Columbia River Project Water Use Plan

Lower Columbia River Fish Management Plan

Lower Columbia River Fish Stranding Assessment and Ramping Protocol

Reference: CLBMON-42

Comprehensive Summary Report

Study Period: 2008 – 2020

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201 Columbia Ave.
Castlegar, BC.

September 29, 2020

REPORT

CLBMON-42: Lower Columbia River Fish Stranding Assessment and Ramping Protocol - 2020

Submitted to:

BC Hydro

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19117420-004-R-Rev0

29 September 2020

Suggested Citation:

Golder Associates Ltd. 2020. CLBMON 42 Lower Columbia River Fish Stranding Assessment and Ramping Protocol Final Summary Report – 2020. Report by for BC Hydro Generations, Water License Requirements, Burnaby, B.C. 33 pp. + 5 app.

Executive Summary

The Lower Columbia River Fish Stranding Assessment and Ramping Protocol (CLBMON-42) was implemented in 2007 as a component of BC Hydro's Water Use Plan for the Columbia River. Since the implementation of CLBMON-42, 13 years (2007/2008 to 2009/2020; study periods were 1 April to 1 April annually) of fish stranding assessments were conducted in response to flow reductions from Hugh L. Keenleyside Dam/Arrow Lakes Generating Station (HLK/ALH) and Brilliant Dam and Brilliant Expansion Powerplant (BRD/X). This study adds to an additional 7-years (2000 to 2006) of stranding assessments that have been conducted after assessment procedures were standardized in 1999. These assessments were designed to collect fish stranding data to assess the impact of flow reductions and flow ramping rates from Hugh L. Keenleyside Dam (HLK)[1] on the native fish species of the lower Columbia River.

The study area encompassed the section of the lower Columbia River from HLK/ALH to the Canada/USA border, and included the lower Kootenay River from BRD/X to the Columbia River confluence. Once an operational flow reduction was planned, a fish stranding risk assessment was conducted following protocols established in *The Canadian Lower Columbia River: Risk Assessment and Response Strategy* (Golder 2011). The risk assessment was based on both current conditions (i.e. risk period, magnitude of flow reduction, resulting river stage, water temperature, and wetted history) as well as results of past stranding assessments stored in the Lower Columbia River Fish Stranding Database. The risk assessment included a query of Lower Columbia River Fish Stranding Database to identify which sites out of 29 established stranding locations had the highest risk for fish stranding.

Fish stranding assessments occurred on the same day as an operational flow reduction from HLK/ALH or BRD/X. During each stranding assessment, a selection of 29 sites on the lower Columbia and Kootenay rivers were visited from high to low priority based on the ranking provided in the database query. In addition, sites were assessed from upstream to downstream following the stage recession. During each site assessment, the total number of new isolated pools or dewatered pools created as a result of the flow reduction were recorded. Pools were assessed for stranded fish using a method suitable to the size and depth of the pool, including backpack electrofishing, seine netting, or visual assessment. Fish were identified to species and life stage if possible and the total number of live, dead, and salvaged fish from each site was recorded. All fish stranding assessment data, as well as discharge in the Columbia River, HLK/ALH, and BRD/X before and after the reduction were recorded for each reduction. Statistical models were used to assess the effects of environmental and operational variables on fish stranding using the 20-year dataset of fish stranding assessments. The variable of primary interest to address the program's management questions were ramping rate (the rate of discharge reduction at the dam), wetted history (the length of time substrate had been inundated before the reduction), and whether or not physical habitat recontouring had been conducted. The models assessed the effect of the predictor variables on both the probability of stranding one or more fish and the number of fish stranded.

The results of modelling on the 20-year dataset of fish stranding assessments indicated no effect of ramping rate on the probability of stranding on the number of fish stranded. This suggests no difference in fish stranding risk within the range of operational ramping rates currently used at HLK/ALH.

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[1] The CLBMON-42 monitoring program is specific to operations at HLK; however, this facility operates in association with Arrow Lakes Generating Station (ALH) and will be referred to as the combined operation of HLK/ALH. The management questions of the program will be presented as written in the CLBMON-42 Terms of Reference (BC Hydro 2007a).

Although not in direct operational control, the period of wetted history prior to an operational flow reduction had a positive relationship with stranding probability and number of fish stranded. The strongest trend in stranding occurred between 1 day and 100 days of wetted history. Over this range, the probability of observing zero stranded fish during an assessment dropped from 0.75 to 0.58. In addition, the predicted number of fish stranded increased from 21 fish at 1 day of wetted history to 52 fish at 50 days of wetted history. These results suggest that fish density in the near-shore area may increase with increased wetted history, and this environmental variable should continue to be considered when planning for a fish assessment or salvage response.

Six fish stranding sites on the lower Columbia River were recontoured between 2001 and 2015 in an effort to reduce fish stranding. A subsequent analysis on fish stranding assessments conducted before and after recontouring indicates a 14% reduction in the probability of stranding one or more fish, and a 66% reduction in the mean number of fish stranded after recontouring. This indicates that recontouring is an effective method of reducing total fish stranded.

These analyses improve understanding of factors that affect fish stranding in the lower Columbia River and can be used to guide future fish stranding protocols.

Table ES1: Summary of final status of the management questions of CLBMON-42

Objective	Management Questions	Summary of Key Results
To assess the impact of flow reductions and flow ramping rates from HLK on the native species of the lower Columbia River.	MQ1: Is there a ramping rate (fast vs. slow, day vs. night) for flow reductions from HLK that reduces the number of fishes stranded (interstitially and pool) per flow reduction event in the summer and winter?	A statistical analysis conducted on the 20-year dataset of fish stranding assessments indicated little or no evidence of an effect of ramping rate within the range of operational ramping rates currently used at HLK/ALH on fish stranding in the lower Columbia River (Appendix C). Flow ramping studies conducted prior to CLBMON-42 also found no effect of ramping rate. Previous analysis indicated that time of day was not a strong predictor of fish stranding risk; however there were few night ramping experiments conducted, and no night-time stranding assessments were conducted. Currently there is insufficient data to determine whether time of day is a significant predictor of the probability of fish stranding. Additional night-time ramping experiments, or night-time reduction events and stranding assessments would be required to balance the dataset and determine if there is any difference in the probability of fish stranding between day and night.
	MQ2: Does wetted history (length of time the habitat has been wetted prior to the flow reduction) influence the number of fishes stranded (interstitially and pool) per flow reduction event for flow reductions from HLK?	In a statistical analysis conducted on the 20-year dataset of fish stranding assessments in the lower Columbia and Kootenay Rivers, wetted history had a statistically significant positive effect on both the probability and number of fish stranding (Appendix D). Modelling indicated that the predicted number of fish stranded increased from 21 fish at 1 day of wetted history to 52 fish at 50 days of wetted history. These findings were consistent with previous analyses conducted on lower Columbia and Kootenay River fish stranding assessment data (Golder and Poisson 2010; Irvine et al. 2014). This supports the idea that substrate that has been inundated for a longer period is more likely to strand fish if dewatered, compared to substrate that is inundated for a shorter period. Given these findings, wetted history is a key variable to assess prior to initiating a fish stranding assessment or fish salvage response to an operation flow reduction.
	MQ3: Can a conditioning flow (temporary, one step, flow reduction of approximately 2 hours to the final target dam discharge that occurs prior to the final flow change) from HLK reduce the stranding rate of fishes?	Experimental flow ramping studies conducted in the summers and winters of 2004, 2005 and 2006 (prior to CLBMON-42) indicated that the use of a conditioning flow reduction appears to reduce the incidence of pool stranding on the Columbia River; however, this relationship was not statistically significant and the analysis was based on limited results and further conditioning flow experiments were recommended (Golder 2007; Irvine et al. 2009). During the 13 year period of CLBMON-42, conditioning flows have not been conducted and there is still considerable uncertainty regarding the efficacy of a conditioning flow at reducing the probability of stranding. Given the limited experiments conducted, a definitive answer regarding whether a conditioning flow can reduce the stranding rate cannot be determined.
	MQ4: Can physical habitat works (i.e., recontouring) reduce the incidence of fish stranding in high risk areas?	Six fish stranding sites on the lower Columbia River were recontoured between 2001 and 2015. To assess the effectiveness of recontouring, a statistical analysis was conducted on the 20 years of lower Columbia River fish stranding data to model the probability of stranding and number of fish stranded before vs. after recontouring (Appendix E). Results indicate a significant reduction in both probability and number of fish stranding after recontouring compared to before recontouring. These results agree with previous analyses (Golder and Poisson 2010, Irvine et al. 2014) on recontouring and suggest that recontouring sites that pose a high stranding risk to fish is an effective mitigation strategy to reduce overall stranding.
	MQ5: Does the continued collection of stranding data, and upgrading of the lower Columbia River stranding protocol, limit the number of occurrences when stranding crews need to be deployed due to flow reductions from HLK?	During the 13 year period of CLBMON-42 the number of annual stranding assessments conducted in response to reduction events from HLK/ALH has not decreased. Over the study, the annual number of stranding assessments conducted due to flow events at HLK/ALH has ranged from 8 to 15 (median = 12; average = 12) with no increasing nor decreasing trend. The stranding protocol was developed in 2011 (Golder 2011) and has not been updated since that time. It is currently undergoing an update based on the findings of the CLBMON-42 program (Golder 2020 in prep.).

Acronyms

BRD/X - Brilliant Dam and Brilliant Expansion Powerplant

CLBMON-42 - Lower Columbia River Fish Stranding Assessment and Ramping Protocol

COFAC - Columbia Operations Fish Advisory Committee

HLK/ALH - Hugh L. Keenleyside Dam and Arrow Lakes Generating Station

kcfs – thousands of cubic feet per second

LUB – Left upstream bank

MID – Mid-stream island

QA/QC - Quality assurance and quality control

RUB – Right upstream bank

ZIGLMM - zero-inflated generalized linear mixed model

Acknowledgements

The Lower Columbia River Fish Stranding Assessment and Ramping Protocol (CLBMON-42) was funded by BC Hydro's Columbia River Water Use Plan. The following organizations and individuals have contributed to the program between 2008 and 2020.

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1.0 INTRODUCTION

Fish stranding has been broadly recognized as a factor contributing to fish mortality. Fish can become stranded when water levels recede within the varial zone (the zone subject to seasonal inundation) of riverine habitats. When this occurs, fish can become stranded in habitats that are disconnected from the main channel (pool stranding) or become stranded between substrate particles in dewatered habitat (interstitial stranding).

Hydroelectric facilities have direct influences on water levels and thus, can affect fish stranding downstream of their operations. The Columbia River water levels below Hugh L. Keenleyside Dam and Arrow Lakes Generating Station (HLK/ALH) and lower Kootenay River below Brilliant Dam and Brilliant Expansion Powerplant (BRD/X) are influenced by the operations of these facilities.

Fish stranding was raised as an environmental issue associated with Hugh L. Keenleyside Dam (HLK) operations by the regulatory agencies in the mid-1990's, at which time environmental monitoring began. Since that time, fish stranding assessments and flow ramping studies have been conducted, dam operations have been reviewed, flow smoothing (reductions in magnitude and frequency of reductions) has occurred, and habitat recontouring of high-risk fish stranding sites has been conducted. In addition, since the mid-1990's fish stranding assessment methods have been improved, standardized and adapted to include Kootenay River operations (BRD/X).

To continue studies related to fish stranding and dam operations, the Lower Columbia River Fish Stranding Assessment and Ramping Protocol (CLBMON-42) was implemented in 2007 as part of BC Hydro's Water Use Plan for the Columbia River (BC Hydro 2007a). The primary objective of CLBMON-42 was to continue the collection of fish stranding data to assess the impact of flow reductions and flow ramping rates from HLK[2] on the native fish species of the lower Columbia River.

The approach to the monitoring program included three components:

- The continued collection of fish stranding data due to flow reduction events that occurred due to HLK/ALH, and the subsequent establishment of a lower Columbia River stranding protocol;
- Conduct flow ramping studies designed to determine the effect of different flow reduction strategies on the stranding rates of fish; and
- Conduct physical habitat works in the form of gravel bar recontouring at locations where high rates of fish stranding occurs.

Since the implementation of CLBMON-42 there have been 13 years (2007/2008 to 2019/2020; study period of 1 April to 1 April annually) of fish stranding assessments conducted on the lower Columbia and Kootenay rivers due to flow reduction events from HLK/ALH and BRD/X. This data adds to 7 years (2000 to 2006) of fish stranding assessments that have been conducted in response to flow reduction events from HLK/ALH and BRD[3] after stranding assessment methods were standardized in 1999. Collectively there is a 20-year dataset to assess the impact of flow reduction and flow ramping rates.

[2] The CLBMON-42 monitoring program is specific to operations at HLK; however, this facility operates in association with Arrow Lakes Generating Station (ALH) and will be referred to as the combined operation of HLK/ALH. The management questions of the program are presented as written in the CLBMON-42 Terms of Reference (BC Hydro 2007a).

[3] Construction of the Brilliant Dam Expansion Generating Station (BRDX) was completed in 2007. Prior to 2007 stranding assessments were conducted in response to flow reductions events from BRD.

Additional components that have been undertaken during CLBMON-42 include:

- The development of a stranding protocol entitled, *The Canadian Lower Columbia River: Risk Assessment and Response Strategy* (Golder 2011). The development of the protocol was guided by a literature review and data analysis (Golder and Poisson 2010) on previous years (1999 to 2009) of fish stranding assessment data collected from the lower Columbia River. This document outlines the roles and responsibilities pertaining to flow reductions for owners and operators of hydroelectric facilities on the lower Columbia and Kootenay rivers and outlines the protocols for conducting fish stranding assessments.
- Physical habitat recontouring of high risk stranding sites occurred at Fort Shepherd Launch (RUB) between fall of 2012 and spring of 2013 (recontouring conducted by Columbia Power Corporation [CPC] as a component of the CPC Owner's Commitment #39 [CPC 2011]), and at Lions Head (RUB) in 2015 (recontouring conducted by BC Hydro). An additional four sites (Lower Cobble Island [MID], Millennium Park [LUB], Norns Creek Fan [RUB], and Genelle Mainland [LUB]) on the lower Columbia River that were recontoured between 2000 and 2007 with the intention of reducing fish stranding.

Experimental flow ramping studies were not conducted as part of CLBMON-42. Flow ramping studies on the lower Columbia and Kootenay rivers downstream of HLK/ALH and BRD/X were conducted prior to CLBMON-42 in the summers and winters of 2004, 2005 and 2006 (Golder 2005, 2006, 2007; Irvine et al. 2009). In 2008, a power analysis was conducted on the existing ramping experiment data (2004 to 2006) and presented to Columbia Operations Fish Advisory Committee (COFAC) to provide an indication of how many more experiments may have to be done to get an acceptable level of statistical power of 0.8 (Peterman 1990) for the experimental variables of conditioning reduction, ramping rate, and time of day (Irvine 2008). To determine if these variables had a statistically significant effect on fish stranding, the effect size from the altered operations would have to be greater than 50% and many more experiments would be required. In response to this analysis, COFAC members determined it was the best use of resources to analyse the stranding assessment data to see what factors may influence fish stranding before proceeding with further ramping studies.

This report provides a summary of the 20 years of fish stranding assessments on the lower Columbia and Kootenay rivers, including a brief overview of the methods (Section 3.0) and a summary of the key results as they relate to the program's management questions (Section 4.0). Results from the final year (2019/2020) of fish stranding assessments conducted under CLBMON-42 are provided in Golder (2020).

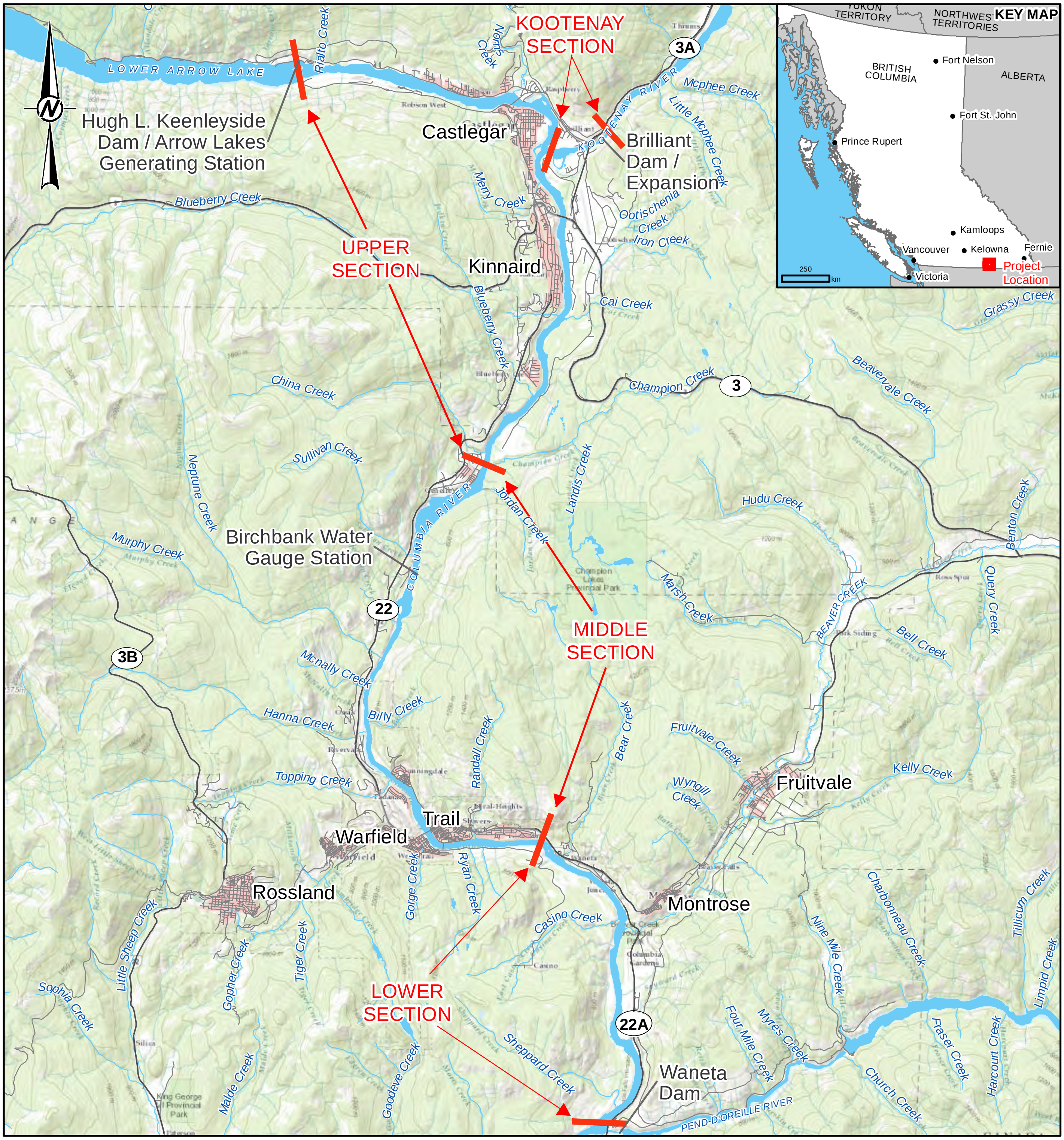
Standardized protocols for fish stranding assessments are provided in Appendix B and additional details regarding methods, results, and discussion for the statistical analyses conducted to address the program's management questions are provided in Appendices C to E.

2.0 STUDY AREA

The CLBMON-42 study area encompasses the approximately 56 km long section of the lower Columbia River from HLK/ALH to the Canada/USA border, and includes the lower Kootenay River (approximately 2.8 km) from BRD/X to the Columbia River confluence (Figure 1). Water levels in the lower Columbia River are primarily regulated by HLK/ALH and BRD/X and are also influenced by several minor tributaries.

At HLK/ALH, discharge changes occur periodically, typically weekly or longer, to provide different base flow levels (minimum daily operating level) to the lower Columbia River. Flow changes from HLK/ALH are usually due to Columbia River Treaty requirements in response to flood control or changes in power demand, with adjustments to meet environmental needs. Discharge changes typically occur during daylight hours and BC Hydro operating restrictions limit changes to 425 m^3/s (15 kcfs [thousands of cubic feet per second]) per day. Flood control or full pool are necessary exceptions to these restrictions (BC Hydro 2007b).

System operations at BRD/X can be more dynamic due to the need to meet system load requirements. When not maintained constant, or passing inflows, load factoring can occur when Kootenay River inflows are between 510 and 1218 m^3/s (18 and 43 kcfs). Load factoring results in shaping average daily inflows into peak discharge during high load hours (0600 to 2200 hrs) and minimum discharge during low load hours (2200 to 0600 hrs). BRD/X target minimum discharge is 510 m^3/s (18 kcfs) year-round except for October and November when the target is 453 m^3/s (16 kcfs).



LEGEND

- ● TOWN
- HIGHWAY
- ROAD
- WATERCOURSE
- RESIDENTIAL AREA
- WATERBODY

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REFERENCES

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DATUM: NAD 1983 UTM ZONE 11N

CLIENT
BC HYDRO

PROJECT
LOWER COLUMBIA RIVER FISH STRANDING ASSESSMENT AND RAMPING PROTOCOL (CLBMON-42)

TITLE
STUDY AREA OVERVIEW

CONSULTANT

GOLDER

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PREPARED	CD
REVIEWED	SR
APPROVED	SR

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3.0 METHODS

3.1 Overview

The Canadian Lower Columbia River: Risk Assessment and Response Strategy (Golder 2011) was developed with the primary objective to mitigate the effects of flow reductions from HLK/ALH and BRD/X on native fish species through flow reduction planning. The document outlines the roles and responsibilities pertaining to flow reductions for owners and operators of hydroelectric facilities on the lower Columbia and Kootenay rivers.
In addition, this document outlines the standardized protocols for conducting a fish stranding risk assessment, and a field-based fish stranding assessment in response to a flow reduction event, which are summarized below.

3.1.1 Fish Stranding Risk Assessment

Once a flow change decision was made, a fish stranding risk assessment was conducted by the BC Hydro Discharge Change Coordinator with input from the Golder Stranding Assessment Supervisor to determine the appropriate environmental response. The risk assessment was based on both the current environmental conditions, as well as results of past stranding assessments stored in the Lower Columbia River Fish Stranding Database. For a proposed flow reduction, risk period (High Risk period [1 June to 30 September] and Low Risk period [1 October to 31 May]), magnitude of flow reduction, resulting river stage (fish stranding risk is generally inversely related to river stage), water temperature and wetted history were all considered. Additionally, a query was conducted on the Lower Columbia River Fish Stranding Database which ranked fish stranding risk at fish stranding sites downstream of HLK/ALH and BRD/X based on historical fish stranding assessment data (year 2000 to present). Based on the above variables and the results of the database query a decision was made by the BC Hydro Discharge Change Coordinator to proceed with the proposed flow reduction either with, or without a field-based fish stranding assessment being conducted.

3.1.2 Fish Stranding Assessments

Standard methodology was followed for each fish stranding assessment as described in The Canadian Lower Columbia River: Risk Assessment and Response Strategy (Golder 2011) and in Appendix B. The primary objective of conducting fish stranding assessments in response to reduction events was to collect information on the effects of flow reduction on fish stranding, and the secondary objective was to conduct a fish salvage (thereby also acting as a mitigation measure for fish stranding).

Fish stranding assessments were conducted in response to flow reduction events from HLH/ALH or BRD/X between 1 January 2000 and 1 April 2020. Fish stranding assessments occurred on the same day as an operational flow reduction from HLK/ALH or BRD/X. The results of the query conducted on the Lower Columbia River Fish Stranding Database (described above in Section 3.1.1) dictated which of the 29 stranding sites on the Lower Columbia and Kootenay rivers (Appendix A) would be the focus for each stranding assessment. Sites from the database query were ranked as follows (Golder 2011):

- ‘Effect’ (>200 fish stranded during a previous reduction)
- ‘Minimal Effect’ (<200 fish stranded during a previous reduction)
- ‘No Pools’ (no pools present based on previous reductions)
- ‘Reconnaissance’ (less than five stranding assessments have been conducted since year 2000).

Stranding sites were assessed in order from high to low priority based on the site ranking from the database query. Sites ranked as ‘Effect’ were the highest priority. The next priorities were ‘Reconnaissance’ ranked sites, and, if time permitted, ‘Minimal Effect’ or ‘No Pools’ ranked sites. In addition, stranding assessments began at the most upstream site identified for assessment by the database query and site assessments continued downstream throughout the day following the stage recession. This standardized order of site assessment ensured that no site would be assessed prior to the effects of the flow reduction reaching each stranding site.

For each fish stranding assessment, the first site visit occurred no later than one hour after the final reduction and typically 7 to 10 sites were assessed throughout the day. The overall sampling design allowed for repeated collection of fish stranding data both spatially and temporally.

At each site, the current conditions (i.e., date, time, weather, air temperature, water temperature, approximate vertical drawdown of the water level, and substrate material) were documented on field forms. The number of isolated pools or dewatered pools that were created as a result of the flow reduction was recorded. Pools were assessed for stranded fish using a method suitable to the size and depth of the pool, including backpack electrofishing, seine netting, or visual assessment. If time permitted, fish were salvaged and returned to the mainstem of the Columbia or Kootenay rivers. Captured fish were identified to species if possible and were classified by life stage (egg, young of year, juvenile, adult). Fish length data were collected from up to 20 individuals of each species per site. All live fish captured were returned to the mainstem of the Columbia or Kootenay river. Interstitial stranding areas (i.e., dewatered substrate) within each site were searched for stranded fish and the total area searched was documented. The total number of live, dead, and salvaged fish from each site were recorded by species and life stage.

3.2 Data

All data from fish stranding assessments conducted prior to, and during CLBMON-42 are stored in the Lower Columbia River Fish Stranding Database in Microsoft Access format. All fish stranding assessment data was entered into the database under a unique reduction event number and each reduction event was identified as occurring due to a flow reduction at HLK/ALH, BRD/X, or a flow reduction from both facilities. In addition, flow data from the Water Survey of Canada Birchbank Gauging Station (Station Number 08NE049; Birchbank), HLK/ALH, and BRD/X was entered into the database for each reduction. The flow data for Birchbank was entered as daily maximum and minimum discharge (to the nearest hour) in kcfs on the day of each flow reduction. Flow data for HLK/ALH and BRD/X was entered as baseflow (in kcfs) before and after the flow reduction and includes number of ramps (i.e., individual drops in flow per reduction) and average ramping rate (total flow reduction divided by number of ramps) as identified by the facility responsible for the flow reduction.

Three separate statistical analyses were conducted on the data from the Lower Columbia River Fish Stranding Database to address the effect of flow ramping, wetted history, and physical habitat recontouring on fish stranding in the lower Columbia and Kootenay rivers (Appendices C to E). These analyses were designed to address management questions 1, 2 and 4 from CLBMON-42 (BC Hydro 2007a). A brief description of the datasets, and methods of the statistical analyses are described in Section 3.2.1 and Section 3.3 below.

Data from the Lower Columbia River Fish Stranding Database was not used address the effect of using a conditioning flow (Management Question 3) to reduce fish stranding. A conditioning flow is an experimental flow regime which creates a short term (1-2 hour) flow reduction approximately 24 hours prior to a normal operational flow reduction. During CLBMON-42, conditioning flows were not conducted; therefore, the fish stranding data from the database is not adequate to answer the effect of a conditioning flow on fish stranding. This management question was discussed using data and analysis from flow ramping experiments in the summers and winters of 2004, 2005 and 2006 (Golder 2005, 2006, 2007; Irvine et al. 2009).

Data from the Lower Columbia River Fish Stranding Database was used to address whether the continued collection of fish stranding and upgrading of the lower Columbia River stranding protocol limited the number of occurrences when stranding crews were deployed for HLK/ALH reduction events (Management Question 5). A statistical analysis was not deemed necessary, and instead the annual total of reduction events and stranding assessments conducted as a result of flow changes at HLK/ALH were plotted to visually assess trends of the period of CLBMON-42.

3.2.1 Data Quality Assurance/Quality Control and Compilation

As stranding survey methods were standardized in 1999, only data from 1999 to 2020 were considered comparable. However, data from 1999 had missing values for one or more variables for many reduction events and were not used. Therefore, the data used for all analyses included reduction events from January 2000 to March 2020 and included reduction events resulting from changes in discharge at HLK/ALH, BRD/X, or both facilities. Although the management questions are specifically directed at flows from HLK, the addition of reduction events from BRD/X in each analysis allowed for the most complete dataset to address environmental and operational variables affecting fish stranding in the lower Columbia and Kootenay rivers.

Prior to analysis, Quality Assurance/Quality Control (QA/QC) of the 20-year dataset described above was conducted including exploratory plotting and checks on maximum and minimum values. During QA/QC, some stranding sites were omitted from analyses due to the small sample size (i.e., few site visits). In addition, some reduction events were omitted from analysis due to key information missing from the database (i.e., ramping rate, or discharge), or because some aspect of the reduction event made the data not comparable or reliable.

Between 2000 and 2020, some reduction events occurred on a single day but others involved reductions on multiple consecutive days. For multi-day reductions, some stranding assessments occurred on each day of the reduction event, but occasionally only one assessment was conducted on the final day of the reduction event. Beginning in 2018, each day of multi-day reductions was entered in the database as a separate reduction event. Because the number of reduction days and assessment days were not always the same between reduction events from 2000 to 2020, the unit of observation was the reduction event (rather than the individual reduction date). To compile the data by reduction event, the number of stranded fish was summed across all survey dates and reduction dates. Similarly, the minimum and maximum discharge at Birchbank was summarized to describe the entire range of discharge across all reduction days where applicable.

For the six sites where physical habitat recontouring was conducted, fish stranding assessments were conducted both before and after the recontouring event. The data allow assessment of the effectiveness of recontouring in reducing fish stranding following a before/after study design. Genelle Lower Cobble Island (MID) site was recontoured in 2001 but this site was not included in the analysis because it could not be

properly assessed without boat access, and the assessments done in recent years were strictly visual surveys from across the river. The assessment surveys at Genelle Lower Cobble Island (MID) are therefore not directly comparable to those conducted at the other sites where recontouring has been conducted.

After QA/QC and data compilation, the total sample size of the datasets used to address the effects of ramping rate, wetted history, and physical habitat recontouring on fish stranding are described in Table 1.

Table 1: Datasets used to address the effects of ramping rate, wetted history, and physical habitat recontouring on fish stranding.

Variable Tested	Number of Site Visits	Total Number of Reduction Events (number per facility responsible for reduction event)	Number of Sites
Ramping Rate	2,571	305 (244 from HLK/ALH, 33 from BRD/X, 27 from both, 1 identified as “Other”)	24
Wetted History	2,764	338 (255 from HLK/ALH, 52 from BRD/X, 30 from both, 1 identified as “Other”)	24
Physical Habitat Recontouring	1,049	321 (244 from HLK/ALH, 33 from BRD/X, 27 from both, 1 identified as “Other”)	5

3.3 Data Analysis

Using the datasets described above, a zero-inflated generalized linear mixed model (ZIGLMM) was used to conduct each statistical analysis to assess the effects of flow ramping rate, wetted history, and physical recontouring on fish stranding in the lower Columbia and Kootenay rivers. This model was selected because it is suitable for modelling count data (i.e., the number of fish stranded) that have many zeroes and a large variability in the counts. For each analysis, the response variable was the number of fish stranded (all life stages and species combined) and the unit of observation was each site visit during each reduction event. The predictor variable of primary interest to the management question for each of the three statistical analyses are briefly described below.

3.3.1 Ramping Rate

Ramping rate describes the rate at which discharge was reduced for each reduction event. Ramping rate was obtained from the LCR Fish Stranding Database, where it was recorded for each day of each reduction event in the field called “AverageRampingChange”. For multi-day reductions, the average of values for all reduction days was used. The value in the database was obtained from information from dam operators prior to the reduction event, which was used instead of the realized rate of change in discharge at Birchbank, because it is more closely linked to operational strategies. Ramping rates are reported as change in kcfs per hour, instead of metric units (m^3/s per hour), following the convention used by dam operators and protocols for ramping rates.

3.3.2 Wetted History

The wetted history is defined as the number of days that habitat had been inundated with water before de-watering. Wetted history was calculated for each reduction event as the number of days prior to the reduction date that discharge was above the minimum discharge reached for that event. Discharge values from the Birchbank gauging station were used to calculate wetted history because this station is downstream of the confluence of the Columbia and Kootenay rivers, and therefore represents changes in the river level resulting from discharge changes at both HLK/ALH and BRD/X. The values of minimum discharge at Birchbank were extracted from the LCR Fish Stranding Database, and the dates for the previous date of lower discharge were obtained from hourly discharge data for Birchbank from BC Hydro’s Columbia Basin Hydrological database. Wetted history was capped at 365 days, such that all values greater than 365 were assigned a value of 365. This was done because the large range of wetted histories (up to 5684 days), combined with the low sample sizes and highly variable counts of fish at large values of wetted history, led to problems with model fitting. The rationale for the maximum value of 365 days was that re-colonization of habitat was expected to occur within one year of re-watering. Wetted history was modeled as a fourth order polynomial, which was necessary to capture the observed trend in the data. Modelling wetted history as a linear or lower order polynomial resulted in trends in the residual error that indicated poor model fit (Appendix D).

3.3.3 Physical Habitat Recontouring

After a site was recontoured, a new site was created in the lower Columbia River Fish Stranding Database; therefore stranding data from before and after the recontouring event was entered separately allowing for comparison of fish stranding at each site before and after recontouring efforts. Physical habitat recontouring was included in the model as a categorical variable with values of “Before” or “After” recontouring.

3.3.4 Effects of Predictor Variables

Other predictor variables included in the models to account for their potential effect on fish stranding were the magnitude of reduction (difference between maximum and minimum discharge at Birchbank for each reduction event), minimum discharge (lowest discharge reached at Birchbank for each reduction event), day of year, load shaping (as a categorical variable), and river kilometre for each stranding site as measured from HLK/ALH. Stranding site and year were included as random effects in the model.

The ZIGLMM was a two-stage hurdle model with one component that described the non-zero counts of stranded fish (conditional model), which was used to assess the severity of stranding (i.e., the number of fish), and one component that described the probability of zero vs. non-zero counts of stranded fish (zero-inflation model), which was used to assess the probability of stranding.

Statistical significance of the effect of predictor variables on the conditional model and on the zero-inflation model was assessed. Effect size was assessed using plots of the predicted values of the response variable versus one of the predictor variables, while holding other continuous predictor variables at their mean values and holding the categorical variable (load shaping) at its reference value of no load shaping. These "population-level" predictions from the fitted model are predictions with the random effects of site and year set to zero, which represents the predictions for an average site and an average year. For the analysis on recontoured sites the effect size was assessed using plots of random-level predictions for each site and year.

In this summary report, the management questions were addressed based on trends in the data, and the effect sizes and statistical significance from the models. Where possible, supporting information from other studies was considered when assessing the effects of environmental variables on fish stranding. Additional details of methods and results from statistical analyses are provided in Appendix C, D, and E. A summary of the results and conclusions are presented below in a section for each of the monitoring program's management questions.

4.0 RESULTS AND DISCUSSION

4.1 Management Question #1

"Is there a ramping rate (fast vs. slow, day vs. night) for flow reductions from HLK that reduces the number of fish stranded (interstitially and pool) per flow reduction event in the summer and winter?"

Based on 20 years of fish stranding assessment and experimental flow ramping studies conducted prior to CLMBON-42, ramping rate within the range of operational ramping rates currently used at HLK/ALH does not appear to influence fish stranding in the lower Columbia River.

Twenty years of data from fish stranding assessments were used to assess the effect ramping rate on the number of fish stranded, using a statistical model that accounted for other variables that can influence stranding, such as magnitude of discharge reduction, day of year of reduction, and river stage. For this analysis, ramping rate was represented as the average ramping rate for each reduction as controlled by the hydroelectric facility responsible for the reduction. The majority of operational ramping rates per reduction were within the range of 1 to 10 kcfs/hour. The available data and modelling results suggest no effect of ramping rate on the likelihood or number of fish stranding (Appendix C). These results agree with a previous analysis of lower Columbia River fish stranding assessments using data from 1999 to 2009. In this previous statistical analysis, ramping rate for each reduction was calculated as the rate of change in cm/hour as measured at Birchbank (Golder and Poisson 2010; Irvine et al. 2014). Ramping rate did not have a statistically significant effect on stranding risk. (Golder and Poisson 2010; Irvine et. al. 2014).

Experimental flow ramping studies also found no significant effect of ramping rate on fish stranding. Between 2004 and 2006, experimental flow ramping studies were conducted in the summer and winter on the Columbia and Kootenay rivers to assess the effect of flow ramping rate on the probability of pool and interstitial stranding of juvenile fishes (Golder 2005, 2006, 2007). Over the range of ramping rates tested (3.9 to 13.3 cm/h for interstitial stranding experiments, and 7.4 to 35.3 cm/h for pool stranding experiments as measured within test sites), ramping rate did not have a statistically significant effect on interstitial or pool stranding (Golder 2007). A subsequent statistical analysis conducted on the three years of experimental flow ramping data found that there was a trend of increased fish stranding frequency with increased ramping rates for pool stranding experiments, but the relationship was fairly weak, and ramping rate was ranked low in terms of variable importance in the statistical models (Irvine et al. 2009). Similar results showing a lack of effect of ramping rate were reported in experimental flow ramping studies conducted in the lower Duncan River (Golder 2008; Irvine et. al. 2009).

As hypothesized by Golder and Poisson (2010), the lack of a detectable effect of ramping rates may be because of the relatively small range of ramping rates observed in the lower Columbia River, compared to studies elsewhere where ramping rates were often much faster. In experimental studies, Salveit et. al. (2001) assessed ramping rates between 14 and 78 cm/hr and found a found a decrease in fish stranding when rates were slow (14-18 cm/hr). Although ramping rate was never a statistically significant predictor on fish stranding in studies in the lower Columbia River, the trend of increased fish stranding with increased ramping rate found during experimental ramping studies (Golder 2005) has resulted in hydroelectric facilities adopting relatively conservative operational ramping rates for reduction events, to allow fish the greatest amount of time to leave the varial zone prior to de-watering.

An additional component of this management question is the effect of time of day, specifically day vs. night, on fish stranding. Some previous analyses have assessed the effect of time of day and reported a weak effect, but there have been few ramping experiments and no stranding assessments conducted during night-time. Therefore, the effect of time of day cannot be conclusively determined with the available data.

A statistical analysis on fish stranding assessment data (years 1999 to 2009) on the lower Columbia River assessed whether time of day had an effect on the probability of stranding fish (Golder and Poisson 2010; Irvine et al. 2014). Four definitions of stranding levels were modelled with greater than or equal to 1, 50, 200, and 1000 stranded fish required to constitute a stranding event. Based on the available data, the highest risk period for stranding was in the late afternoon. The relationship between time of day and fish stranding probability was significant only with the model that considered a stranding event to be equal to or greater than one fish; therefore it was not considered to be a strong predictor of stranding risk (Golder and Poisson 2010; Irvine et al. 2014). It should also be noted that stranding assessments used for this analysis were all conducted during the day, which causes inherent bias when assessing whether more fish strand during the day or night.

The effect of time of day (day vs. night) on fish stranding was also tested in experimental flow ramping studies in the summer and winter in 2004 and 2005 on the Columbia and Kootenay rivers (Golder 2005, 2006). Results indicated a weak trend for interstitial stranding to occur more at night than during the day in winter (Golder 2005), however an analysis conducted on all years of flow ramping studies revealed that time of day was not a statistically significant predictor for the probability of interstitial stranding in winter, or pool stranding in summer (Golder 2007; Irvine et al. 2009). The dataset for the analysis on all years of flow ramping studies was limited to seven night experiments and 65 day experiments. Other studies on the effect of time of day on juvenile fish stranding have provided conflicting results. In some studies, more fishes were stranded at night (e.g., Salveit 2001) while other studies noted greater stranding occurring during daytime (e.g., Bradford et al. 1995).

Additional night-time ramping experiments, or night-time reduction events and stranding assessments would be required to balance the dataset and determine if there is any difference in the probability of fish stranding between day and night.

4.2 Management Question #2

"Does wetted history (the length of time the habitat has been wetted prior to the flow reduction) influence the number of fish stranded (interstitially and pool) per flow reduction event for flow reductions from HLK?"

Based on 20 years of fish stranding assessments and experimental flow ramping studies conducted prior to CLBMON-42, wetted history does influence the number of fish stranded due to reduction events at HLK/ALH.

In the statistical analysis conducted on the 20-year dataset of fish stranding assessments in the lower Columbia and Kootenay Rivers, wetted history had a statistically significant positive effect on both the probability and number of fish stranding (Appendix D). This supports the idea that substrate that had been inundated for a longer period was more likely to strand fish if dewatered, compared to substrate that was inundated for a shorter period. The predicted probability of stranding zero fish decreased from 0.75 at 1 day of wetted history to 0.58 at 100 days of wetted history. The predicted number of fish stranded per site, based the combined models, increased from 21 fish at 1 day of wetted history to 52 fish at 50 days, and 93 fish at 200 days (Figure 2). At greater than 200 days of wetted history, there was large variability in the mean numbers of fish stranded, which resulted in large uncertainty in model predictions. As there were 24 stranding sites included in the analysis, a difference of 70 fish per site between 1 and 200 days wetted history suggests a biological meaningful effect of wetted history on stranding risk.

These results are supported by a previous statistical analysis of the lower of the lower Columbia River fish stranding assessment data (years 1999 to 2009), that found wetted history had a statistically significant effect on the probability of fish stranding (Golder and Poisson 2010). In that statistical model, when stranding was defined as greater than or equal to one fish, the probability of stranding was 18% at 0 days and approximately 40% at 90 days of wetted history. Additionally, there was a statistically significant increase in the probability of stranding after a wetted history of greater than 10 days (approximately 35%) versus a wetted history of less than ten days (approximately 17%). The reason for greater fish stranding with increased wetted history may be related to improved habitat in the near-shore area over time. Shallow near-shore habitat provides both cover for juvenile fish, and food availability. As a result, fish density likely increases in the near-shore habitat over time.

The effect of wetted history on fish stranding was also tested during three years (2004 and 2006) of experimental flow ramping studies on the lower Columbia and Kootenay rivers (Golder 2005, 2006, 2007). The experiments took place in the summer and winter of each year and assessed the effect of wetted history on the probability of pool and interstitial stranding. There was a general trend of increased fish stranding with increased wetted history; however this was not a significant indicator of fish stranding risk during flow ramping studies (Golder 2007). Irvine et. al. (2009) conducted a subsequent statistical analysis, on all years of experimental flow ramping studies to rank the effect of each tested variable (wetted history, time of day, natural fish density and conditioning flow) on interstitial and pool fish stranding risk. Wetted history ranked high in relative importance for fish stranding in pools, suggesting that the longer the varial zone is inundated with water prior to a flow reduction event, the greater likelihood more fish will strand as a result of the flow reduction.

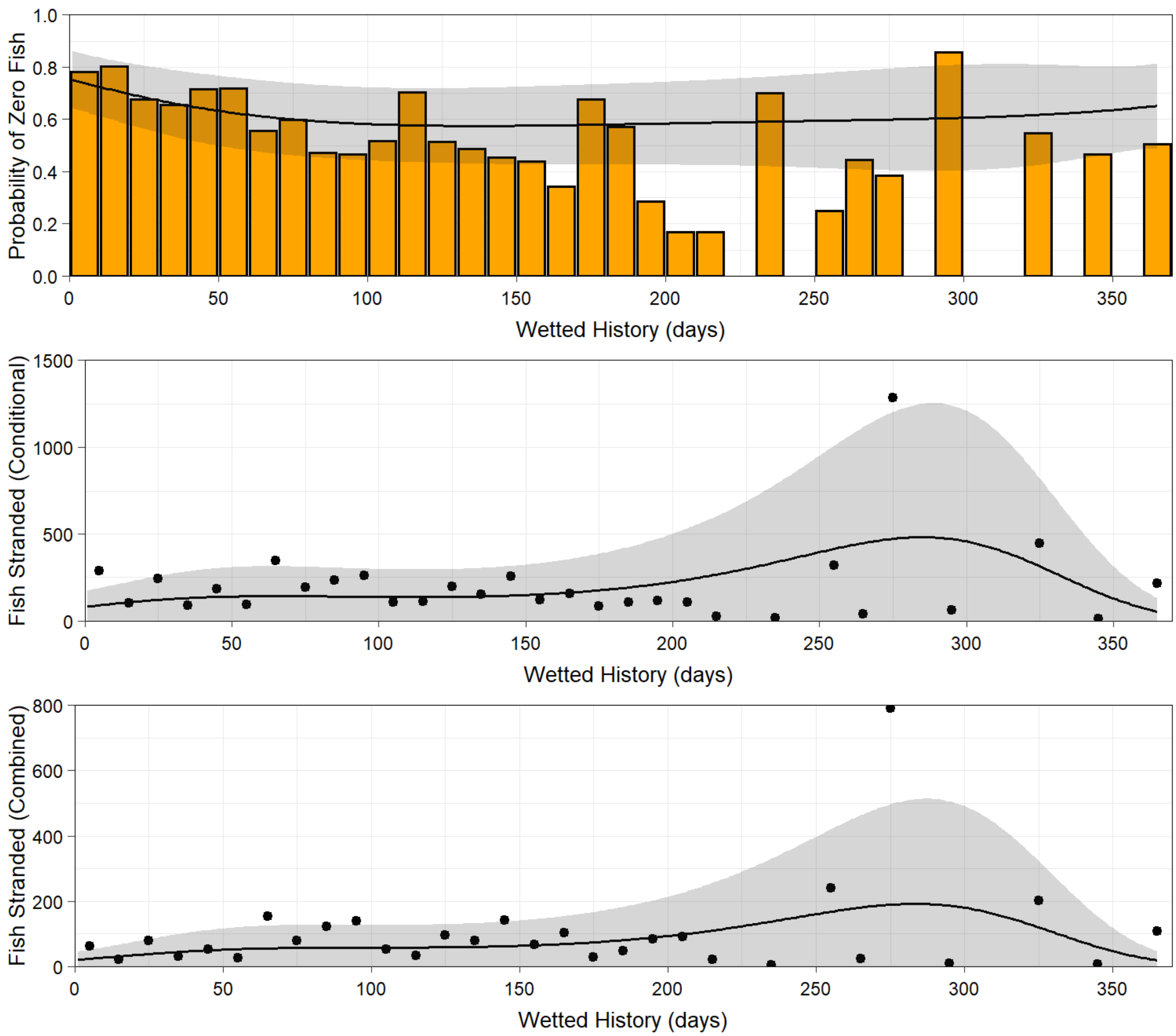

Figure 2: Predicted fish stranding versus wetted history in the lower Columbia River, 2000 to 2020. Predictions are from a negative binomial two-stage hurdle model where the top panel is the probability of zero fish stranded, the middle panel is the number of fish stranded for non-zero stranding events, and the bottom panel is the combined prediction based on the probability and magnitude of stranding. Orange bars and black points are the mean values of the observed data by 10-day bins of wetted history. Black line is the mean prediction and grey ribbon is the approximate 95% confidence interval.

4.3 Management Question #3

"Can a conditioning flow (a temporary, one step, flow reduction of approximately 2 hours to the final target dam discharge that occurs prior to the final flow change) from HLK reduce the stranding rate of fish?"

Due to limited conditioning flow experiments conducted the effect of this potential fish stranding mitigation measure cannot be determined.

The theory of a conditioning reduction is to create a 'learned' behaviour in fish inhabiting the varial zone. If a short-term (1-2 hour) flow reduction were to take place prior to the normal planned reduction, then fish inhabiting the varial zone may react with a flight response, leaving the near-shore area, thereby reducing overall fish density within the varial zone. If fish density was reduced in the varial zone due to the conditioning flow, then perhaps this would result in less fish stranding when the normal operational flow reduction follows.

The concept of a conditioning reduction and its potential as a fish stranding mitigation strategy was based on quantitative and qualitative observations that the number of fish in the near-shore area and the number of fish stranded both decreased through time on the Columbia and Kootenay River systems in the first phase of flow ramping experiments (Golder 2005). As a result of these observations, investigating the effect of a conditioning reduction on fish stranding in the lower Columbia and Kootenay rivers was the primary objective of flow ramping experiments conducted in the summer of 2006 downstream of HLK/ALH. Results of these experiments suggest that a conditioning flow appeared to reduce the incidence of pool stranding on the Columbia river (Golder 2007; Irvine et al. 2009); When the effects of the conditioning reduction as the single predictor variable were tested for significance using a quasibinomial distribution, the predicted value of the proportion of stranded fish in experiments without a conditioning reduction was 34.22% (95% CI: 23.4 to 46.2%), and the predicted value of the proportion of stranded fish with a conditioning reduction was 24.95% (95% CI: 11.6 to 45.52%) (Golder 2007). As these confidence levels overlap, the effect is not significant. However, these results were based on a limited number of experiments and a recommendation was made that additional experiments be conducted to verify the results (Golder 2001; Irvine et al. 2009).

As part of CLBMON-42, additional flow ramping experiments were not conducted (see Section 1.0), and the 20-year dataset of fish stranding assessments does not provide the necessary data to answer this management question. The fish stranding assessments were conducted in response to normal operational flow reductions, and conditioning flows were not implemented at HLK/ALH as a fish stranding mitigation strategy.

To further clarify the preliminary results regarding the effects of a conditioning flow on the rate of fish stranding, additional ramping experiments would be required. It is understood that additional ramping experiments would be an added cost and would require the manipulation of flows from HLK/ALH strictly for experimental purposes which may be challenging given Columbia River Treaty obligations.

The value of implementing conditioning flows may require an assessment of the operational risk versus the biological rationale. The implementation of conditioning reductions would result in an extra reduction for every normal operational reduction, effectively doubling the number of total reductions. Although the preliminary data from summer ramping experiments in 2006 suggest that a conditioning flow may reduce fish stranding, there is also the possibility that a conditioning reduction may in itself cause significant mortality. The time from dewatering until death is variable but can be less than 30 minutes (Hessevik 2002). In observations made on the lower Duncan River during ramping experiments conducted in the fall of 2009, less than 10% survival was noted for juvenile Mountain Whitefish that were aggregated in a pool that drained over the 30 minutes the water was absent (Poisson and Golder 2010).

4.4 Management Question #4

"Can physical habitat works (i.e., recontouring) reduce the incidence of fish stranding in high risk areas?"

Physical habitat recontouring conducted at high risk stranding sites on the lower Columbia River has reduced the incidence of fish stranding.

Physical habitat recontouring on the lower Columbia River has been conducted by using heavy equipment during periods of low river stage to remove or fill in potential stranding pools, decrease habitat cover, and increase channel slope. The intention of physical habitat recontouring is to minimize habitat features that may be conducive to fish stranding. **Table *2*** identifies the fish stranding sites on the lower Columbia River where physical habitat recontouring was conducted.

Table 2: Site and year of physical habitat recontouring on the lower Columbia River

Site	Year of Physical Habitat Recontouring
Genelle Lower Cobble Island (MID)	2001
Millenium Park (LUB)	2001
Norns Creek Fan (RUB)	2002
Genelle Mainland (LUB)	2003
Fort Shepherd Launch (RUB) [a]	Between Fall of 2012 and Spring of 2013
Lions Head (RUB)	2015

Notes

MID = mid-stream island; LUB = left bank as viewed facing upstream; RUB = right banks as viewed facing upstream

[a] The Fort Shepherd Launch (RUB) site was recontoured by Columbia Power Corporation (CPC) as a component of the CPC Owner's Commitment #39 ([Revised 10 November 2006] [CPC 2011]). This commitment included the development of a Shallow water Habitat Compensation Plan which was designed as the "Fort Shepherd Bar-Shallow-water Habitat Compensation Site" at the Fort Shepherd Launch (RUB) site.

Twenty years of data from fish stranding surveys were used to assess the effect of recontouring on the number of fish stranded using a statistical model that accounted for other variables that can influence stranding, such as magnitude of discharge reduction, day of year of reduction, and river stage (Appendix E). Results of modelling indicate a substantial reduction in both the probability and number of fish stranded after recontouring at all five sites assessed. Model predictions indicate a 14% reduction in the probability of stranding one or more fish, and a 66% reduction in the mean number of fish stranded, on average, after recontouring. When both the probability of stranding >0 fish and the predicted number of fish stranded models were combined, the model indicated a 71% decrease in the mean number of stranded fish, on average, after recontouring (Figure 3).

In 2010, an analysis on the fish stranding assessment data from 1999 to 2009 identified a significantly higher probability of a stranding event (identified as ≥200 fishes) occurring before recontouring (approximately 8%) compared to after recontouring (approximately 3%) (Golder and Poisson 2010, Irvine et al. 2014). This trend was also statistically significant when a stranding event was defined as greater than or equal to 1 fish, and greater than or equal to 50 fish.

These findings indicate that physical habitat recontouring does reduce overall fish stranding; however it is not known whether recontouring makes it easier for fish to escape during a reduction, or if the process of recontouring reduces favourable habitat and as a result there are fewer fish inhabiting these sites compared to before recontouring. The results may also indicate a combination of both scenarios. As the five sites in the lower Columbia River were recontoured between 2001 and 2015, trends in the predicted number of fish stranded suggest a persistent reduction in stranding that has lasted for many years after physical habitat recontouring.

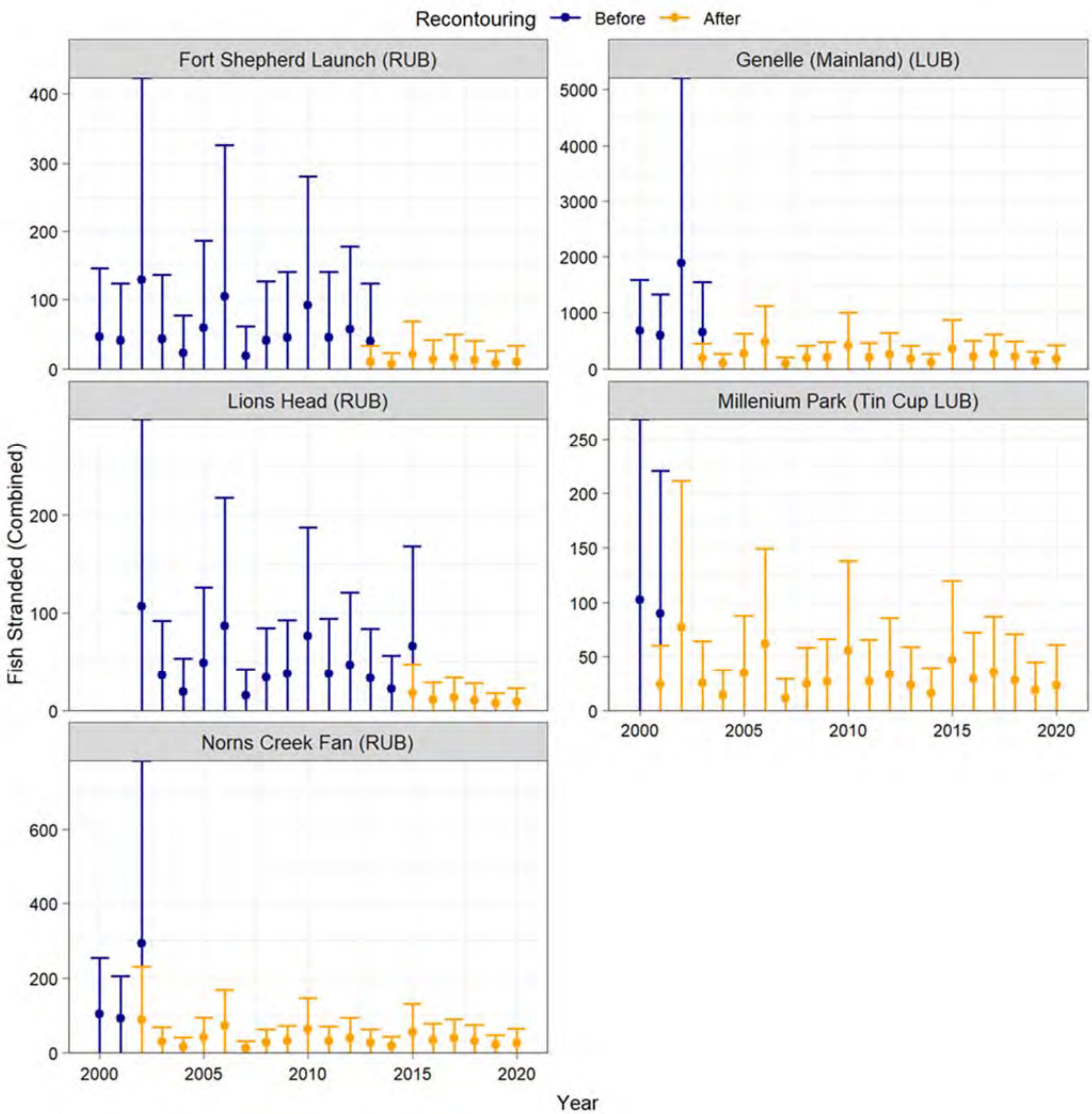

Figure 3: Predicted number of stranded fish in the lower Columbia River by year, site, and before/after recontouring. Points are predicted values and error bars are approximate 95% confidence intervals. Predicted values are the expected mean number of fish stranded based on the combined probability of stranding >0 fish, and predicted number of fish for non-zero events, from a negative binomial two-stage hurdle model.

4.5 Management Question #5

"Does the continued collection of stranding data, and upgrading of the lower Columbia River stranding protocol, limit the number of occurrences when stranding crews need to be deployed due to flow reductions from HLK?"

Over the 13-year period of CLBMON-42, the number of annual stranding assessments that have been conducted in response to reduction events from HLK/ALH has not decreased.

For every reduction event, the facility responsible for the reduction was identified and entered in the Lower Columbia River Fish Stranding database as either HLK, BRD, or both facilities (when a discharge reduction occurred at HLK and BRD). Figure 4 identifies which facility was responsible for annual reduction events and the stranding assessments that were conducted in response those reduction events for the duration of the 13-year CLMBON-42 period. The number of annual stranding assessments conducted due to HLK/ALH reduction events has ranged from 8 to 15 (median = 12; average = 12) and there has been no increasing nor decreasing trend since the 2007/2008 study period.

Another way to approach this management question is to look at annual fish stranding assessment response rate (the percent of yearly reduction events that are responded to with a stranding assessment) The response rate for HLK/ALH reduction events has varied from 60 to 92% (median = 82%), and in recent years the response rate has declined (92% in 2016/2017, 83% in 2017/2018, 65% in 2018/2019, and 60% in 2019/2020). It should be noted that response rate is affected by how a reduction event is defined. As identified in Section 3.2.1. some of reduction events occurred on a single day but others involved reductions on multiple consecutive days, so inconsistency in how a reduction event is defined influences both absolute number of annual reduction events and response rate.

Potential reasons for not seeing a noticeable decline in the number of stranding assessments conducted due to reduction events at HLK/ALH may be due to a change in focus of the fish stranding assessments over the duration of CLBMON-42. At the beginning of the program there were many data gaps pertaining to variables (i.e., river stage, wetted history, day of year, etc.) that affect fish stranding so there was a focus to conduct a number of 'Reconnaissance' assessments to fill these data gaps. As the program progressed, the focus shifted to a salvage approach. After the establishment of *The Canadian Lower Columbia River: Risk Assessment and Response Strategy* (Golder 2011), the database query, which identified which stranding sites had higher stranding risk than others (based on historical stranding data), became an important component for the decision making process of initiating a stranding response. Sites that were high risk were ranked as 'Effect' (>200 fish stranded during a previous reduction) and these sites became the focus of stranding assessments. Once a site was ranked as an 'Effect' site it could not be changed to a lower ranking. Additionally, as more stranding assessments were conducted over the years, a greater number of sites became ranked as 'Effect' sites, leading to a greater likelihood of a stranding assessment being conducted.

The Canadian Lower Columbia River: Risk Assessment and Response Strategy has not been updated since it was developed in 2011. An update to the protocol is currently being conducted (Golder in prep) and it will be used to guide the decision making process for initiation a fish stranding assessment response due to future flow reductions in lower Columbia and Kootenay rivers. For the update, the definition of 'Significant Fish Stranding' and 'Effect' will be re-examined and the results of CLBMON-42 will be incorporated.

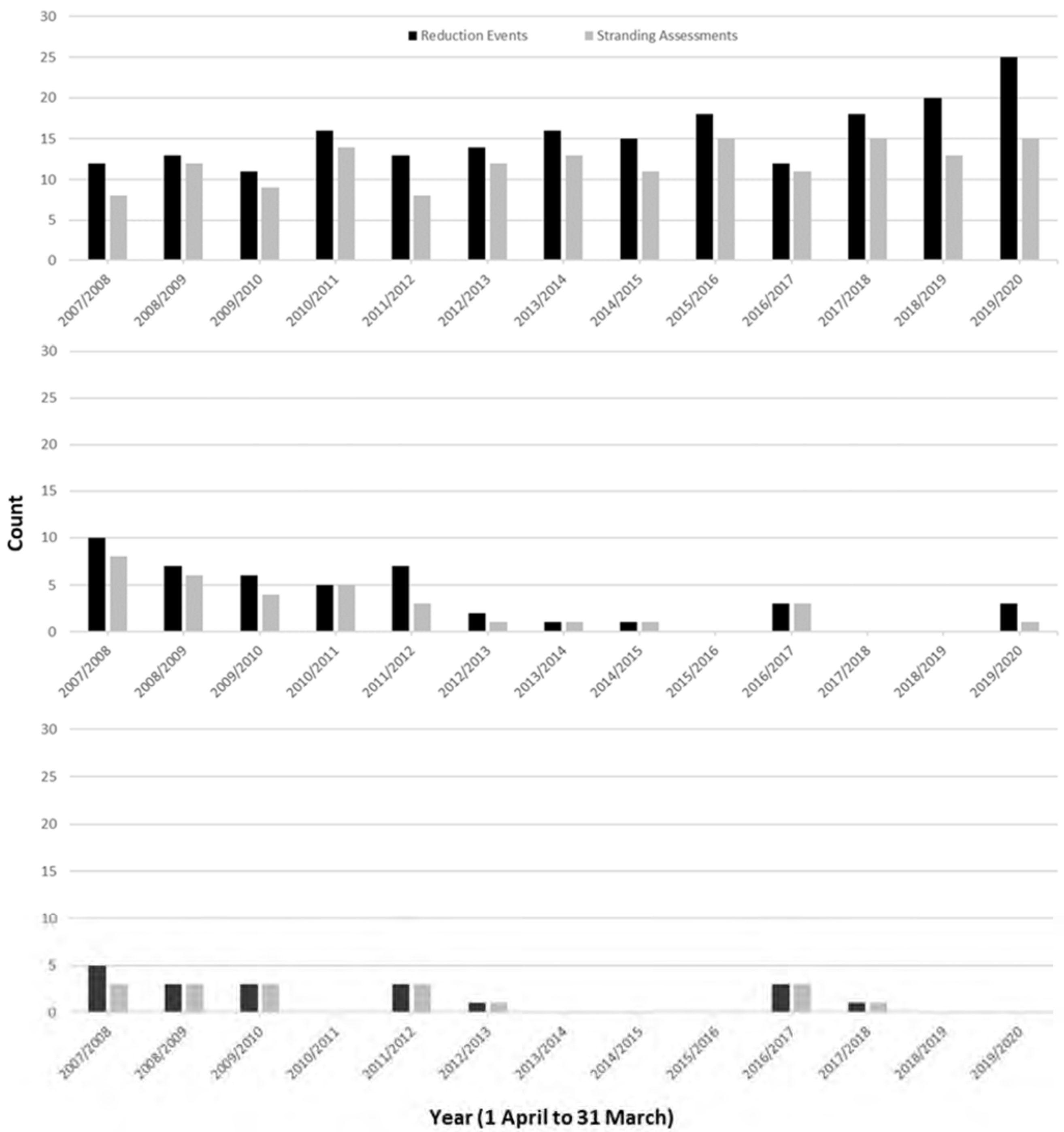

Figure 4: Annual reduction events (black bars) and stranding assessments (grey bars) conducted due to discharge reductions at HLK/ALH (top panel), BRD/X (middle panel) and discharge reductions from HLK/ALH and BRD/X at the same time (bottom panel).

4.6 Summary of Additional Key Findings

Additional predictor variables not directly related to the management questions of CLBMON-42, were also included in the statistical analyses conducted on the 20-year dataset of fish stranding assessments. These variables were included in models to assess their potential effect on fish stranding in the lower Columbia River. Results, in terms of significance of each variable on the probability and number of fish stranded were similar between the three analyses (Appendix C to E). For an indication of effect size, the analyses for wetted history (Appendix D) was used since this analysis had the most complete dataset from the Lower Columbia River Fish Stranding Database.

The magnitude of reduction was a significant predictor of both probability of stranding and predicted number of fish stranded; however, the trends were conflicting. There was a positive relationship between magnitude of reduction and probability of fish stranding. The probability of observing zero stranded fish decreased from 0.70 at a reduction magnitude of 25 m^3/s (0.9 kcfs) to 0.49 at a reduction magnitude of 500 m^3/s (17.7 kcfs). In contrast, the predicted number of fish stranded decreased from 66 fish at a reduction magnitude of 25 m^3/s (0.9 kcfs) to 50 fish at a reduction magnitude of 500 m^3/s (1.7 kcfs). The negative relationship between magnitude of reduction and the number of fish stranded was the opposite of the expected positive relationship and may be explained by the high variability and relatively small number of observations at very low and very high magnitudes of reduction. Overall, the results support a positive effect of magnitude of reduction on the probability of fish stranding (>0 fish) and a small and possibly spurious negative effect of magnitude of reduction on the number of fish stranded per site visit. Previous analysis conducted on the lower Columbia River fish stranding assessment data also found an increased stranding risk with an increase in reduction magnitude (Golder and Poisson 2010; Irvine et al. 2014).

The predictor variable of minimum discharge was included in the statistical analyses as a proxy to assess the effect of river stage on fish stranding. Minimum discharge was a statistically significant predictor of both the probability of stranding and number of fish stranded. The probability of observing zero stranded fish increased from 0.31 at a minimum discharge of 1000 m^3/s (35.3 kcfs) to 0.91 at a minimum discharge of 3000 m^3/s (105.9 kcfs). Outputs from the conditional model indicated some uncertainties in predictions at the extreme high (>3000 m^3/s [105.9 kcfs]) and low ends (<900 m^3/s [31.8 kcfs]) of minimum discharge; however, the results suggest increasing likelihood and severity of fish stranding with decreasing river stage in the lower Columbia River.

Golder and Poisson (2010) found the same trend when assessing the effect of minimum discharge on stranding. The probability of stranding one or more fish increased from 0.1 at 3000 m^3/s (105.9 kcfs) to 0.4 at 1000 m^3/s (35.3 kcfs) (Golder and Poisson 2010). In addition, minimum discharge was a significant predictor of stranding risk at all modelled levels of fish stranding (≥1, ≥50, ≥100, and ≥1000 fish). Increased stranding at lower river stage may be a result of differences in the slope, channel shape, and substrate types at different elevations of the riverbed. A gently sloped shoreline is more likely to strand fish compared to a steep shoreline due to the greater physical area that becomes de-watered (Nagrodski et al. 2012). At low water levels, hundreds of small depressions in the substrate at some low-angle stranding sites (i.e. Lions Head [RUB]) have been observed to strand fish.

Day of year was included in the statistical models to account for seasonal variation in stranding risk. Day of year was a statistically significant predictor of both the probability of stranding and number of fish stranded, with the predicted highest number of stranded fish (61 fish per site visit) occurring on June 26. Elevated numbers of fish stranded from April 10 to September 13 (10 or more fish stranded per site visit) and fewer than 10 fish predicted for dates outside of this range; however, observed data showed events with large numbers of stranded fish also occurred outside of this range of dates, particularly in October and November. While some studies on salmonids have found a much greater incidence of standing during the winter months (Heggenes and Salveit 1990; Salveit et al. 2001), results from fish stranding assessments indicate that summer is the highest risk season for fish stranding on the lower Columbia River (Golder and Poisson 2010; Irvine et al 2014). The increased risk of stranding in the summer is likely due to fish assemblage (i.e. greater numbers of young-of-year Sucker spp., and Cyprinids) and increased fish density in varial zone during summer months.

Relationships between the number of fish stranded and other predictor variables, such as the magnitude of reduction, minimum discharge, and day of year improve understanding of factors that affect fish stranding in the lower Columbia River and can be used to guide future fish stranding assessments and protocols.

5.0 CONCLUSION

The CLBMON-42 Management Questions ask if there are operational controls and environmental factors that influence the number of fish stranded due to flow reductions from HLK. Data collected over 20 years of fish stranding assessments on the lower Columbia and Kootenay rivers was analyzed using statistical models to address the management questions. Results from experimental flow ramping studies conducted prior to CLBMON-42 were also used to address the management questions where possible. This stranding assessment dataset was adequate to answer most management questions; however, some could not be conclusively answered due to limited data.

There was no evidence of an effect of ramping rate on the probability of stranding or the number of fish stranded. This suggests no difference in fish stranding risk within the range of operational ramping rates (1 to 5 kcfs/hr) currently used at HLK/ALH. The longer the period of time that a site is underwater (i.e. wetted history) prior to an operational flow reduction, the greater the probability of stranding fish, and the greater the number of fish stranded. This finding suggests that fish density in the near-shore area, where the majority of fish stranding sites are located, may increase with increased wetted history, and this environmental variable should continue to be considered when planning for a fish assessment or salvage response.

Physical habitat recontouring conducted at high risk stranding sites on the lower Columbia River has been a long-lasting effective method of reducing total numbers of fish stranded. The effect of time of day (day vs. night) and implementation of a conditioning flow on fish stranding risk could not be determined during this study; however, previous studies from the Lower Columbia River indicate that these likely do not have a strong effect on fish stranding.

6.0 CLOSURE

We trust that this report meets your current requirements. If you have any further questions, please do not hesitate to contact the undersigned.

Golder Associates Ltd.

Kevin Little, BSc
Aquatic Biologist

David Roscoe, MSc, RPBio
Fisheries Biologist

Shawn Redden, RPBio
Associate, Senior Fisheries Biologist

KL/DR/SR/cmc

https://golderassociates.sharepoint.com/sites/104258/project files/6 deliverables/draft - final wup report/19117420-004-r-rev0-wup lcr stranding 29sep_20.docx

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APPENDIX A

Fish Stranding Sites on Lower Columbia River

LEGEND

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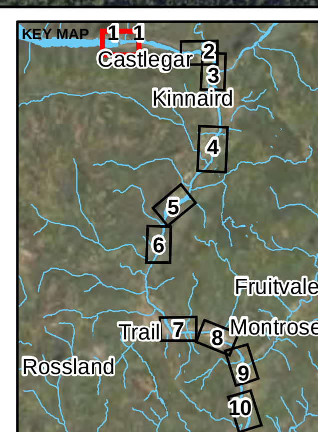
- WATERCOURSE



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3. DATUM: NAD83 PROJECTION UTM 11

CLIENT
BC HYDRO

PROJECT
LOWER COLUMBIA RIVER FISH STRANDING ASSESSMENT AND RAMPING PROTOCOL (CLBMON-42)

CONSULTANT

GOLDER

YYYY-MM-DD	2020-09-29
DESIGNED	KL
PREPARED	CD
REVIEWED	SR
APPROVED	SR

TITLE
FISH STRANDING ASSESSMENT SITES (JANUARY 2020 TO APRIL 2020)

PROJECT NO.	PHASE	REV.	FIGURE
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STRANDING SITE

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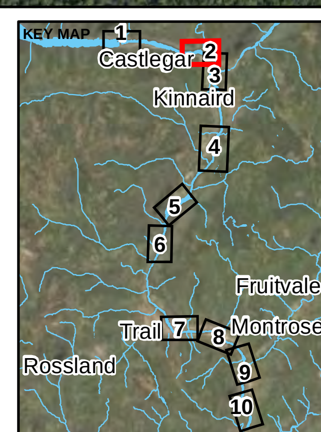

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BC HYDRO

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CONSULTANT

GOLDER

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APPROVED	SR

TITLE
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- STRANDING SITE
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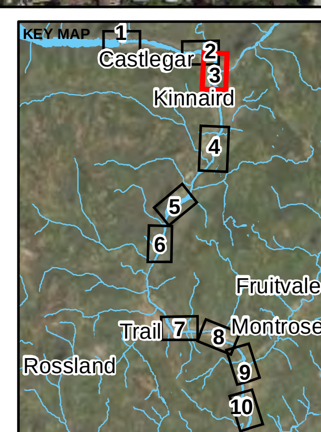

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PROJECT
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CONSULTANT

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FISH STRANDING ASSESSMENT SITES (JANUARY 2020 TO APRIL 2020)

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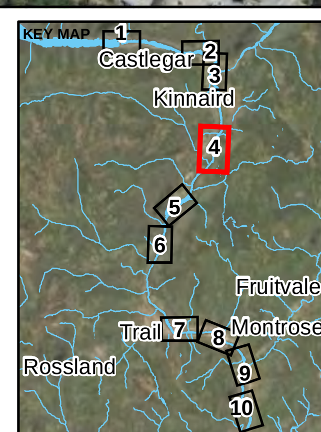

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3. DATUM: NAD83 PROJECTION UTM 11

CLIENT

BC HYDRO

PROJECT

LOWER COLUMBIA RIVER FISH STRANDING ASSESSMENT AND RAMPING PROTOCOL (CLBMON-42)

CONSULTANT

GOLDER

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FISH STRANDING ASSESSMENT SITES (JANUARY 2020 TO APRIL 2020)

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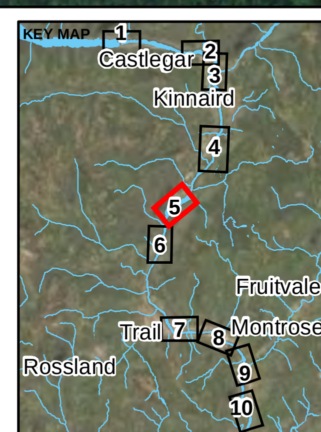

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CLIENT
BC HYDRO

CONSULTANT
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PROJECT
LOWER COLUMBIA RIVER FISH STRANDING ASSESSMENT AND RAMPING PROTOCOL (CLBMON-42)

TITLE
FISH STRANDING ASSESSMENT SITES
(JANUARY 2020 TO APRIL 2020)

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- STRANDING SITE
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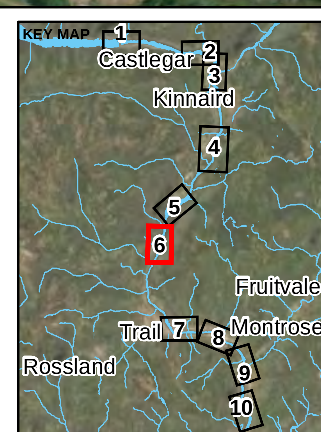

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3. DATUM: NAD83 PROJECTION UTM 11

CLIENT
BC HYDRO

CONSULTANT
GOLDER

YYYY-MM-DD	2020-09-29
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PROJECT
LOWER COLUMBIA RIVER FISH STRANDING ASSESSMENT AND RAMPING PROTOCOL (CLBMON-42)

TITLE
FISH STRANDING ASSESSMENT SITES (JANUARY 2020 TO APRIL 2020)

PROJECT NO.	PHASE	REV.	FIGURE
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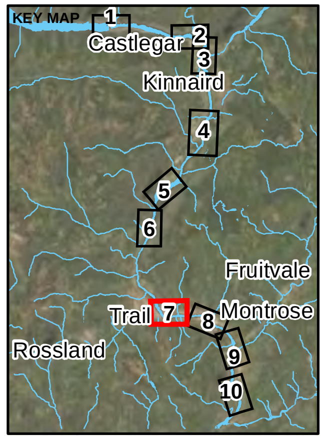
WATERCOURSE



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CLIENT
BC HYDRO

PROJECT
LOWER COLUMBIA RIVER FISH STRANDING ASSESSMENT AND RAMPING PROTOCOL (CLBMON-42)

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FISH STRANDING ASSESSMENT SITES (JANUARY 2020 TO APRIL 2020)

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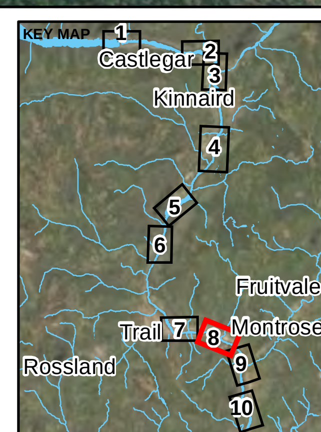
- STRANDING SITE
- WATERCOURSE



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PROJECT
LOWER COLUMBIA RIVER FISH STRANDING ASSESSMENT AND RAMPING PROTOCOL (CLBMON-42)

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FISH STRANDING ASSESSMENT SITES (JANUARY 2020 TO APRIL 2020)

PROJECT NO.	PHASE	REV.	FIGURE
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STRANDING SITE

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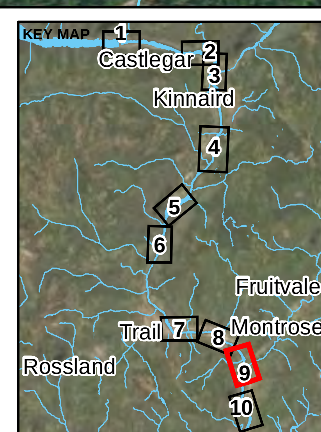

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TITLE
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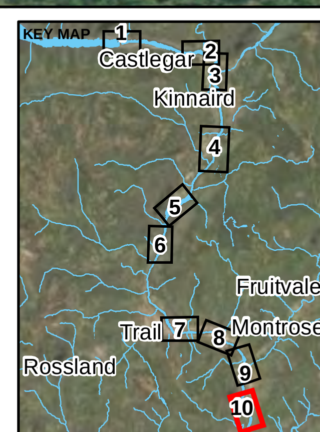

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3. DATUM: NAD83 PROJECTION UTM 11

CLIENT
BC HYDRO

PROJECT
LOWER COLUMBIA RIVER FISH STRANDING ASSESSMENT AND RAMPING PROTOCOL (CLBMON-42)

CONSULTANT
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APPENDIX B

Fish Stranding Assessment Procedure and Data Forms

Fish Stranding Assessment Procedure

The following procedure has been developed to formalize fish stranding data collection methods associated with flow reductions at hydro-electric dams on the lower Columbia and Kootenay rivers. Consistency in methods for every site assessment is very important to ensure that data can be used for long-term trend analysis.

1.0 MOBILIZATION

- The BC Hydro Environmental Discharge Change Coordinator will ensure the Stranding Survey Contact Form (Appendix B, Form 1) is completed. This task includes identifying the Stranding Assessment Supervisor and Field Crew Leader(s).
- The Stranding Assessment Supervisor will review the Project Health & Safety Plan.
- The Field Crew Leader(s) will consult the Equipment Checklist located at the end of this document to ensure that all necessary equipment is mobilized for the flow reduction assessment.
- Survey all the sites that indicate historic ‘Effects’ checked on Stranding Risk Assessment Output (database query); these are priority sites. Sites that have ‘Recon’ or ‘Minimal Effect’ are secondary sites but should also be surveyed (as time permits) to confirm information in the database. At least two sites identified as ‘Recon’ should be visited by crew(s) for each stranding assessment to meet the objective of obtaining data on stranding risk for those sites currently lacking information. The summary of effects table will be reviewed to determine which sites should be targeted for further assessments. This table provides the field crew with a listing of sites known to isolate pools by water level and effects from previous fish stranding assessments.
- The level of effort and types of data collected for every site assessment must be consistent to allow analysis of long-term trends. **The primary objective of these surveys is assessment as outlined in the procedures below.**

2.0 FISH STRANDING FIELD PROCEDURES

The following standardized procedures must be followed when conducting the field portion of the fish stranding assessment within each area of concern identified throughout the lower Columbia and lower Kootenay rivers. Assessments are to begin at the upstream site and follow the stage recession downstream. Depending on the identified potential effects associated with the discharge change, the crew should be on site no later than one hour after the initiation of flow reduction for HLK/ALH and at the time of the reduction for BRD/X.

1. The Stranding Assessment Supervisor will meet with field crew(s) at a common location before starting work to discuss the assessment priorities, crew deployment, exchange contact information and review expected effects and monitoring activities.

2. Create a separate field form for EACH SITE. Fill out the top portion of the Lower Columbia Fish Stranding Assessment Field Form (Appendix B, Form 2). The details are outline in Table 1 below.

Fish Stranding Assessment Procedure

Table 1. Lower Columbia River Fish Stranding Assessment Data Collection Details

Name	**Description**
Crew	Indicate initials for full time staff; if part-time or local assistance present use full name.
Site	Indicate the local name of the area and its proper local (e.g., upstream/downstream); check database for commonly used names.
UTM	If a new site has been sampled that is not present in the database, take a general UTM for the site.
Date	Date the survey was conducted (example 29 Jun 2011).
Time	Time the survey was conducted at this site.
Weather	Qualitative description of the weather conditions presently observed at the site (e.g., overcast, slight drizzle).
Air Temp	In degrees Celsius.
No. New Pools Present	Indicate the number of new pools present at the site due to the current flow reduction. Do not indicate pools that have previously been sampled from another flow reduction event. You can indicate that pools are present from another event in the comments section of the form.
Sampling Gear Used	E = backpack electrofisher; S = seine; D = dip net; M = minnow trap; B = boat electroshocking; G = grid survey.
Mainstem Water Temperature	Take the water temperature of the mainstem being surveyed at each site.
No. Pools Sampled	Indicate the number of pools assessed at each site during the survey. If the number is greater than the number of new pools, indicate that previously formed pools were also re-sampled.
Vertical Drop (m)	Estimate the vertical reduction in water levels at the site.
Fish Life Stages	To create consistency, the following life stages are to be recorded: Egg Young of the Year, Juvenile (1= to adult), and Adult.

3. Observe and record the number of **new** isolated pools that are created at the site as a result of the flow reduction. Make sure that the pools resulted from the current flow reduction event. This can be identified by determining which pools lay within the drawdown zone (wetted area) if the environmental conditions are dry and the crew is on site in time to determine what was wetted. Alternately, the presence of periphyton or aquatic invertebrates can be used to identify the drawdown zone during wet weather or very hot conditions where the wetted area has already dried prior to crew arrival.

   Note: If pools were isolated as a result of a previous reduction, any data is to be compiled against the reduction event when the pool was isolated.

4. Visually inspect each pool for fish. For each pool, associated cover types (and percentages within the pool) in the pool are recorded on the Lower Columbia Fish Stranding Assessment Field Form (Appendix B, Form 2). If fish are not initially observed and substrate/depth provides cover, use a backpack electrofisher to determine the presence of fish in each pool. If there are no fish captured during the first pass, proceed to the next pool. Based on available time, larger pools with the potential to contain fish should be sampled using the multiple pass removal method. The effort in the first pass should be consistent with each subsequent pass.

   Use standard fisheries techniques for collecting fish specific data.

a. Captured fish should be placed in separate buckets (1 for each pass) immediately.

b. The number of live fish observed and/or captured in each pool for each pass, as well as the number of fish salvaged, and the number of dead fish will be recorded. These numbers should be separated by species and life stage (if easily identifiable). If not identifiable to species, collect voucher samples grouped by morphology and submit for identification to species.

c. A sub-sample of large quantities of stranded fish or unidentifiable species must be either keyed out in the field or preserved for identification to ensure stranding risk by species and relative abundance estimates can be developed. A sub-sample of any potentially listed species (but identity is uncertain) should also be preserved for positive identification. The sub-sampling protocol will assess either number of fish present or area to be sampled and sample a proportion of the total. For sampled area, approximately 10-20% of the total area should be sampled from representative habitat throughout. For numbers, approximately 10% of the area should be sampled and then up to 30 fish of each species or morphospecies should be identified or kept for identification.

d. The length of each fish captured will be recorded. If numbers of fish are high and time does not allow measuring all fish, a representative subsample of all salvaged fish should be measured so stranding risk by size class can be analysed.

5. At times of year when isolated pools contain large numbers of fish, larvae, and alevins, electrofishing and other fish sample methods are ineffective at capturing fish. In this instance, estimate the number of fish in the pool and collect a sub-sample from which to identify the relative abundance of species and size class(es).

* If significant numbers of fish (>5000 estimated fish) are observed at any time during the survey, the Field Crew Leader(s) must immediately notify the Stranding Assessment Supervisor; the Stranding Assessment Supervisor will contact other crew leaders to determine any additional stranding issues noted and notify the Discharge Change Coordinator. The Discharge Change Coordinator, in consultation with the Stranding Assessment Supervisor will review potential remedial actions (additional crews, modified ramping rate) based on anticipated effects and consult with the agencies as required.

6. Return salvaged fish to the main channel of the Columbia or Kootenay rivers.

7. Record the number of pools sampled and sampling gear used in the sections provided on the field form.

8. Observe and record the number of rainbow trout redds (Feb-June) exposed by the current drawdown, or whitefish eggs found during stranding assessments. These data are for use in other programs. Report these results to the DCC upon completion of the assessment. The DCC will communicate with study teams working on the rainbow redd monitoring program to avoid duplication of effort.

   Check recently exposed substrate within the site for any fish/egg stranding (i.e., interstitial stranding). Record the number of live fish/eggs observed, the number of fish/eggs salvaged, and the number of dead fish/eggs within the interstitial sample site. These numbers should be divided by species and life stage (includes egg stage) as indicated in Step 6 above. Record the size of the area (m^2) that was sampled and the dominant and subdominant substrate in each stranding mechanism (interstitial and pool) should be recorded using the Modified Wentworth Scale. (i.e., sand, gravel, cobble, boulder) for interstitial fish/egg stranding.

Rainbow Trout redds
Rainbow Trout are known to begin spawning in the lower Columba and Kootenay rivers in February and continue into June with emergence complete by July. BC Hydro maintains an annual Rainbow Trout redd monitoring program to estimate spawning population size and identify those redds that may be dewatered as discharge decreases to Rainbow Trout protection flow targets on April 1. If a dewatered Rainbow Trout redd is discovered, the Stranding Assessment Supervisor will contact the DCC immediately to allow action to be taken as necessary.

Mountain Whitefish egg stranding
Mountain Whitefish spawn in the lower Columbia River starting in November and continuing into early February with emergence of fry complete by April 1. BC Hydro has developed a predictive model to assess the effects of winter flow fluctuations on whitefish egg mortality to assist with operations planning.

9. Indicate if further flow reductions (next 0.5 m stage decrease) may result in future stranding issues (provide a description). Indicate the number of pools that remain connected to the main channel that may be isolated during future flow reductions (use comments section of the field form).

10. In the comments section of the field form indicate the success of the salvage and any other observations that are pertinent to the specific site and assessment.

11. Indicate in the comments section whether a follow-up survey (dependent on water level stability, # fish observed, required salvage efforts) is necessary at the site and state why – identifying pools so that future crews can find the appropriate location.

12. Review all sections of the field form. Ensure that all sections have been filled out appropriately. This includes adding zero’s or not applicable (NA). **Please do not leave any section blank.**

13. Photographs the site from a high vantage point can be used to obtain an overall picture of the flow reduction event. Indicate the camera used, roll number, photograph number, and photo direction, (i.e., upstream, downstream, across the stream from a particular bank) on the field form.

14. If further follow up is required for the site or significant fish stranding is observed, sketch the site and assessment areas on the Stranding Assessment Field Form in the space provided. Draw in the Columbia or Kootenay river mainstem and use an arrow indicating the direction of flow.

15. Repeat the above procedures for each site sampled during the fish stranding assessment.[1]

---

[1] **Restrictions for electrofishing** Electrofishing may not be conducted in the vicinity of spawning gravel, redds, or spawning fish, or around gravels which are capable of supporting eggs or developing embryos of any species of salmonid at a time of year when such eggs or embryos may be present.

3.0 POST REDUCTION REQUIREMENTS

The **field crew leader is required** to ensure all appropriate field information is filed **at the end of each field day**.

1) Phone message to the DCC at the end of each field day to apprise of results.
2) Please **ensure all of the following information is filed** at the end of each assessment in the following order:
    - ✓ *Flow Reduction Details and Stranding Risk Assessment Form*
    - ✓ Scheduled flow change email from BC Hydro
    - ✓ Completed *Stranding Survey Field Data Forms* (review and ensure all appropriate fields are filled out, including reduction event number and project number)
    - ✓ Fish stranding database query

3) For significant stranding events (> 5000 fish stranded at one site) the Stranding Assessment Supervisor (or designate) will generate a **stranding survey memo** with accompanying figures for significant stranding events.

4) The memo and figures will be checked/edited by the Stranding Assessment Supervisor (if applicable) or a senior staff member.

5) The Stranding Assessment Supervisor (or designate) will forward the completed memo to the Stranding Assessment Supervisor and the Discharge Change Coordinator for distribution and filing.

4.0 EQUIPMENT CHECKLIST

- Fish Collection Permit
- First Aid Kit and AED
- Site Maps
- Field Forms (one per site sampled)
- Field Notebook
- Backpack electrofisher(s) + charged batteries
- Beach seine
- Buckets
- Dip Nets
- Electrofisher nets
- Electrofisher gloves
- Camera
- Thermometer
- Measuring tape
- Global Positioning System (GPS) for new sites
- Cell phone and relevant phone numbers;
- Fish Identification book
- Fish preservation kit
- Personal protective gear (e.g., chest waders, boots, glasses, hat, copy of electrofishing certificate, personal first aid kit)

Lower Columbia River Fish Stranding Assessment Form 1

Fish Stranding Assessment Contact Form

Flow Reduction Event ____________

The following information must be completed and made available to all persons involved with the fish stranding assessment effort.

DATE and TIME stranding assessment request initiated: ____________________________

BC Hydro Environmental Discharge Change Coordinator (DCC):
The BC Hydro individual (BC Hydro Biologist) that is responsible for discussions with the Operations Planning Engineer, agencies, and others to provide environmental management advice on flow change management.

Name: __________________________
Telephone/contact numbers: Office: _____________
Home: _____________
Cell: _____________

Stranding Assessment Supervisor:
The individual (BC Hydro or Consultant) that is responsible for supervising stranding assessment activities and field crews during the flow reduction. This person will be the point of contact for coordinating crew deployment and discussing unexpected events with the DCC. Depending upon monitoring needs, the Stranding Assessment Supervisor and Field Crew Leader can be the same individual.

Name: ______________________

Affiliation: ______________________

Telephone/contact numbers: Office: ________________
Home: ________________
Cell: ________________

Field Crew Leader:
The individual(s) that is/are responsible for leading a field crew.

Name of Field Crew Leader 1: _________________________________
Field Areas Responsible for Salvage: _________________________________
Contact Numbers: Cell: _________________________________
Work: _________________________________
Home: _________________________________

Name of Field Crew Leader 2: _________________________________
Field Areas Responsible for Salvage: _________________________________
Contact Numbers: Cell: _________________________________
Work: _________________________________
Home: _________________________________

Name of Field Crew Leader 3: _________________________________
Field Areas Responsible for Salvage: _________________________________
Contact Numbers: Cell: _________________________________
Work: _________________________________
Home: _________________________________

Lower Columbia River Fish Stranding Assessment - Form 2

Facility Responsible for Flow Reduction | **Reduction Event No.**

Mop-Up? Yes / No

Site Name:____

Crew:_____/_____/_____ **Date:**_____/_______/_____ **Time:**_________

Air Temperature:_____°C **Mainstem Water Temp:**_____°C **Cond:**_____

Estimated Vertical Drop[a]:____cm **Slope% (Circle): < or > than 4%**

Substrate Type (% of 100) : Boulder____Cobble____Gravel____Sand____

Photodocumentation

Image #	Orientation	Comments

Instream Cover Types and Percent Available (% of 100):	Interstices	Woody debris	Aquatic veg	Terra veg	Cloud cover (circle)	Mostly cloudy (51 - 90%)		Partly Cloudly (10-50%)	
						Fog	Clear	Overcast	

Isolated Pool Stranding

Number of New Pools Present:____ **Effort:**______**(sec)**

Number of Pools Sampled:_______ **BP EF Settings: Volts______ Freq______ PW_______**

Sampling Gear	Fish Species	Life Stage	# Live[b]	# Dead[c]	# Salvaged[d]

Isolated Pool Stranding (de-watered pools or depressions)

Number of New De-watered Pools Present:_______

Substrate Type (% of 100): Boulder___ Cobble___ Gravel___ Sand___

Sampling Gear	Fish Species	Life Stage	# Live[b]	# Dead[c]	# Salvaged[d]

Interstitial Egg & Fish Stranding Check

Size of Area Sampled:_________m^2

Substrate Type (% of 100): Boulder___ Cobble___ Gravel___ Sand___

Sampling Gear	Fish Species	Life Stage	# Live[b]	# Dead[c]	# Salvaged[d]

Comments (i.e., # large/small pools; evidence of predation; drainage rate; survey success; problems encountered; include number of pools that are still connected to the mainstem, isolated pools water temps, avian predation, why interstitial survey was not completed (e.g., viewed from lookout))

Future flow reduction problems if river drops another 0.5m?: Yes / No

Other Comments:____

____

____

____

____

____

____

____

____

Site Sketch (Reference the Columbia or Kootenay River with an arrow indicating direction of flow)

[a] The estimated vertical drop from the drawdown zone of the previous water elevation to the current water elevation.

[b] The number of live fish captured & observed during the survey

[c] The number of dead fish captured & observed during the survey

[d] The number of live fish removed from isolated pools or substrate and returned to the mainstem

APPENDIX C

Effects of Flow Ramping Rate Analysis

1.0 INTRODUCTION

Discharge reductions in regulated rivers can result in fish becoming stranded either in pools isolated from the main river or interstitially in the substrate, both of which can ultimately lead to mortality. In the lower Columbia River between Hugh L. Keenleyside Dam and Arrow Lake Generating Stations (HLK/ALH) and the Canada-US border, fish stranding can occur due to discharge reductions at HLK/ALH, or at Brilliant Dam and Brilliant Expansion Powerplant (BRD/X). BRD/X is located on the Kootenay River 3 km upstream from the confluence of the Kootenay and Columbia rivers. Fish stranding was raised as an environmental issue associated with HLK operations by regulatory agencies in the mid-1990's. Since the mid-1990s, surveys have been conducted to assess the numbers of fish stranded following discharge reductions. Beginning in 2007, fish stranding surveys were conducted as part of the Lower Columbia River Fish Stranding Assessment and Ramping Protocol (CLBMON-42), which was implemented in 2007 as part of BC Hydro's Water Use Plan for the Columbia River. The primary objective of CLBMON-42 was to collect fish stranding data to assess the impact of flow reductions and flow ramping rates from HLK on the native fish species of the lower Columbia River.

Data collected during CLBMON-42 are used to address five management questions (Golder 2020). One of the management questions is:

- Is there a ramping rate (fast vs. slow, day vs. night) for flow reductions from HLK that reduces the number of fish stranded (interstitially and pool) per flow reduction event in the summer and winter?

The management hypothesis related to this question is:

- The number of stranded fish is independent of either the ramping rate or time of day of flow reductions in the summer and winter.

Although the management question and hypothesis mention several variables including ramping rate, time of day, and season (summer or winter), this analysis focuses primarily on the effect of ramping rate, while accounting for other variables that influence stranding. Time of day was not assessed because very few reductions were conducted at night. Seasonal differences in the number of fish stranded were assessed by including day of year as a predictor variable in the analysis. For more detailed discussion of the effects of time of day and season (summer/winter) on fish stranding based on a literature review, and previous experiments in the lower Columbia River, refer to Golder and Poisson (2010).

Fish stranding data collected during surveys in the lower Columbia River are stored in the Lower Columbia River Fish Stranding Database. The database includes data from 1995 to 2020, but survey methods were only standardized beginning in 1999. As 2020 was the final year of monitoring as part of BC Hydro's WUP, the final report includes analyses to address the management questions using all available data from the monitoring program. This appendix provides details of the statistical analysis to address the management question above regarding the effect of ramping rate on fish stranding in the lower Columbia River. The appendix focuses on the statistical methods, results, and interpretation. For additional details regarding the project, including background information and methods for data collection, readers are referred to Golder 2020.

2.0 METHODS

2.1 Data QAQC and compilation

Quality Assurance/Quality Control (QAQC) of data extracted from the database included exploratory plotting and checks of minimum and maximum values. The database includes data from surveys from 1995 to March 2020. As stranding survey methods were standardized in 1999, only data from 1999 to 2020 were considered comparable. Data from 1999 had missing values for one or more variables for many reduction events and were not used. Therefore, the data used for analysis were from January 2000 to March 2020. The analysis included reduction events resulting from changes in discharge at HLK/ALH, BRD/X, or both facilities. The numbers of fish stranded during each site visit included the combined total of all life stages, fish species, and survey methods, from both pool and interstitial stranding.

The following sites were omitted because the sample sizes (i.e., number of site visits) were too small: Birchbank Snye (LUB), Beach Eddy/Northshore Eddies (RUB), General, Norns Creek Fan to Kootenay River, REA Side Channel (HLK), Waldie's Island (MID), and Waterloo Eddy (RUB). In addition, Genelle Lower Cobble Island (MID) was omitted because the site could not be properly surveyed without boat access, and the data in the database from visual surveys from across the river were not considered reliable.

The following reduction events were omitted from analysis: 200001, 200002, 200013, 200014, 200106, 200499, 200727, 200813, 200814, 200820, 200912, 200915, 200920, 201011, 201113, 201209, 201416, 201501, and 201605. These reduction events were omitted because key information such as the discharge was missing, or because some aspect of the reduction event made the data not comparable or reliable. Examples of data that were not comparable or reliable are reduction dates where discharge data did not show a decrease (possibly due to within-day fluctuations referred to as load shaping), and non-typical surveys for other objectives such as egg stranding reconnaissance surveys, or monitoring of load shaping that did not involve a persistent decrease in base flow. In addition, three reduction events were omitted from the model because wetted history could not be calculated (200507, 201708, and 201709). Thirty-three reduction events could not be included because ramping rate was not included in the database and was unknown.

Between 2000 and 2020, some of reduction events occurred on a single day but others involved reductions on multiple consecutive days. Of the 305 reduction events used in the analysis, 16% (48 reduction events) were multi-day reductions. For multi-day reductions, most often stranding surveys occurred on each day of the reduction event, but sometimes only one survey was conducted on the final day of the reduction event. Beginning in 2018, each day of multi-day reductions was entered in the database as a separate reduction event. Because the number of reduction days and sample days was not always the same between reduction events from 2000 to 2020, the unit of observation for this analysis was the reduction event (rather than the individual reduction date). To compile the data by reduction event, the number of fish was summed across all survey dates and reduction dates. Similarly, the minimum and maximum discharge at Birchbank was summarized to describe the entire range of discharge across all reduction days (where applicable).

A small number of observations were excluded because they were outliers that caused problems with model fitting or convergence. These observations included 1 reduction event (201208) that had extremely high minimum discharge (4831 m^3/s) and three site visits that had between 10,000 and 13,500 fish stranded.

After cleaning and compiling the data, the total sample size was 2,571 site visits from 305 reduction events and 24 sites. In the database, reduction events were coded as “HLK”, “BRD”, or “Both” based on the dam where the reduction occurred. Of the 305 reduction events used for analysis, 244 were from HLK, 33 were from BRD, 27 were from both, and a single reduction event was coded as “Other”. The cleaned data set was the same as the data used for the analysis of wetted history (Appendix D), except for 33 reduction events that could not be used in this analysis because of missing ramping rate.

2.2 Statistical Analysis

A zero-inflated generalized linear mixed model (ZIGLMM) was used to assess the effect of ramping rate on fish stranding. This model is suitable for modelling count data (i.e., the number of fish stranded) that have a large number of zeroes and large variability in the counts. The response variable was the number of fish stranded of all life stages and species combined. The unit of observation was each site visit during each reduction event. Site and year were included as random effects in the model. Predictor variables (fixed effects) included in the model were the following:

- **Ramping rate** was the predictor variable of primary interest and was used to describe the rate at which discharge was reduced. Ramping rate was obtained from the Lower Columbia River Fish Stranding Database, where it was recorded for each day of each reduction event in the field called “AverageRampingChange”. For multi-day reductions, the average of value for all reduction days was used. The value in the database was obtained from information from dam operators prior to the reduction event, which was used instead of the realized rate of change in discharge of the Columbia River at the Birchbank gauging station, because it is more closely linked to operational strategies. Ramping rates are reported the change in kcfs (thousands of cubic feet per second) per hour, instead of metric units (m^3/s per hour), following the convention used by dam operators and protocols for ramping rates.
- The magnitude of the discharge reduction (‘**magnitude of reduction’**) was calculated as the difference between the maximum and minimum discharge at the Birchbank gauging station for each reduction event, as provided in the Lower Columbia River Fish Stranding Database. The Birchbank gauging station was used because it is downstream of the confluence of the Columbia and Kootenay rivers, and therefore represents changes in the river level resulting from discharge changes at both HLK/ALH and BRD/X. The Birchbank gauging station also provided a more complete discharge data set than data from HLK/ALH or BRD/X, which both had more periods with missing discharge data. Minimum and maximum values at Birchbank in the database were typically the minimum and maximum value during each 24-hour period of the reduction day. In some cases, if the discharge subsequently increased after the discharge reduction, the values in the database are the minimum and maximum preceding and following the reduction event, not including subsequent changes in discharge on the same day.
- The minimum discharge of the Columbia River at the Birchbank gauging station after the reduction event (‘**minimum discharge’**) was obtained from the Lower Columbia River Fish Stranding Database. Minimum discharge was used as an indicator of the river stage. Minimum discharge was modelled as a second-order polynomial based on exploratory plotting, which suggested a U-shaped distribution with the greatest number of fish stranded at very low and very high river stage, rather than a linear trend.

- **Wetted history** was calculated as the number days between the reduction date and the most recent previous date when discharge was lower than the minimum discharge at Birchbank after the reduction event. The values of minimum discharge at Birchbank were from the Lower Columbia River Fish Stranding Database, and the data for the previous date of lower discharge were obtained from hourly discharge data for the Birchbank station from BC Hydro's Columbia Basin Hydrological Database. Wetted history was capped at 365 days, such that all values greater than 365 were assigned a value of 365. This was done because the large range of wetted histories (up to 5684 days), combined with the low sample sizes and highly variable counts of fish at large values of wetted history, led to problems with model fitting. The rationale for the maximum value of 365 days was that re-colonization of habitat was expected to occur within one year of re-watering. Wetted history was modelled as a fourth order polynomial, which was necessary to capture the observed trend in the data. Modelling wetted history as a linear or lower order polynomial resulted in trends in the residual error that indicated poor model fit.
- **Load shaping** is defined as within-day variation in discharge due to changes in generation at a hydroelectric facility to meet power demands. In the study area, load shaping can occur at BRD/X but not at HLK/ALH. Load shaping was a binary categorical variable to indicate whether or not load shaping occurred on the reduction day. For multi-day reduction events, if load shaping occurred on any of the days, the reduction event was considered to have had load shaping.
- River kilometre for each site was obtained from the Lower Columbia River Fish Stranding Database and was included in the model to account for attenuation in the risk of stranding with increasing distance downstream from the dams.
- Day of year was included to account for seasonal differences in stranding risk. Day of year was modelled as a cubic regression spline, similar to previous analysis of the stranding data (Golder and Poisson 2010), to account for the non-linear relationship observed in exploratory plotting. The degrees of freedom, which determines the amount of smoothing, was set to five.

All predictor variables were standardized by subtracting their mean and dividing by their standard deviation. Interactions between the predictor variables were not included in the model. The model was a two-stage model, also known as a "hurdle" model, that had one component that described the non-zero counts of fish, referred to as the conditional model, and one component that described the probability of zero versus non-zero counts of stranded fish, referred to as the zero-inflation model. The conditional model assumed a negative binomial distribution to describe the non-zero counts of fish. The zero-inflation model was equivalent to a logistic regression to predict whether or not one or more stranded fish were observed during a site visit. Both components of the model included all seven fixed effects and the two random effects above, because all of these variables could potentially affect both the probability of stranding and the number of fish stranded. Models were fit using the package glmmTMB (Brooks et al. 2017) in the statistical environment R (R Core Team 2019).

Model diagnostics included checks of model assumptions including linearity of effects, homoscedasticity, and normality of residual errors. Plots of residuals versus predicted values and residuals versus predictor variables were created to look for residual trends that would indicate poor model fit. All of these checks used simulated residuals produced using the DHARMa package (Hartig 2020) in R.

Statistical significance of the effect of predictor variables on the conditional model and on the zero-inflation model was assessed using a Wald's test. Effect size was assessed using plots of the predicted values of the response variable versus one of the predictor variables, while holding other continuous predictor variables at their mean values and holding the categorical predictor, load shaping, at its reference value of no load shaping. These "population-level" predictions from the fitted model are predictions with the random effects of site and year set to zero, which represents the predictions for an average site and an average year. In plots of predicted values,

observed data were also included as points. As the model predicts the mean number of fish, mean values of the observed data are shown, instead of raw values for each site visit, which allows better visualization of model fit with the data.

3.0 RESULTS

Nearly all of the observed ramping rates were between 1 and 10 kcfs/hr (Figure 1), except for two reduction events with much greater ramping rates (27 and 41 kcfs/hr). Ramping rate did not have a statistically significant effect on either the probability of observing zero stranded fish or the number of fish stranded (Table 1). Plots of predicted and observed values of fish stranding versus ramping rate did not indicate any strong trends (Figure 2). The results suggest no effect of ramping rate on the probability of stranding or the number of fish stranded in the lower Columbia River, within this range of ramping rates, based on the available data.

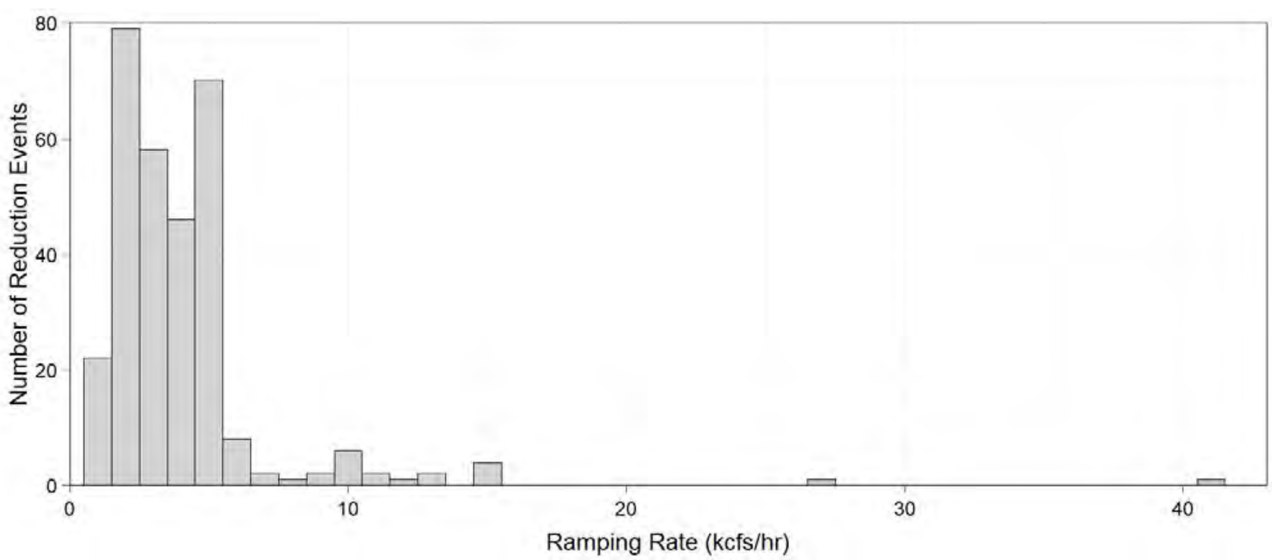

Figure 1: Histogram showing the number of reduction events by ramping rate.

Wetted history had a statistically significant effect on both the probability of observing zero stranded fish, and the number of fish stranded (Table 1). The predicted probability of observing zero stranded fish decreased from 0.74 at 1 day of wetted history to 0.57 at 100 days wetted history (top panel; Figure 3). At greater than 100 days wetted history, the predicted probably of zero stranded fish was stable, except for an increase in the probability of zero fish at wetted history greater than 300 days, which was likely related to small sample sizes. The predicted number of fish stranded increased from 18 fish at 1 day of wetted history to 53 fish at 50 days, 113 fish at 200 days, and 237 fish at 285 days (bottom panel; Figure 3). The rapid increase in the predicted number of stranded fish from 200 to 280 days of wetted history, and the sharp decrease after 300 days, had large confidence intervals and likely reflects uncertainty due to small sample sizes and highly variable counts of fish at these higher values of wetted history. In summary, the results support a positive relationship between wetted history and stranding risk. The probability of stranding one or more fish plateaued after approximately 100 days of wetted history. The predicted number of fish increased between 1 and 50 days of wetted history, and more slowly after 50 days, with a highly uncertain trend after 200 days.

Day of year was included in the models to account for seasonal variation in stranding risk. Day of year was a statistically significant predictor of both the probability of stranding and number of fish stranded (Table 1). The predicted peak number of stranded fish occurred on June 24 (66 fish per site visit), with elevated numbers of fish stranded from April 10 to September 11 (10 or more fish stranded per site visit) and fewer than 10 fish predicted for dates outside of this range (Figure 4). The predicted probability of observing zero stranded fish showed a similar trend as the predicted number of fish stranded, except that the peak stranding risk occurred later in the summer. The predicted probability of observing zero fish was stable between January 1 and mid-April (0.74–0.76), decreased to a minimum of 0.52 on August 4, and was greatest mid-November (0.86; Figure 4).

Although the predicted numbers of fish stranded showed a peak in late June, the observed mean number of fish per for each 10-day period (black points in Figure 4) showed large variability in the numbers of stranded fish. For instance, large numbers of stranded fish were often observed in late March (before the predicted peak), and late September to early November (after the predicted peak). Based on previous analyses and exploratory plotting, day of year was included as a second-order polynomial which allows for a single peak in fish stranding. Alternative models that included higher-order polynomials or smoothers to allow more than one period of greater numbers of stranded fish did not improve the fit (results not shown), suggesting that the single peak best described the seasonal trend in fish stranding. Therefore, model predictions indicate increased numbers of stranded fish from April to September, but the observed data show large numbers of fish can also be stranded outside of this period, especially in October and November.

Magnitude of reduction was a statistically significant predictor of both the probability of stranding and number of fish stranded (Table 1). The component of the model that predicted whether or not any fish stranding occurred suggested increasing risk of stranding (decreasing probability of zero fish stranded) with increasing magnitude of reduction. The probability of observing zero stranded fish decreased from 0.70 during a reduction of 25 m^3/s to 0.47 during a reduction of 500 m^3/s and 0.24 during a reduction of 1000 m^3/s (top panel; Figure 5). In contrast, there was a negative relationship between magnitude of reduction and the number of fish stranded, with the predicted number of fish stranded decreasing from 67 fish during a reduction of 25 m^3/s to 59 fish at a reduction of 500 m^3/s and 40 fish during a reduction of 1000 m^3/s (bottom panel; Figure 5).

The negative relationship between magnitude of reduction and the number of fish stranded was the opposite of the expected positive relationship and may be explained by the high variability and relatively small number of observations at very low and very high magnitudes of reduction. For instance, there were site visits during discharge reductions less than 5 m^3/s where several thousand larval or young-of-the-year fish were stranded. There were only two discharge reductions and 11 site visits during discharge reductions greater than 1000 m^3/s, and very few stranded fish were observed. Although the model indicated a statistically significant negative relationship, the effect size was small with only a 12% decrease in the number of fish stranded (67 to 59 fish) when the magnitude of reduction increased from 25 to 500 m^3/s, which was half of the entire observed range (bottom panel; Figure 5). Overall, the results support a positive effect of magnitude of reduction on the probability of fish stranding (>0 fish) and a small and possibly spurious negative effect of magnitude of reduction on the number of fish stranded per site visit.

Minimum discharge reached during the reduction event was used as a proxy to assess the effect of river stage on fish stranding. Minimum discharge was a statistically significant predictor of both the probability of stranding and number of fish stranded (Table 1). The probability of observing zero stranded fish increased from 0.27 at a minimum discharge of 1000 m^3/s to 0.91 at a minimum discharge of 3000 m^3/s (top panel; Figure 6). The predicted number of fish stranded, based on the combined model of probability and severity of fish stranding, decreased from 388 fish at 1000 m^3/s to 42 fish at 3000 m^3/s (bottom panel; Figure 6). However, predictions of the non-zero counts of fish stranded (middle panel; Figure 6) indicated unrealistic predictions at very high and low values of minimum discharge. The drastic decrease in predicted values at low minimum discharge and drastic increase at high minimum discharge were attributed small sample sizes and highly variable counts, which caused problems with the polynomial fit at extreme values. Therefore, the data support a small decrease in the number fish stranded between low (~900 m^3/s) and moderate (2000 m^3/s) discharge but the predictions and effect sizes at the highest (greater than 3000 m^3/s) and lowest (less than 900 m^3/s) minimum discharges are not reliable. Despite uncertainties at the extreme values of discharge, these results suggest increasing likelihood and severity of fish stranding with decreasing river stage in the lower Columbia River.

Load shaping was not a significant predictor of fish stranding (Table 1). River kilometre did not have a significant effect on the number of fish stranded but did have a significant effect on the probability of stranding zero fish (Table 1). There was an increasing probability of zero stranding with increasing distance downstream (Figure 7). Observed mean proportions of site visits with no stranded fish detected ranged from 0.43 to 0.66 between river kilometres 0 and 11, compared to values of 0.67 to 0.90 from river kilometres 40 to 54 (Figure 7). River kilometre and load shaping were not of primary interest to the project's management questions but were included to account for their potential effect on fish stranding.

Table 1: Statistical significance of predictor variables in the model of fish stranding in the lower Columbia River, 2000 to 2020.

Predictor Variable	Effect on Number of Fish (Conditional Model)	Effect on Probability of Zero Stranding (zero-inflation model)
	***P*-value**	***P*-value**
Ramping Rate	0.2	0.2
Wetted History	**0.002**	**0.0003**
Magnitude of Reduction	**0.007**	**<0.0001**
Minimum Discharge	**0.0004**	**<0.0001**
Day of Year	**<0.0001**	**<0.0001**
River Kilometre	0.8	**0.006**
Load Shaping	0.7	0.1

Note: Direction of the effect, estimated coefficients, and their uncertainty are not presented because many of the predictor variables were modelled as polynomial or cubic splines (i.e., wetted history, minimum discharge, and day of year), which means that they had multiple coefficients per variable, which makes it not possible to interpret the standardized coefficients as effect sizes. Instead, effect size is presented in terms of the change in predicted values relative to each predictor variable, while holding other variables at their mean values (Figures 2 to 7). Variables significant at the 0.05 level are shown in **bold**.

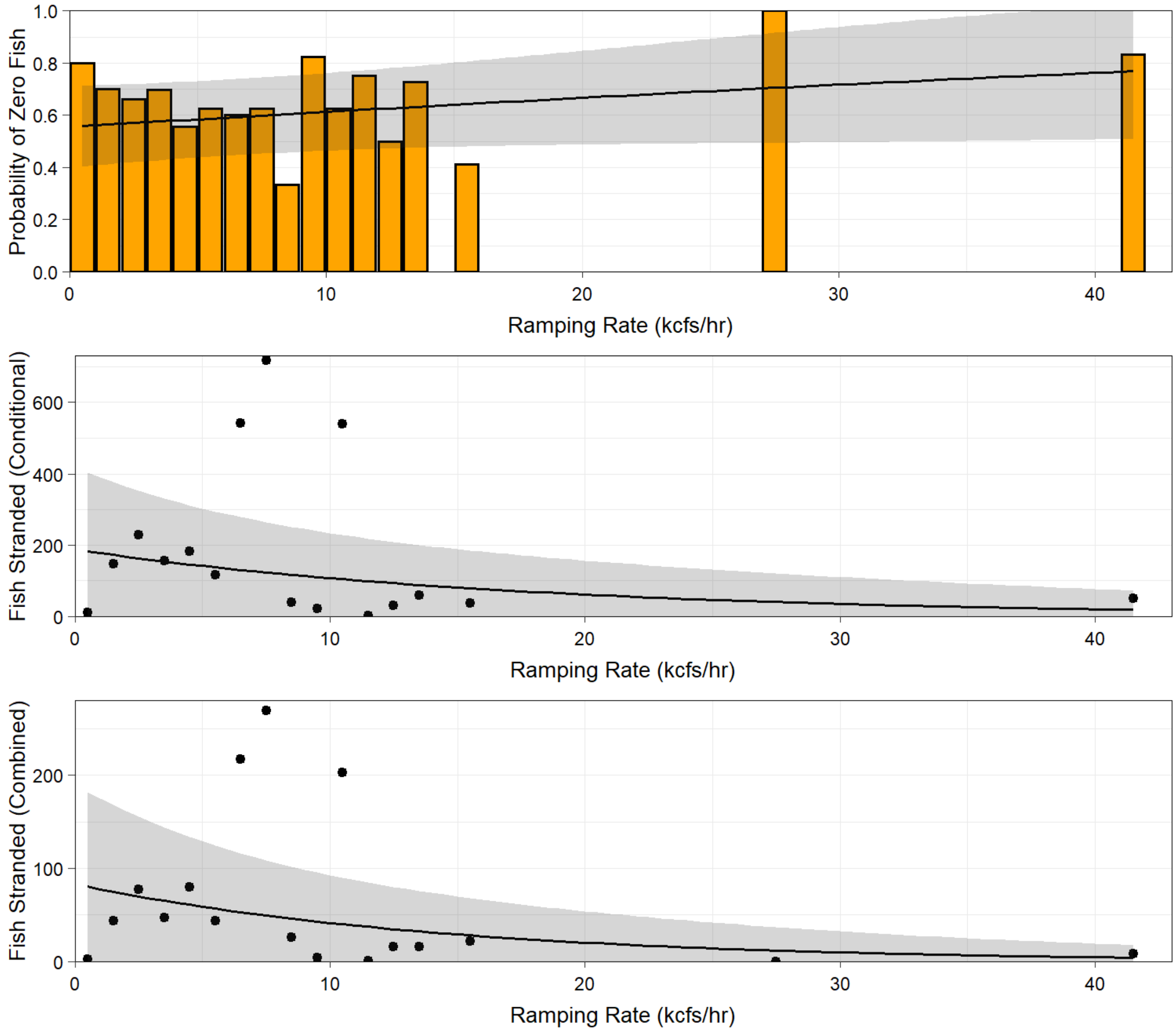

Figure 2: Predicted fish stranding versus ramping rate in the lower Columbia River, 2000 to 2020. Predictions are from a negative binomial two-stage hurdle model where the top panel is the probability of zero stranded fish, the middle panel is the number of fish stranded for non-zero stranding events, and the bottom panel is the combined prediction based on the probability and magnitude of stranding. Orange bars and black points are the mean values of the observed data by 1 kcfs/hr bins of ramping rate. Black line is the mean prediction and grey ribbon is the approximate 95% confidence interval. Ramping rate was not a statistically significant predictor of either the probability of zero stranding fish or the number of fish stranded.

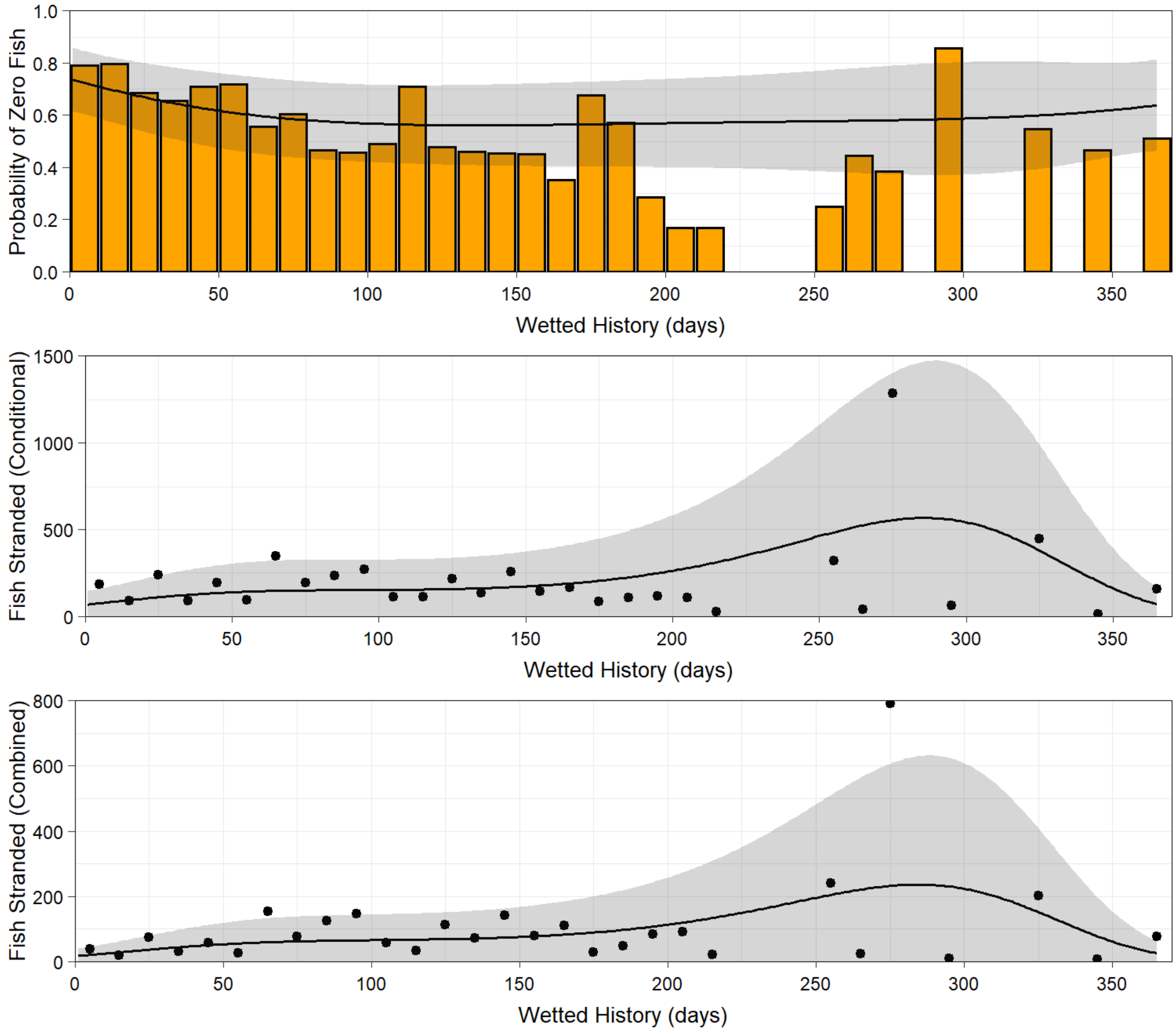

Figure 3: Predicted fish stranding versus wetted history in the lower Columbia River, 2000 to 2020. Predictions are from a negative binomial two-stage hurdle model where the top panel is the probability of zero stranded fish, the middle panel is the number of fish stranded for non-zero stranding events, and the bottom panel is the combined prediction based on the probability and magnitude of stranding. Orange bars and black points are the mean values of the observed data by 10-day bins of wetted history. Black line is the mean prediction and grey ribbon is the approximate 95% confidence interval.

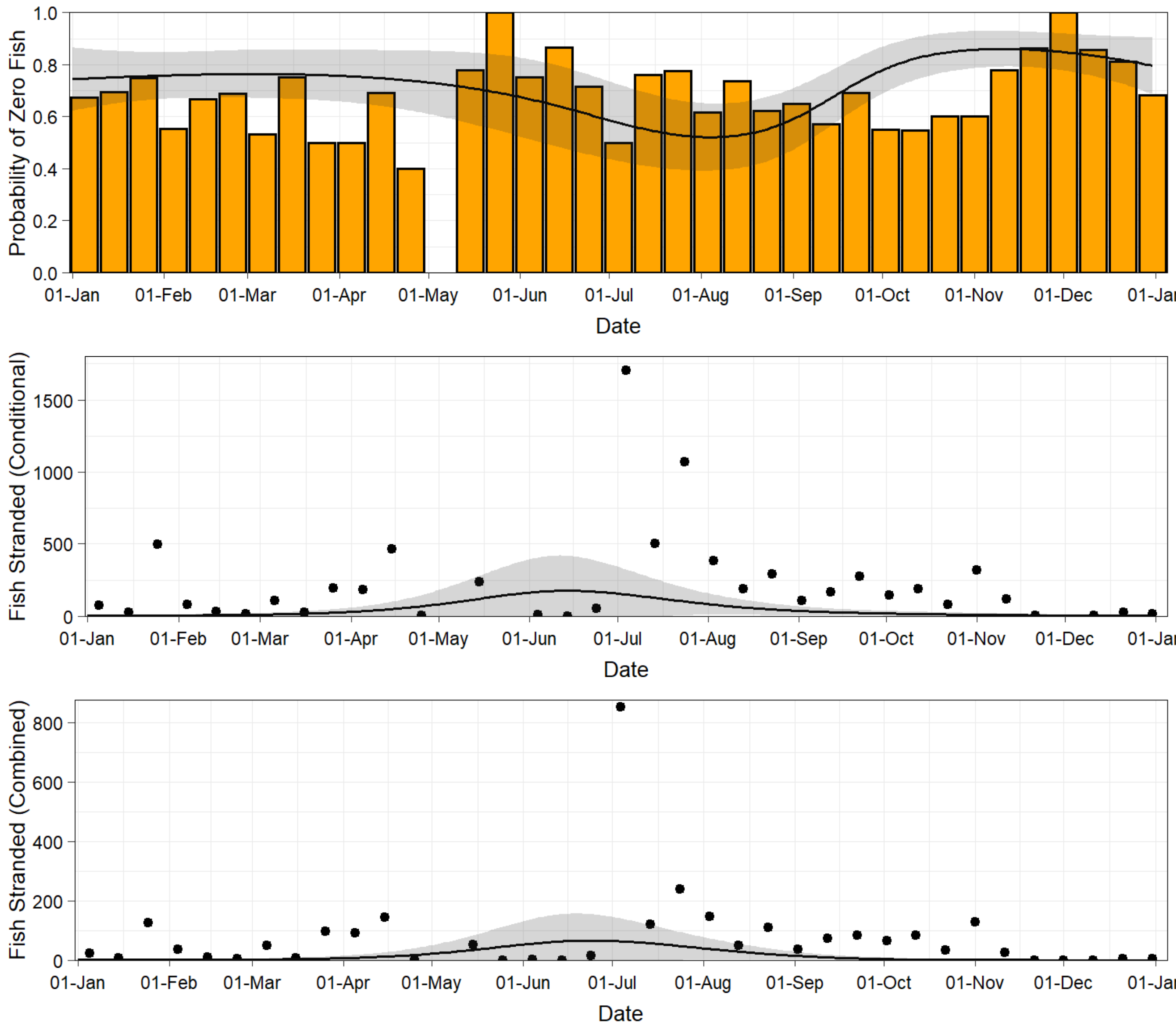

Figure 4: Predicted fish stranding versus day of year in the lower Columbia River, 2000 to 2020. Predictions are from a negative binomial two-stage hurdle model where the top panel is the probability of zero stranded fish, the middle panel is the number of fish stranded for non-zero stranding events, and the bottom panel is the combined prediction based on the probability and magnitude of stranding. Orange bars and black points are the mean values of the observed data by 10-day bins of day of year. Black line is the mean prediction and grey ribbon is the approximate 95% confidence interval.

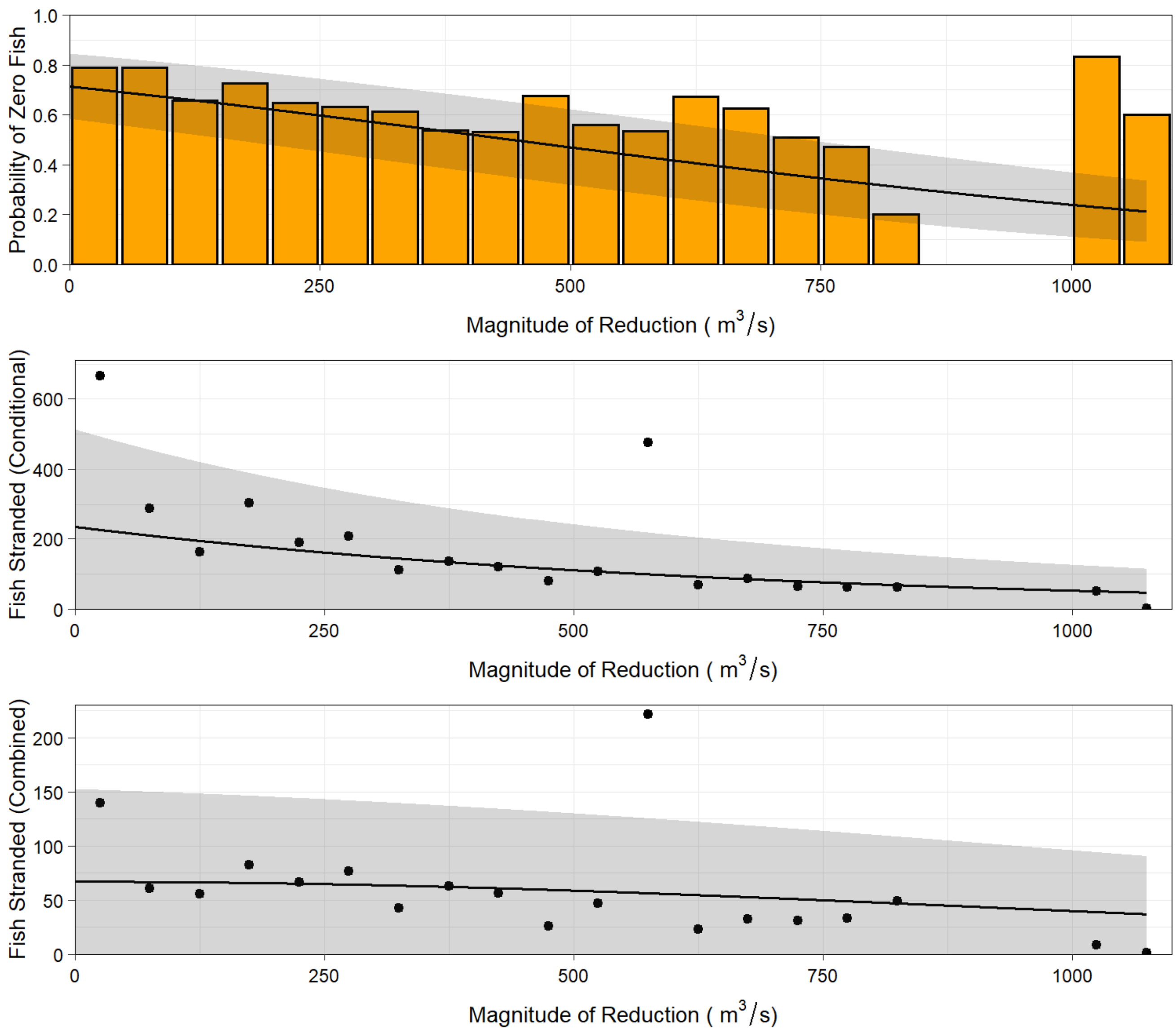

Figure 5: Predicted fish stranding versus magnitude of discharge reduction in the lower Columbia River, 2000 to 2020. Predictions are from a negative binomial two-stage hurdle model where the top panel is the probability of zero stranded fish, the middle panel is the number of fish stranded for non-zero stranding events, and the bottom panel is the combined prediction based on the probability and magnitude of stranding. Orange bars and black points are the mean values of the observed data by 50 m³/s bins of magnitude of reduction. Black line is the mean prediction and grey ribbon is the approximate 95% confidence interval.

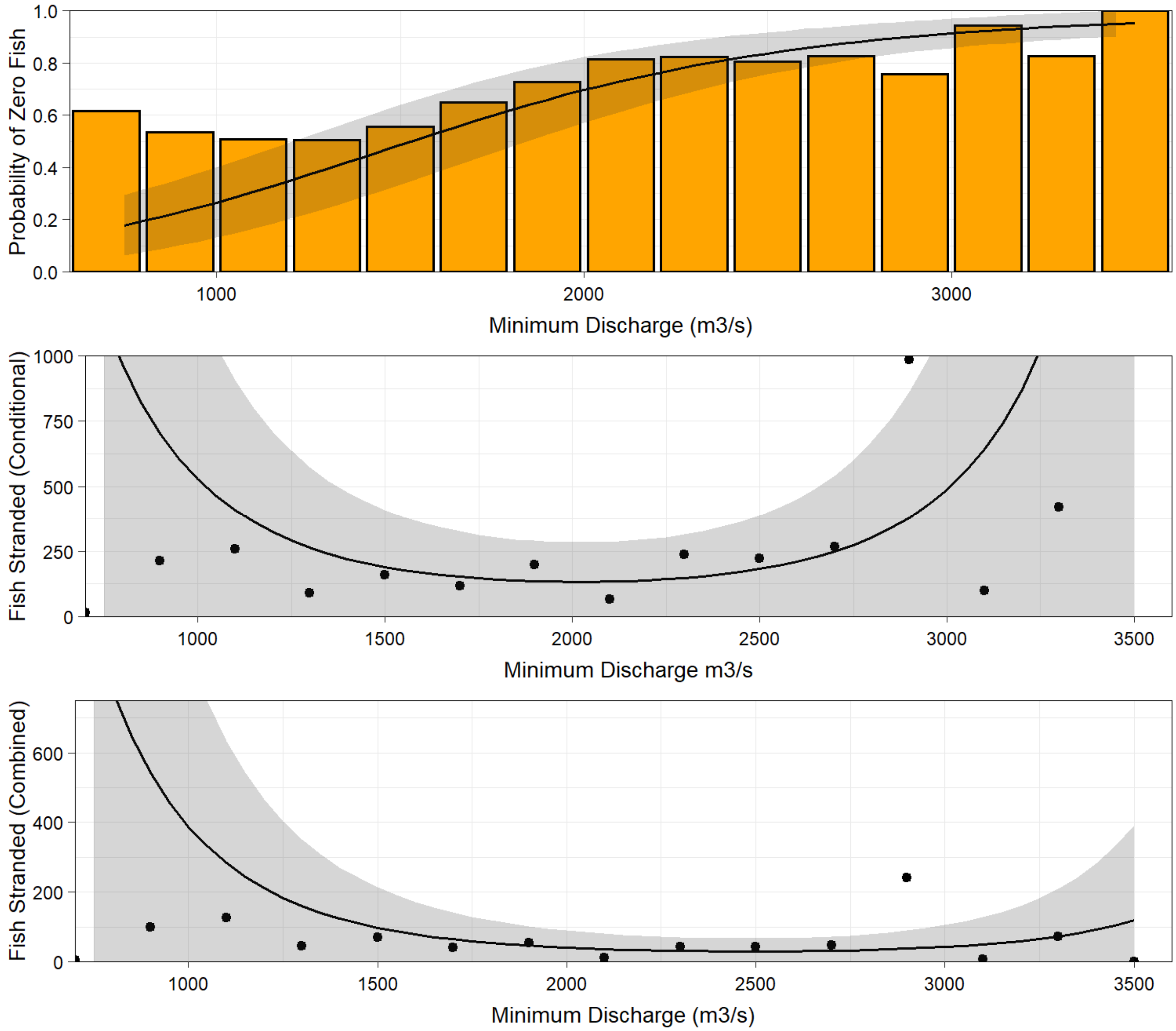

Figure 6: Predicted fish stranding versus minimum discharge reached during the reduction in the lower Columbia River, 2000 to 2020. Predictions are from a negative binomial two-stage hurdle model where the top panel is the probability of zero stranded fish, the middle panel is the number of fish stranded for non-zero stranding events, and the bottom panel is the combined prediction based on the probability and magnitude of stranding. Orange bars and black points are the mean values of the observed data by 200 m³/s bins of magnitude of reduction. Black line is the mean prediction and grey ribbon is the approximate 95% confidence interval.

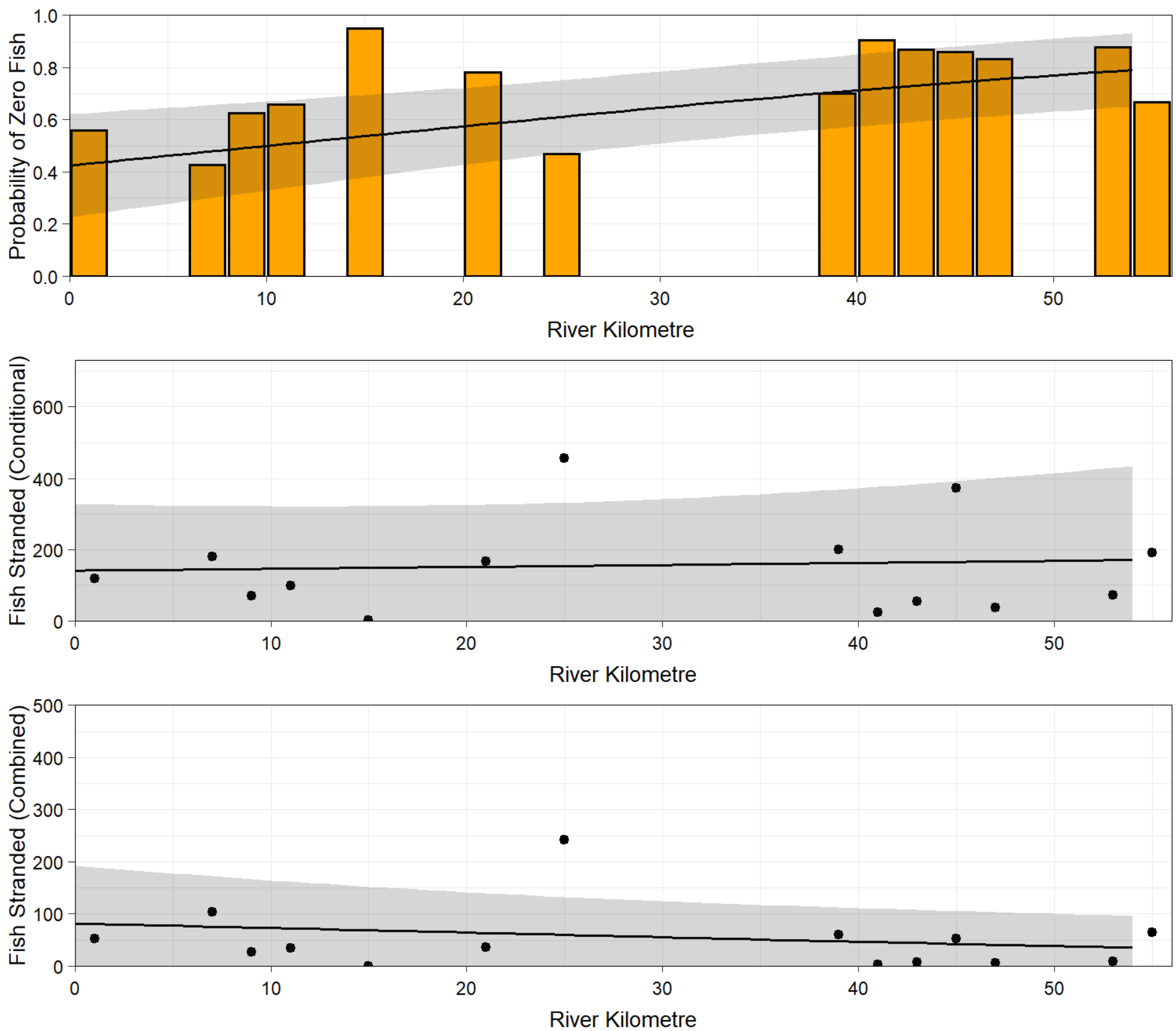

Figure 7: Predicted fish stranding versus river kilometre in the lower Columbia River, 2000 to 2020. Predictions are from a negative binomial two-stage hurdle model where the top panel is the probability of zero stranded fish, the middle panel is the number of fish stranded for non-zero stranding events, and the bottom panel is the combined prediction based on the probability and magnitude of stranding. Orange bars and black points are the mean values of the observed data by 2 km bins of river kilometre. Black line is the mean prediction and grey ribbon is the approximate 95% confidence interval.

4.0 DISCUSSION

Twenty years of data from fish stranding surveys were used to assess the effect ramping rate on the number of fish stranded, using a statistical model that accounted for other variables that can influence stranding, such as magnitude of discharge reduction and river stage. The model assessed the effect of ramping rate on both the likelihood of stranding fish, and the severity of fish stranding in terms of the number of fish stranded. The available data and modelling results suggest no effect of ramping rate on the likelihood or severity of fish stranding.

These results agree with a previous analysis of the lower Columbia River stranding data, which did not find any effect of ramping rate on the probability of stranding (Golder and Poisson 2010). Experimental studies of ramping rates in the lower Columbia River found a positive association between ramping rate and the probability of fish stranding, but the relationship was fairly weak, and ramping rate was ranked low in terms of variable importance in the statistical models (Irvine et al. 2009). As hypothesized by Golder and Poisson (2010), lack of a detectable effect of ramping rates may be because of the relatively small range of ramping rates observed in the lower Columbia River, compared to studies elsewhere where ramping rates were often much larger.

Wetted history had a statistically significant positive effect on both the probability and severity of fish stranding. This supports the idea that substrate that had been inundated for a longer period was more likely to strand fish if dewatered, compared to substrate that was inundated for a shorter period. The predicted number of fish stranded per site, based the combined probability of stranding and severity of stranding, increased from 18 fish at 1 day of wetted history to 53 fish at 50 days, and 113 fish at 200 days. These predictions are for an average year and an average site. As there were 24 stranding sites included in the analysis, a difference of nearly 100 fish per site between 1 and 200 days wetted history suggests a biological meaningful effect of wetted history on stranding risk. At greater than 200 days wetted history, there was large variability the mean numbers of fish stranded, which resulted in the large uncertainty in model predictions. A previous analysis of the lower Columbia River stranding data also found increased probability of stranding with increasing wetted history (Golder and Poisson 2010). The previous analysis by Golder and Poisson (2010) used a maximum value of wetted history of 90 days, whereas the current analysis used 365 days as a maximum value of wetted history.

Seasonal differences in stranding risk were accounted for by including day of year in the model. Model predictions indicate peak numbers of fish stranding in late June, with elevated stranding risk from April to September. However, observed data showed events with many stranded fish also occurred outside of this range of dates, particularly in October and November.

Figure 4 shows predicted mean numbers of stranded fish by day of year while holding other predictor variables at their mean values. Observed data in the figure correspond to a wide range of values of the predictor variables. This difference explains some of the differences between the predicted and observed numbers of stranded fish. For instance, large numbers of stranded fish were predicted in June at the mean values of the other predictors, whereas the observed data showed relative low mean numbers of fish. This is likely because other predictor variables were typically at values corresponding to low stranding risk in June, such as short wetted history, and large values of minimum discharge. The interpretation is that if other predictors were at mean values in June, then large numbers of stranded fish would be predicted, even though this was rarely observed in the data. Therefore, discrepancies between predicted and observed values in the figures do not necessarily indicate poor model fit.

The results support a positive effect of magnitude of reduction on the probability of fish stranding (>0 fish). As an example of the effect size, the probability of observing zero stranded fish at a site decreased from 0.70 during a reduction of 25 m^3/s to 0.47 during a reduction of 500 m^3/s and 0.24 during a reduction of 1000 m^3/s. There was an unexpected negative relationship between discharge magnitude and the number of fish stranded per reduction event. This relationship may be spurious and possibly related to small sample sizes and highly variable counts of fish at the lowest and highest observed magnitudes of reduction.

The results indicate that stranding risk is greater in the lower Columbia River during low river levels. River stage could influence stranding risk because of differences in the slope, channel shape, and substrate types at different elevations of the river bed. Minimum discharge reached during the reduction was used as a proxy for river stage in this analysis. The results showed a decrease in the probability of stranding, and a decrease in the predicted number of fish stranded, with increasing minimum discharge. As an example of effect size, the probability of observing zero stranded fish increased from 0.27 at a minimum discharge of 1000 m^3/s to 0.91 at a minimum discharge of 3000 m^3/s, which suggests a large difference in the probability of stranding across the range of typical discharges in the lower Columbia River. The predicted number of fish stranded, and therefore effect size in terms of the number fish stranded, was less reliable, because of highly variable counts of fish and small sample sizes at the lowest and highest observed discharges. The finding of greater probability of stranding at low river stage in the lower Columbia River was also reported in previous analyses of the Lower Columbia River Fish Stranding Database (Golder and Poisson 2010).

Discharge fluctuations in the lower Columbia River can result from changes in discharge in either the Kootenay and Columbia rivers. Discharge in the Kootenay River, including within-day fluctuations called load shaping, can moderate the magnitude and rate of the river stage reduction in the Columbia River, and vice versa. The complex nature of the discharge variability in the two rivers is a challenge when assessing the effects of discharge reductions on fish stranding in the lower Columbia River. For instance, discharge measured at the Birchbank gauging station, located downstream of confluence of the Kootenay and Columbia rivers, was selected to best represent the combined effects of the dams, but may not always accurately represent the reduction in river stage at sites further upstream in the Kootenay or Columbia rivers. Load shaping could also mask potential effects, such as when a reduction in discharge at HLK/ALH is counteracted by temporary increases in discharged at BRD/X. These types of situations may explain some of the outliers and the high variability in the relationship between discharge variables (magnitude of reduction and minimum discharge) and the number of fish stranded.
For instance, there were sites visits where several thousand fish were stranded by a discharge reduction of less than 50 m^3/s at Birchbank.

Other challenges and limitations of the data set and statistical analysis include the following:

- The numbers of fish stranded had very high variability, including a large number of zeroes (approximately two thirds of observations), a majority of non-zero observations between 0 and 200, and ten observations between 4,000 and 10,000. The zero-inflated negative binomial model was suitable to model this type of data, but the high variability across the range of predictor variables resulted in large uncertainty in the effect of some predictor variables. This was especially true at the extreme (highest and lowest) values of the predictors, where sample sizes were generally smaller.
- For the analysis, the number of fish was summed across all species and life stages. Many of the observations of large numbers (thousands) of fish were larval or very small young-of-the-year. As the population impacts of mortality of larval versus juvenile or adult stages are different, this should be considered when interpreting the results.
- Although field survey methods were standardized in 2000, the nature of discharge reductions and objectives of field surveys and data collection have varied between 2000 and 2020 (see Section 2.1 for examples). Data identified as being not comparable or unreliable were excluded from analysis but there are likely other inconsistencies in the 20-year data set, which may contribute to large variability and uncertainty in the modelled relationships.

The main objective of this appendix was to assess the effect of ramping rate on the number of fish stranded during discharge reductions. The available data and modelling results did not support any effect of ramping rate on fish stranding in the lower Columbia River. Therefore, the null hypothesis that ramping rate does not affect the number of fish stranded cannot be rejected. Relationships between the number of fish stranded and other predictor variables, such as the day of year, minimum discharge, and magnitude of reduction, improve understanding of factors that affect fish stranding in the lower Columbia River and can be used to guide future fish stranding protocols.

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APPENDIX D

Effects of Wetted History Analysis

1.0 INTRODUCTION

Discharge reductions in regulated rivers can result in fish becoming stranded either in pools isolated from the main river or interstitially in the substrate, both of which can ultimately lead to mortality. In the lower Columbia River between Hugh L. Keenleyside Dam and Arrow Lake Generating Station (HLK/ALH) and the Canada-US border, fish stranding can occur due to discharge reductions at HLK/ALH, or at Brilliant Dam and Brilliant Expansion Powerplant (BRD/X). BRD/X is located on the Kootenay River 3 km upstream from the confluence of the Kootenay and Columbia rivers. Fish stranding was raised as an environmental issue associated with HLK operations by regulatory agencies in the mid-1990's. Since the mid-1990s, surveys have been conducted to assess the numbers of fish stranded following discharge reductions. Beginning in 2007, fish stranding surveys were conducted as part of the Lower Columbia River Fish Stranding Assessment and Ramping Protocol (CLBMON-42), which was implemented in 2007 as part of BC Hydro's Water Use Plan for the Columbia River. The primary objective of CLBMON-42 was to collect fish stranding data to assess the impact of flow reductions and flow ramping rates from HLK on the native fish species of the lower Columbia River.

Data collected during CLBMON-42 are used to address five management questions (Golder 2020). One of the management questions of CLBMON-42 is:

- Does wetted history (the length of time the habitat has been wetted prior to the flow reduction) influence the number of fish stranded (interstitially and pool) per flow reduction event for flow reductions from HLK?

The management hypothesis related to this question is:

- Wetted history does not influence the stranding rate of fish (both interstitially and pool stranding) for flow reductions from HLK.

Fish stranding data collected during surveys in the lower Columbia River are stored in the Lower Columbia River Fish Stranding Database. The database includes data from 1995 to 2020, but survey methods were only standardized beginning in 1999. As 2020 was the final year of monitoring as part of BC Hydro's WUP, the final report includes analyses to address the management questions using all available data from the monitoring program. This appendix provides details of the statistical analysis to address the management question above regarding the effect of wetted history on fish stranding in the lower Columbia River. The appendix focuses on the statistical methods, results, and interpretation. For additional details regarding the project, including background information and methods for data collection, readers are referred to Golder 2020.

2.0 METHODS

2.1 Data QAQC and compilation

Quality Assurance/Quality Control (QAQC) of data extracted from the database included exploratory plotting and checks of minimum and maximum values. The database includes data from surveys from 1995 to March 2020. As stranding survey methods were standardized in 1999, only data from 1999 to 2020 were considered comparable. Data from 1999 had missing values for one or more variables for many reduction events and were not used. Therefore, the data used for analysis were from January 2000 to March 2020. The analysis included reduction events resulting from changes in discharge at HLK/ALH, BRD/X, or both facilities. The numbers of fish stranded during each site visit included the combined total of all life stages, fish species, and survey methods, from both pool and interstitial stranding.

The following sites were omitted because the sample sizes (i.e., number of site visits) were too small: Birchbank Snye (LUB), Beach Eddy/Northshore Eddies (RUB), General, Norns Creek Fan to Kootenay River, REA Side Channel (HLK), Waldie's Island (MID), and Waterloo Eddy (RUB). In addition, Genelle Lower Cobble Island (MID) was omitted because the site could not be properly surveyed without boat access, and the data in the database from visual surveys from across the river were not considered reliable.

The following reduction events were omitted from analysis: 200001, 200002, 200013, 200014, 200106, 200499, 200727, 200813, 200814, 200820, 200912, 200915, 200920, 201011, 201113, 201209, 201416, 201501, and 201605. These reduction events were omitted because key information such as the discharge was missing, or because some aspect of the reduction event made the data not comparable or reliable. Examples of data that were not comparable or reliable are reduction dates where discharge data did not show a decrease (possibly due to within-day fluctuations referred to as load shaping), and non-typical surveys for other objectives such as egg stranding reconnaissance surveys, or monitoring of load shaping that did not involve a persistent decrease in base flow. In addition, three reduction events were omitted from the model because wetted history could not be calculated (200507, 201708, and 201709).

Between 2000 and 2020, some of reduction events occurred on a single day but others involved reductions on multiple consecutive days. For multi-day reductions, most often stranding surveys occurred on each day of the reduction event, but sometimes only one survey was conducted on the final day of the reduction event. Beginning in 2018, each day of multi-day reductions was entered in the database as a separate reduction event. Because the number of reduction days and sample days was not always the same between reduction events from 2000 to 2020, the unit of observation for analysis was the reduction event (rather than the individual reduction date). To compile the data by reduction event, the number of fish was summed across all survey dates and reduction dates. Similarly, the minimum and maximum discharge at Birchbank was summarized to describe the entire range of discharge across all reduction days (where applicable). Of the 339 reduction events used in the analysis, 14% (48 reduction events) were multi-day reductions.

A small number of observations were excluded because they were outliers that caused problems with model fitting or convergence. These observations included 1 reduction event (201208) that had extremely high minimum discharge (4831 m^3/s) and three site visits that had between 10,000 and 13,500 fish stranded.

After cleaning and compiling the data, the total sample size was 2,764 site visits from 338 reduction events and 24 sites. In the database, reduction events were coded as “HLK”, “BRD”, or “Both” based on the dam where the reduction occurred. Of the 338 reduction events used for analysis, 255 were from HLK, 52 were from BRD, 30 were from both, and a single reduction event was coded as “Other”.

2.2 Statistical Analysis

A zero-inflated generalized linear mixed model (ZIGLMM) was used to assess the effect of wetted history on fish stranding. This model is suitable for modelling count data (i.e., the number of fish stranded) that have a large number of zeroes and large variability in the counts. The response variable was the number of fish stranded of all life stages and species combined. The unit of observation was each site visit during each reduction event. Site and year were included as random effects in the model. Predictor variables (fixed effects) included in the model were the following:

- The magnitude of the discharge reduction (‘magnitude of reduction’) was calculated as the difference between the maximum and minimum discharge of the Columbia River at the Birchbank gauging station for each reduction event, as provided in the Lower Columbia River Fish Stranding Database. The Birchbank gauging station was used because it is downstream of the confluence of the Columbia and Kootenay rivers, and therefore represents changes in the river level resulting from discharge changes at both HLK/ALH and BRD/X. The Birchbank gauging station also provided a more complete discharge data set than data from HLK/ALH or BRD/X, which both had more periods with missing discharge data. Minimum and maximum values at Birchbank in the database were typically the minimum and maximum value during each 24-hour period of the reduction day. In some cases, if the discharge subsequently increased after the discharge reduction, the values in the database are the minimum and maximum preceding and following the reduction event, not including subsequent changes in discharge on the same day.
- The minimum discharge of the Columbia River at the Birchbank gauging station after the reduction event (‘minimum discharge’) was obtained from the Lower Columbia River Fish Stranding Database. Minimum discharge was used as an indicator of the river stage. Minimum discharge was modelled as a second-order polynomial based on exploratory plotting, which suggested a U-shaped distribution with the greatest number of fish stranded at very low and very high river stage, rather than a linear trend.
- Wetted history was the predictor variable of primary interest and was calculated as the number days between the reduction date and the most recent previous date when discharge was lower than the minimum discharge at Birchbank after the reduction event. The values of minimum discharge at Birchbank were from the Lower Columbia River Fish Stranding Database, and the data for the previous date of lower discharge were obtained from hourly discharge data for the Birchbank station from BC Hydro’s Columbia Basin Hydrological Database. Wetted history was capped at 365 days, such that all values greater than 365 were assigned a value of 365. This was done because the large range of wetted histories (up to 5684 days), combined with the low sample sizes and highly variable counts of fish at large values of wetted history, led to problems with model fitting. The rationale for the maximum value of 365 days was that re-colonization of habitat was expected to occur within one year of re-watering. Wetted history was modelled as a fourth order polynomial, which was necessary to capture the observed trend in the data. Modelling wetted history as a linear or lower order polynomial resulted in trends in the residual error that indicated poor model fit.
- Load shaping is defined as within-day variation in discharge due to changes in generation at a hydroelectric facility to meet power demands. In the study area, load shaping can occur at BRD/X but not at HLK/ALH. Load shaping was a binary categorical variable to indicate whether or not load shaping occurred on the reduction day. For multi-day reduction events, if load shaping occurred on any of the days, the reduction event was considered to have had load shaping.
- River kilometre for each site was obtained from the Lower Columbia River Fish Stranding database and was included in the model to account for attenuation in the risk of stranding with increasing distance downstream from the dams.

- Day of year was included to account for seasonal differences in stranding risk. Day of year was modelled as a cubic regression spline, similar to previous analysis of the stranding data (Golder and Poisson 2010), to account for the non-linear relationship observed in exploratory plotting. The degrees of freedom, which determines the amount of smoothing, was set to five.

All predictor variables were standardized by subtracting their mean and dividing by their standard deviation. Interactions between the predictor variables were not included in the model. The model was a two-stage model, also known as a “hurdle” model, that had one component that described the non-zero counts of fish, referred to as the conditional model, and one component that described the probability of zero versus non-zero counts of stranded fish, referred to as the zero-inflation model. The conditional model assumed a negative binomial distribution to describe the non-zero counts of fish. The zero-inflation model was equivalent to a logistic regression to predict whether or not one or more stranded fish were observed during a site visit. Both components of the model included all six fixed effects and the two random effects above, because all of these variables could potentially affect both the probability of stranding and the number of fish stranded. Models were fit using the package glmmTMB (Brooks et al. 2017) in the statistical environment R (R Core Team 2019).

Model diagnostics included checks of model assumptions including linearity of effects, homoscedasticity, and normality of residual errors. Plots of residuals versus predicted values and residuals versus predictor variables were created to look for residual trends that would indicate poor model fit. All of these checks used simulated residuals produced using the DHARMa package (Hartig 2020) in R.

Statistical significance of the effect of predictor variables on the conditional model and on the zero-inflation model was assessed using a Wald’s test. Effect size was assessed using plots of the predicted values of the response variable versus one of the predictor variables, while holding other continuous predictor variables at their mean values and holding the categorical predictor, load shaping, at its reference value of no load shaping. These “population-level” predictions from the fitted model are predictions with the random effects of site and year set to zero, which represents the predictions for an average site and an average year. In plots of predicted values, observed data were also included as points. As the model predicts the mean number of fish, mean values of the observed data are shown, instead of raw values for each site visit, which allows better visualization of model fit with the data.

The model to assess the effect of wetted history was similar to the model used to assess the effect of ramping rate (Appendix C), except that ramping rate was not included in the present analysis, and that the sample sizes were different because more site visits had to be excluded for the ramping rate model (Appendix C) than the wetted history model (Appendix D) due to missing ramping rate data.

3.0 RESULTS

Wetted history had a statistically significant effect on both the probability of observing zero stranded fish and the number of fish stranded (Table 1). The predicted probability of observing zero stranded fish decreased from 0.75 at 1 day of wetted history to 0.58 at 100 days wetted history (top panel; Figure 1). At greater than 100 days wetted history, the predicted probably of zero stranded fish was stable, except for an increase in the probability of zero fish at wetted history greater than 300 days, which was likely related to small sample sizes. The predicted number of fish stranded increased from 21 fish at 1 day of wetted history to 52 fish at 50 days, 93 fish at 200 days, and 192 fish at 284 days (bottom panel; Figure 1). The rapid increase in the predicted number of stranded fish from 200 to 280 days of wetted history, and the sharp decrease after 300 days, had large confidence intervals and likely reflects uncertainty due to small sample sizes and highly variable counts of fish at these higher values of wetted history. In summary, the results support a positive relationship between wetted

history and stranding risk. The probability of stranding one or more fish plateaued after approximately 100 days of wetted history. The predicted number of fish increased between 1 and 50 days of wetted history, and more slowly after 50 days, with a highly uncertain trend after 200 days.

Day of year was included in the models to account for seasonal variation in stranding risk. Day of year was a statistically significant predictor of both the probability of stranding and number of fish stranded (Table 1). The predicted peak number of stranded fish occurred on 26 June (61 fish per site visit), with elevated numbers of fish stranded from 10 April to 13 September (10 or more fish stranded per site visit) and fewer than 10 fish predicted for dates outside of this range. The predicted probability of observing zero stranded fish showed a similar trend as the predicted number of fish stranded, except that the peak stranding risk occurred later in the summer. The predicted probability of observing zero fish was stable between 1 January and mid-April (0.73-0.74), decreased to a minimum of 0.54 on 9 August, and was greatest mid-November (0.84; Figure 2).

Although the predicted numbers of fish stranded showed a peak in late June, the observed mean number of fish per for each 10-day period (black points in Figure 2) showed large variability in the numbers of stranded fish. For instance, large numbers of stranded fish were often observed in late March (before the predicted peak), and late September to early November (after the predicted peak). Based on previous analyses and exploratory plotting, day of year was included as a second-order polynomial which allows for a single peak in fish stranding. Alternative models that included higher-order polynomials or smoothers to allow more than one period of greater numbers of stranded fish did not improve the fit (results not shown), suggesting that the single peak best described the seasonal trend in fish stranding. Therefore, model predictions indicate increased numbers of stranded fish from April to September, but the observed data show that large numbers of fish can also be stranded outside of this period, especially in October and November.

Magnitude of reduction was a statistically significant predictor of both the probability of stranding and number of fish stranded (Table 1). The component of the model that predicted whether or not any fish stranding occurred suggested increasing risk of stranding (decreasing probability of zero stranded fish) with increasing magnitude of reduction. The probability of observing zero stranded fish decreased from 0.70 during a reduction of 25 m^3/s to 0.49 during a reduction of 500 m^3/s and 0.28 during a reduction of 1000 m^3/s (top panel; Figure 3). In contrast, there was a negative relationship between magnitude of reduction and the number of fish stranded, with the predicted number of fish stranded decreasing from 66 fish during a reduction of 25 m^3/s to 50 fish at a reduction of 500 m^3/s and 30 fish during a reduction of 1000 m^3/s (bottom panel; Figure 3).

The negative relationship between magnitude of reduction and the number of fish stranded was the opposite of the expected positive relationship and may be explained by the high variability and relatively small number of observations at very low and very high magnitudes of reduction. For instance, there were four site visits during small discharge reductions (less than 50 m^3/s) where more than 4000 larval or young-of-the-year fish were stranded. There were only two discharge reductions and 11 site visits during discharge reductions greater than 1000 m^3/s, and very few stranded fish were observed. Although the model indicated a statistically significant negative relationship, the effect size was fairly small with only a 24% decrease in the number of fish stranded (66 to 50 fish) when the magnitude of reduction increased from 25 to 500 m^3/s, which was half of the entire observed range (bottom panel; Figure 3). Overall, the results support a positive effect of magnitude of reduction on the probability of fish stranding (>0 fish) and a small and possibly spurious negative effect of magnitude of reduction on the number of fish stranded per site visit.

Minimum discharge reached during the reduction event was used as a proxy to assess the effect of river stage on fish stranding. Minimum discharge was a statistically significant predictor of both the probability of stranding and number of fish stranded (Table 1). The probability of observing zero stranded fish increased from 0.31 at a minimum discharge of 1000 m^3/s to 0.91 at a minimum discharge of 3000 m^3/s (top panel; Figure 4).
The predicted number of fish stranded, based on the combined model of probability and severity of fish stranding, decreased from 339 fish at 1000 m^3/s to 27 fish at 3000 m^3/s (bottom panel; Figure 4). However, predictions of the non-zero counts of fish stranded (middle panel; Figure 4) indicated unrealistic predictions at very high and low values of minimum discharge. The drastic decrease in predicted values at low minimum discharge and drastic increase at high minimum discharge were attributed small sample sizes and highly variable counts, which caused problems with the polynomial fit at extreme values. Therefore, the data support a small decrease in the number fish stranded between low (~900 m^3/s) and moderate (2000 m^3/s) discharge but the predictions and effect sizes at the highest (greater than 3000 m^3/s) and lowest (less than 900 m^3/s) minimum discharges are not reliable. Despite uncertainties at the extreme values, these results suggest increasing likelihood and severity of fish stranding with decreasing river stage in the lower Columbia River.

Load shaping was not a significant predictor of fish stranding (Table 1). River kilometre did not have a significant effect on the number of fish stranded but did have a significant effect on the probability of stranding zero fish (Table 1). The estimated coefficient for the effect of river kilometre on the probability of zero stranding was positive (estimate: 0.48, standard error: 0.17), indicating increasing chance of zero stranding, or decreasing risk of fish stranding, with increasing distance downstream. These variables were not of primary interest to the project's management questions but were included to account for their potential effect on fish stranding.

Table 1: Statistical significance of predictor variables in the model of fish stranding in the lower Columbia River, 2000 to 2020.

Predictor Variable	Effect on Number of Fish (Conditional Model)	Effect on Probability of Zero Stranding (zero-inflation model)
	P-value	*P*-value
Wetted History	**0.005**	**<0.0001**
Magnitude of Reduction	**0.002**	**<0.0001**
Minimum Discharge	**0.0005**	**<0.0001**
Day of Year	**<0.0001**	**<0.0001**
River Kilometre	0.7	**0.006**
Load Shaping	0.9	0.8

Note: Direction of the effect, estimated coefficients, and their uncertainty are not presented because many of the predictor variables were modelled as polynomial or cubic splines (i.e., wetted history, minimum discharge, and day of year), which means that they had multiple coefficients per variable, which makes it not possible to interpret the standardized coefficients as effect sizes. Instead, effect size is presented in terms of the change in predicted values relative to each predictor variable, while holding other variables at their mean values (Figures 1 to 4). Variables significant at the 0.05 level are shown in **bold**.

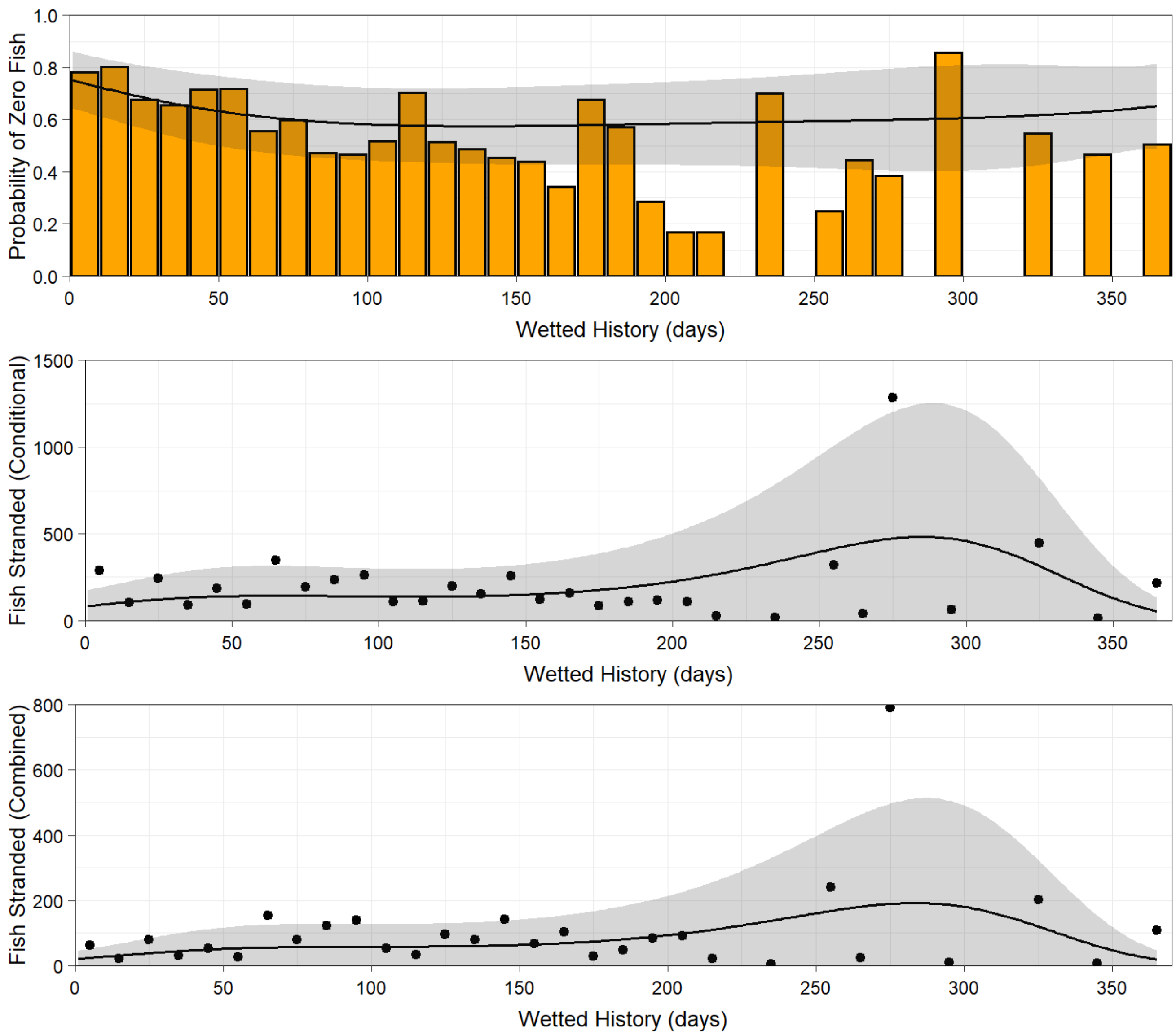

Figure 1: Predicted fish stranding versus wetted history in the lower Columbia River, 2000 to 2020. Predictions are from a negative binomial two-stage hurdle model where the top panel is the probability of zero fish stranded, the middle panel is the number of fish stranded for non-zero stranding events, and the bottom panel is the combined prediction based on the probability and magnitude of stranding. Orange bars and black points are the mean values of the observed data by 10-day bins of wetted history. Black line is the mean prediction and grey ribbon is the approximate 95% confidence interval.

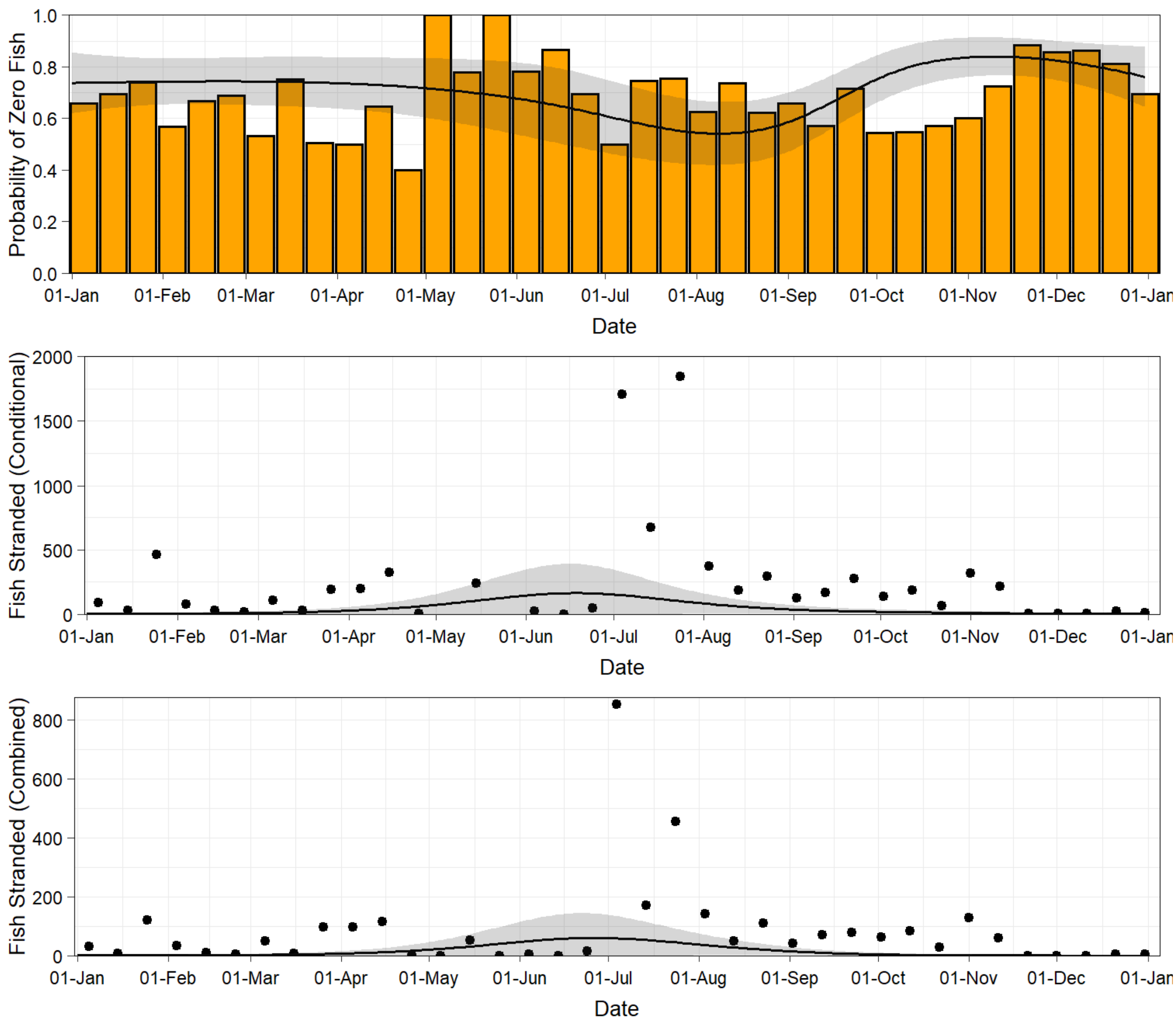

Figure 2: Predicted fish stranding versus day of year in the lower Columbia River, 2000 to 2020. Predictions are from a negative binomial two-stage hurdle model where the top panel is the probability of zero fish stranded, the middle panel is the number of fish stranded for non-zero stranding events, and the bottom panel is the combined prediction based on the probability and magnitude of stranding. Orange bars and black points are the mean values of the observed data by 10-day bins of day of year. Black line is the mean prediction and grey ribbon is the approximate 95% confidence interval.

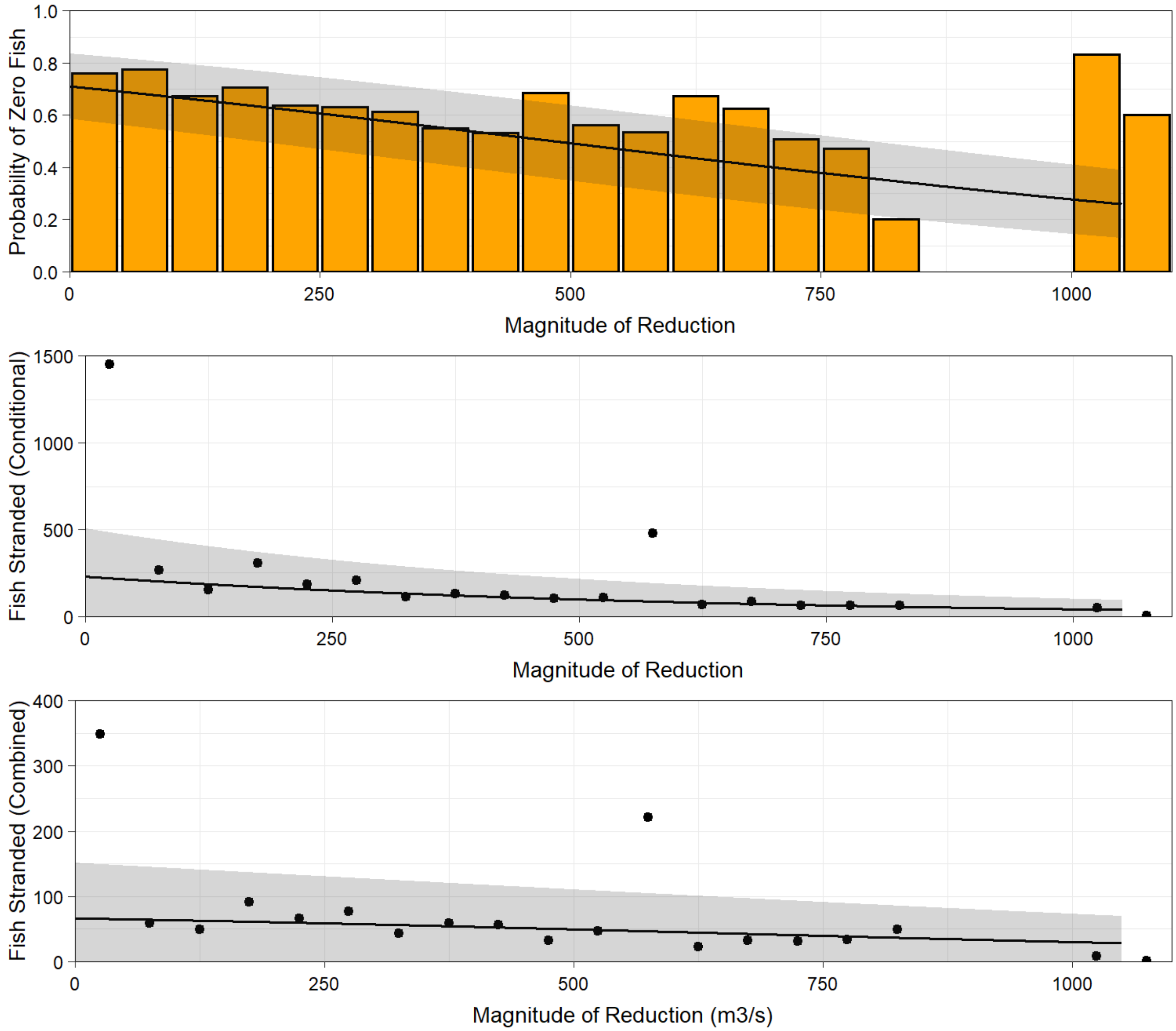

Figure 3: Predicted fish stranding versus magnitude of discharge reduction in the lower Columbia River, 2000 to 2020. Predictions are from a negative binomial two-stage hurdle model where the top panel is the probability of zero fish stranded, the middle panel is the number of fish stranded for non-zero stranding events, and the bottom panel is the combined prediction based on the probability and magnitude of stranding. Orange bars and black points are the mean values of the observed data by 50 m³/s bins of magnitude of reduction. Black line is the mean prediction and grey ribbon is the approximate 95% confidence interval.

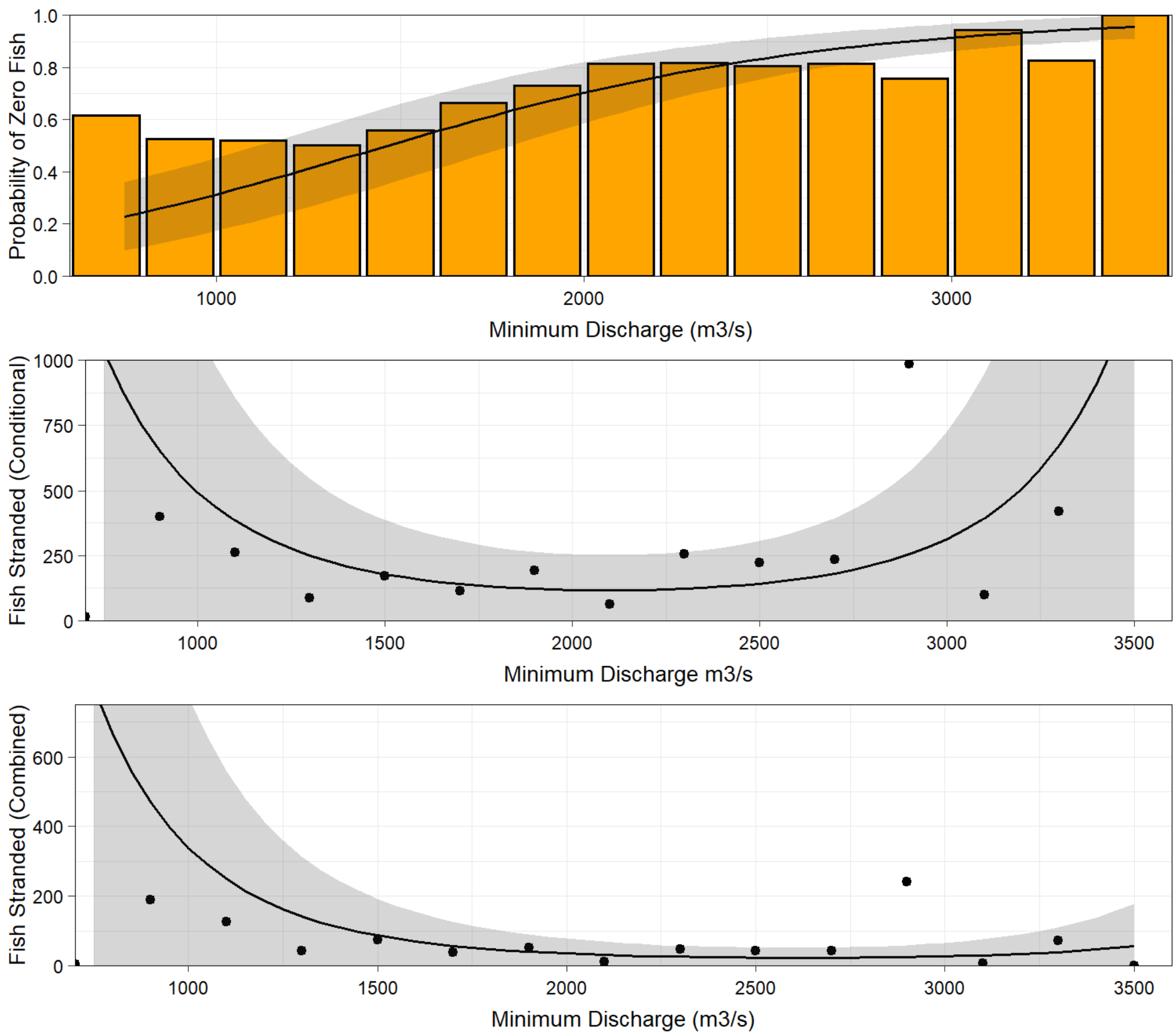

Figure 4: Predicted fish stranding versus minimum discharge reached during the reduction in the lower Columbia River, 2000 to 2020. Predictions are from a negative binomial two-stage hurdle model where the top panel is the probability of zero fish stranded, the middle panel is the number of fish stranded for non-zero stranding events, and the bottom panel is the combined prediction based on the probability and magnitude of stranding. Orange bars and black points are the mean values of the observed data by 200 m³/s bins of magnitude of reduction. Black line is the mean prediction and grey ribbon is the approximate 95% confidence interval.

4.0 DISCUSSION

Twenty years of data from fish stranding surveys were used to assess the effect of wetted history on the number of fish stranded, using a statistical model that accounted for other variables that can influence stranding, such as magnitude of discharge reduction and river stage. The model assessed the effect of wetted history on both the likelihood of stranding fish, and the severity of fish stranding in terms of the number of fish stranded.

Wetted history had a statistically significant positive effect on both the probability and severity of fish stranding.

This supports the idea that substrate that had been inundated for a longer period was more likely to strand fish if dewatered, compared to substrate that was inundated for a shorter period. The predicted number of fish stranded per site, based the combined probability of stranding and severity of stranding, increased from 21 fish at 1 day of wetted history to 52 fish at 50 days, and 93 fish at 200 days. These predictions are for an average year and an average site. As there were 24 stranding sites included in the analysis, a difference of 70 fish per site between 1 and 200 days wetted history suggests a biological meaningful effect of wetted history on stranding risk. At greater than 200 days wetted history, there was large variability the mean numbers of fish stranded, which resulted in the large uncertainty in model predictions. A previous analysis of the lower Columbia River stranding data also found increased probability of stranding with increasing wetted history (Golder and Poisson 2010). The previous analysis by Golder and Poisson (2010) used a maximum value of wetted history of 90 days, whereas the current analysis used 365 days as a maximum value of wetted history.

Seasonal differences in stranding risk were accounted for by including day of year in the model. Model predictions indicate peak numbers of fish stranding in late June, with elevated stranding risk from April to September. However, observed data showed events with large numbers of stranded fish also occurred outside of this range of dates, particularly in October and November.

The results support a positive effect of magnitude of reduction on the probability of fish stranding (>0 fish). As an example of the effect size, the probability of observing zero stranded fish at a site decreased from 0.70 during a reduction of 25 m^3/s to 0.49 during a reduction of 500 m^3/s and 0.28 during a reduction of 1000 m^3/s. There was an unexpected negative relationship between discharge magnitude and the number of fish stranded per reduction event. This relationship may be spurious and possibly related to small sample sizes and highly variable counts of fish at the lowest and highest observed magnitudes of reduction.

The results indicate that stranding risk is greater in the lower Columbia River during low river levels. River stage could influence stranding risk because of differences in the slope, channel shape, and substrate types at different elevations of the river bed. Minimum discharge reached during the reduction was used as a proxy for river stage in this analysis. The results showed a decrease in the probability of stranding, and a decrease in the predicted number of fish stranded, with increasing minimum discharge. As an example of effect size, the probability of observing zero stranded fish increased from 0.31 at a minimum discharge of 1000 m^3/s to 0.91 at a minimum discharge of 3000 m^3/s, which suggests a large difference in the probability of stranding across the range of typical discharges in the lower Columbia River. The predicted number of fish stranded, and therefore effect size in terms of the number fish stranded, was less reliable, because of highly variable counts of fish and small sample sizes at the lowest and highest observed discharges. The finding of greater probability of stranding at low river stage in the lower Columbia River was also reported in previous analyses of the lower Columbia River database (Golder and Poisson 2010).

Discharge fluctuations in the lower Columbia River can result from changes in discharge in either the Kootenay and Columbia rivers. Discharge in the Kootenay River, including within-day fluctuations called load shaping, can moderate the magnitude and rate of the river stage reduction in the Columbia River, and vice versa. The complex nature of the discharge variability in the two rivers is a challenge when assessing the effects of discharge reductions on fish stranding in the lower Columbia River. For instance, discharge measured at the Birchbank gauging station, located downstream of confluence of the Kootenay and Columbia rivers, was selected to best represent the combined effects of the dams, but may not always accurately represent the reduction in river stage at sites further upstream in the Kootenay or Columbia rivers. Load shaping could also mask potential effects, such as when a reduction in discharge at HLK/ALH is counteracted by temporary increases in discharged at BRD/X. These types of situations may explain some of the outliers and the high variability in the relationship between discharge variables (magnitude of reduction and minimum discharge) and the number of fish stranded. For instance, there were sites visits when several thousand fish were stranded by a discharge reduction of less than 50 m^3/s at Birchbank.

Other challenges and limitations of the data set and statistical analysis include the following:

- The numbers of fish stranded had very high variability, including a large number of zeroes (approximately two thirds of observations), a majority of non-zero observations between 0 and 200, and ten observations between 4,000 and 10,000. The zero-inflated negative binomial model was suitable to model this type of data, but the high variability across the range of predictor variables resulted in large uncertainty in the effect of some predictor variables. This was especially true at the extreme (highest and lowest) values of the predictors, where sample sizes were generally smaller.
- For the analysis, the number of fish was summed across all species and life stages. Many of the observations of large numbers (thousands) of fish were larval or very small young-of-the-year. As the population impacts of mortality of larval versus juvenile or adult stages are different, this should be considered when interpreting the results.
- Although field survey methods were standardized in 2000, they nature of discharge reductions and objectives of field surveys and data collection have varied between 2000 and 2020 (see Section 2.1 for examples). Data identified as being not comparable or unreliable were excluded from analysis but there are likely other inconsistencies in the 20-year data set, which may contribute to large variability and uncertainty in the modelled relationships.

The main objective of this appendix was to assess the effect of wetted history on the number of fish stranded during discharge reductions. The analysis presented here supports the rejection of the null management hypothesis that wetted history does not affect the number of fish stranded. The modelled relationship indicated a statistically significant effect of wetted history, and a biologically significant effect size, as the number of predicted fish stranded more than doubled (from 21 to 52 fish) when wetted history increased from 1 to 50 days. Relationships between the number of fish stranded and other predictor variables, such as the day of year, minimum discharge, and magnitude of reduction, improve understanding of factors that affect fish stranding in the lower Columbia River and can be used to guide future fish stranding protocols.

5.0 REFERENCES

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APPENDIX E

Effects of Recontouring Analysis

1.0 INTRODUCTION

Discharge reductions in regulated rivers can result in fish becoming stranded either in pools isolated from the main river or interstitially in the substrate, both of which can ultimately lead to mortality. In the lower Columbia River between Hugh L. Keenleyside Dam and Arrow Lake Generating Station (HLK/ALH) and the Canada-US border, fish stranding can occur due to discharge reductions at HLK/ALH, or at Brilliant Dam and Brilliant Expansion Powerplant (BRD/X). BRD/X is located on the Kootenay River 3 km upstream from the confluence of the Kootenay and Columbia rivers. Fish stranding was raised as an environmental issue associated with HLK operations by regulatory agencies in the mid-1990's. Since the mid-1990s, surveys have been conducted to assess the numbers of fish stranded following discharge reductions. Beginning in 2007, fish stranding surveys were conducted as part of the Lower Columbia River Fish Stranding Assessment and Ramping Protocol (CLBMON-42), which was implemented in 2007 as part of BC Hydro's Water Use Plan for the Columbia River. The primary objective of CLBMON-42 was to collect fish stranding data to assess the impact of flow reductions and flow ramping rates from HLK on the native fish species of the lower Columbia River.

Data collected during CLBMON-42 are used to address five management questions (Golder 2020). One of the management questions of CLBMON-42 is:

- Can physical habitat works (i.e., recontouring) reduce the incidence of fish stranding in high risk areas?

The management hypothesis related to this question is:

- Physical habitat manipulation does not reduce the stranding rate of fish in the lower Columbia River.

Physical habitat modifications intended to reduce the incidence of stranding were conducted at six sites in the lower Columbia River between 2002 and 2015. The modifications were primarily recontouring of the river bed to fill in depressions to prevent pool formation. All of the recontoured sites have been monitored during fish stranding surveys following discharge reductions during years before and after recontouring. These data allow assessment of the effectiveness of recontouring in reducing fish stranding following a before/after study design.

Fish stranding data collected during surveys in the lower Columbia River are stored in the Lower Columbia River Fish Stranding Database. The database includes data from 1995 to 2020, but survey methods were only standardized beginning in 1999. As 2020 was the final year of monitoring as part of BC Hydro's WUP, the final report includes analyses to address the management questions using all available data from the monitoring program. This appendix provides details of the statistical analysis to address the management question above regarding the effect of recontouring on fish stranding in the lower Columbia River. The appendix focuses on the statistical methods, results, and interpretation. For additional details about the project, including background information and methods for data collection, readers are referred to Golder 2020.

2.0 METHODS

2.1 Data QAQC and compilation

Quality Assurance/Quality Control (QAQC) of data extracted from the database included exploratory plotting and checks of minimum and maximum values. The database includes data from surveys from 1995 to March 2020. As stranding survey methods were standardized in 1999, only data from 1999 to 2020 were considered comparable. Data from 1999 had missing values for one or more variables for many reduction events and were not used. Therefore, the data used for analysis were from January 2000 to March 2020. The analysis included reduction events resulting from changes in discharge at HLK/ALH, BRD/X, or both facilities. The numbers of fish stranded during each site visit included the combined total of all life stages, fish species, and survey methods, from both pool and interstitial stranding.

The analysis included the following five sites that were recontoured: Fort Shepherd Launch (RUB), Genelle (Mainland) (LUB), Lions Head (upstream of Norns Fan) (RUB), Millenium Park (Tin Cup LUB), and Norns Creek Fan (RUB). Genelle Lower Cobble Island (MID) was recontoured but was omitted from analysis because the site could not be properly surveyed without boat access, and the data in the database from visual surveys from across the river were not considered reliable.

The following reduction events were omitted from analysis: 200001, 200002, 200013, 200014, 200106, 200499, 200727, 200813, 200814, 200820, 200912, 200915, 200920, 201011, 201113, 201209, 201416, 201501, and 201605. These reduction events were omitted because key information such as the discharge was missing, or because some aspect of the reduction event made the data not comparable or reliable. Examples of data that were not comparable or reliable are reduction dates where discharge data did not show a decrease (possibly due to within-day fluctuations referred to as load shaping), and non-typical surveys for other objectives such as egg stranding reconnaissance surveys, or monitoring of load shaping that did not involve a persistent decrease in base flow. In addition, three reduction events were omitted from the model because wetted history could not be calculated (200507, 201708, and 201709).

Between 2000 and 2020, some of reduction events occurred on a single day but others involved reductions on multiple consecutive days. For multi-day reductions, most often stranding surveys occurred on each day of the reduction event, but sometimes only one survey was conducted on the final day of the reduction event. Beginning in 2018, each day of multi-day reductions was entered in the database as a separate reduction event. Because the number of reduction days and sample days was not always the same between reduction events from 2000 to 2020, the unit of observation for the analysis was the reduction event (rather than the individual reduction date). To compile the data by reduction event, the number of fish was summed across all survey dates and reduction dates. Similarly, the minimum and maximum discharge at Birchbank was summarized to describe the entire range of discharge across all reduction days (where applicable). Of the 321 reduction events used in the analysis, 15% (49 reduction events) were multi-day reductions.

A small number of observations were excluded because they were outliers that caused problems with model fitting or convergence. These observations included 1 reduction event (201208) that had extremely high minimum discharge (4831 m^3/s) and three site visits that had between 10,000 and 13,500 fish stranded.

After cleaning and compiling the data, the total sample size was 1,049 site visits from 321 reduction events and 5 sites. In the database, reduction events were coded as “HLK”, “BRD”, or “Both” based on the dam where the reduction occurred. Of the 321 reduction events used for analysis, 248 were from HLK, 43 were from BRD, 29 were from both, and a single reduction event was coded as “Other”. The cleaned data set was the same as the data used for the analysis of wetted history (Appendix D), except that only data from the five recontoured sites were used.

2.2 Statistical Analysis

A zero-inflated generalized linear mixed model (ZIGLMM) was used to assess the effect of recontouring on fish stranding. This model is suitable for modelling count data (i.e., the number of fish stranded) that have a large number of zeroes and large variability in the counts. The response variable was the number of fish stranded of all life stages and species combined. The unit of observation was each site visit during each reduction event. Site and year were included as random effects in the model. Predictor variables (fixed effects) included in the model were the following:

- **Recontouring** was a categorical variable with values of “Before” or “After”.
- The magnitude of the discharge reduction (‘magnitude of reduction’) was calculated as the difference between the maximum and minimum discharge of the Columbia River at the Birchbank gauging station for each reduction event, as provided in the Lower Columbia River Fish Stranding Database. The Birchbank gauging station was used because it is downstream of the confluence of the Columbia and Kootenay rivers, and therefore represents changes in the river level resulting from discharge changes at both HLK/ALH and BRD/X. The Birchbank gauging station also provided a more complete discharge data set than data from HLK/ALH or BRD/X, which both had more periods with missing discharge data. Minimum and maximum values at Birchbank in the database were typically the minimum and maximum value during each 24-hour period of the reduction day. In some cases, if the discharge subsequently increased after the discharge reduction, the values in the database are the minimum and maximum preceding and following the reduction event, not including subsequent changes in discharge on the same day.
- The minimum discharge of the Colubmia River at the Birchbank gauging station after the reduction event (‘minimum discharge’) was obtained from the Lower Columbia River Fish Stranding Database. Minimum discharge was used as an indicator of the river stage. Minimum discharge was modelled as a second-order polynomial based on exploratory plotting, which suggested a U-shaped distribution with the greatest number of fish stranded at very low and very high river stage, rather than a linear trend.
- Wetted history was calculated as the number days between the reduction date and the most recent previous date when discharge was lower than the minimum discharge at Birchbank after the reduction event. The values of minimum discharge at Birchbank were from the Lower Columbia River Fish Stranding Database, and the data for the previous date of lower discharge were obtained from hourly discharge data for the Birchbank station from BC Hydro’s Columbia Basin Hydrological Database. Wetted history was capped at 365 days, such that all values greater than 365 were assigned a value of 365. This was done because the large range of wetted histories (up to 5684 days), combined with the low sample sizes and highly variable counts of fish at large values of wetted history, led to problems with model fitting. The rationale for the maximum value of 365 days was that re-colonization of habitat was expected to occur within one year of re-watering. Wetted history was modelled as a fourth order polynomial, which was necessary to capture the observed trend in the data. Modelling wetted history as a linear or lower order polynomial resulted in trends in the residual error that indicated poor model fit.

- Load shaping is defined as within-day variation in discharge due to changes in generation at a hydroelectric facility to meet power demands. In the study area, load shaping can occur at BRD/X but not at HLK/ALH. Load shaping was a binary categorical variable to indicate whether or not load shaping occurred on the reduction day. For multi-day reduction events, if load shaping occurred on any of the days, the reduction event was considered to have had load shaping.
- River kilometre for each site was obtained from the Lower Columbia River Fish Stranding Database and was included in the model to account for attenuation in the risk of stranding with increasing distance downstream from the dams.
- Day of year was included to account for seasonal differences in stranding risk. Day of year was modelled as a cubic regression spline, similar to previous analysis of the stranding data (Golder and Poisson 2010), to account for the non-linear relationship observed in exploratory plotting. The degrees of freedom, which determines the amount of smoothing, was set to five.

All predictor variables were standardized by subtracting their mean and dividing by their standard deviation. Interactions between the predictor variables were not included in the model. The model was a two-stage model, also known as a “hurdle” model, that had one component that described the non-zero counts of fish, referred to as the conditional model, and one component that described the probability of zero versus non-zero counts of stranded fish, referred to as the zero-inflation model. The conditional model assumed a negative binomial distribution to describe the non-zero counts of fish. The zero-inflation model was equivalent to a logistic regression to predict whether or not one or more stranded fish were observed during a site visit. Both components of the model included all seven fixed effects and the two random effects above, because all of these variables could potentially affect both the probability of stranding and the number of fish stranded. Models were fit using the package glmmTMB (Brooks et al. 2017) in the statistical environment R (R Core Team 2019).

Model diagnostics included checks of model assumptions including linearity of effects, homoscedasticity, and normality of residual errors. Plots of residuals versus predicted values and residuals versus predictor variables were created to look for residual trends that would indicate poor model fit. All of these checks used simulated residuals produced using the DHARMa package (Hartig 2020) in R.

Statistical significance of the effect of predictor variables on the conditional model and on the zero-inflation model was assessed using a Wald’s test. Effect size was assessed using plots of the predicted values. Population-level predictions had the random effects set to zero, and therefore represent predictions for an average site and an average year. Random-level predictions were generated to show predicted values for each site and year. For both types of predictions, continuous predictor variables were held at their mean values and the categorical predictor, load shaping, was held at its reference value of no load shaping. Day of year was set to September 1 for all predictions. This date was selected as an example date during the period considered high risk by BC Hydro (1 June to 30 September, Golder [2020]), but after the period of peak stranding risk, based on analyses in Appendix C and D. Therefore, predictions for the example date of September 1 can be considered a period of intermediate risk, lower than the peak risk, but greater than during the low risk period.

Effect size is only presented for the predictor variable of primary interest for this appendix, which was recontouring. For other predictor variables included in the model, effect sizes are not presented, and readers are referred to Appendices C and D for detailed discussion of their effect on fish stranding. The analyses in

Appendices C and D are similar to the present analysis but include all sample sites, instead of only the five recontoured sites, and are therefore considered more reliable assessments of the effect of the other predictor variables.

3.0 RESULTS

Recontouring had a statistically significant effect on both the probability of stranding fish and on the number of fish stranded (Table 1). Effect size for recontouring is shown by the random-level predictions for each site and year (Figures 1 to 3) and the population-level predictions, which represent the effect for an average site and year (discussed below). In the model, wetted history, magnitude of reduction, minimum discharge, and day of year had a statistically significant effect on fish stranding, whereas river kilometre and load shaping did not (Table 1). These predictors were included to account for their potential effect on fish stranding but are not of primary interest to the management question regarding recontouring. Therefore, effect sizes for other predictor variables are not presented in this appendix. The effects of these predictor variables are discussed in detail in Appendices C and D.

The predicted probability of stranding zero fish was greater after recontouring than before recontouring at all five sites (Figure 1). At Genelle Mainland (LUB), the predicted probability of no stranding increased from 0.11 in years before recontouring to 0.18 to 0.22 in years after recontouring. The effect size was similar at Norn's Creek Fan (RUB), with an increase in the probability of no stranding from 0.14 before recontouring to 0.25 after recontouring. The effect size was slightly larger at the other three sites. At Fort Shepherd Launch (RUB), the predicted probability of no stranding was 0.25 to 29 in years before recontouring and 0.41 to 0.43 in years after recontouring. At Lionshead (RUB), the predicted probability of no stranding was 0.28 to 0.33 before recontouring and 0.46 to 0.48 after recontouring. At Millenium Park (Tin Cup LUB), the predicted probability of no stranding was 0.28 before recontouring and 0.44 to 0.47 after recontouring. Overall, these predictions suggest a 10% to 20% decrease in the probability of stranding due to recontouring, depending on the site and year.

For events when one or more fish were stranded, the conditional (non-zero) model predicted smaller numbers of fish stranded after recontouring than before at all five sites (Figure 2). At all sites, confidence intervals around the predictions were large, which reflects the large variation in the number of fish stranded in the data, ranging from 1 to several thousand between reduction events. The largest predictions were at Genelle Mainland (LUB), where the predicted number of stranded fish ranged from 729 to 2,107 in years before recontouring and 109 to 604 after recontouring.

The combined model, including the zero-inflation (probability of stranding) and conditional (number of fish) model, predicted smaller numbers of fish stranded after recontouring than before at all five sites (Figure 3). The 95% confidence intervals overlapped among years, reflecting the large variation in the number of stranded fish between reduction events, and uncertainty in the number of fish that will be stranded during a particular site visit. However, the predicted numbers of stranded fish before versus after recontouring indicate substantial differences. For instance, at Lionshead (RUB), the predicted mean number of fish stranded per reduction event ranged from 15 to 107 in years before recontouring and 7 to 17 fish in years after recontouring.

Population-level predictions were used to show the effect size of recontouring for an average site in an average year. The predicted probability of observing zero stranded fish was 0.21 (confidence interval [CI]: 0.10 to 0.32) before recontouring and 0.35 (CI: 0.20 to 0.49) after recontouring, with other predictors held at their first level values (i.e. no load shaping) or at their mean values, and with September 1 used as the date. These estimates indicate that recontouring resulted in a 14% decrease, on average, in the probability of stranding one or more fish. The large and overlapping confidence intervals between before and after recontouring reflect variability and uncertainty in fish stranding for a particular site visit.

For site visits when fish were stranded, the conditional (non-zero) model predicted that the mean number of stranded fish stranded was 155 (CI: 0 to 365) before recontouring and 54 (CI: 0 to 124) after recontouring. For events when fish are stranded, these predictions suggest a 66% decrease in the number of fish stranded (from 155 to 54 fish), when other predictors were at their mean or first level values, and with September 1 used as the date.

The combined model, including the zero-inflation (probability of stranding) and conditional (number of fish) model, predicted that the mean number of stranded fish per site and reduction event was 122 (CI: 0 to 289) before recontouring and 35 (CI: 0 to 81) after recontouring, at an average site during an average year. These predictions are for September 1, with other predictors held at their mean and first level values. The combined model indicates a 71% decrease (from 122 to 35) in the number of fish stranded, on average, due to recontouring.

Table 1: Statistical significance of predictor variables in the model of fish stranding in the lower Columbia River, 2000 to 2020.

Predictor Variable	Effect on Number of Fish (Conditional Model)	Effect on Probability of Zero Stranding (zero-inflation model)
	P-value	*P*-value
Recontouring	**0.007**	**0.0003**
Wetted History	**0.01**	**0.01**
Magnitude of Reduction	0.1	**<0.0001**
Minimum Discharge	**0.003**	**<0.0001**
Day of Year	**<0.0001**	**<0.0001**
River Kilometre	0.9	0.4
Load Shaping	0.9	>0.9

Note: Variables significant at the 0.05 level are shown in **bold**. Direction of the effect, estimated coefficients, and their uncertainty are not presented because many of the predictor variables were modelled as polynomial or cubic splines (i.e., wetted history, minimum discharge, and day of year), which means that they had multiple coefficients per variable, which makes it not possible to interpret the standardized coefficients as effect sizes. Effect size for the predictor of primary interest, recontouring, is shown using predicted values of fish stranding, while holding other variables at their mean values (Figures 1 to 3). For all other predictor variables, readers are referred to Appendices C and D, where similar models are presented, included prediction plots showing effect sizes for all predictor variables.

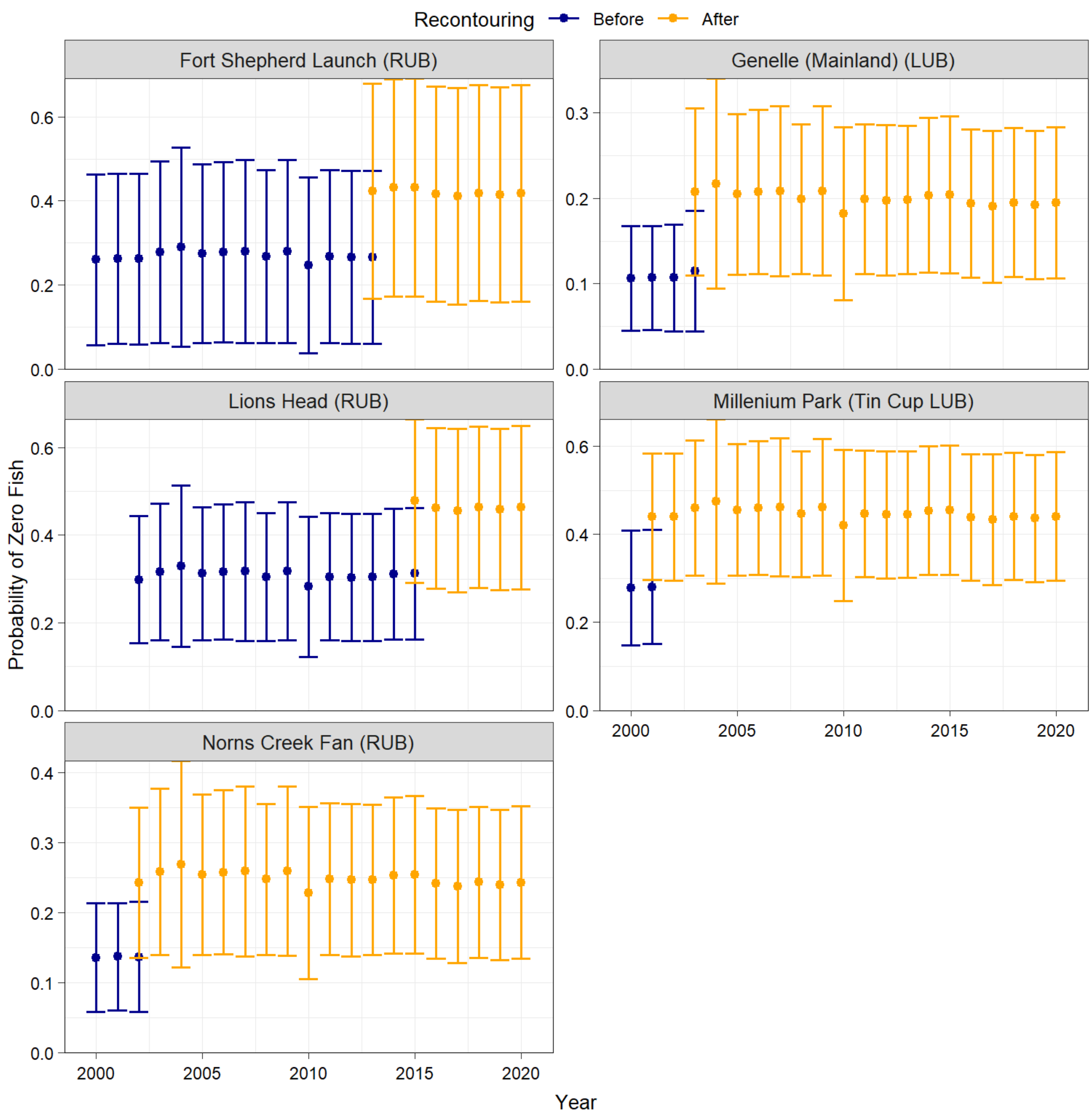

Figure 1: Predicted probably of observing zero stranded fish in the lower Columbia River by year, site, and before/after recontouring. Points are predicted values and error bars are approximate 95% confidence intervals. Predicted values are the expected probability of stranding zero fish from the zero-inflation component of a negative binomial two-stage hurdle model.

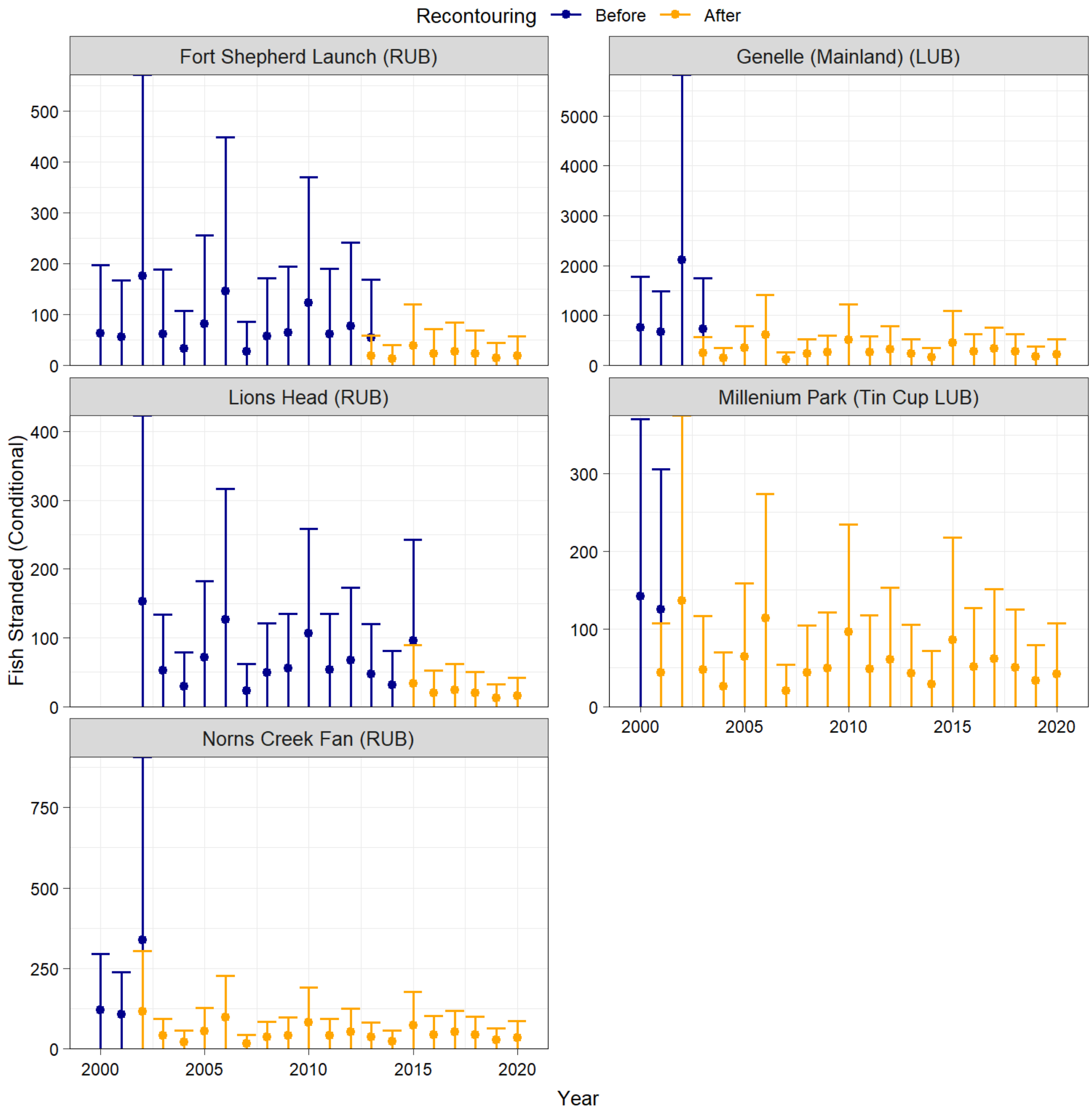

Figure 2: Predicted number of fish stranded in the lower Columbia River by year, site, and before/after recontouring. Points are predicted values and error bars are approximate 95% confidence intervals. Predicted values are the expected mean number of fish stranded during site visits were 1 or more fish were stranded, which were produced by the conditional (non-zero) component of a negative binomial two-stage hurdle model.

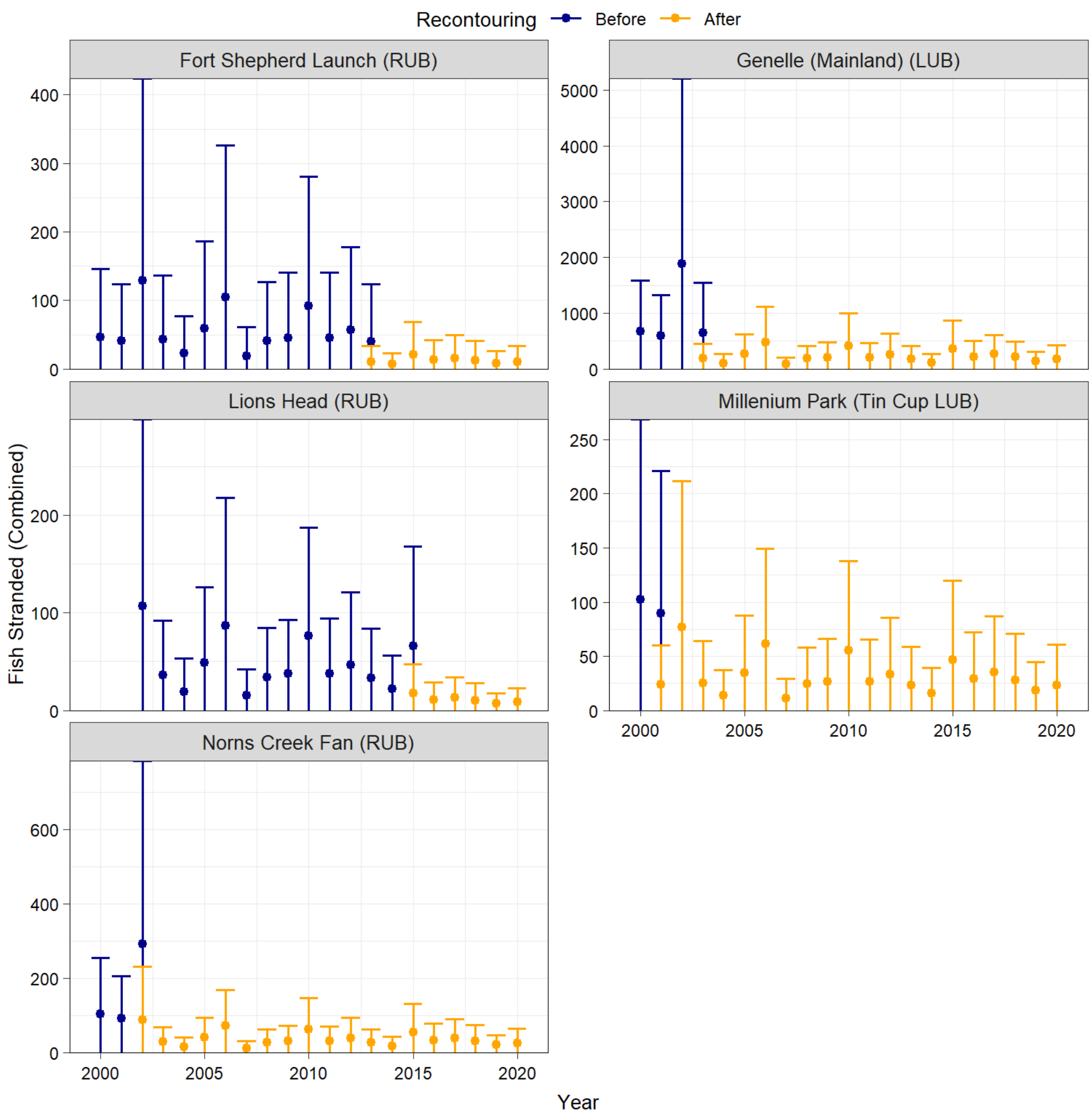

Figure 3: Predicted number of stranded fish in the lower Columbia River by year, site, and before/after recontouring. Points are predicted values and error bars are approximate 95% confidence intervals. Predicted values are the expected mean number of fish stranded based on the combined probability of stranding >0 fish (Figure 1), and predicted number of fish for non-zero events (Figure 2), from a negative binomial two-stage hurdle model.

4.0 DISCUSSION

Twenty years of data from fish stranding surveys were used to assess the effect of recontouring on the number of fish stranded using a statistical model that accounted for other variables that can influence stranding, such as magnitude of discharge reduction and river stage. The model assessed the effect of recontouring on both the likelihood of stranding fish and the severity of fish stranding in terms of the number of fish stranded. The results indicate a substantial reduction in both the probability and severity of fish stranding after recontouring at all five sites assessed. Model predictions indicate a 14% reduction in the probability of stranding one or more fish, and a 66% reduction in the mean number of fish stranded, on average, after recontouring. As the five sites in the lower Columbia River were recontoured between 2001 and 2015, trends in the number of and probability of fish stranded (Figures 1 to 3) suggest persistent benefits from recontouring that have lasted for many years after the physical habitat manipulation.

These effect sizes and conclusions are based on the data from Lower Columbia River Fish Stranding database and the statistical models presented in this appendix. Some challenges and limitations of the data set and analysis are discussed in Section 4.0 of Appendices C and D. Model predictions of the number of fish stranded in a particular site, year, or before/after recontouring had large uncertainty, which was attributed to the large variability in the numbers of stranded fish observed between reduction events. Despite these uncertainties, the data support a statistically significant and large effect of recontouring on fish stranding. These results demonstrate the effectiveness of physical habitat manipulations in reducing the number of fish stranded at the five sites in the lower Columbia River.

5.0 REFERENCES

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