio in 2003 in CBRHC is the same in WHC both in 2003 and in other years. This assumption only holds if the evacuation rates in the two canals are similar, which is unlikely due to differences in hydraulic geometry, flow, and the areal extent of salvage efforts relative to fish distribution when flows in the canals are shut off. It is also worth noting that the entrainment estimate for 2003 from Post et al. (2006) is uncertain. While the model used here accounts for uncertainty in the 2003 entrainment estimate, it likely underestimates uncertainty in the entrainment-to-salvage ratio used in the model calculations due to variation in residence time (as discussed in the Methods). In addition, the entrainment estimates in Post et al. (2006) for the targeted sportfish (Rainbow Trout, Brown Trout, Mountain Whitefish) may be biased because the catchability and residence time estimates used in their assessment were based on marking and recapturing White Suckers (*Catostomus commersonii*) because sufficient numbers of the target sportfish were unavailable. Owing to all these uncertainties, additional field studies to better quantify entrainment and proportional entrainment would be useful, assuming that management actions or authorizations will in part be based on these quantities. This section of the report provides ideas and recommendations for future entrainment studies, expanding on the work of Van Poorten and Post (2004) and Post et al. (2006).

There are two alternatives for estimating the total entrainment into a canal over an entrainment season, and the proportion of a Bow River population that is entrained. The whole-river (WR) method involves tagging a large number of sportfish in the Bow River with Passive Integrated Transponder (PIT) tags, and then detecting those tags in a canal using a PIT tag antenna system. In contrast, a Within-Canal (WC) approach would follow the method developed by Post et al. (2006), where mark-recapture in the canal is used to estimate the number entrained over the entrainment season. The WR-approach requires an estimate of abundance in the Bow River to translate the estimate of proportional entrainment into entrainment numbers, while the WC approach needs a Bow River population estimate to translate the estimate of number entrained into proportional entrainment. Thus, whichever method is selected for a future study, it is important that a Bow River population estimate is available for the year the entrainment study is conducted. Details of these two approaches are described below.

5.1 Whole River Approach

The Whole-River approach would provide a direct estimate of the proportion of a sportfish population that is entrained into a canal (p). If the abundance of a population in the Bow River is available (N) in the same year, the total entrainment number to the canal (E) would then be calculated ($E=p\cdot N$). The WR approach would require that at least two PIT tag antennas are installed in series within a canal so the proportion of tags passing over the series that is detected can be determined. This gross detection efficiency would be estimated using standard mark-recapture modelling that depends on the number of tags detected at both antennas and the numbers detected at only one of the antennas. The challenge of the WR approach is the number of PIT tagged fish detected in the canal may be low, leading to high uncertainty in the estimate of the proportion of the population entrained, which in turn would lead to uncertainty in the absolute number entrained. Post et al. (2006) attempted the WR approach. They marked a total of 1,175 Rainbow Trout, Brown Trout, and Mountain Whitefish in three sampling periods (May, July, September) in the Bow River and only recovered one of these marked fish in the CBRH canal over the entire 2003 study period. Post et al. (2006) suggested that the low recapture of tagged fish was due to the low proportion of the river populations that were marked and the rapid evacuation rate of fish in the canal. Their ability to detect entrained fish was very low, a factor that could be potentially remedied in a future study with a PIT tag antenna system.

In this report, the efficacy of the WR approach is evaluated by calculating the coefficient of variation in the estimate of the proportion of a population entrained into a canal as a function of the number of PIT tagged fish released in the Bow River, the proportion that are entrained into a canal, and the detection efficiency of the canal antenna system. The number of PIT tag detections in the canal is logically considered a binomially-distributed random variable,

$$r \sim binomial(pDet, NTent)$$

where r is the number of detections, $pDet$ is the gross efficiency of the PIT antenna system, and $NTent$ is the number of tagged fish entrained in the canal. Given a mark-recapture-based estimate of $pDet$ (described above), and an observed number of detections r, a point estimate of $NTent$ can be calculated by expanding r by $pDet$ (i.e., $NTent=r/pDet$). This in turn can be used to estimate the proportion of the tagged population that is entrained via,

$$p = NTent/Ntagged$$

where $Ntagged$ is the number of fish that were PIT tagged in the Bow River and p remains the estimate of the proportion entrained. This model assumes there is no mortality between the time when fish are tagged (~ April or May) and when they are entrained into a canal (~May-Sep). An estimate of survival rate between tagging and entrainment (S) can be added to the model by replacing the denominator with $Ntagged \cdot S$, or p can be thought of as the product of the probability of surviving between tagging and entrainment and the probability of being entrained.

Van Poorten and Post (2004) estimated an annual survival rate of Rainbow Trout in the Bow River based on a catch curve analysis of 35%. Annual survival rates for Rainbow Trout in other systems, determined from open population model mark-recapture studies, range from approximately 40% (Korman et al. 2016) to 50% (Cilbiz and Yalim 2017). All these estimates translate to a survival of about 90% between tagging and entrainment about two months later. This figure probably underestimates survival from tagging to entrainment because there can be considerable mortality immediately after spawning which is accounted for in annual survival rate estimates, but would likely occur prior to tagging in the Bow River. Hence the *p* used in the calculation of the number of tagged fish entering the canal is largely determined by the proportion of the population entrained. However, we simulated scenarios which assumed 100% survival between tagging and entrainment and 90% survival to evaluate the effects of survival on the precision of proportional entrainment estimates.

The uncertainty in the estimate of the proportion of the population entrained can be calculated analytically from,

$$CV(p) = \sqrt{\frac{1 - pDet}{Ntagged \cdot Survival \cdot pEnt}}$$

where *CV(p)* is the coefficient of variation in the estimate of the proportion entrained (Hilborn and Mangel 1997, p. 66), *Survival* is the proportion of fish that are tagged in the Bow River and survive until the period when they would be entrained, and *pEnt* is the assumed proportional entrainment. Here we can see that the precision of the estimates of proportional entrainment (lower *CV(p)*) increase with increases in the antenna detection efficiency (*pDet*) and with increases in the number of tagged fish entrained in the canal, which depends on the number of fish tagged in the Bow River (*Ntagged*) and the actual proportional entrainment (*pEnt*), and to a lesser extent on survival between tagging and entrainment.

The uncertainty in the proportion entrained can also be calculated by simulation in R using the following code,

```
#produces n (5000) simulated # of tag detections
sim_r=rbinom(n=5000, size= Ntagged*Surv*True_p, prob=pDet)
pEst =sim_r/ (pDet·Ntagged·Surv*True_p) # estimate of proportion entrainment given sim_r
# get the CV across the n (5000) simulated estimates of proportional entrainment.
```

CV(pEst)=sd(pEst)/mean(pEst)

Here *True_p* is the assumed proportion of the population entrained used in the simulation, and *pEst* is the estimate of proportion entrained, which accounts for sampling error in the number of detections (*sim_r*), from which a *CV(p)* can be computed.

The analytical method was to calculate the CV of proportional entrainment estimates across a range in the number of fish that could be tagged in the Bow River (500-3000), a range of potential detection efficiencies of an antenna system in the CBRH canal (0.025 – 0.2), and a range of proportional entrainments as defined by the historical estimates from Rainbow Trout presented in this report (0.025 – 0.15). The range of potential detection efficiencies should be considered uncertain but could be quite low during periods when flows in the canal are high. However multiple antennas in sequence could lead to higher detection efficiency even in challenging flow conditions. The number of tags that could be applied to sportfish in the Bow River was determined based on historical catch rates and information on the amount of time to electrofish a distance of shoreline and process fish. The number of tagged fish were based on scenarios where two crews (boats) electrofished the Bow River over two weeks in spring, just prior to the entrainment season. The number of fish tagged varied with assumptions about whether all Rainbow Trout, Brown Trout, and Mountain Whitefish were landed and processed or whether only Rainbow Trout and Brown Trout were landed and processed. A third scenario also included tagging of Rainbow Trout and Brown Trout from volunteer anglers at fishing hotspots. Details of the tagging scenarios are provided in Section A3.

As expected, under an assumed level of proportional entrainment, the CV of proportional entrainment estimate increased with increases in the number of PIT-tagged fish released in the Bow River, and with increases in antenna detection efficiency in the canal (Figure 15). At the low end of our estimated interannual range of proportional entrainment for Rainbow Trout (0.025), a design with 1000 tags released in the Bow River combined with an optimistic antenna efficiency of 0.15 had a CV for the estimate of proportional entrainment of about 0.5 (a fairly uninformative estimate). However, that CV improved substantially (< 0.3) if 2500 tags were released and antenna efficiency was 0.2. As expected, the precision (lower CV) of proportional entrainment estimates increased with the assumed level of proportional entrainment because more tagged fish would be entrained. At the average level of proportional entrainment for

Rainbow Trout at CBRHC (see Figure 6, mean of 0.084 reflected ~ by the sim_*pEnt*=0.1 scenario in Figure 15), tagging only 1000 fish in the Bow River with a detection efficiency of 0.1 in the canal resulted in a coefficient of variation in the proportional entrainment estimate of about 0.3. These patterns and magnitudes of the CVs were similar when we assumed 100% survival (Figure 15a) or 90% survival (Figure 15b) between tagging and entrainment.

As mentioned above, the greatest uncertainty in the WR entrainment study design is the detection efficiency of the PIT tag antenna system in the canal. Thus, a logical way to proceed with this effort if funded, is to first install and test the antenna efficiency using 'dummy' tags that would have the approximate size and buoyancy of fish that to be tagged in the Bow River. Or better capture some fish from the Bow River or from the canal, tag them, and purposefully release them into the top of the canal. The antenna location and configuration could be adjusted to achieve an efficiency that provides an adequately precise estimate of proportional entrainment given a realistic number of tags that could be applied of ~1,000-2000. Once the target antenna efficiency has been obtained, tagging in the mainstem could begin. It may be worth testing the antenna efficiency over the course of the entrainment season, or at least over the full range of canal discharges that would be encountered. The WR method lends itself to partnerships for implementation owing to its two distinct elements (tagging in the Bow River, PIT tag antenna in the CBRHC).

The WR method provides a direct and simple means of evaluating whether the estimates of proportional entrainment and total entrainment provided in this report are realistic. If the estimates presented here are too high, the precision of proportional entrainment estimates for the WR design presented here are overestimated. A modification to the WR study design could hedge against this possibility. The proposed WR study involves capturing fish over the entire 169 km study area and determining the proportion entering the CBRHC. An alternate design would focus the tagging effort closer to the CBRHC, under the assumption that fish located closer to the canal have a higher probability of entrainment. As the distance from tag release to the canal would be known, it would be possible to estimate a model which predicts entrainment probability as a function of distance from the canal. This model could then be applied to more distant regions outside of the area where tagging occurred to make an inference about entrainment probability for the wider population. To do this, the Bow River would be broken up into a series of sections with an estimate of entrainment probability for each section determined from the distance-entrainment proportion model. The probabilities would then be multiplied by the abundance in each section to estimate the total number entrained and the proportion of the total population entrained. The abundance in each section could be determined based on the assumption that the target species is evenly distributed over the 169 km length. Alternatively, a spatially explicit population model could be developed that would allow for differences in density among sections.

The efficacy of this distance-stratified WR approach depends on the behaviours that are leading to entrainment. One behavioural hypothesis is that fish are being entrained as they make longer distance migrations when adults return from spawning grounds (e.g., Rainbow Trout in the Highwood River), when juveniles that emerge following mainstem spawning redistribute themselves in the mainstem (Brown Trout), or when fish drift and re-distribute after emergence or move to overwintering habitats (Mountain Whitefish). Distance from the canal may not be a good predictor of entrainment probability for such migrating fish because fish distant and closer to the canal may have equal probability of passing in front of the canal. A second behavioural hypothesis applies to fish that are not migrating or dispersing but instead making smaller movements as they search for better habitat or feeding opportunities within a smaller home range. We would expect a stronger distance-entrainment probability relationship for this group of more resident fish. Unfortunately, the relative contributions of fish exhibit long range and shorter movement distances is not known, hence the improvement from a more focused tagging program closer to the CBRCH is uncertain.

5.2 Within-Canal Approach

The second approach to estimate entrainment and proportional entrainment would follow the method developed by Post et al. (2006) with modifications based on newer technology. Their approach involves estimating fish abundance in the canal periodically (e.g., every 10 days) over an entrainment season. A model is then used to estimate the entrainment between each survey period given an estimate of the residence time in the surveyed area within the canal. This approach is very similar to the commonly-used Area-Under-the-Curve (AUC) methodology to estimate the escapement (abundance) of Pacific Salmon and Steelhead when they are migrating into rivers to spawn. Like Post et al. (2006), the AUC approach requires estimating the abundance of fish at different times over the period when fish are migrating or spawning (equivalent to the time period when fish are being entrained into a canal), usually based on mark-recapture or mark-resight. The abundance estimates are then plotted as a function of time and used to calculate the area under the abundance-time curve by integration (summing the area under the curve). The AUC is then divided by the residence time of fish in the surveyed area (also termed ‘survey’ life) to calculate the total number of fish that entered the survey area (escapement to stream or entrainment in canal).

Survey life can be estimated in a variety of ways and is most commonly done using radio or acoustic telemetry. Historically, the abundance-time curve was defined by linear interpolation of the abundance estimates over time, and usually required assumptions about the first day fish entered the river and the last day they could be present. More modern implementations (Hilborn et al. 1999) fit parameters of a continuous parametric arrival timing curve (cumulative normal or beta distributions) to estimate the proportion of the run that has arrived by each timestep (pa[t]). Given a fixed survey life (or a temporally varying one, Korman et al. 2007), the timing of departure (pd[t]) is then defined by simply shifting the arrival curve forward in time based on survey life (e.g., pd[t+survey_life[t]]=pa[t]). The product of the total escapement (i.e., entrainment over the season) and the difference in the cumulative proportions of arrivals and departures on any date defines the number present at any time ($N[t] = E \cdot (pa[t] - pd[t])$). The model is fit to the data by comparing the predicted estimates of abundance over time (N[t]) with the observed estimates from mark-recapture.

All the data used in this procedure can be included in a single model to jointly estimate time-specific abundance during surveys, total escapement (or entrainment), survey life, and arrival timing parameters (Korman et al. 2007). The integrated approach jointly accounts for the uncertainty in all elements including the abundance estimates and survey life. This modelling framework in conjunction with simulations can be used to quantify the gains in precisions associated with the number of periods when abundance is estimated, changing the timing of when the abundance surveys are conducted, and gains from increasing effort to quantify survey life (more tags or better tag detection efficiency, Korman et al. 2007).

The more modern modelling approach described above would improve estimates of entrainment from the Within-Canal study design pioneered by Post et al. (2006). Application of modern technology that was not available (or too expensive) at the time of the 2003 entrainment study would also be helpful. For example, PIT tags could be used instead of anchor tags, allowing a PIT tag antenna system downstream of the study area to better determine residence time (survey life) in the canal study area and better quantify the number of tags present in the area where abundance is being estimated. Radio or acoustic telemetry could also be used to better define residence time and perhaps link it to environmental conditions like flow in the canal.

The main challenge of the Within-Canal study design is the availability of target sportfish in the canal. Post et al. (2006) used White Suckers for marking as surrogates for Rainbow Trout and Brown Trout because “sufficient numbers of the target species were unavailable”. The extent to which White Suckers represent the catchability and residence time for the sportfish species they are supposed to represent seems highly uncertain, and is perhaps the most significant limitation of the WC approach. A smaller scale study in 1999 tagged 164 fish in the CBRHC and results suggested that suckers evacuated downstream faster than Rainbow Trout and Brown Trout (RL&L 2000). The cost of the WC approach would also likely be higher than the WR approach as it would require a multi-person crew to work at the canal for the entire 6-month entrainment period. Infrastructure costs would likely be similar to the WR approach since both would require a PIT tag antenna system.

5.3 Study Design Summary

Based on a preliminary analysis, a whole-river tagging approach for estimating entrainment and proportional entrainment appears feasible. This would be a significant effort, requiring two boat electrofishing crews to conduct a two-week PIT tagging effort in the Bow River in spring prior to or concurrent with the start of the diversion period. Additionally, a PIT tag antenna system would have to be installed in CBRHC to detect fish that are entrained. Based on the estimates of proportional entrainment in this report, the whole-river approach should provide reasonably precise estimates of proportional entrainment assuming the efficiency of the PIT antenna system in the canal is greater than about 0.1 detections per occurrence (passage of a tagged fish). If the actual proportional entrainment in the year of a future entrainment study is lower than the range estimated in this report, the precision of the proportional entrainment estimate would be lower than estimated here. While an imprecise estimate would not be desirable, it may be sufficient to indicate that proportional entrainment is likely low in the year of study, which could be a useful result for making future management decisions.

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Table 1. Annual number of fish salvaged from standardized fish rescue sites in Carseland Bow River Headworks Canal (CBRHC) and Western Headworks Canal (WHC).

	Carseland Bow River Headworks Canal			**Western Headworks Canal**		
Year	**Rainbow Trout**	**Brown Trout**	**Mountain Whitefish**	**Rainbow Trout**	**Brown Trout**	**Mountain Whitefish**
2000	na	na	na	19	9	1864
2001	412	222	790	40	80	168
2002	355	691	714	38	202	714
2003	51	147	2352	10	141	473
2004	429	292	61	62	95	667
2005	48	415	546	4	93	108
2006	20	158	277	6	54	398
2007	238	345	591	5	16	0
2008	121	376	2780	7	17	31
2009	158	63	1	42	168	151
2010	162	87	66	0	19	120
2011	62	321	2445	79	179	50
2012	89	672	2441	33	205	86
2013	74	238	5330	1	5	1
2014	24	145	1466	8	25	373
2015	33	86	247	4	38	356
2016	296	26	272	17	14	113
2017	419	244	1849	15	98	257
2018	502	71	507	72	103	279
2019	592	277	1280	16	67	280
2020	159	195	1927	4	53	294
2021	358	146	1775	47	86	1357
2022	912	628	2554	1	27	3276
2023	120	217	1791	8	23	208

Table 2. Covariates used to predict the proportion of Bow River sportfish populations entrained into the CBRH and WH canals.

Covariate	**Hypothesis of Flow Covariate on Proportional Entrainment**
BQ_4-10	Mean of daily flows in the Bow River during the period when the canal is operating between April and October
BQ_6-8	Mean of daily flows in the Bow River between June and August
BQ_8-10	Mean of daily flows in the Bow River between August and October when the canal is operating
CQ_4-10	Mean of daily flows in the canal (CBRHC or WHC) when the canal is operating between April and October
CQ_6-8	Mean of daily flows in the canal (CBRHC or WHC) between June and August
CQ _8-10	Mean of daily flows in the canal (CBRHC or WHC) between August and October when the canal is operating
CBQ_4-10	Ratio of the mean of canal to Bow River flows between April and October when the canal is operating
CBQ_6-8	Ratio of the mean of canal to Bow River flows between June and August
CBQ_8-10	Ratio of the mean of canal to Bow River flows between August and October when the canal is operating
DoD_Tot	The total number of days of diversion
DoD_Jun	The number of days of diversion before June
DoD_Sep15	The number of days of diversion after September 15

Table 3. Comparison of covariate models predicting the annual proportion of Bow River Rainbow Trout (a), Brown Trout (b), and Mountain Whitefish (c) populations entrained into the Carseland Bow River Headworks Canal from 2001-2023. Hypotheses on the effects of covariate on proportional entrainment are described in Table 2. Statistics in the table show the mean (β1_mu) and coefficient of variation (β1_cv) of the standardized covariate effect, and the probability that the covariate effect is greater than zero (prob(β1>0). Fit statistics include the magnitude of unexplained interannual variation in proportional entrainment (σ), and the proportion of the interannual variation in the log of observed salvage predicted by the model (r^2). Information statistics include the number of effective parameters (pD), the Deviance Information Criteria (DIC) score, and the difference between each model's DIC score and the lowest DIC among models (ΔDIC relative to the most predictive model). Shaded rows identify the most predictive models that have ΔDICs within ~ 2 units of the lowest DIC model.

a) Rainbow Trout

	Covariate Effect			**Unexplained**	**Fit**			
Covariate	**β1_mu**	**β1_cv**	**prob(β1>0)**	**Variation (σ)**	**(r^2)**	**pD**	**DIC**	**ΔDIC**
Null				0.78	0.99	12.74	22.33	3.34
BQ_4-10	-0.22	1.29	0.20	0.81	0.99	12.76	22.14	3.14
BQ_6-8	-0.17	1.72	0.26	0.83	0.99	12.80	22.10	3.11
BQ_8-10	-0.32	0.83	0.11	0.76	0.98	12.63	22.12	3.12
CQ_4-10	0.75	0.24	1.00	0.22	0.95	9.89	18.99	0.00
CQ_6-8	0.69	0.28	1.00	0.32	0.95	10.77	21.22	2.22
CQ_8-10	0.20	1.37	0.78	0.80	0.99	12.71	21.95	2.95
CBQ_4-10	0.41	0.66	0.94	0.68	0.98	12.47	22.13	3.14
CBQ_6-8	0.30	0.92	0.88	0.76	0.98	12.62	22.09	3.10
CBQ_8-10	0.21	1.32	0.79	0.81	0.99	12.79	22.15	3.15
DoD_Tot	0.24	1.25	0.81	0.81	0.99	12.73	22.03	3.04
DoD_Jun	0.05	5.90	0.58	0.84	0.99	12.76	22.01	3.01
DoD_Sep15	0.12	2.57	0.66	0.83	0.99	12.84	22.20	3.21

Table 3. Con't.

b) **Brown Trout**

Covariate	Covariate Effect β1_mu	β1_cv	prob(β1>0)	Unexplained Variation (σ)	Fit (r^2)	pD	DIC	ΔDIC
Null				1.11	0.98	13.26	22.43	0.32
BQ_4-10	0.43	0.81	0.90	1.08	0.98	13.18	22.16	0.05
BQ_6-8	0.55	0.62	0.95	1.01	0.98	13.10	22.14	0.03
BQ_8-10	0.41	0.84	0.89	1.07	0.98	13.18	22.18	0.07
CQ_4-10	-0.62	0.51	0.02	0.95	0.97	13.05	22.21	0.10
CQ_6-8	-0.71	0.42	0.01	0.87	0.96	12.89	22.12	0.01
CQ_8-10	-0.59	0.51	0.03	0.94	0.96	12.99	22.12	0.01
CBQ_4-10	-0.49	0.69	0.06	1.04	0.98	13.23	22.30	0.19
CBQ_6-8	-0.59	0.58	0.03	0.98	0.97	13.04	22.11	0.00
CBQ_8-10	-0.57	0.55	0.04	0.97	0.97	13.03	22.13	0.02
DoD_Tot	0.16	2.50	0.67	1.17	0.99	13.29	22.22	0.11
DoD_Jun	0.31	1.14	0.82	1.12	0.98	13.24	22.19	0.08
DoD_Sep15	0.00	370.00	0.50	1.18	0.99	13.27	22.16	0.05

Table 3. Con’t.

c) Mountain Whitefish

	Covariate Effect							
Covariate	**β1_mu**	**β1_cv**	**prob(β1>0)**	**Unexplained Variation (σ)**	**Fit (r^2)**	**pD**	**DIC**	**ΔDIC**
Null				1.58	0.97	12.40	21.07	0.47
BQ_4-10	0.44	1.47	0.77	1.72	0.98	12.30	20.77	0.17
BQ_6-8	0.54	1.18	0.83	1.70	0.98	12.18	20.59	0.00
BQ_8-10	0.16	3.62	0.63	1.74	0.98	12.32	20.95	0.35
CQ_4-10	-0.09	6.29	0.42	1.75	0.98	12.35	21.01	0.41
CQ_6-8	-0.23	2.48	0.34	1.73	0.98	12.36	21.08	0.49
CQ_8-10	0.36	1.51	0.76	1.69	0.98	12.14	20.65	0.05
CBQ_4-10	0.06	10.36	0.53	1.74	0.98	12.31	20.98	0.39
CBQ_6-8	-0.07	8.59	0.45	1.73	0.98	12.40	21.09	0.50
CBQ_8-10	0.12	4.62	0.59	1.73	0.98	12.29	20.96	0.37
DoD_Tot	0.16	3.39	0.63	1.71	0.98	12.32	21.04	0.45
DoD_Jun	-0.18	3.19	0.38	1.75	0.98	12.37	20.88	0.28
DoD_Sep15	0.37	1.52	0.77	1.67	0.97	12.20	21.09	0.49

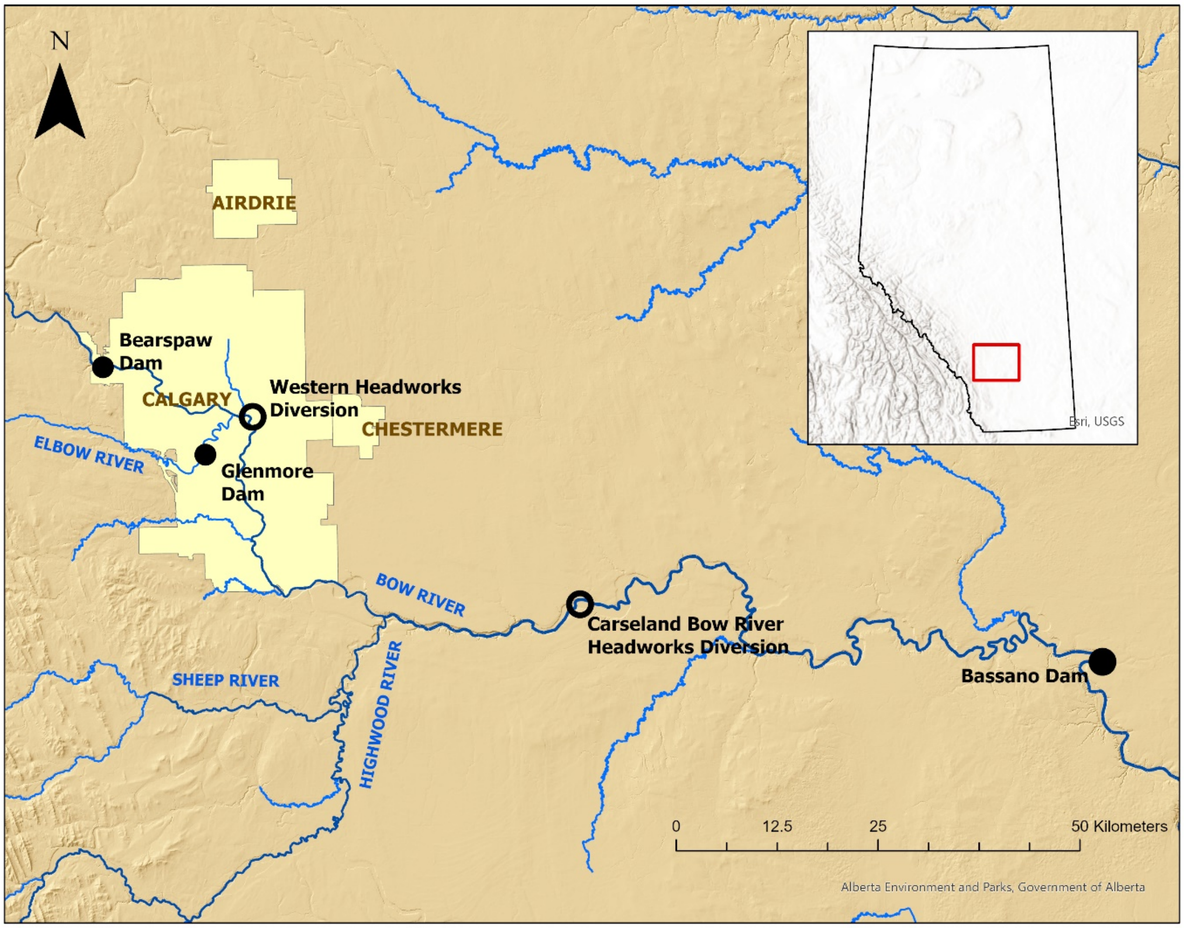


Figure 1. Map of the Bow River study area between Bearspaw and Bassano Dams, showing the location of headworks for the Western Irrigation District and Carseland Bow River Headworks canals.

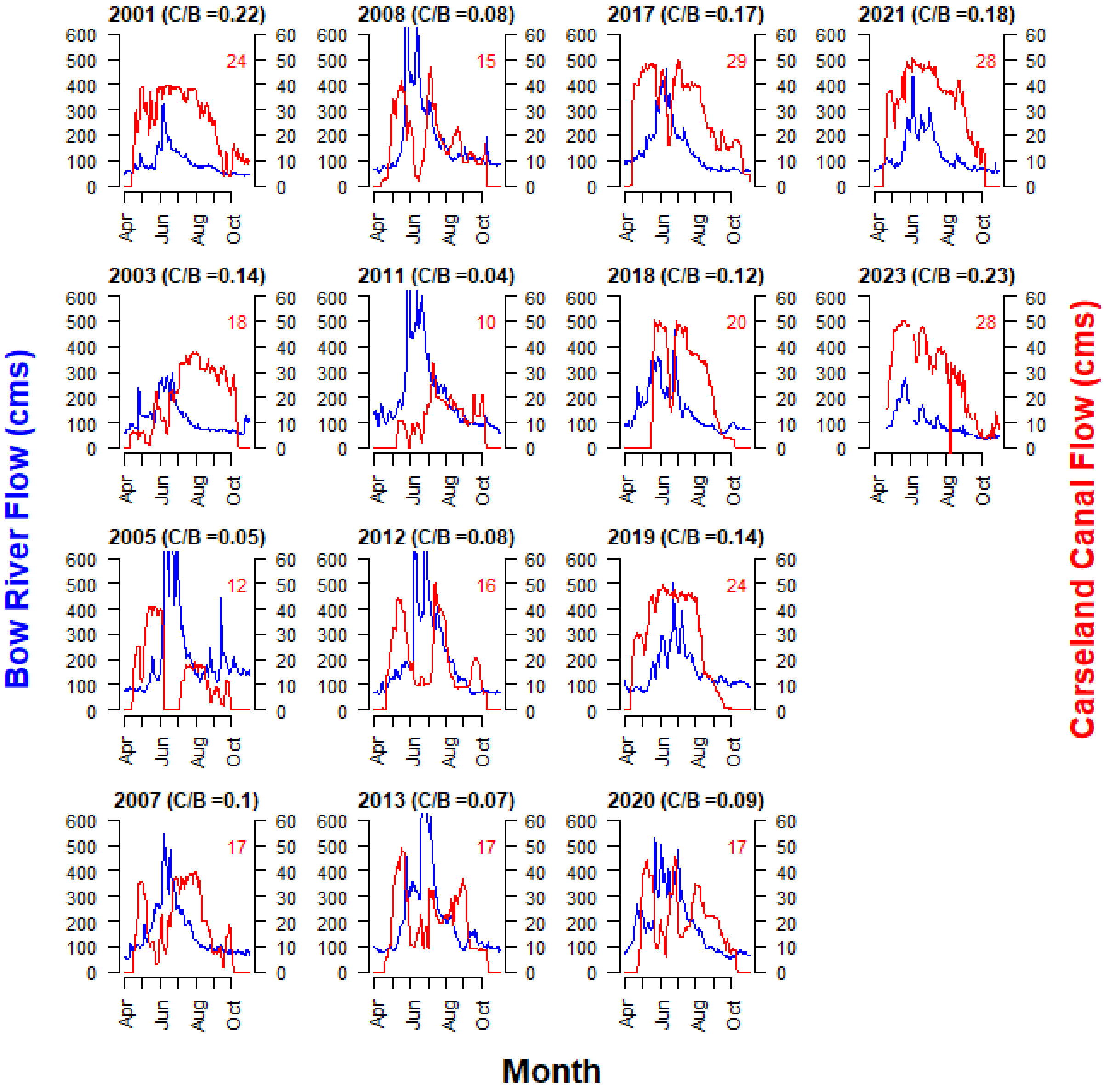


Figure 2. Mean daily flow in the Bow River immediately upstream of the Carseland Weir (05BM002 + 05BM021) and at the headgates of the Carseland-Bow River Headgates Canal (CBRHC, 05BM021) for years with canal fish salvage and Bow River population estimates. The proportion of the total Bow River flow diverted during the period of canal operation (~ April – October) is shown in parentheses (C/B). The red text in the upper-right corner of each panel shows the average CBRHC flow over the diversion period.

a) Rainbow Trout

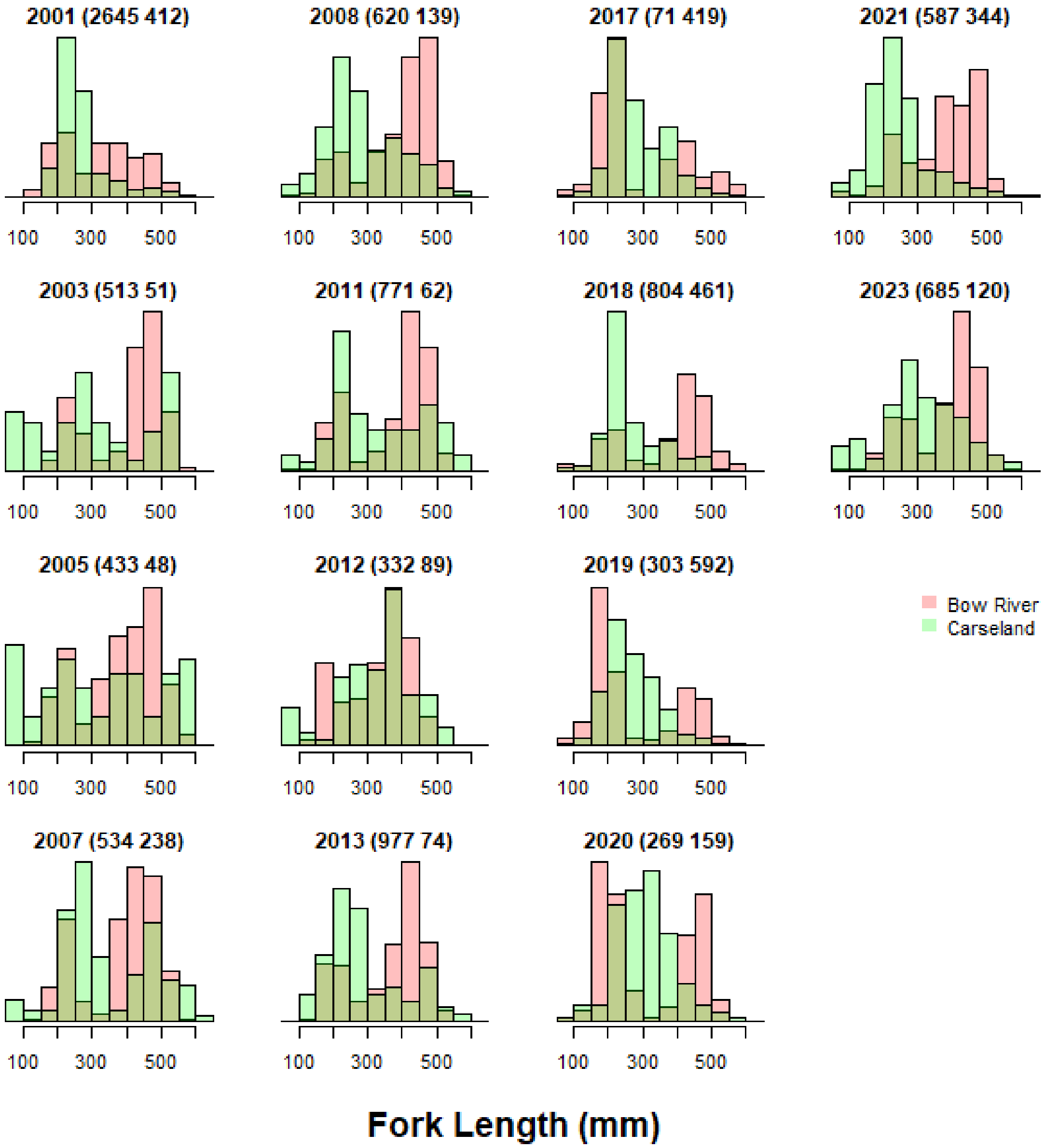


Figure 3. Comparison of length frequency distributions for Rainbow Trout (a), Brown Trout (b), and Mountain Whitefish (c) captured in the Bow River during population monitoring and from salvage in the Carseland-Bow River Headgates Canal in years with both fish salvage and Bow River population sampling. Numbers in parentheses are the sample sizes of fish measured from the Bow River (left) and the CBRHC (right). The length frequencies for Mountain Whitefish in CBRHC are adjusted to account for fish < 200 mm that are not measured (the sample size in parentheses reflects the number of fish measured and not the total salvage).

b) Brown Trout

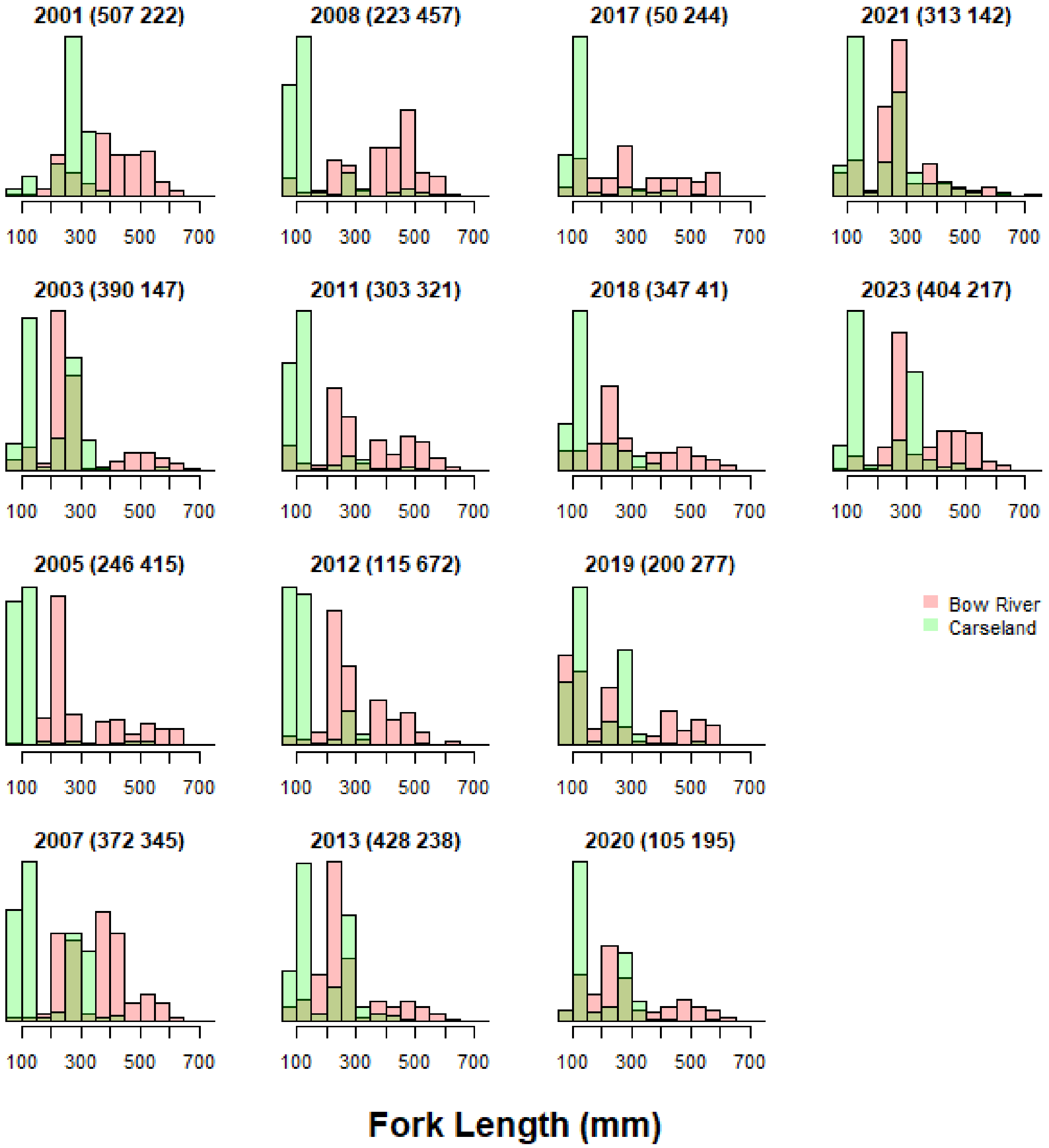


Figure 3. Con't.

c) Mountain Whitefish

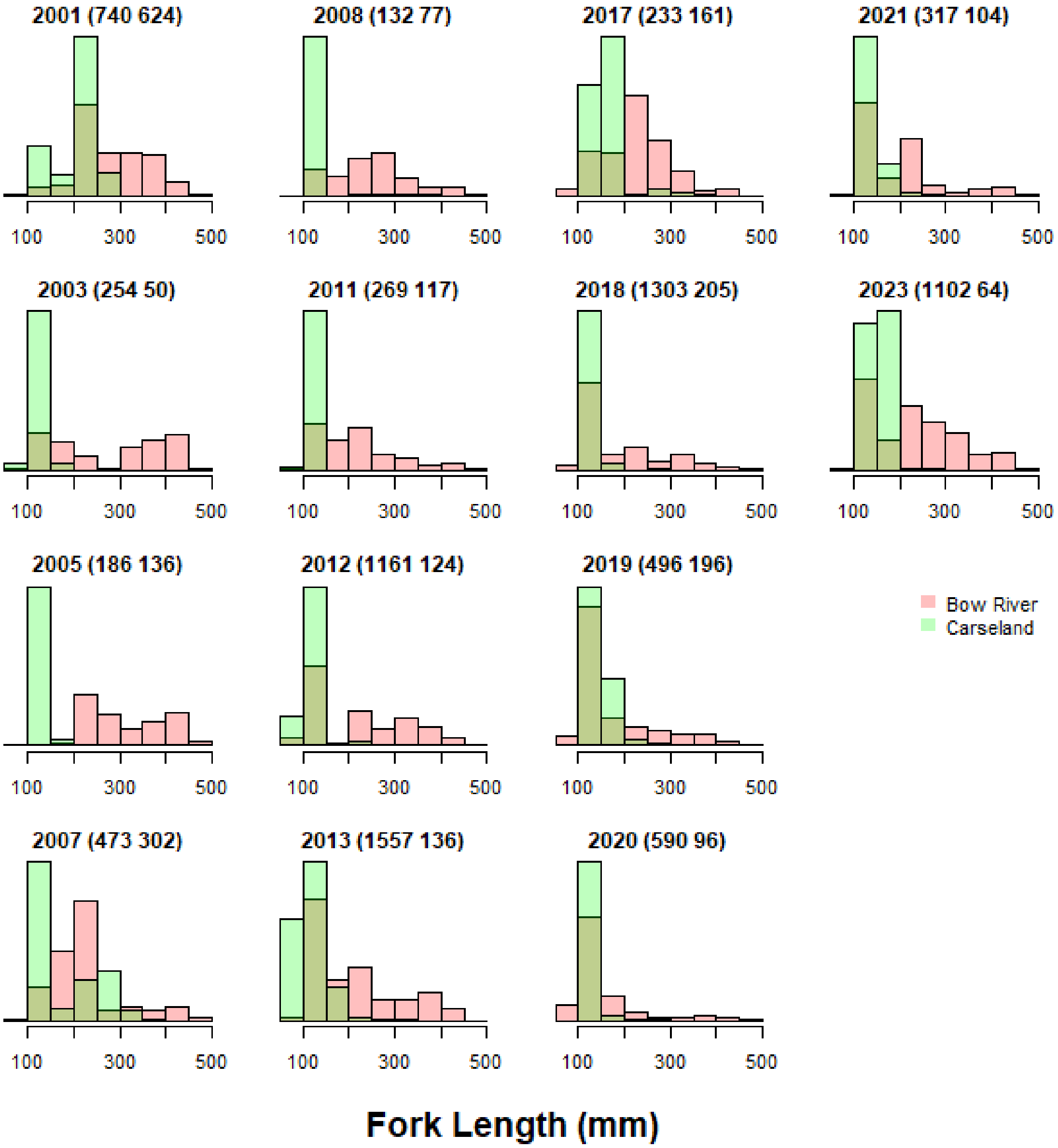


Figure 3. Con’t.

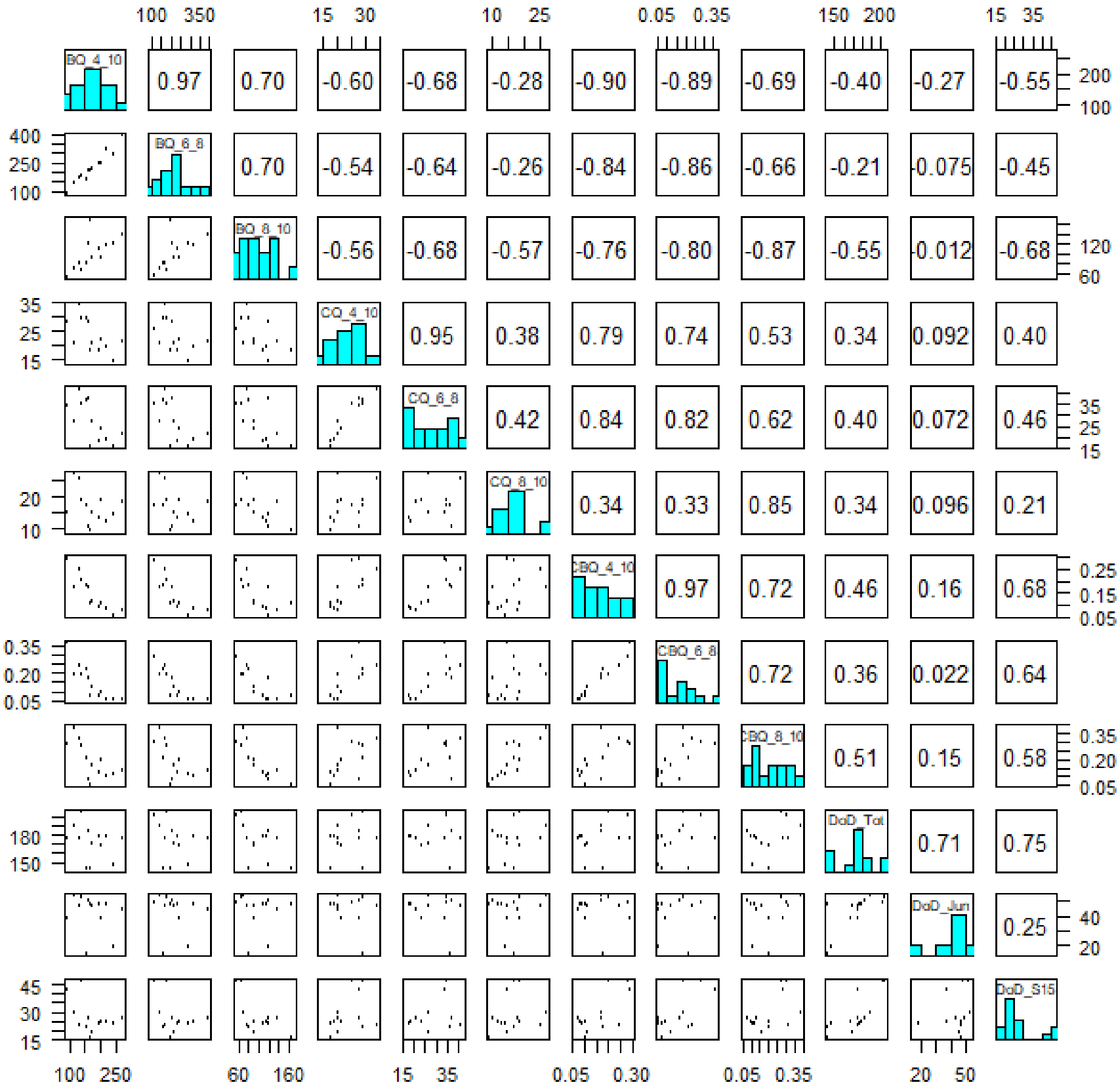


Figure 4. Pairs plot showing the relationship between 12 covariates used to predict interannual variation in the proportion of Bow River fish populations entrained into the CBRHC. The histograms on the diagonal show the distribution of annual covariate values (see Table 2 for a description of covariates). The panels below the diagonal show the relationship among annual covariate values. The panels above the diagonal show the Pearson correlation (r) between each of the 12 covariate types.

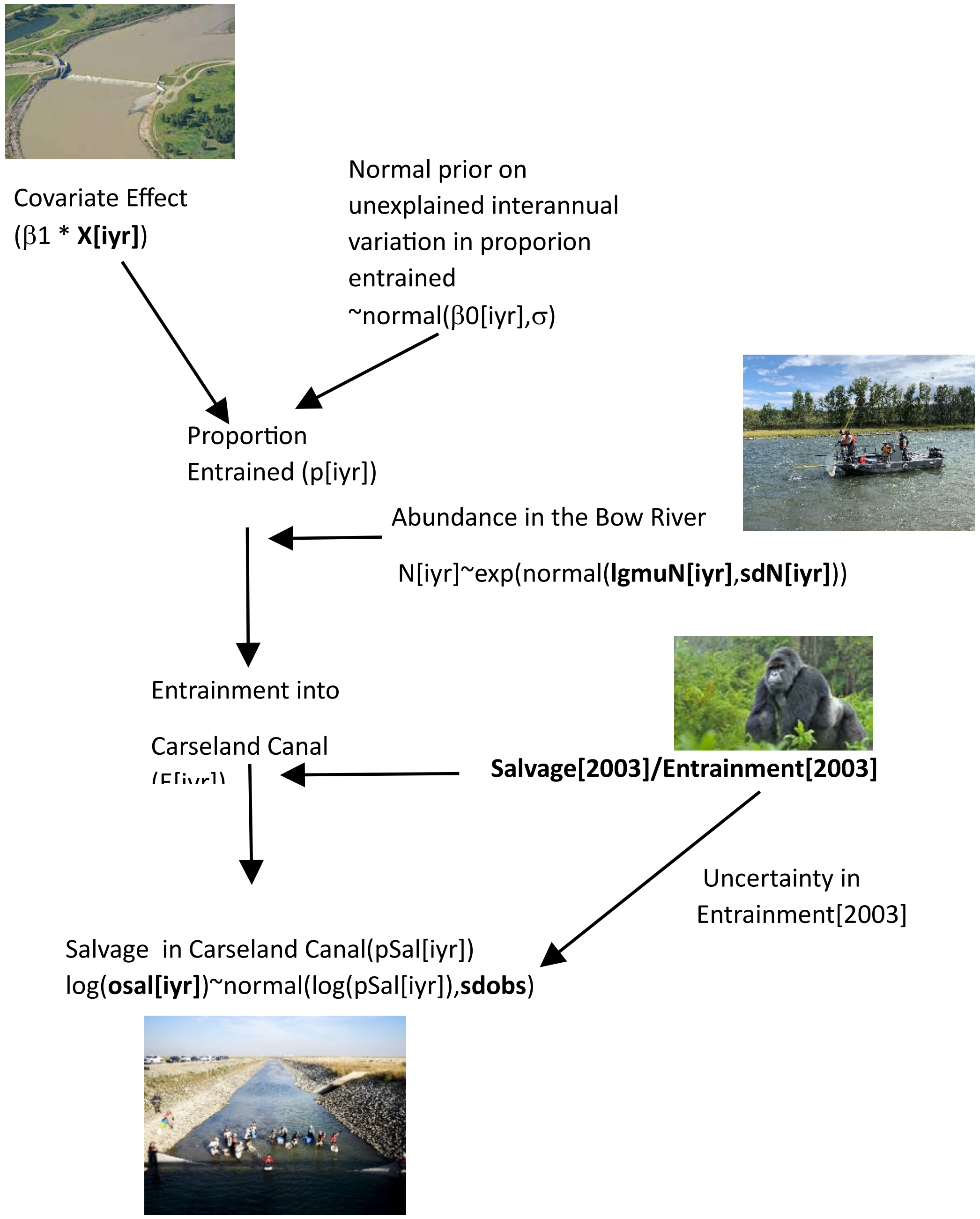


Figure 5. Schematic representation of the model used to predict salvage in the CBRH and WH canals based on annual estimates of proportional entrainment and abundance in the Bow River. See text for details of model equations. Bolded text denotes variables that are data or treated as data.

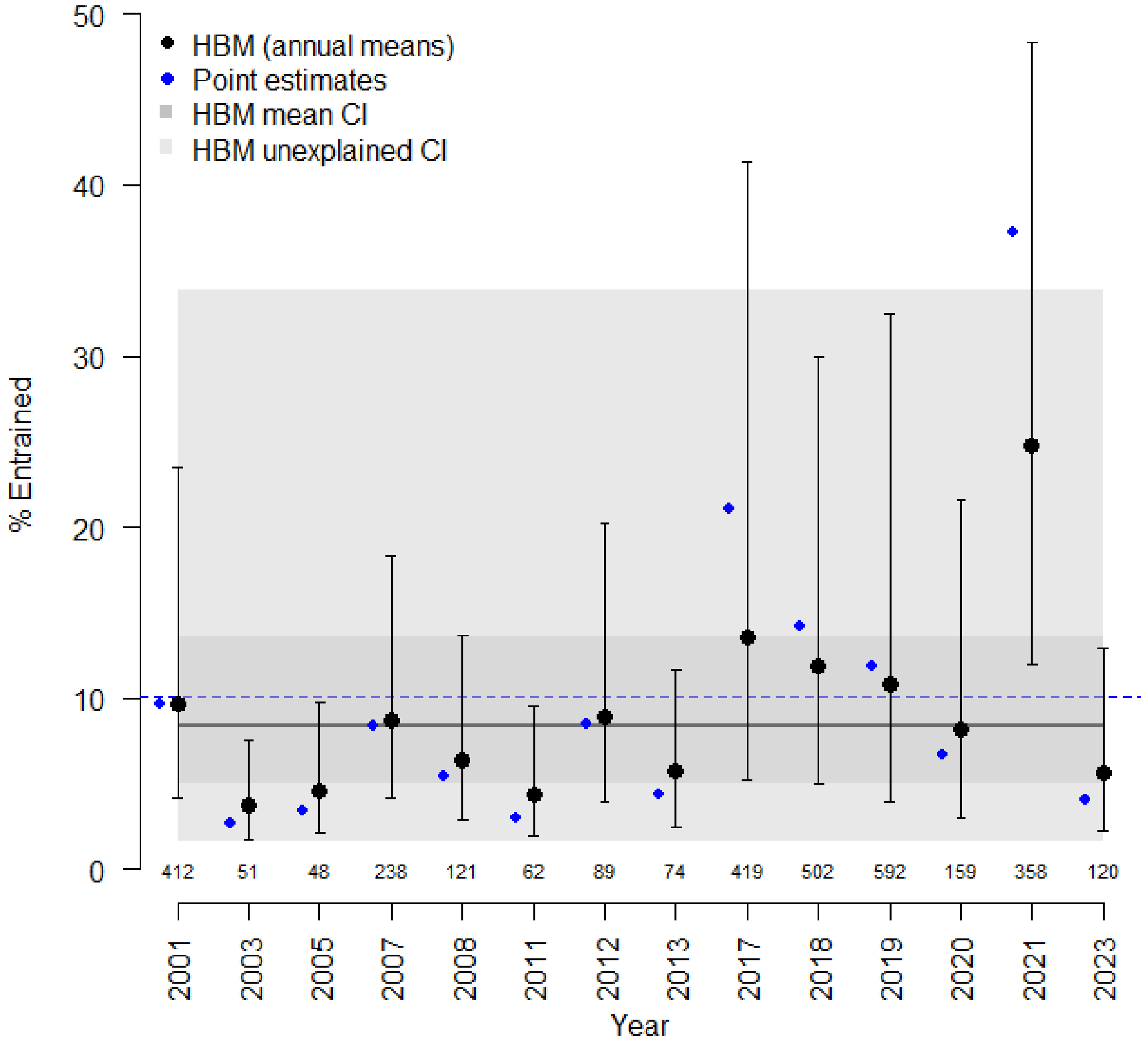


Figure 6. Predictions of the proportion of the Bow River Rainbow Trout population entrained in the CBRH canal. The blue points show the point estimates. The black points show the median and credible intervals from the hierarchical Bayesian null model (no covariate effects). The text at the bottom of the plot shows the annual salvage values. The horizontals lines show the estimated across-year mean of the entrainment proportion from the hyper-distribution of the Bayesian model (black) and the mean of the point estimates (dashed blue line). The dark grey area shows the 95% credible interval of the mean proportion of the population entrained over all years. The lighter gray area includes uncertainty in the mean but also the extent of unexplained interannual variation in the proportion entrained (process error, σ).

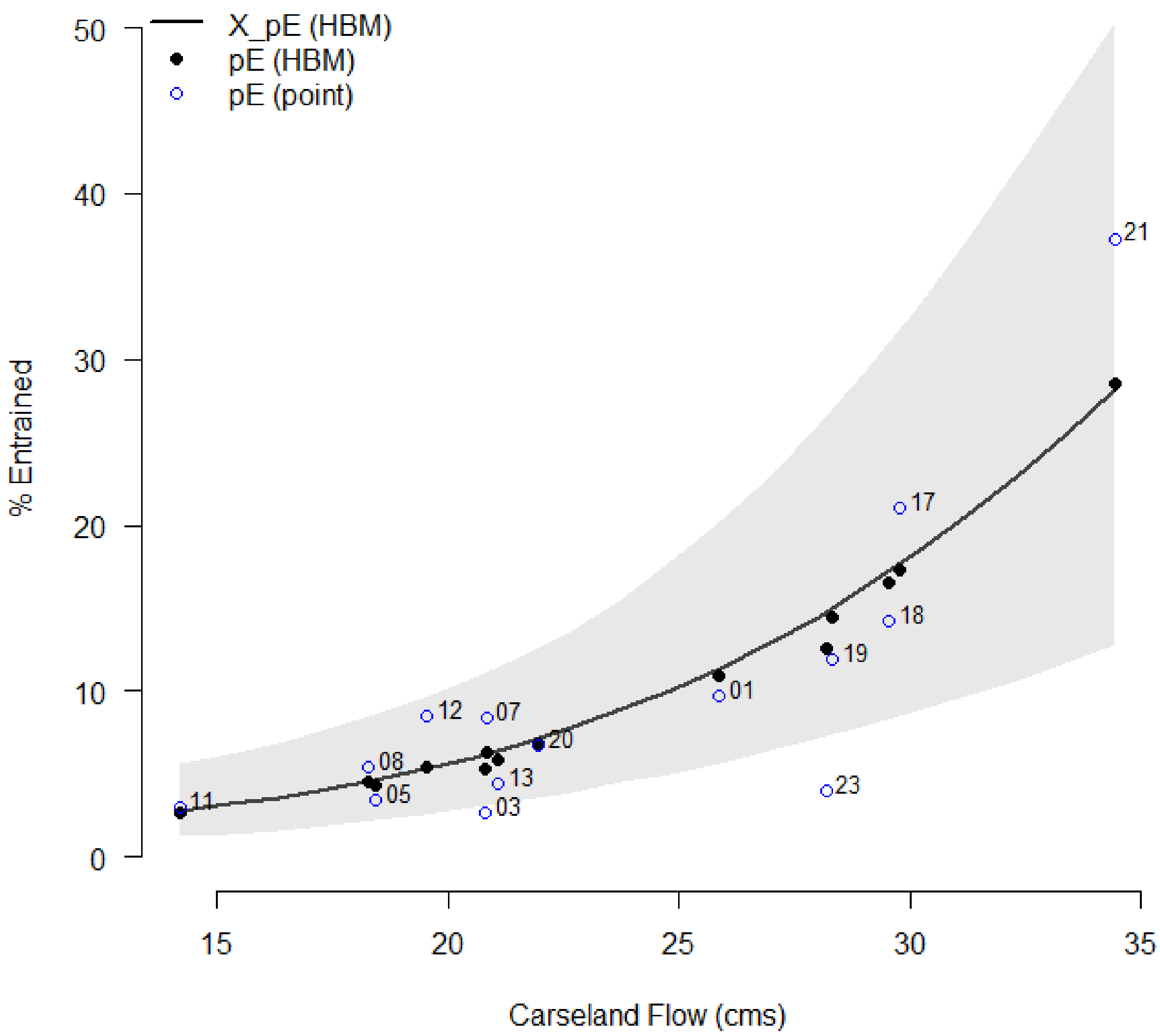


Figure 7. Estimated relationship between average flow in the CBRHC between April and October and the proportion of the Bow River Rainbow Trout population that is entrained. The solid line and grey shaded area show the mean and 95% credible intervals of the relationship estimated from the Bayesian model. The blue points are the point estimates of annual entrainment, and the black points are the mean annual estimates from the HBM. Note how they are shrunken towards the flow-dependent mean (black line) relative to the independently derived point estimates. The text beside each point estimates denotes the year.

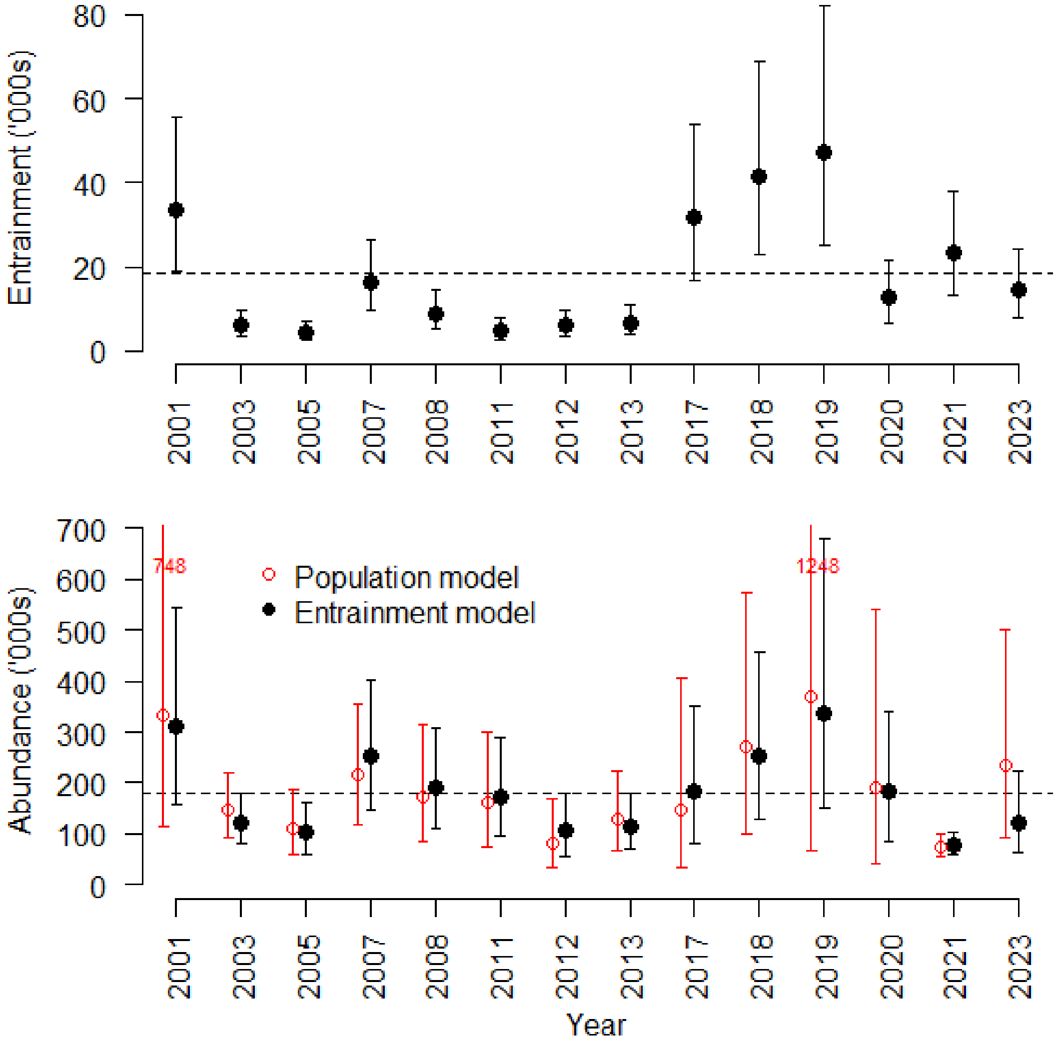


Figure 8. Annual estimates of Rainbow Trout entrainment into CBRHC predicted from the average flow in the canal from April-October (top) and abundance in the Bow River (bottom). Points and error bars show the means and 95% credible intervals. The abundance estimates from the closed population model (red) are compared to the abundance estimates from the entrainment model (black). Red text in the lower panel shows the upper credible interval for years when it extends beyond the y-axis maximum.

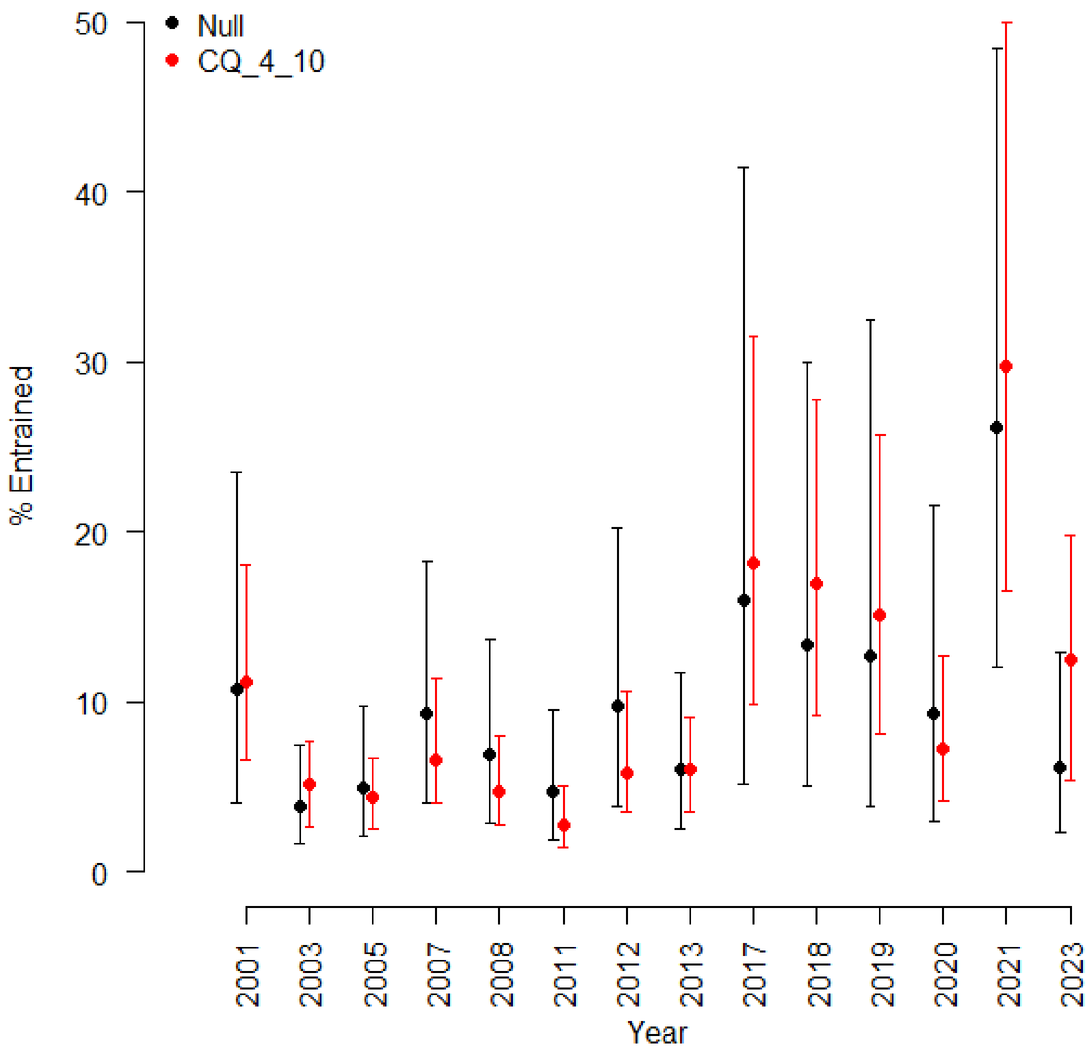


Figure 9. Estimates of the proportion of the Bow River Rainbow Trout population entrained into CBRHC based on two different models. The null model does not include a covariate effect to predict the proportion entrained. CQ_4_10 predicts entrainment as a function of the average flow in the canal between April and October. Points and error bars show the means and 95% credible intervals.

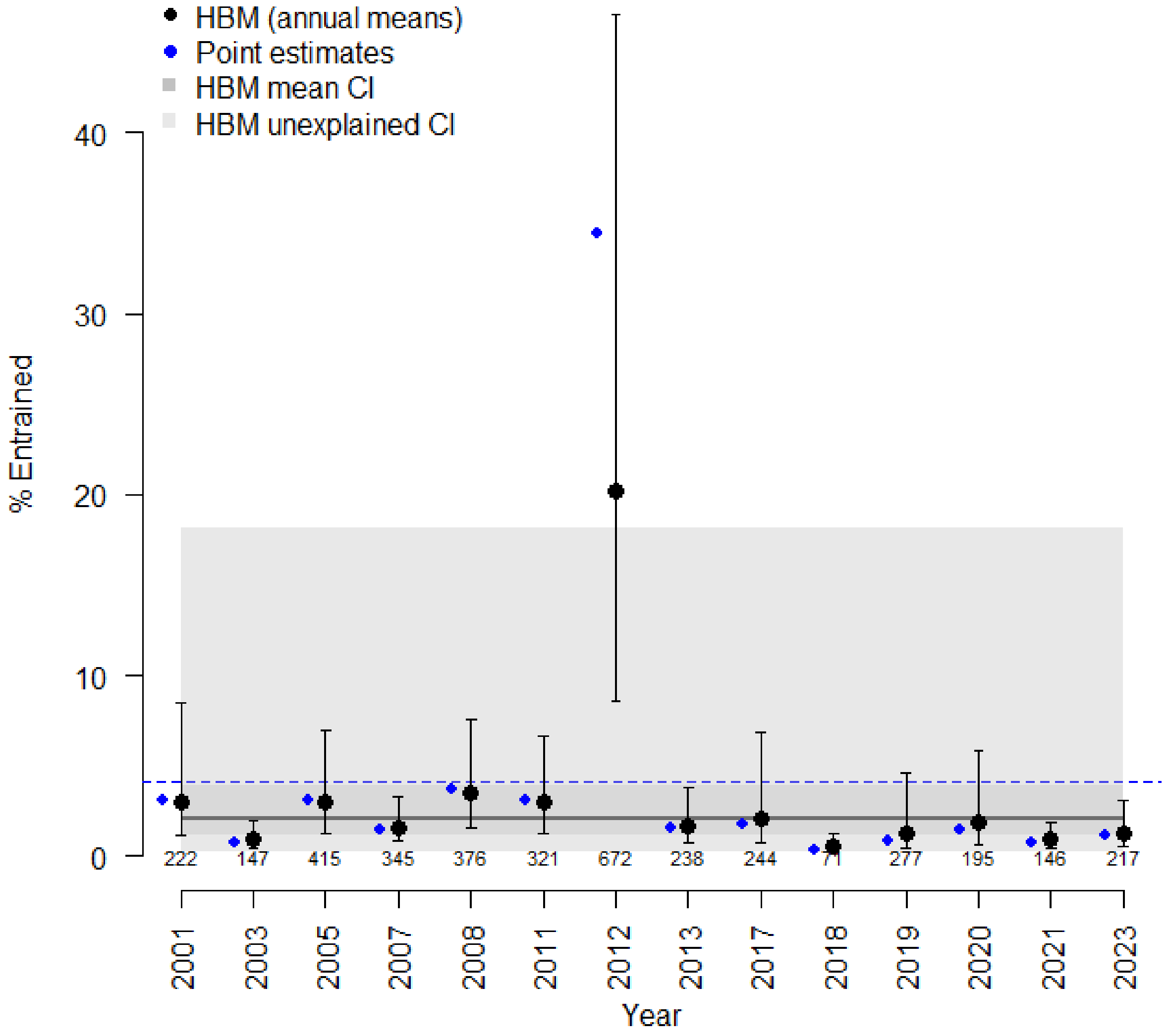


Figure 10. Predictions of the proportion of the Bow River Brown Trout population entrained in the CBRH canal. The blue points show the point estimates. See caption for Figure 6 for additional details.

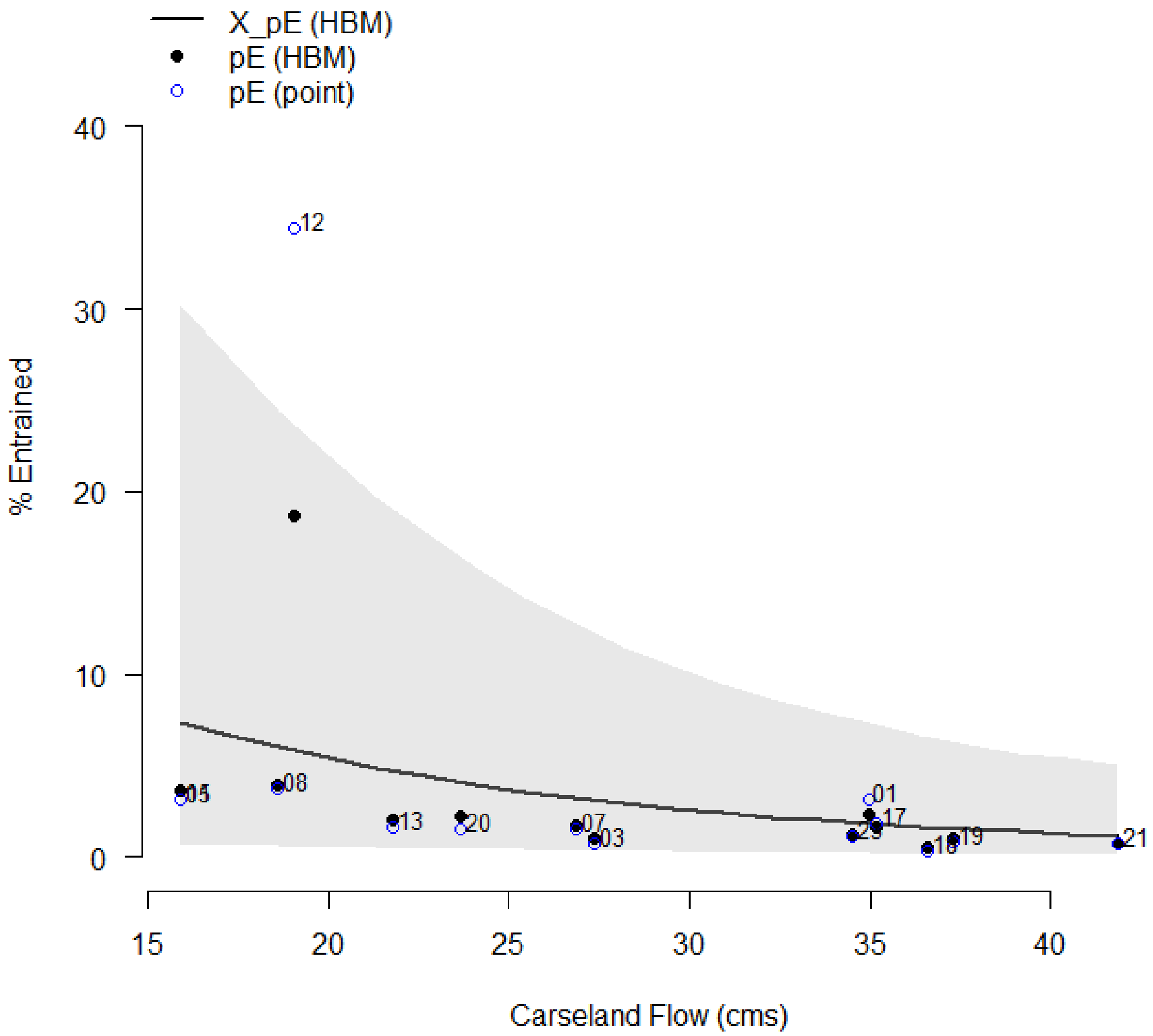


Figure 11. Estimated relationship between average flow in the CBRH canal between June and August and the proportion of the Bow River Brown Trout population that is entrained. The solid line and grey shaded area show the mean and 95% credible intervals of the relationship estimated from the Bayesian model. The blue points are the point estimates of annual entrainment, and the black points are the mean estimates from the HBM.

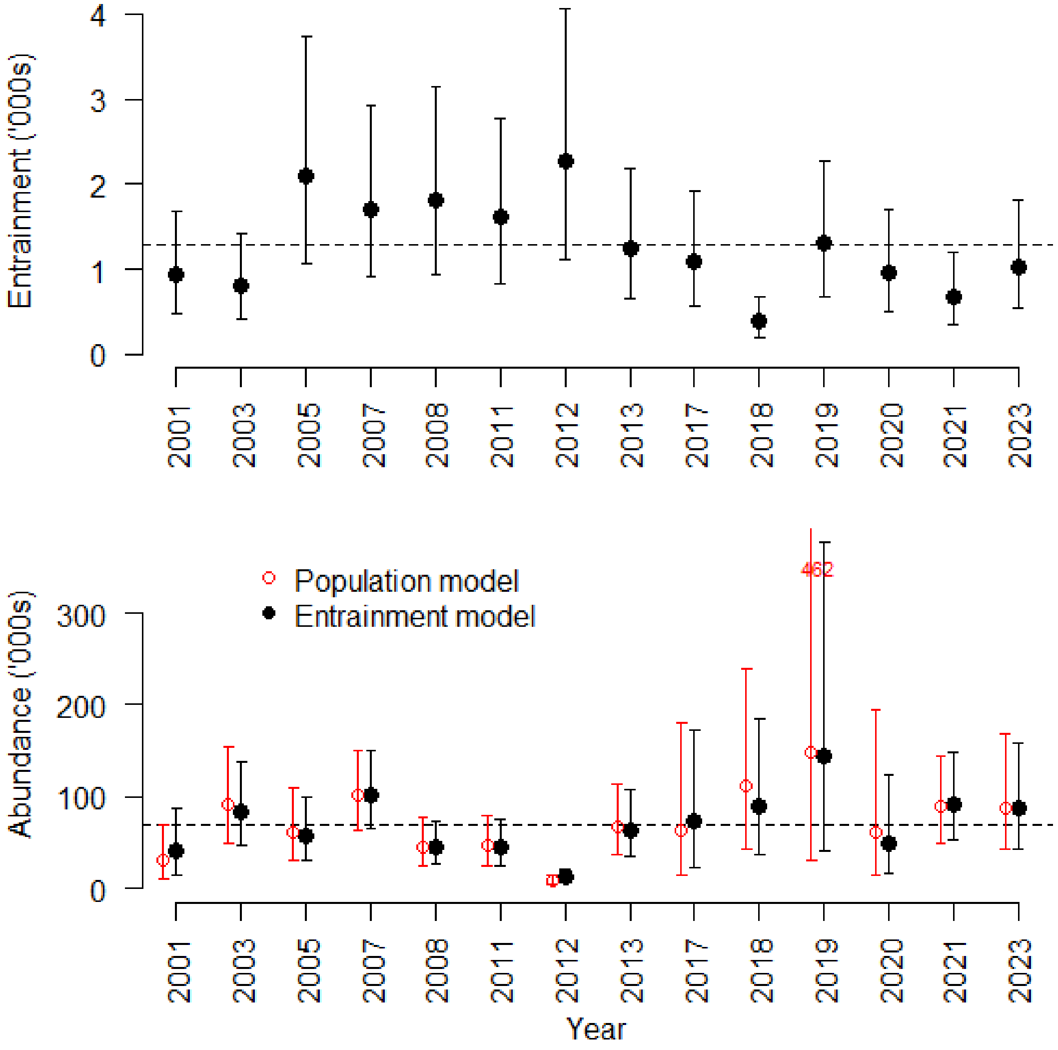


Figure 12. Annual estimates of Brown Trout entrainment into CBRHC based on the null model (top) and abundance in the Bow River (bottom). Points and error bars show the means and 95% credible intervals. Statistics for the abundance estimates from the closed population model (red) are compared to statistics for the estimate abundance in the entrainment model (black). Red text in the lower panel shows the upper credible interval for years when it extends beyond the y-axis maximum.

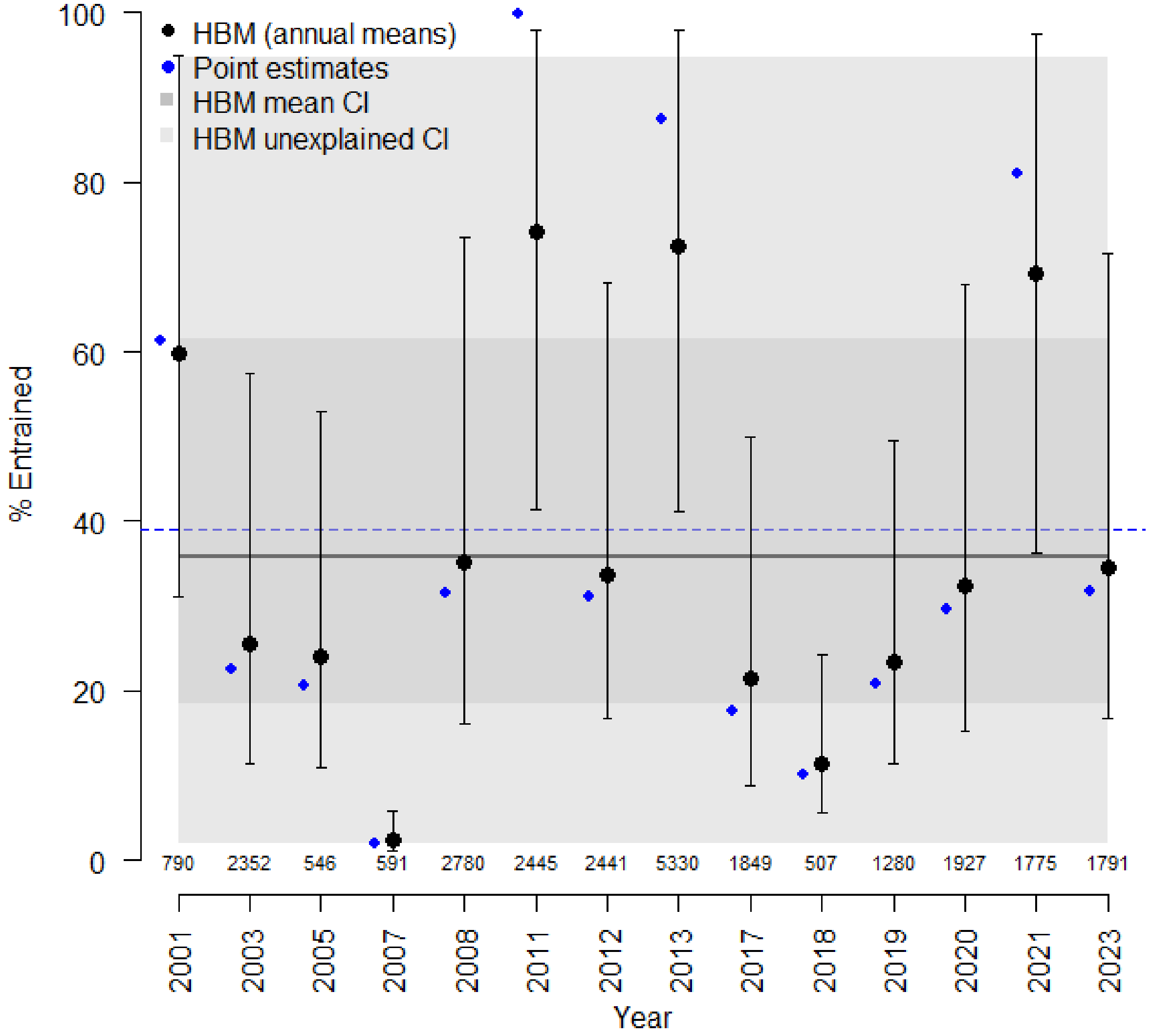


Figure 13. Predictions of the proportion of the Bow River Mountain Whitefish population entrained in the CBRH canal. The blue points show the point estimates. See caption for Figures 6 for additional details.

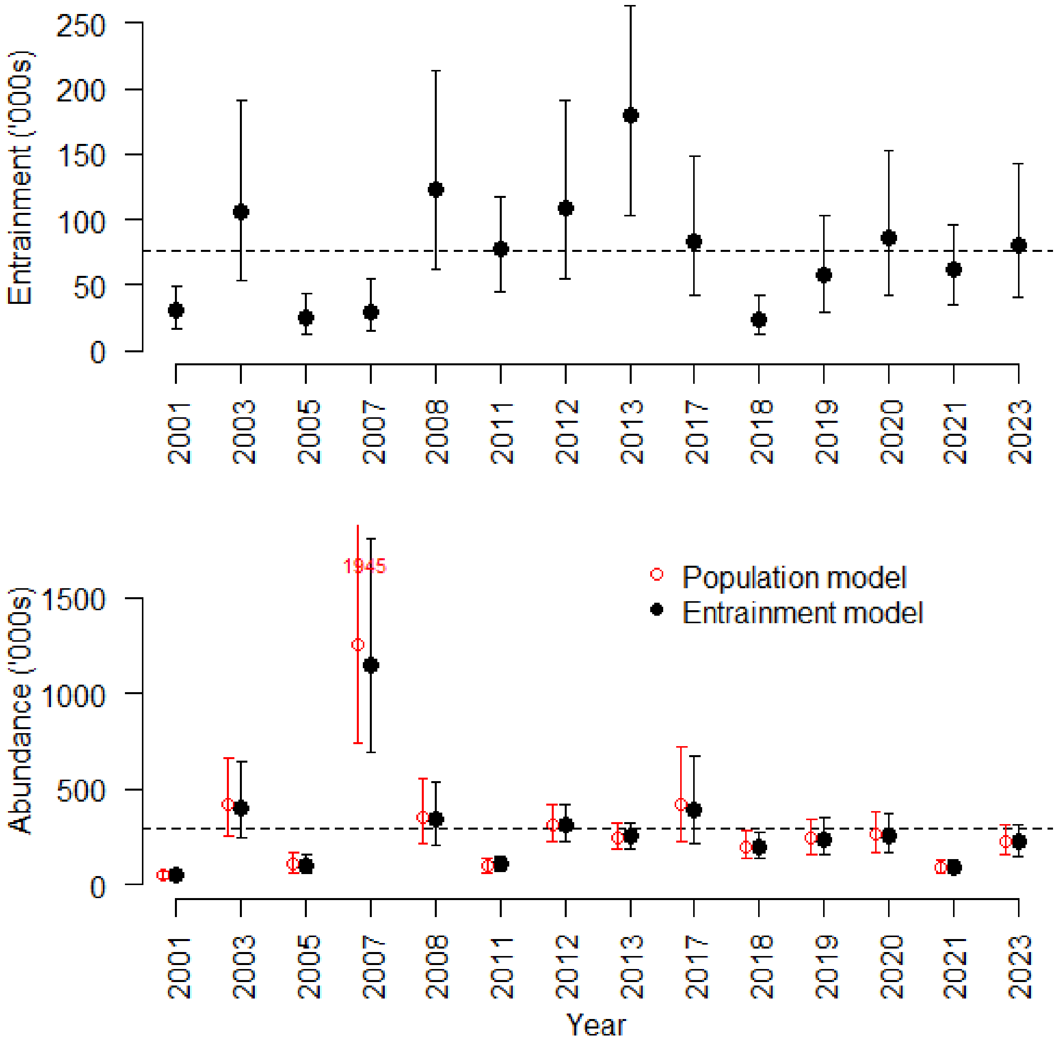


Figure 14. Annual estimates of Mountain Whitefish entrainment into CBRHC based on the null model (top) and abundance in the Bow River (bottom). Points and error bars show the means and 95% credible intervals. Statistics for the abundance estimates from the closed population model (red) are compared to statistics for the estimates abundance in the entrainment model (black). Red text in the lower panel shows the upper credible interval for years when it extends beyond the y-axis maximum.

a) 100% survival from tagging to entrainment

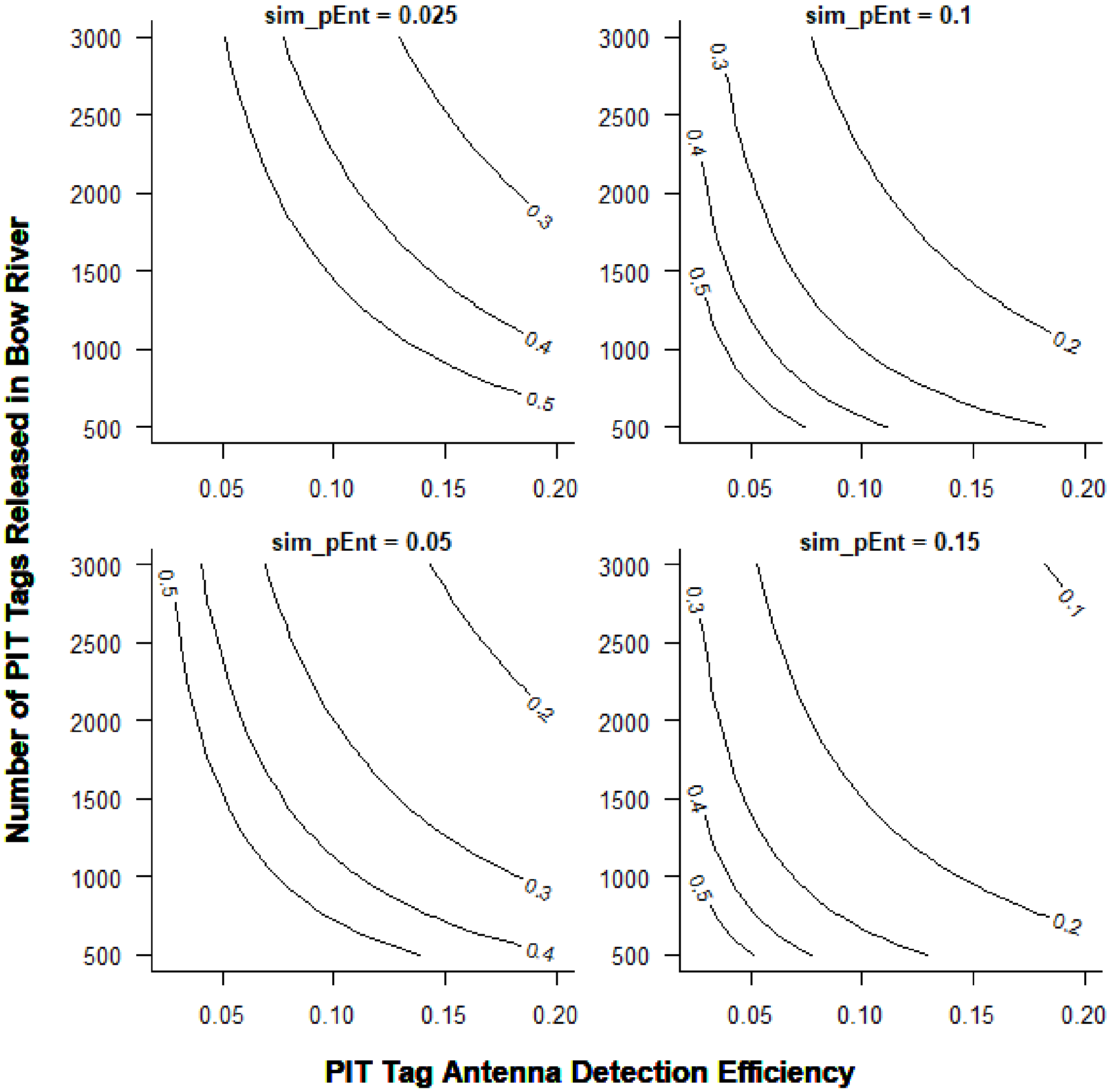


Figure 15. Coefficient of variation (CV; contours) of estimates of the proportion of a population entrained in a canal as a function of the number of fish PIT-tagged in the Bow River and the overall detection efficiency of a PIT tag antenna system in the canal. Panels represent the range of simulated potential proportional entrainments (sim_pEnt) based on estimates for Rainbow Trout for CBRHC from the historical data. Results are shown for simulations where 100% of tagged fish are assumed to survive prior to entrainment (a), and where 90% are assumed to survive (b).

b) 90% survival from tagging to entrainment

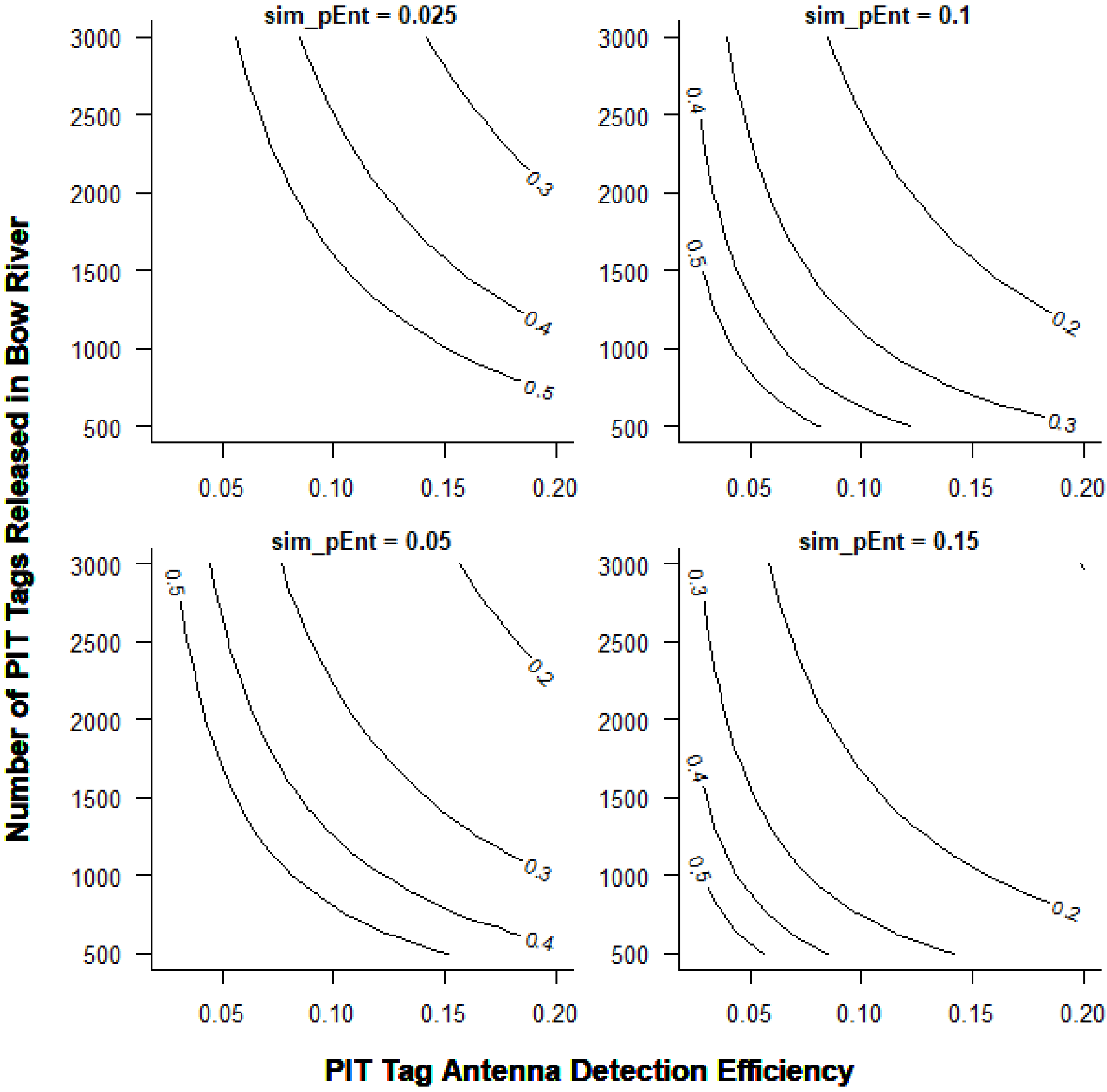


Figure 15. Con’t.

Appendix A: Supporting Information

This appendix is a repository of results that are less certain than those presented in the main body of the text, and also includes details for some analyses presented in the main body of the text. Section A1 describes the details of the Bow River Mountain Whitefish population model. This model required more restrictive assumptions compared to those for Rainbow Trout and Brown Trout due to much lower and variable capture probabilities. This required changes to the model relative to the one presented in Korman (2023) for Rainbow and Brown Trout. Estimates of the proportions of the Bow River Mountain Whitefish population that are entrained are more uncertain due to possible bias in abundance estimates in the Bow River owing to the more restricted abundance model.

Section A2 includes entrainment predictions for the Western Irrigation District Canal (WHC), which are more uncertain than for the Carseland Bow River Headworks Canal (CBRHC) because of the assumption that entrainment-to-salvage ratio in the WHC is the same as estimated for CBRHC in 2003. This assumption represents a doubling-down on the gorilla assumption used to calculate CBRHC entrainment (the salvage-to-entrainment ratio in 2003 applies to all other years).

Section A3 describes the methodology used to estimate the number of sportfish that could be tagged in the Bow River during a two-week sampling session to support a direct estimate of proportional entrainment in CBRHC.

Section A4 describes the modelling input data and output data and the program workflow.

A1. Details of the Bow River Mountain Whitefish Population Model

Very few Mountain Whitefish marked in the Bow River have been recaptured. Across all years when Mountain Whitefish were marked (note no Mountain Whitefish were marked in 2001, 2007, and 2008 when Rainbow Trout and Brown Trout were marked), only 86 of 3,555 marked fish were recaptured (Table A1.1). The average % of marked fish recaptured was 2.4% and 2.5% for fish <=300 mm and > 300 mm, respectively. Differences in recapture rates across these two size classes was variable across years, likely due to the high sampling error driven by low capture probability which results in very few recaptures within a year. Capture probability appeared elevated in 2005 and 2012, but sample size was generally very low within years, making it difficult to determine the extent of interannual variation in capture probability.

The population model structure used successfully for Rainbow and Brown Trout populations in the Bow River (Korman 2023) failed to converge for Mountain Whitefish, even when the model was simplified by estimating capture probability for only two size classes (compared to six for Rainbow Trout and Brown Trout). Here I first describe the standard model used for Rainbow Trout and Brown Trout populations and then identify the changes made to the Mountain Whitefish model.

Capture probability (P) is defined as the proportion of fish at a sampling site that are captured by one pass of sampling effort. The logit of capture probability for each year (y), site (s), pass (p), and size class (l) is predicted using a linear mixed effects model,

A.1.1) $$logit(P_{y,s,p,l}) = \beta_l + \beta_p + \beta_s + \beta_y + \varepsilon_{y,s,p,l}$$

where β_l is a fixed effect predicting the capture probability (in logit space) for each size class 'l' on the first pass (p=1), β_p is a fixed effect predicting differences in capture probability on passes 2-5 relative to pass one (thus $\beta_{p=1}$=0). β_y and β_s are random effects predicting differences in capture probability across sites and years, respectively. $\varepsilon_{y,s,p,l}$ is a process error deviate drawn from a zero-centered normal distribution with a standard deviation σ_p ($\varepsilon_{y,s,p,l}$~norm(0, σ_p)). Process error deviates account for unmodelled variation due to limitations in model structure. For example, the fixed effect β_p assumes that the pass effect on capture probability is consistent across all years, sites, and size classes. Similarly, the fixed effect of fish size (β_l) is assumed to be constant across years, sites, and passes. $\varepsilon_{y,s,p,l}$ deviates allow the model to more closely fit the data given such structural limitations.

Owing to the limited number of recaptures for Mountain Whitefish we simplified the capture probability model to,

A.1.2) $$logit(P_{y,s,p,l}) = \beta + \varepsilon_{y,s,p,l}.$$

A single mean capture probability (β) is estimated along with errors that are unique to each year, site, pass, and fish size class ($\varepsilon_{y,s,p,l}$). Note we do not explicitly estimate effects of fish size, pass, site, or year. Variability due to these effects are accounted for in the error term (Figure A1.1). We explored models of intermediate complexity such as inclusion of a year effect, but the recapture data were too sparse to reliably estimate them.

We estimated abundance for three size classes of Mountain Whitefish (≤150 mm, 151-300 mm, and > 300 mm). These size classes were chosen to allow comparison of the Bow River Mountain Whitefish abundance estimate in Post et al. (2006) for fish > 150 mm. As capture probability does not vary among size classes in our restricted Mountain Whitefish model there is no cost to precision by splitting abundance estimates into multiple size classes. However, this comes at the cost of potentially high bias in abundance estimates if there is substantive variation in capture probability across size classes as observed for both Rainbow Trout and Brown Trout.

A much higher proportion of marked Mountain Whitefish were recaptured in sites other than the ones they were marked in (within the sampling year) compared to Rainbow Trout and Brown Trout (Figure A1.2). The average across years for Mountain Whitefish was close to 40%, considerably higher than the averages for Rainbow Trout and Brown Trout of 15% and 18%, respectively. The model does account for mark loss due to this out-of-site movement. Mountain Whitefish <=300 mm dominated the population estimate, and the total across all three size classes averaged ~ 1800 fish/km (Figure A1.3). Annual estimates of abundance appear relatively precise, but this is largely due to the highly constrained capture probability model. Post et al. (2006) estimated that Mountain Whitefish >=150 mm in 2001 was 301,173 (95% confidence interval of 291,600 – 313,000). Our model estimate, scaled from fish/km to the total population over 169 km (as in Post et al 2006) was 52,000 (95% credible interval of 38,000 – 70,000). This large difference highlights the considerable uncertainty in Mountain Whitefish population estimates due to sparse recapture data.

A2. Western Irrigation District Canal Results

Salvage in the Western Irrigation District canal largely consists of smaller Rainbow Trout relative to those present in the Bow River and those entrained into the Carseland Canal (Figure A2.2). The size distribution of Brown Trout and Mountain Whitefish in both Western and Carseland Canals is dominated by smaller fish.

Bow River flow diversion rates into the WHC were lower those for CBRHC and were often less than 10% (Figure A2.1 vs Fig 2). This result is not surprising as WHC diverts considerably less flow than CBRHC and a lower proportion of Bow River Flows. Between 2001 and 2023 in years when both salvage and Bow River population estimates were available, average flows in CBRHC and WHC over the irrigation season were 19.6 and 7.9 m^3/s, respectively. The average proportion of Bow River flows diverted into CBRHC and WHC at the point of diversion was 0.12 and 0.05, respectively.

As for the CBHRC, some flow covariates used to predict proportional entrainment in WHC were correlated (Figure A2.3) because they shared some of the daily time series of flows (e.g., April-October vs. June-August), or because they were an element of another covariate (e.g., WHC flows are part of the WHC/Bow covariate calculation).

Flow covariates were not useful predictors of proportional entrainment for Rainbow Trout and Brown Trout in the WHC (Table A2.1). Note the uncertainty in covariate effects was very high (CV's of >0.8 and often much higher) and thus there was no substantive reduction in unexplained variation. We therefore used the null model to estimate entrainment and the proportion of the populations entrained (Figure A2.4). Inclusion of covariates in predicting proportional entrainment substantively lowered the unexplained variation for Mountain Whitefish. The models sensibly predicted declines in proportional entrainment with higher flows in the Bow River, and increases in proportional entrainment with higher flows in the WHC. As for Rainbow Trout in CBRHC, average flows in the WHC canal during the diversion period (April-October) and between June and August were the most predictive models. However, inspection of these models revealed large uncertainty in the prediction of proportional entrainment as a function of flow (Figure A2.5). The positive slope was caused by two years with very high proportional entrainment (2000 and 2021) which were shrunken considerably towards the mean predicted by flow. The effect of flow was not seen in the majority of years based on the point estimates. We consider the flow based-models unreliable and use the null model for prediction of annual proportional entrainment loss and entrainment.

Proportional entrainment of Rainbow Trout into the WH canal averaged 0.7% which was about 20-fold lower than proportional entrainment into CBRHC (8.4%, Figure A2.6). The proportion of Brown Trout entrained in WHC was about 0.4% which was about 1/4 of the proportional entrainment estimate for CBRHC (2.1%). Proportional entrainment of Brown Trout in 2012 was high at both WHC (about 8%) and CBRHC (about 20%) owing to the very low abundance estimate in the Bow River (see text in main body of report). The proportion of the Mountain Whitefish population entrained into WHC averaged 3.1%. Proportional entrainment was considerably higher in 2000 and 2021 owing to relatively high salvages (Table 1) combined with low population estimates in the Bow River (see bottom panel of Fig A2.6).

Annual entrainment to the WHC averaged about1,900 for Rainbow Trout, 360 for Brown Trout, and 16,000 for Mountain Whitefish (Figure A2.6), compared to 18,000, 1,200, and 77,000 in the CBRHC, respectively (Figure's 8, 12, and 14). The scale of entrainment and proportional entrainment estimates in the WHC should be considered highly uncertain because the salvage-to-entrainment expansion ratio has never been estimated, requiring us to assume the ratio estimated for CBRHC is the same in WHC. In addition, interannual variation in entrainment and proportional entrainment in both canals depends on the assumption there is no variation in the mean of the salvage-to-entrainment expansion ratio across years.

A3. How many fish could be tagged to support an entrainment study on the Bow River?

Kenton Neufeld, March 26, 2024

We provide 3 scenarios to demonstrate the range of possible numbers of Rainbow Trout, Brown Trout (Brown Trout), Mountain Whitefish captured and tagged to support an entrainment study. These are all estimates based on catch rates from previous studies and assumptions about sampling effort. If an entrainment study were to proceed, a more thorough investigation into the numbers of tagged fish needed would be conducted prior to implementing a sampling program.

Details of scenarios are provided below.

Scenario	Rainbow Trout Tagged	Brown Trout Tagged	Mountain Whitefish Tagged
Scenario 1	1238	781	1639
Scenario 2	2012	1227	0
Scenario 3	2412	1327	0

Scenario 1 – Standard Boat Electrofishing

- Rainbow Trout, Brown Trout, and Mountain Whitefish would all be captured and tagged
- Sampling methodology would follow the large river survey standards, the same standard that has been used for the one-pass sampling in previous surveys
    - 2 km sites broken into 500 m sections, with all Rainbow Trout, Brown Trout, and Mountain Whitefish sampled and tagged every 500m.
- Estimate that 2 weeks of electrofishing with 2 boats could be allocated
- Using past efficiencies from 1st pass electrofishing, it is estimated that average catch rates (CUEs) will be:

Year	Brown Trout CUE (#/km)	Mountain Whitefish CUE (#/km)	Rainbow Trout CUE (#/km)
1999	12.25	34.25	7.25
2000	7.5	8.75	10.5
2001	1.202532	12.63291	6.917722
2003	29.5	7.75	26.5
2005	18.5	4.75	28
2007	26	49.25	29.75
2008	14	13	30.8
2011	23	37.5	53.75
2012	10.75	87.5	19.25
2013	15.11111	46.77778	22
2017	4.25	19.41667	6
2018	6.785714	21.14286	14.5

2019	7.692308	19.11538	11.73077
2020	4.115385	22.69231	10.38462
2021	20.25	27	36.75
2023	7.392857	25.46429	16.17857
Average	**13.01874**	**27.31201**	**20.64135**

- Assume a boat can sample 3km of river per day (2023 rate of sampling at one-pass sites).
- 2 weeks * 2 boats = 20 boat days of sampling = 60 river km sampled
- 60km * CUE = estimated total fish caught and tagged over the 2 week period
    - **Rainbow Trout = 1238**
    - **Brown Trout = 781**
    - **Mountain Whitefish = 1639**
- We are assuming that CUEs in the spring will be the same as those from September when the Bow sampling is usually completed.

Scenario 2 – Intensive Boat Electrofishing

- Sampling is modified from standard large river method to increase efficiency of capture and tagging of Rainbow Trout and Brown Trout
- Boat electrofishing is conducted only at sections of river with higher Rainbow Trout and Brown Trout catch rates (Bonnybrook Water Treatment Plant to Carseland). This may increase the number of trout tagged, but will exclude some sections from the study (upstream of Bonnybrook and downstream of Carseland). This will limit the conclusions we can draw about susceptibility of fish in these areas to entrainment.
- Mountain Whitefish will not be netted or tagged, with the sole focus being Rainbow Trout and Brown Trout. This will increase sampling speed (km/day) because we will not be processing and tagging Mountain Whitefish. It will also increase Rainbow Trout and Brown Trout CUE because netters will be focused on capturing trout and ignoring Mountain Whitefish.
- Using past CUEs from 1st pass sampling between Bonnybrook and Carseland, it is estimated that average CUEs will be:

Year	Brown Trout CUE (#/km)	Mountain Whitefish CUE (#/km)	Rainbow Trout CUE (#/km)
1999	12.25	34.25	7.25
2000	7.5	8.75	10.5
2001	1.852941	9.602941	7.470588
2003	29.5	7.75	26.5
2005	18.5	4.75	28
2007	26	49.25	29.75
2008	14	13	30.8
2011	23	37.5	53.75
2013	15.375	45.25	24.25
2017	5.5	11.16667	11.16667

2018	7.75	15.4	18.65
2019	9.555556	20.88889	15.61111
2020	3.944444	24.61111	13.16667
2021	20.25	27	36.75
2023	9.6	24	21.7
Average	**13.63852941**	**22.21130719**	**22.35433551**

- Assume that a boat can sample 1.5x the river length as when Mountain Whitefish are included in the sampling (3km/day * 1.5 = 4.5km/day). Plan for 2 weeks of electrofishing with 2 boats.
- 2 weeks * 2 boats = 20 boat days of sampling = 90 river km sampled
- 90km * CUE = estimated total fish caught and tagged over a 2 week period
    - **Rainbow Trout = 2012**
    - **Brown Trout = 1227**
- We are assuming that CUEs in the spring will be the same as those from September when the Bow sampling is usually completed.

Scenario 3 – Intensive Boat Electrofishing plus Targeted Angling

- Same electrofishing as conducted in the intensive boat electrofishing (Scenario 2) with the addition of anglers at fishing hotspots catching and tagging Rainbow Trout and Brown Trout as well.
- There will be a lot of uncertainty in the estimate of Rainbow Trout and Brown Trout that can be tagged using anglers. It would depend not only on uncertain catch rates, but the number of anglers who participate and the logistics of tagging angler caught fish. We will try to estimate on the upper end of the possible spectrum to set the bounds for the maximum number of Rainbow Trout and Brown Trout we could expect to tag.
- 2006 Bow River Sport Fish Angler Survey (Ripley and Council, 2006) provides estimates of Rainbow Trout and Brown Trout catch rates.
    - The section with the highest Rainbow Trout angler catch rates in April and May was from Hwy 22x to Carseland.

	Rainbow Trout Caught	Brown Trout Caught	Effort	Rainbow Trout CUE (#/Angler hour)	Brown Trout CUE (#/angler hour)
April	470	70	2584		
May	5630	1997	25071		
Total	6100	2067	27655	0.22	0.07

- We will assume 20 exceptional anglers sign up for the program and can dedicate 2 10 hour days each. Assume CUEs are about 4 times the average of about1 Rainbow Trout/hour, and about 0.25 Brown Trout/hour.
- 20 hours * 20 anglers = 400 angler hours.
- 400 angler hours * CUE = # fish caught and tagged
    - Rainbow Trout = 400

  - Brown Trout = 100
- When we add that to the number of fish captured in the intensive electrofishing, we get:
  - **Rainbow Trout = 2412**
  - **Brown Trout = 1327**

A4. Workflow for Entrainment Modelling

This appendix provides brief descriptions of the workflow for the entrainment model used in this report. Input data, R scripts, and the WinBUGS program to estimate entrainment and proportional entrainment are stored in a single directory. Model output for CBRHC and WHC are stored in subdirectories Carseland and WID, respectively. The names of these directories and their organization can easily be modified but requires making changes to the paths in some R scripts.

All the data used for the entrainment modelling is stored in Entrainment_Model_Data.xlsx. This file includes sheets that store flow data (BowBelowCar_Flow, Carseland_Flow, and WID_Flow), salvage count data (Salvage_Careseland, Salvage_WID), and salvage fish length measurements (ForkLengths_Carseland, ForkLengths_WID). This file also contains a sheet ‘File_Code_Linkages” which shows the relationships among file and workflow (Figures A3.1-A3.5).

The main model input file Entrainment_Model_Data.xlsx uses Excel links to link the values provide in files from Alberta Agriculture and Irrigation (Figure A3.1). The entrainment model uses a series of annual statistics on flow in the Bow River and in the canals, as well as statistics on the number of days of operation. These statistics are stored in Careslenad_covar.txt and WIC_covar.txt files which are created by the R script Process_Daily_Hydrology.R (Figure A3.2).

The main R script used to run the entrainment model is Model_Ent.R (Figure A3.3). This program reads in salvage data stored in Entrainment_Model_Data.xlsx, flow covariate statistics (e.g., Carseland_covar.txt), and population estimates from the closed population model (BT_CP/Sp_Sz_sum.out and BT_CP/Year_indexing.txt). The user defines the species (e.g. RNTR) and size class file (e.g., Sz6 for the 6-size class run) that were run using the closed population modelling. Model_Ent.R formats these data so they can be read in by the BUGS program pEntrain.bug which estimates annual entrainments and proportional entrainment. The results are stored in text files with .out extensions. Model results are specific to each flow covariate and species-size class from the Bow River population model, and results across flow covariates can be summarized in a single file using the Summarize.R script.

Model output is displayed graphically using a number of R scripts (Figure A3.4). Scripts used for plotting length frequency data, for the simulation to assess field study design, and to calculate the uncertainty in the Salvage to Entrainment Ratio are described in Figure A3.5.

Table A1.1. The number of Mountain Whitefish marked and recaptured (<= 300 or > 300 mm in fork length) during Bow River population surveys. Also shown are the percentages of marked fish that were recaptured.

	Marks			**Recaptures**			**% Recaptured**		
Year	**<=300**	**>300**	**Total**	**<=300**	**>300**	**Total**	**<=300**	**>300**	**Total**
1999	45	175	220	0	2	2	0.0%	1.1%	0.9%
2000	286	309	595	6	7	13	2.1%	2.3%	2.2%
2003	2	83	85	0	3	3	0.0%	3.6%	3.5%
2005	56	110	166	3	3	6	5.4%	2.7%	3.6%
2011	4	54	58	0	0	0	0.0%	0.0%	0.0%
2012	61	241	302	9	20	29	14.8%	8.3%	9.6%
2013	465	423	888	15	4	19	3.2%	0.9%	2.1%
2018	267	217	484	2	5	7	0.7%	2.3%	1.4%
2021	99	23	122	1	1	2	1.0%	4.3%	1.6%
2023	404	231	635	4	1	5	1.0%	0.4%	0.8%
Total	1689	1866	3555	40	46	86	2.4%	2.5%	2.4%

Table A2.1. Comparison of covariate models predicting the annual proportion of Bow River Rainbow Trout (a), Brown Trout (b), and Mountain Whitefish (c) populations entrained into the Western Irrigation District Canal from 2001-2023. Hypotheses on the effects of covariate on proportional entrainment are described in Table 2. Statistics in the table show the mean (β1_mu) and coefficient of variation (β1_cv) of the covariate effect, and the probability that the covariate effect is greater than zero (prob(β1>0). Fit statistics include the magnitude of unexplained interannual variation in proportional entrainment (σ), and the proportion of the interannual variation in the log of observed salvage predicted by the model (r^2). Information theory statistics include the number of effective parameters (pD), the Deviance Information Criteria (DIC) score, and the difference between each model's DIC score and the lowest DIC among models (ΔDIC relative to the most predictive model).

a) Rainbow Trout

	Covariate Effect			Unexplained	Fit			
Covariate	**β1_mu**	**β1_cv**	**prob(β1>0)**	**Variation (σ)**	**(r^2)**	**pD**	**DIC**	**ΔDIC**
Null				1.28	1.00	14.35	23.90	0.27
BQ_4-10	–0.25	1.57	0.24	1.31	1.00	14.30	23.75	0.12
BQ_6-8	–0.22	1.75	0.26	1.32	1.00	14.32	23.77	0.14
BQ_8-10	–0.34	1.08	0.17	1.28	1.00	14.23	23.63	0.00
CQ_4-10	0.36	1.01	0.85	1.28	1.00	14.31	23.81	0.18
CQ_6-8	0.44	0.84	0.90	1.24	1.00	14.24	23.69	0.06
CQ_8-10	0.22	1.71	0.74	1.32	1.00	14.30	23.71	0.09
CBQ_4-10	0.20	1.94	0.70	1.32	1.00	14.38	23.87	0.25
CBQ_6-8	0.23	1.67	0.73	1.31	1.00	14.32	23.79	0.17
CBQ_8-10	0.23	1.65	0.74	1.31	1.00	14.29	23.70	0.07
DoD_Tot	0.42	0.93	0.87	1.27	1.00	14.35	23.88	0.25
DoD_Jun	0.39	1.03	0.85	1.27	1.00	14.26	23.68	0.05
DoD_Sep15	–0.28	1.45	0.22	1.31	1.00	14.32	23.77	0.14

Table A2.1. Con’t.

b) Brown Trout

	Covariate Effect			Unexplained	Fit			
Covariate	**β1_mu**	**β1_cv**	**prob(β1>0)**	**Variation (σ)**	**(r^2)**	**pD**	**DIC**	**ΔDIC**
Null				1.57	1.00	14.58	24.06	0.29
BQ_4-10	0.15	3.18	0.63	1.63	1.00	14.44	23.77	0.00
BQ_6-8	0.22	2.09	0.71	1.62	1.00	14.48	23.84	0.07
BQ_8-10	0.01	36.62	0.52	1.64	1.00	14.48	23.83	0.06
CQ_4-10	–0.04	11.85	0.45	1.65	1.00	14.61	24.06	0.29
CQ_6-8	–0.04	12.38	0.46	1.64	1.00	14.46	23.79	0.02
CQ_8-10	0.22	2.11	0.68	1.63	1.00	14.59	24.04	0.27
CBQ_4-10	–0.17	2.77	0.33	1.63	1.00	14.54	23.98	0.21
CBQ_6-8	–0.17	2.61	0.34	1.62	1.00	14.51	23.89	0.13
CBQ_8-10	0.10	4.76	0.60	1.64	1.00	14.55	23.95	0.19
DoD_Tot	0.61	0.75	0.92	1.52	1.00	14.42	23.78	0.01
DoD_Jun	0.58	0.79	0.90	1.51	1.00	14.44	23.83	0.07
DoD_Sep15	–0.56	0.81	0.10	1.52	1.00	14.42	23.79	0.02

Table A2.1. Con't.

c) Mountain Whitefish

Covariate	Covariate Effect β1_mu	β1_cv	prob(β1>0)	Unexplained Variation (σ)	Fit (r^2)	pD	DIC	ΔDIC
Null				4.58	1.00	13.98	23.25	0.65
BQ_4-10	-1.91	0.53	0.04	4.33	1.00	13.40	23.08	0.48
BQ_6-8	-1.78	0.54	0.04	4.39	1.00	13.76	23.27	0.66
BQ_8-10	-0.99	1.09	0.14	4.56	1.00	13.85	23.26	0.66
CQ_4-10	3.25	0.22	1.00	3.43	1.00	13.49	23.00	0.39
CQ_6-8	3.37	0.24	1.00	3.53	1.00	13.04	22.60	0.00
CQ_8-10	2.59	0.28	1.00	3.93	1.00	13.95	23.37	0.77
CBQ_4-10	2.53	0.33	1.00	4.04	1.00	13.80	23.30	0.70
CBQ_6-8	2.37	0.42	1.00	4.11	1.00	13.72	23.21	0.60
CBQ_8-10	1.87	0.55	0.93	4.33	1.00	13.97	23.37	0.77
DoD_Tot	1.76	0.68	0.94	4.58	1.00	13.45	22.91	0.31
DoD_Jun	1.87	0.40	0.99	4.34	1.00	13.74	23.19	0.59
DoD_Sep15	-1.16	1.04	0.19	4.61	1.00	13.90	23.31	0.71

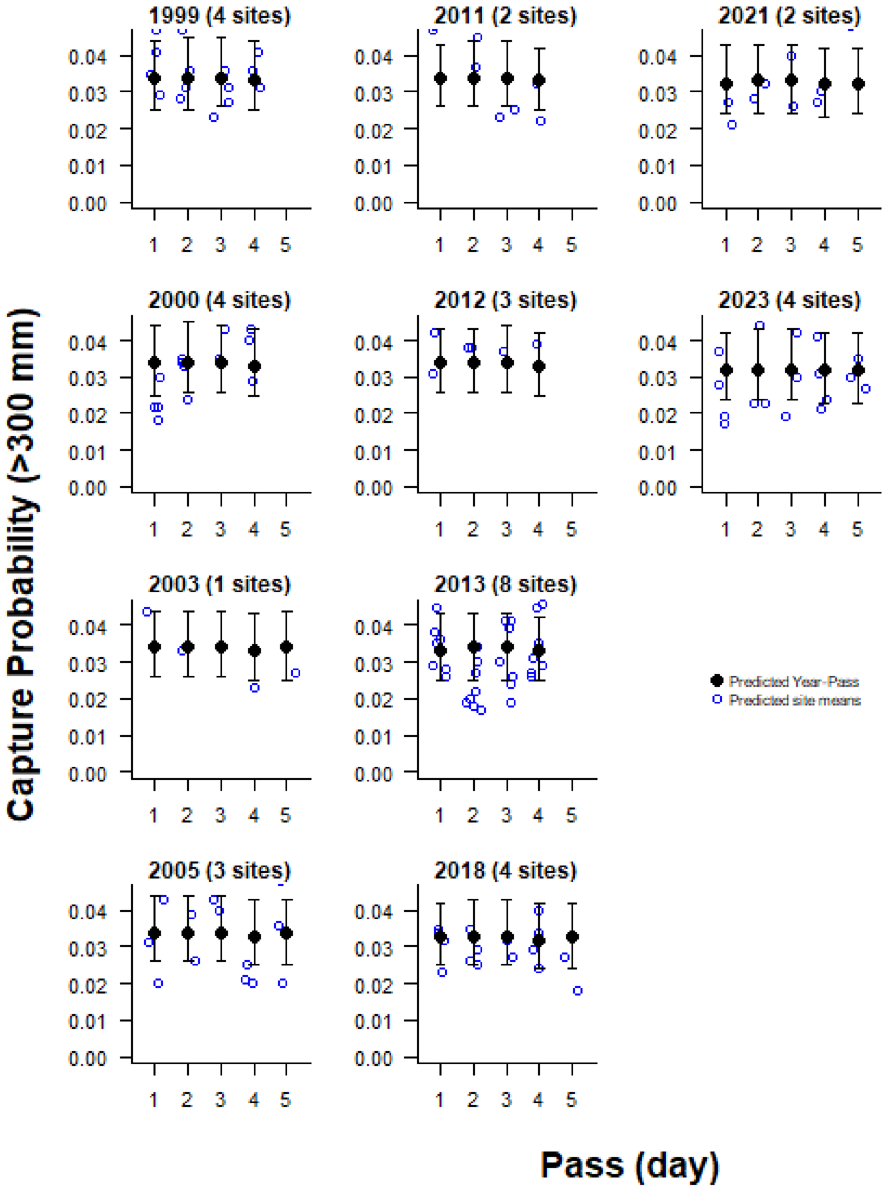


Figure A1.1. Mountain Whitefish capture probability estimates for the >300 mm size class by year (panel) and pass (x-value). The black points and error bars represent the median and 95% credible intervals based on transformed values from equation A1.2. Unlike Rainbow Trout and Brown Trout population models, capture probability for Mountain Whitefish is not allowed to vary across passes, years, or size classes. The open blue points represent the estimates by site and vary due to modelled process error $\varepsilon_{y,s,p,l}$.

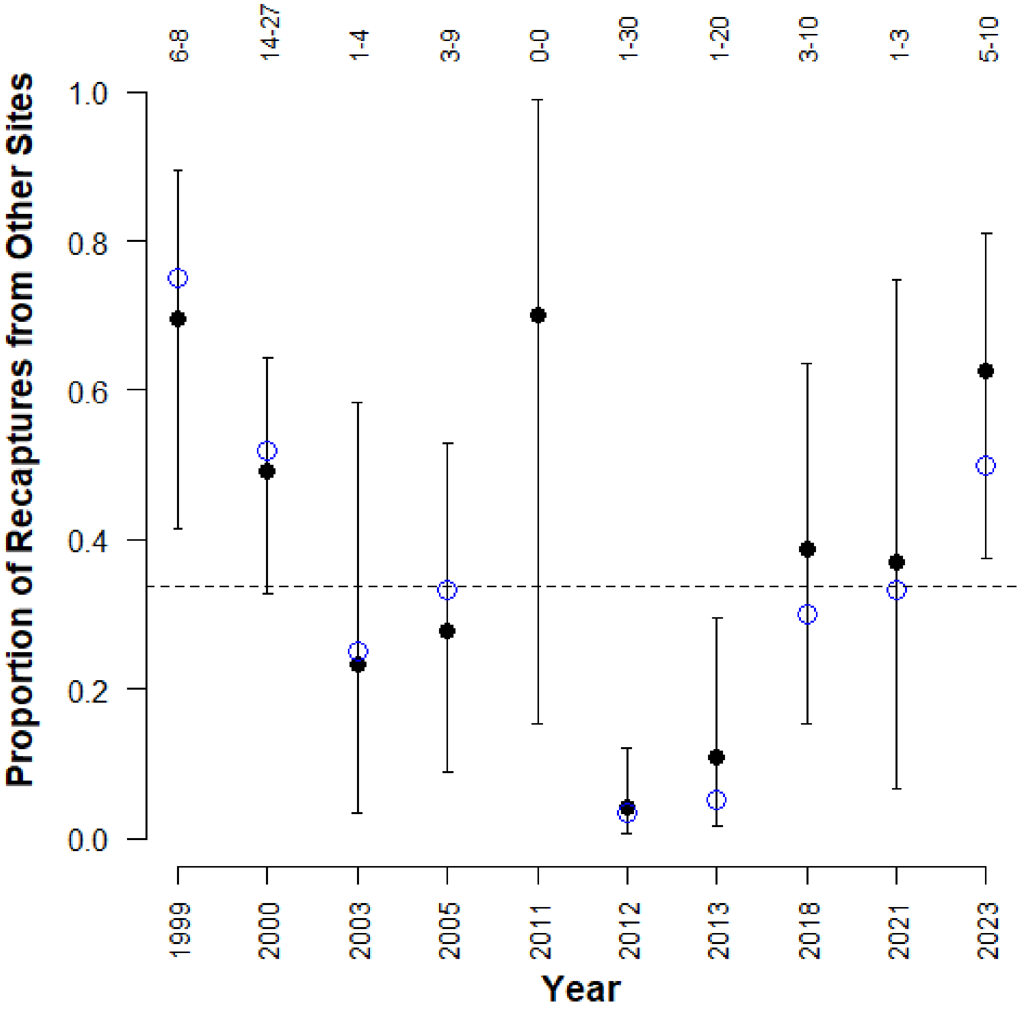


Figure A1.2. Estimates of the proportion of recaptured Mountain Whitish caught in sites other than the one they were originally marked in, by sampling year (θ_y). The black points and error bars show the medians and 95% credible intervals of θ_y estimates from the model. The black dashed horizontal line shows the transformed median estimate for the mean of the hyper-distribution for θ_y (μ_θ). Blue open points show independent estimates of θ_y (right column of Table 3). The text at the top of the panel shows the number of across-site recaptures and the total number of recaptures by year. The ratio of the two values is the expected independent estimate of θ_y (blue points).

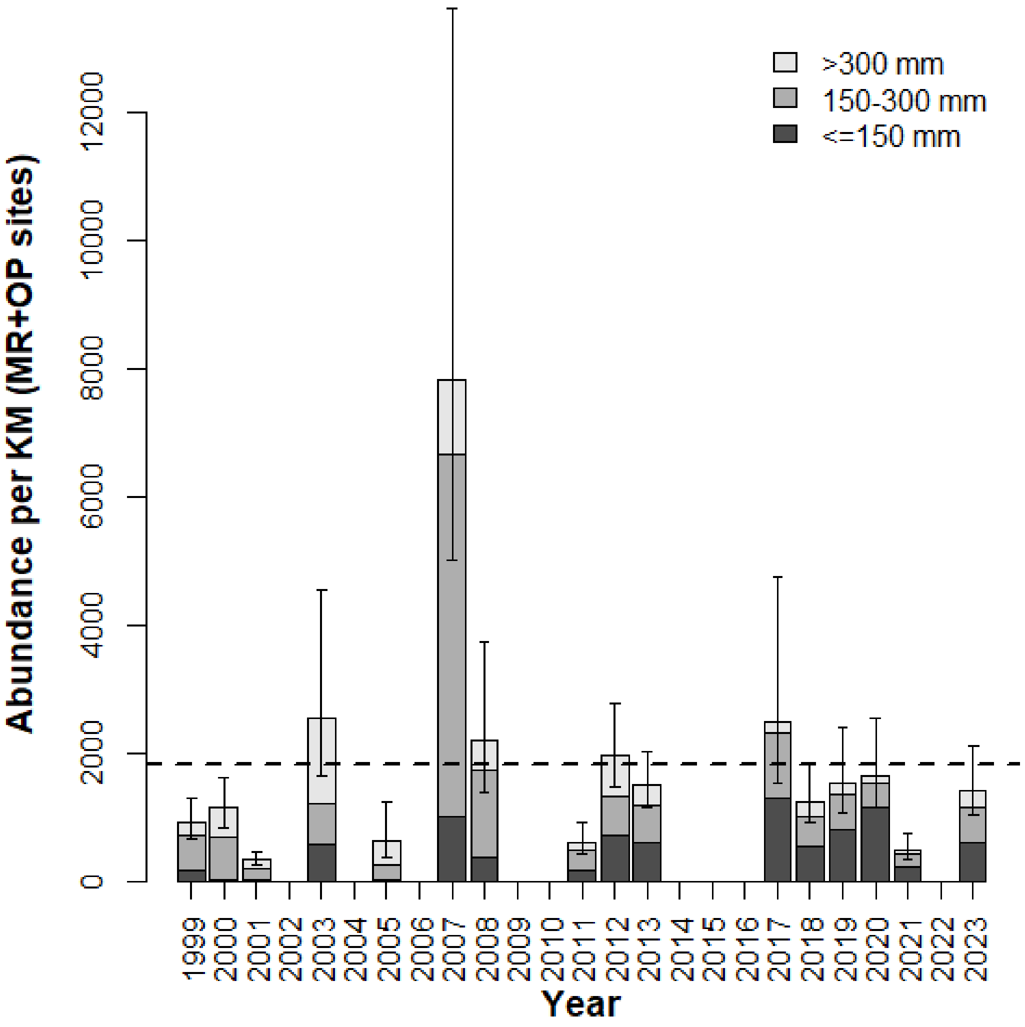


Figure A1.3. Annual abundance estimates for Mountain Whitefish in the Bow River based on all available data for each year (mark-recapture (MR) only, one-pass (OP) only, or mark-recapture and one-pass). The dashed horizontal line represents the interannual mean of size-aggregated annual abundance estimates.

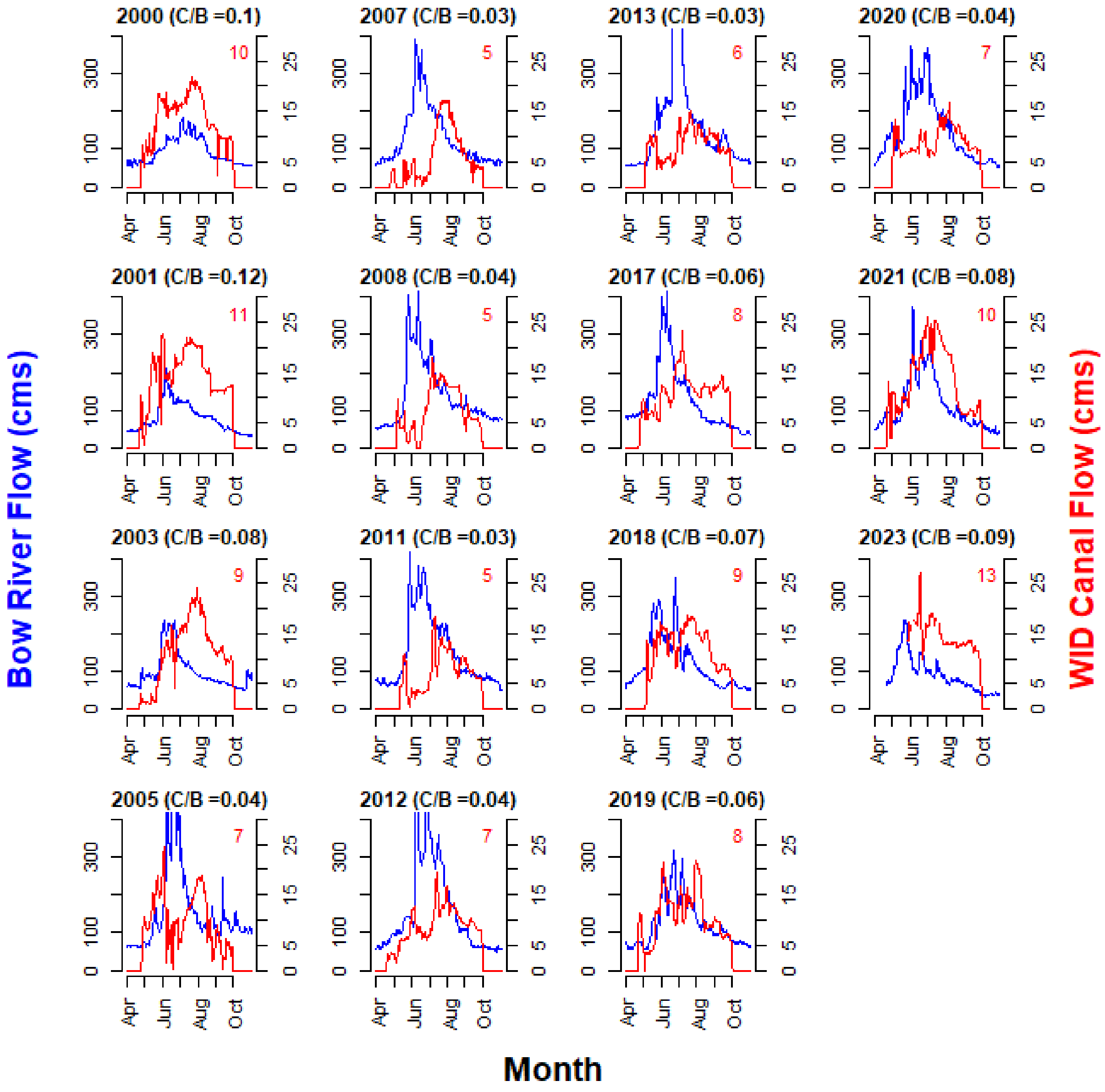


Figure A2.1. Mean daily flow in the Bow River immediately upstream of the Western Headworks Canal (05BH004+ 05BJ001 and at the headgates of the Western Headworks Canal (WHC) (05BM015) for years with canal salvage and Bow River population estimates. The proportion of the total Bow River flow during the period of canal operation (~ April – October) is shown in parentheses (C/B). The red text in the upper-right corner of each panel shows the average WH canal flows over the April-October diversion period.

a) Rainbow Trout

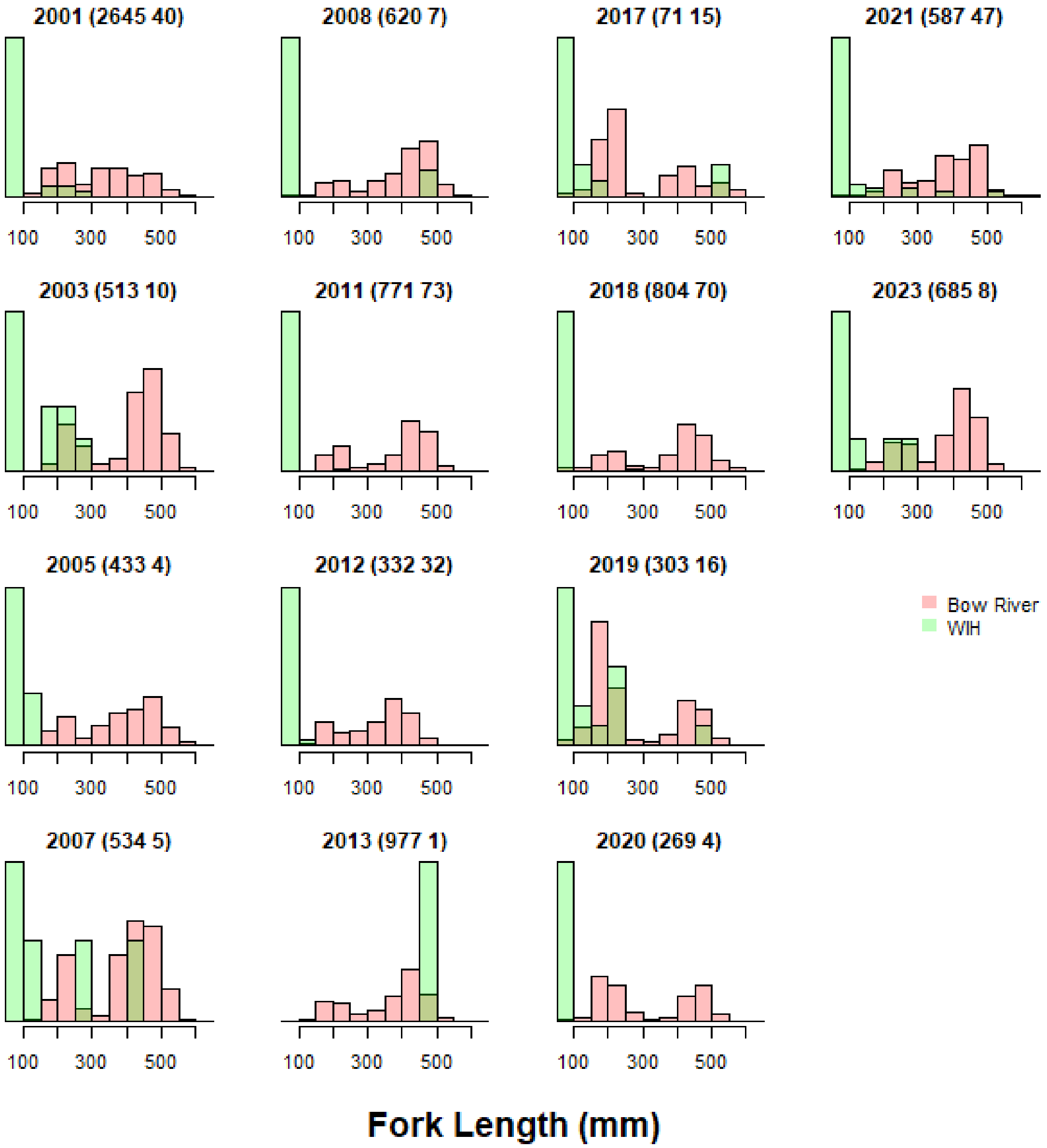


Figure A2.2. Comparison of length frequency distributions for Rainbow Trout (a), Brown Trout (b), and Mountain Whitefish (c) captured in the Bow River during population monitoring and from salvage in the Western Headworks Canal (WHC) in years with both fish rescue and Bow River population sampling. Numbers in parentheses are the sample sizes of fish measured from the Bow River (left) and the WHC (right). The length frequencies for Mountain Whitefish in the WHC are adjusted to account for fish < 200 mm that are not measured (the sample size in parentheses reflects the number of fish measured and not the total salvage).

b) *Brown Trout*

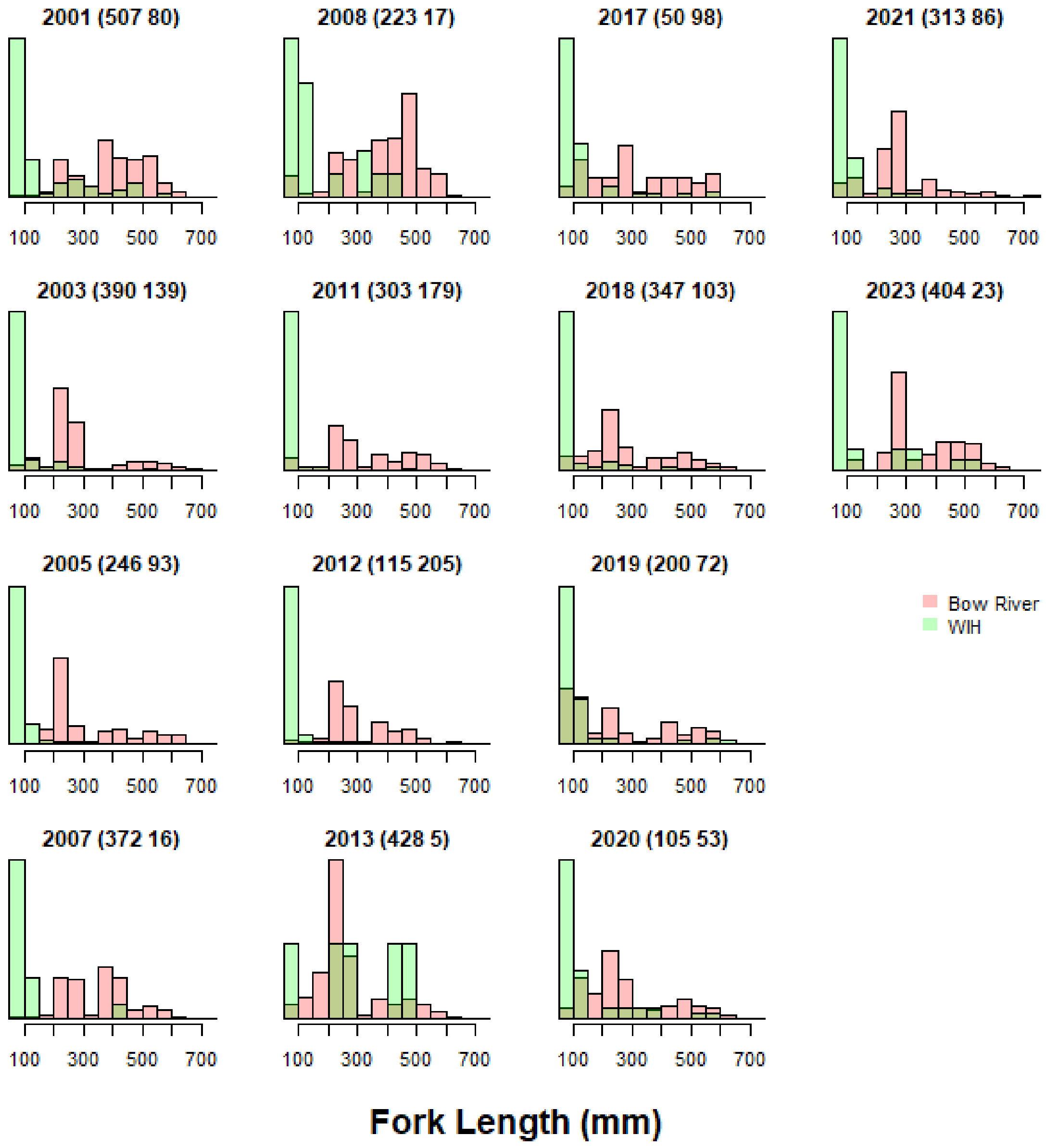


Figure A2.2. Con’t.

c) Mountain Whitefish

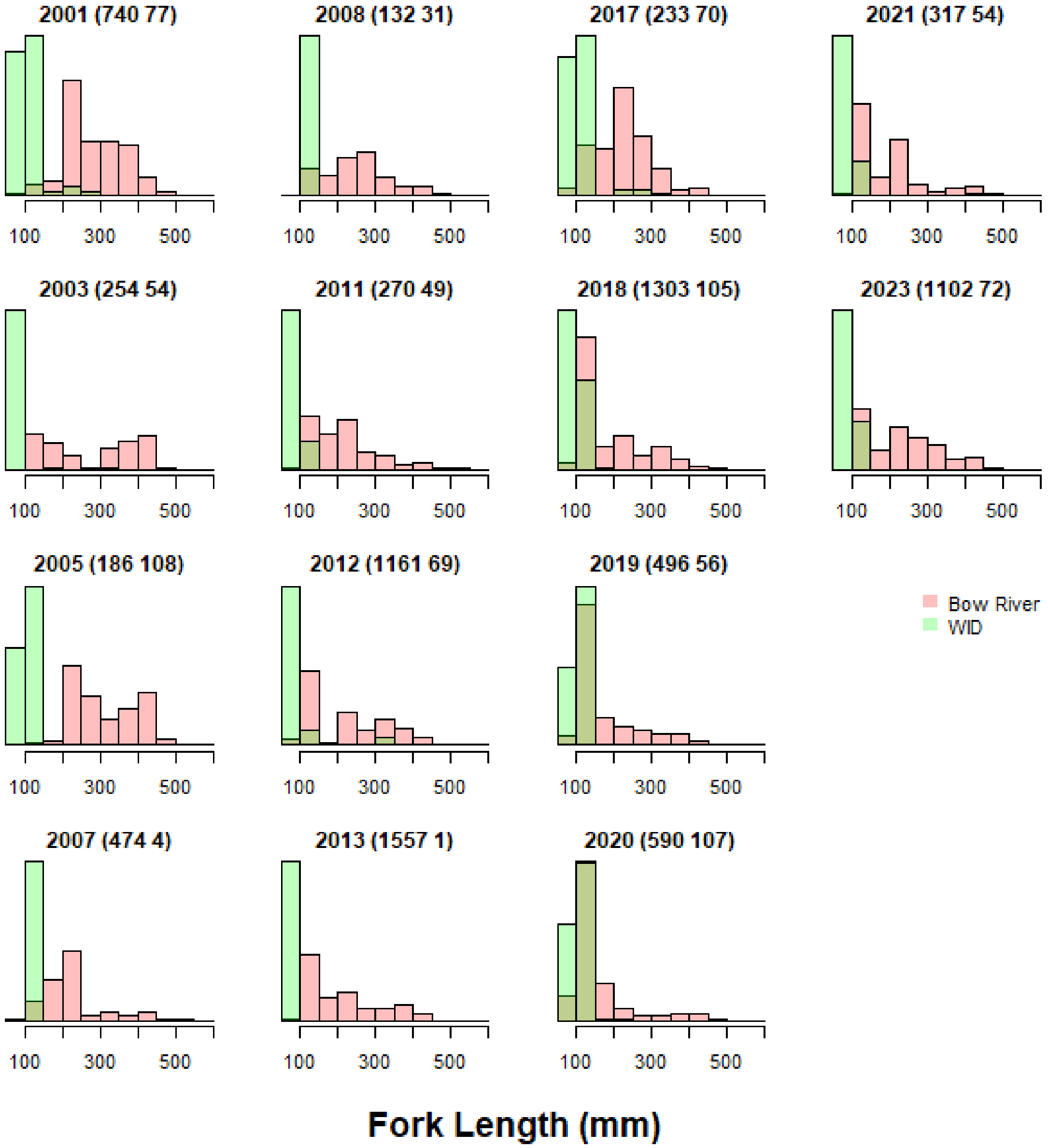


Figure A2.2. Con't.

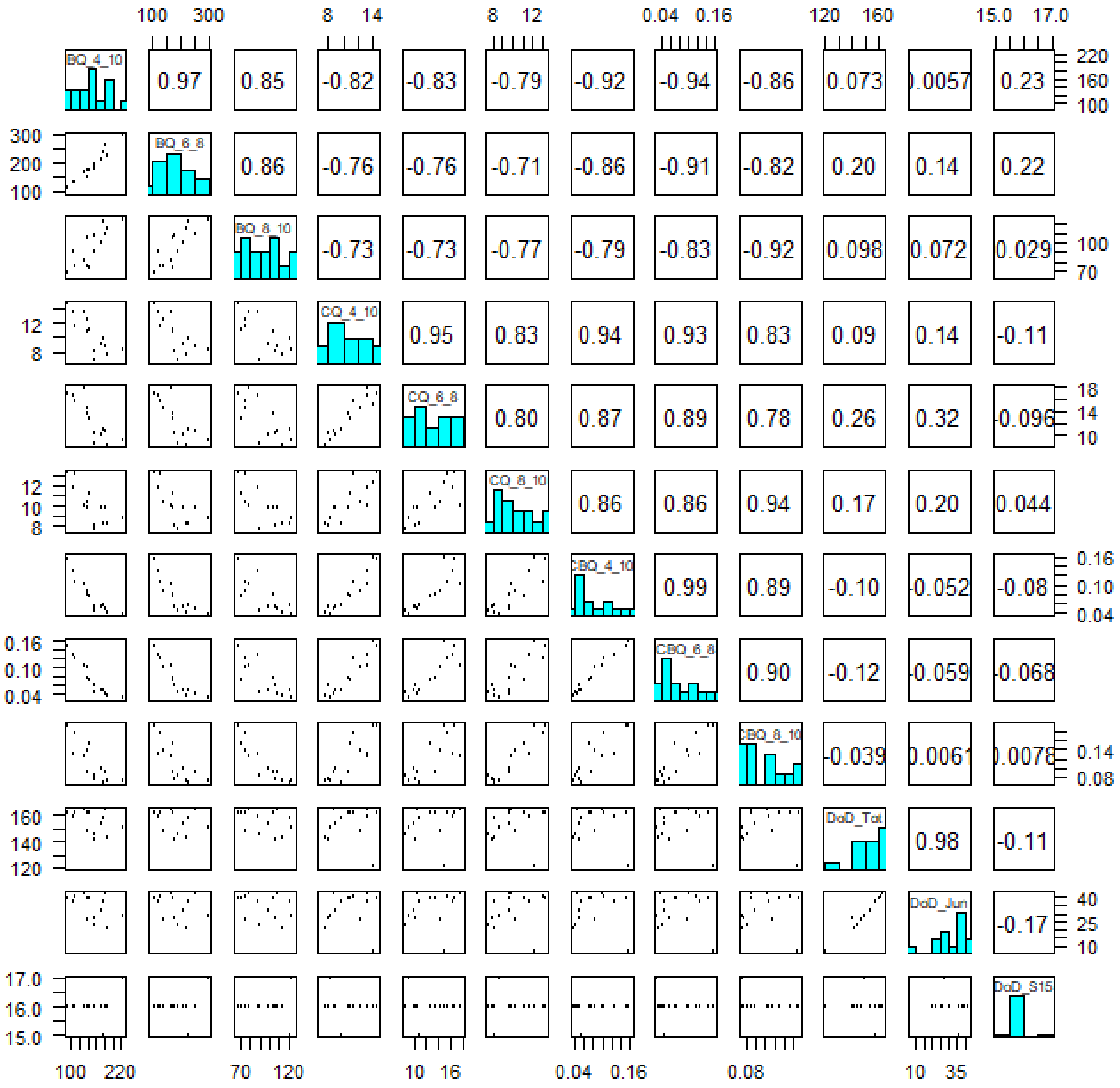


Figure A2.3. Pairs plot showing the relationship between 12 covariates used to predict interannual variation in the proportion of Bow River fish populations entrained into the Western Irrigation District Canal. The histograms on the diagonal show the distribution of annual covariate values (see Table 1 for a description of covariates). The panels below the diagonal show the relationship among covariates (each point represents an annual value). The panels above the diagonal show the Pearson correlation (r) between each of the 12 covariate types.

a) Rainbow Trout

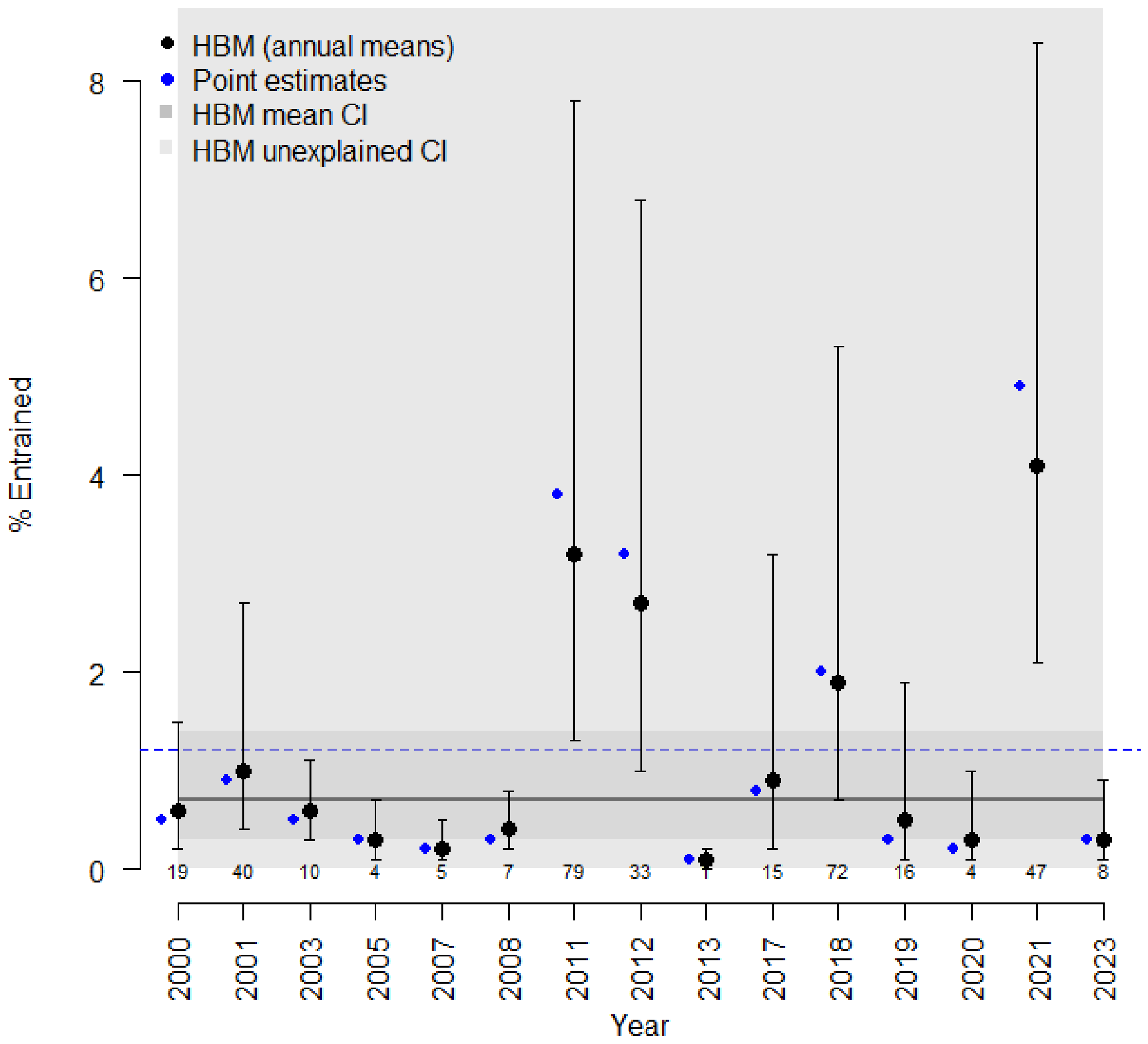


Figure A2.4. Predictions of the proportion of the Bow River Rainbow Trout (a), Brown Trout (b), and Mountain Whitefish (c) populations entrained in the WH canal. The blue points show the point estimates. The black points show the median and credible intervals from the hierarchical Bayesian null model (no covariate effects). The text at the bottom of the plot shows the annual salvage values. The horizontals lines show the estimated across-year mean of the entrainment proportion from the hyper-distribution of the Bayesian model (black) and the mean of the point estimates (blue). The dark grey area shows the 95% credible interval of the mean proportion of the population entrained over all years. The lighter gray area includes uncertainty in the mean but also the extent of true unexplained interannual variation in the proportion entrained (process error, σ).

b) Brown Trout

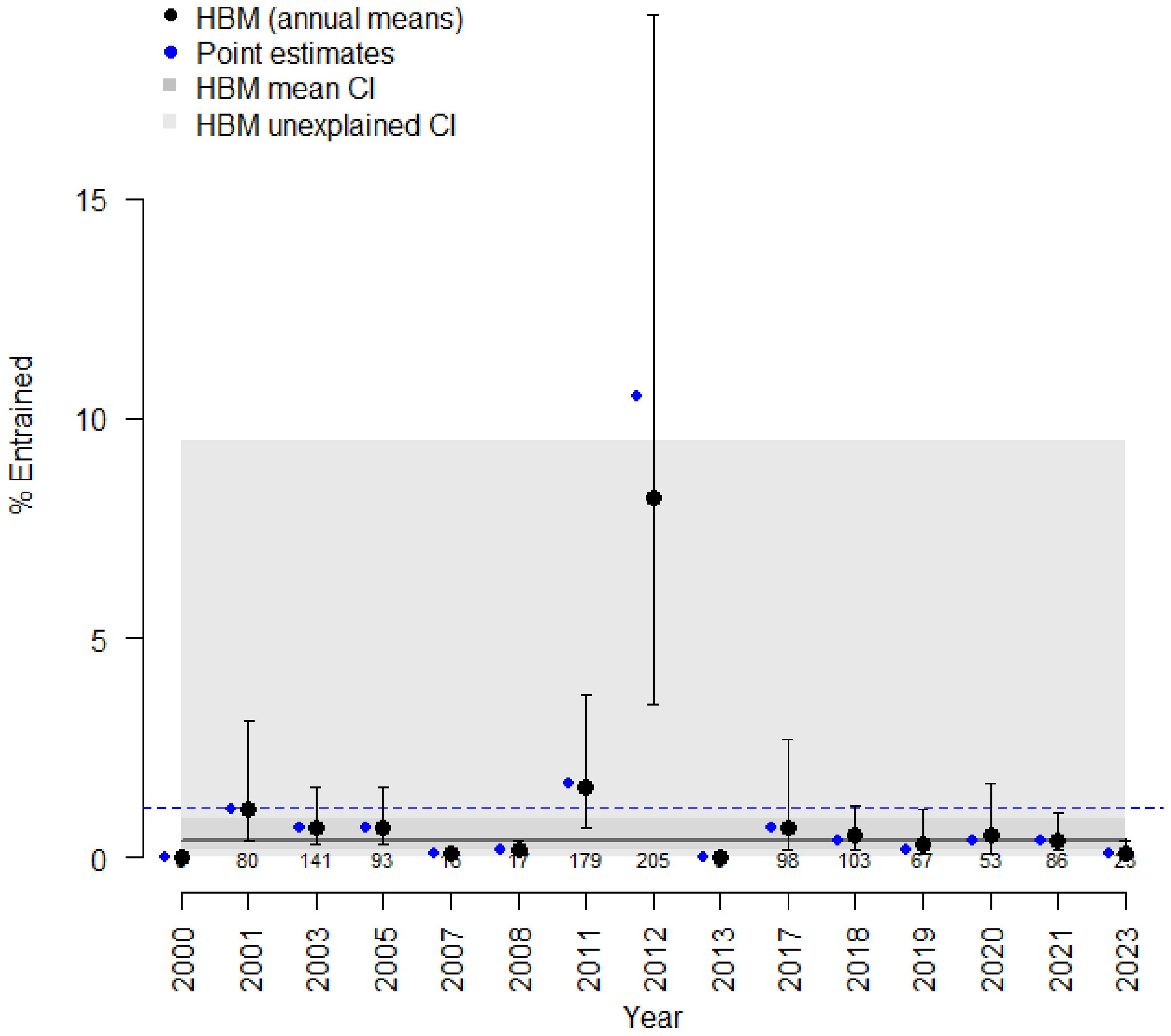


Figure A2.4. Con’t.

c) Mountain Whitefish

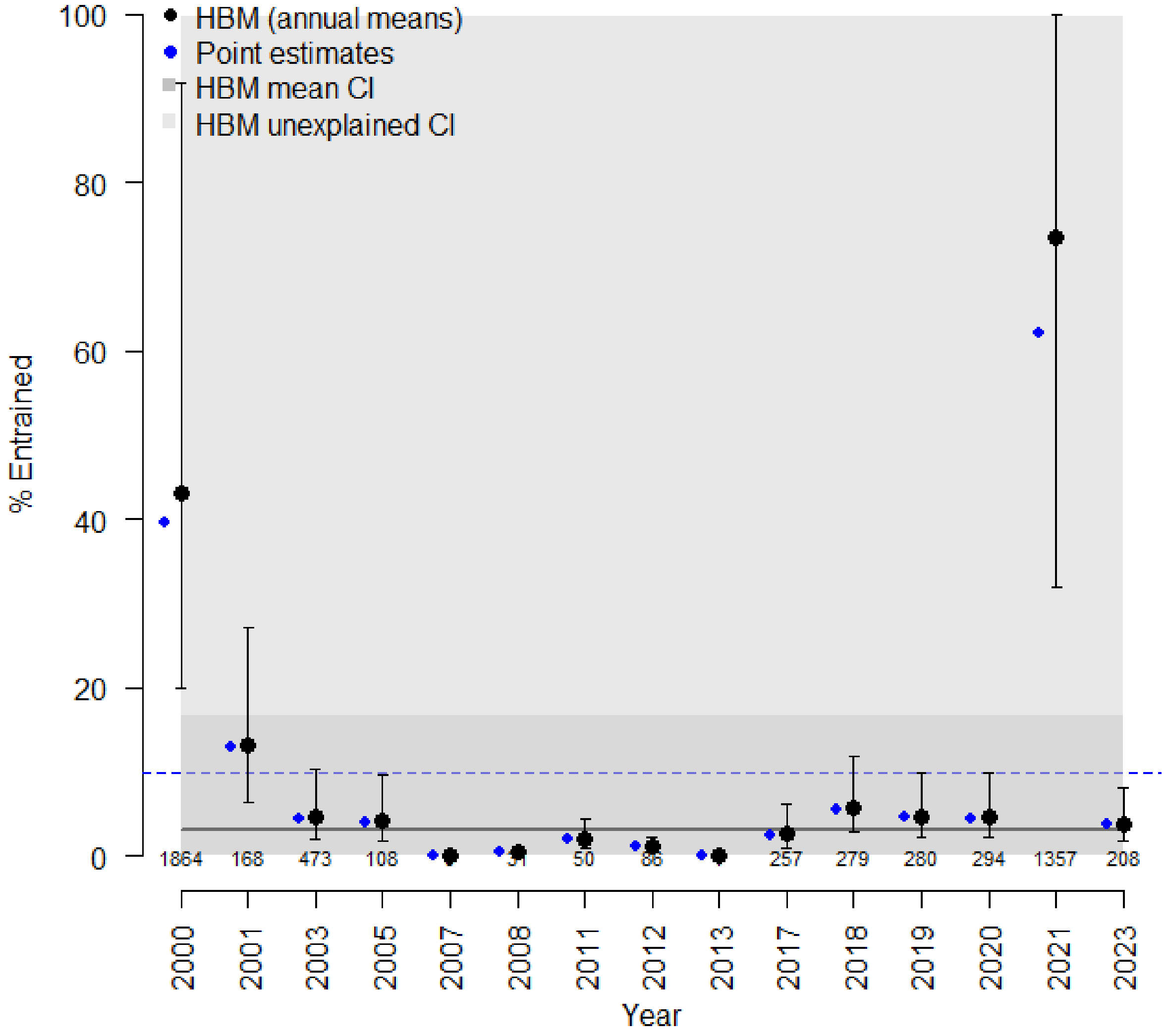


Figure A2.4. Con’t

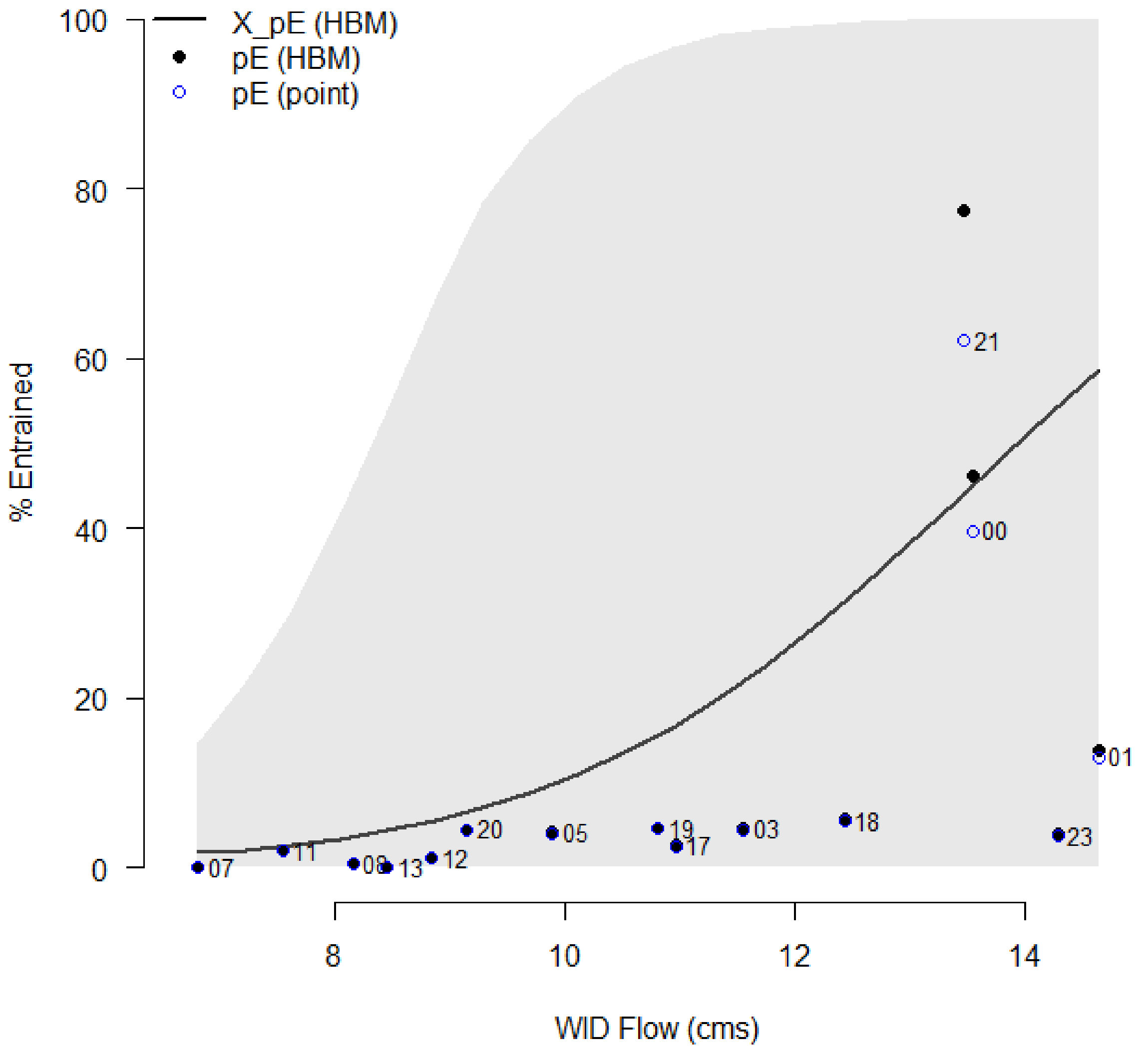


Figure A2.5. Estimated relationship between average flow in the Western Irrigation District Canal between April and October and the proportion of the Bow River Mountain Whitefish population that is entrained. The solid line and grey shaded area show the mean and 95% credible intervals of the relationship estimated from the Bayesian model. The blue points are the point estimates of annual entrainment, and the black points are the mean estimates from the HBM.

a) Rainbow Trout

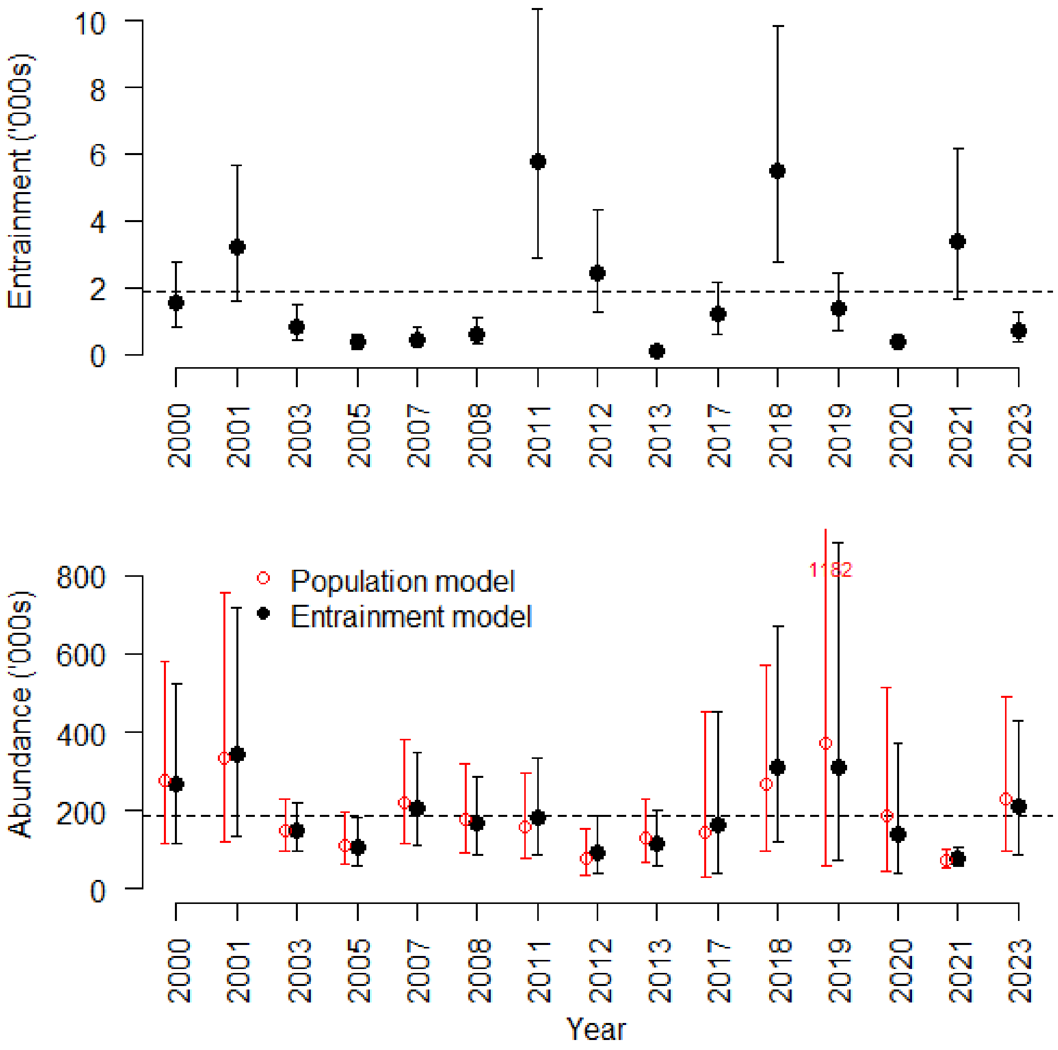


Figure A2.6. Annual estimates of Rainbow Trout (a), Brown Trout (b) and Mountain Whitefish (c) entrainment into Western Irrigation District Canal based on the null model (top) and abundance in the Bow River (bottom). Points and error bars show the means and 95% credible intervals. The abundance estimates from the closed population model (red) are compared to the simulated abundance in the entrainment model (black). Red text in the lower panel shows the upper credible interval for years when it extends beyond the y-axis maximum.

b) Brown Trout

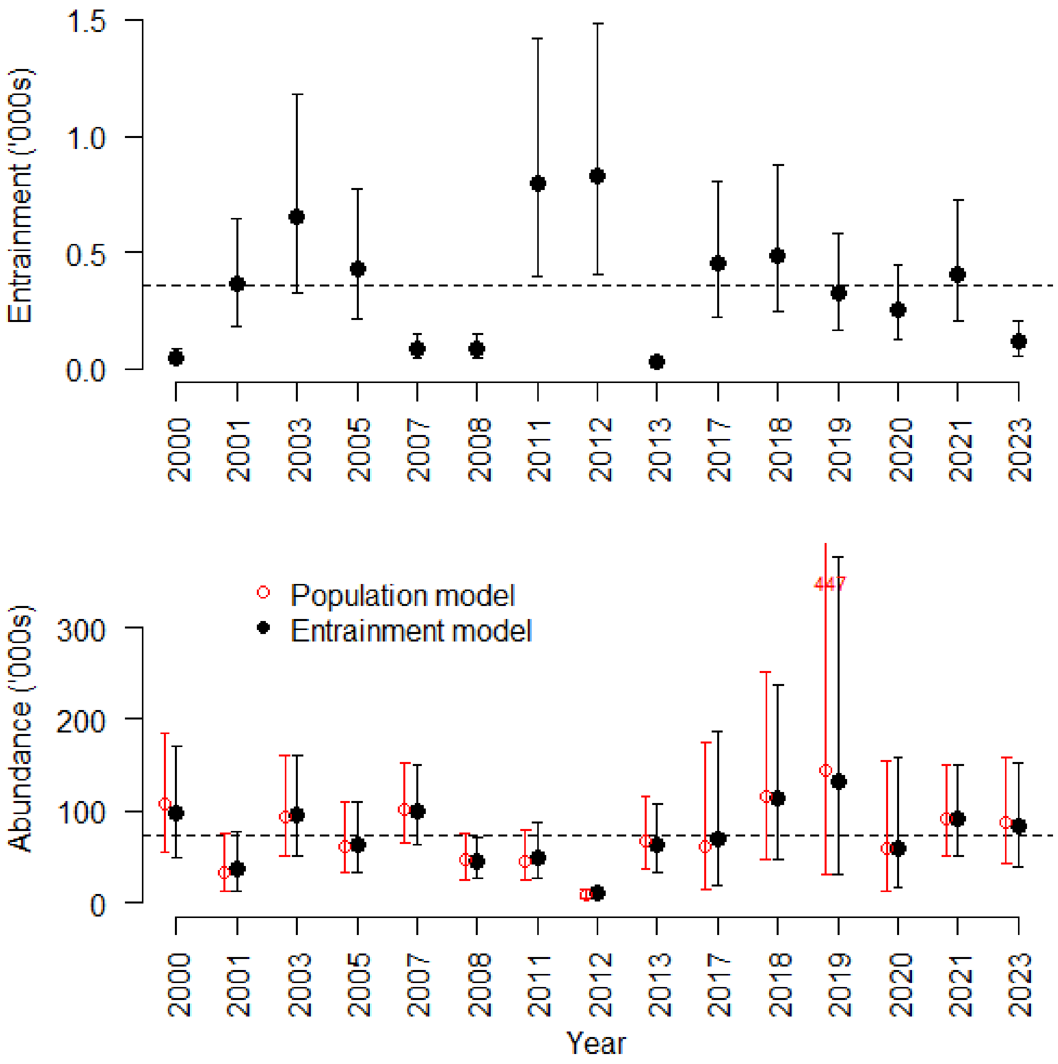


Figure A2.6. Con't.

c) Mountain Whitefish

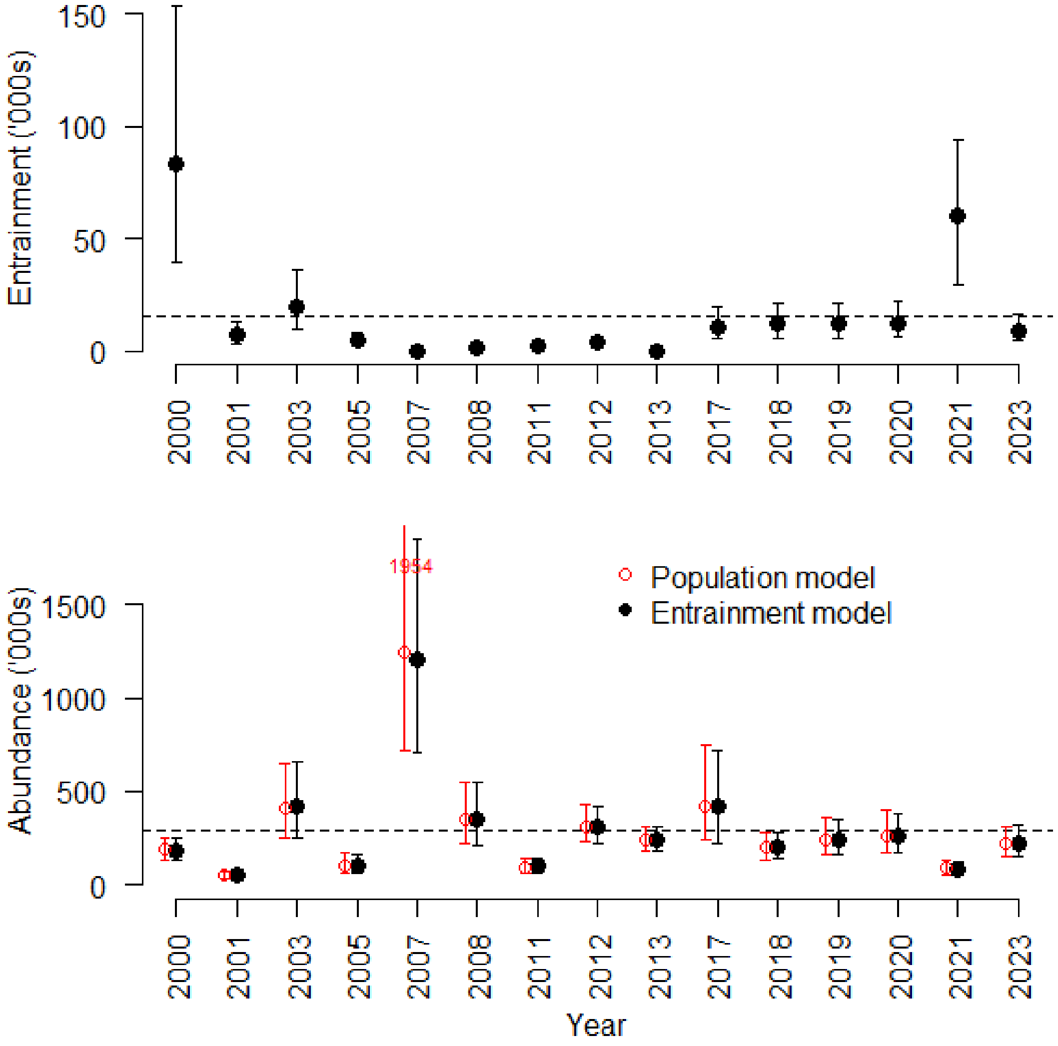


Figure A2.6. Con't.

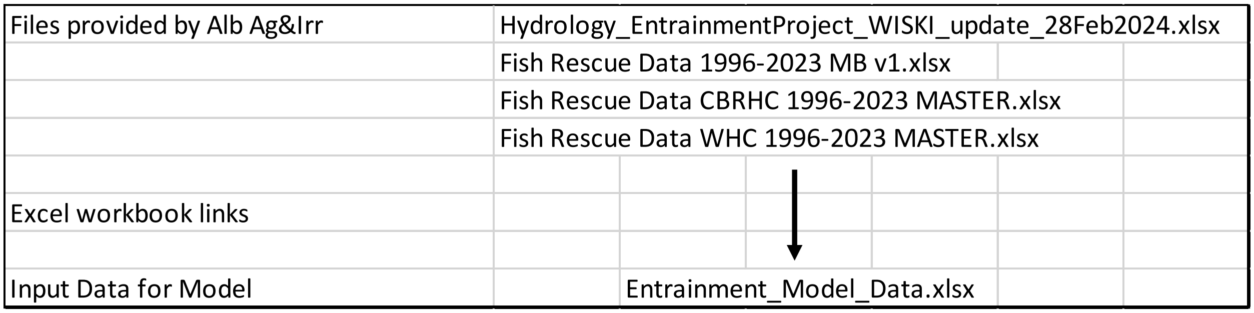


Figure A3.1. Files provided by Alberta Agriculture and Irrigation to create Entrainment_Model_Data.xlsx which is the input file used for the entrainment modelling.

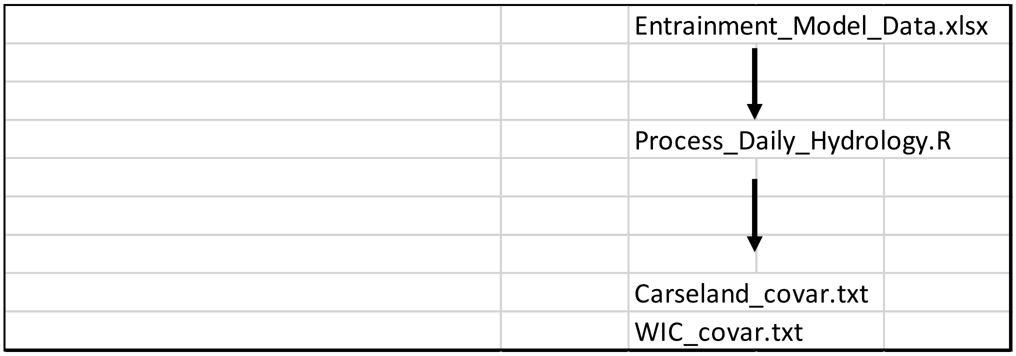
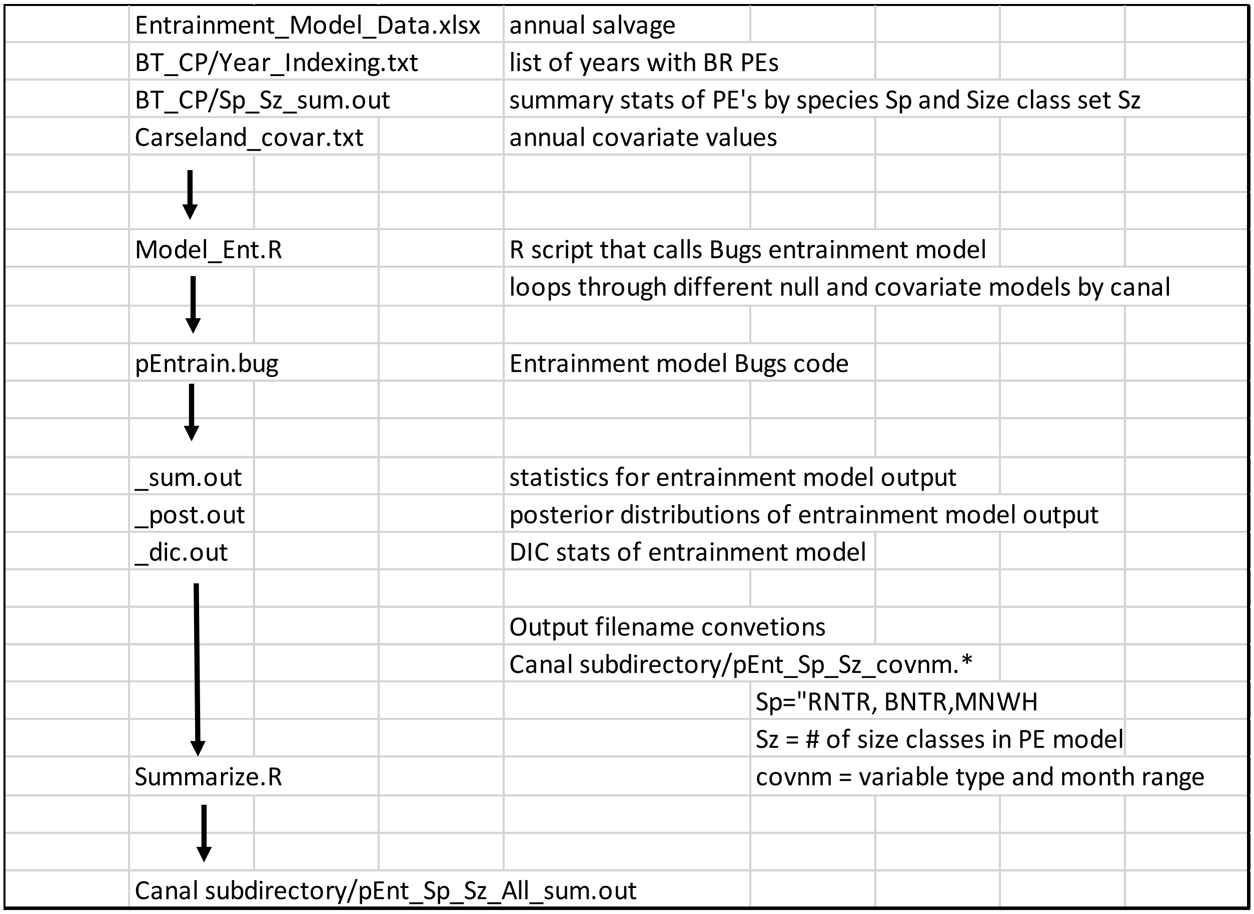
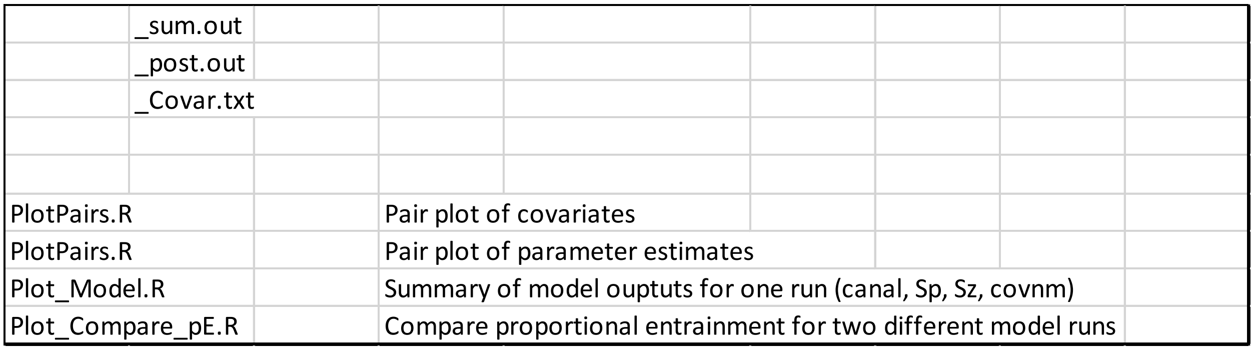


Figure A3.2. Files and R script used to create annual flow covariate statistics files used in the entrainment modelling.



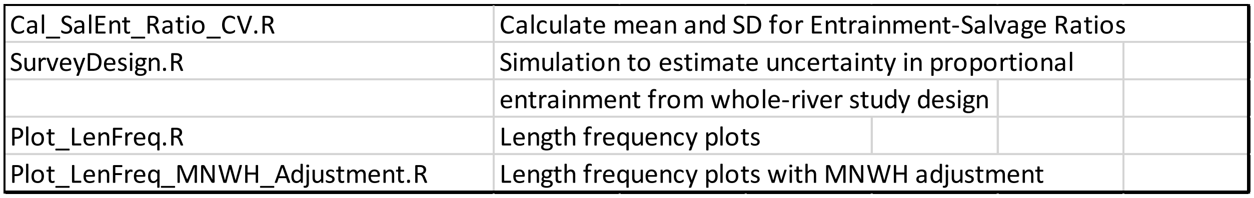
Entrainment_Model_Data.xlsx	annual salvage	
BT_CP/Year_Indexing.txt	list of years with BR PEs	
BT_CP/Sp_Sz_sum.out	summary stats of PE's by species Sp and Size class set Sz	
Carseland_covar.txt	annual covariate values	
↓		
Model_Ent.R	R script that calls Bugs entrainment model	
↓	loops through different null and covariate models by canal	
pEntrain.bug	Entrainment model Bugs code	
↓		
_sum.out	statistics for entrainment model output	
_post.out	posterior distributions of entrainment model output	
_dic.out	DIC stats of entrainment model	
↓	Output filename convetions	
	Canal subdirectory/pEnt_Sp_Sz_covnm.*	
		Sp="RNTR, BNTR,MNWH
		Sz = # of size classes in PE model
Summarize.R		covnm = variable type and month range
↓		
Canal subdirectory/pEnt_Sp_Sz_All_sum.out		

Figure A3.3. Input files, R scripts, BUGS program, and model output files used or created when running the entrainment model.



_sum.out	
_post.out	
_Covar.txt	
PlotPairs.R	Pair plot of covariates
PlotPairs.R	Pair plot of parameter estimates
Plot_Model.R	Summary of model ouptuts for one run (canal, Sp, Sz, covnm)
Plot_Compare_pE.R	Compare proportional entrainment for two different model runs

Figure A3.4. Entrainment model output files and R scripts used for graphical output of entrainment model results.



Cal_SalEnt_Ratio_CV.R	Calculate mean and SD for Entrainment-Salvage Ratios
SurveyDesign.R	Simulation to estimate uncertainty in proportional entrainment from whole-river study design
Plot_LenFreq.R	Length frequency plots
Plot_LenFreq_MNWH_Adjustment.R	Length frequency plots with MNWH adjustment

Figure A3.5. Miscellaneous scripts used for entrainment modelling.