Duncan Dam Project Water Use Plan

LOWER DUNCAN RIVER HYDRAULIC MODEL DEVELOPMENT

Reference: DDMMON-3

Performance Measure Reassessment – Lower Duncan River Hydraulic Modelling

Study Period: 2009 – 2019

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Lower Duncan River

Monitoring Program No. DDMMON-3

Lower Duncan River Performance Measure Reassessment – Hydraulic Modelling Year 10 Report

Final Report

Prepared for

BC Hydro Generation
Water Licence Requirements

6911 Southpoint Drive
Burnaby, BC

BC Hydro Reference # DA 16858 PR 10134637

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Cover photos:

Lower Duncan River below the dam

ACRONYMS AND ABBRIVIATIONS

BC Hydro	British Columbia Hydro and Power Authority
cms	Cubic Metre per Second
CPM	Continued Product Method
DDM	Duncan Dam
DDMMON	Duncan Dam Monitoring
DDMMON-2	LDR Fish Habitat Use Monitoring
DDMMON-3	LDR Hydraulic Model Development
DDMMON-4	LDR Kokanee Spawning Monitoring
DDMMON-16	Fish Stranding Impact Monitoring
DDM WUP	Duncan Dam Water Use Plan
DEM	Topographic Digital Elevation Model
HSI	Habitat Suitability Index
HUC	Habitat Use Curve
K	Thousands
km	kilometer
l	litre
LDR	Lower Duncan River
m	metre
m^3/s	Cubic Metre per Second
M	Millions
masl	metres above sea level
max	maximum value
min	minimum value
MWF	Mountain Whitefish
n	sample size
NHC	Northwest Hydraulics Consultants Ltd.
RBT	Rainbow Trout
SD	standard deviation
STD	standardized
UTM	Universal Transverse Mercator
XS	Cross section
WSC	Water Survey of Canada
WUA	Weighted Usable Area

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EXECUTIVE SUMMARY

The Lower Duncan River (LDR) hydraulic model development (DDMMON-3) is one of several programs associated with the Duncan Dam Water Use Plan. DDMMON-3 was implemented over a 10-year period, with works occurring in Years 1, 2, 5 & 10. The scope of the program included surveying, hydraulic and habitat modelling of the LDR to assess channel change and operation impacts on fisheries habitat, for consideration in future flow planning processes and to help define ramping rate protocols. The scope of this final report is to address the integration of the habitat use data from other programs (i.e., DDMMON-2, 4 and 16) into the 2020 hydraulic model update and to conduct a re-assessment of the performance measures that generally include flow-habitat relationships, transient habitat distribution analysis, and stranding risk assessment.

The re-assessment was carried out using an updated version of the 2020 two-dimensional hydraulic model of the LDR developed by BC Hydro. The model was programmed in the Telemac2D modelling platform and incorporated more recent bathymetric and environmental data. Depth and velocity conditions were extracted from the steady state simulation results along the LDR mainstem and side channels. Depth and velocity, in conjunction with substrate data, were used to estimate habitat suitability indices (HSI) for Kokanee (*Oncorhynchus nerka*), Gerrard Rainbow Trout (*Oncorhynchus mykiss*), and Mountain Whitefish (*Prosopium williamsoni*). HSI data were used to estimate the Weighted Usable Area (WUA) for each species and life stage to provide an indication of the suitable habitat available for a species at a given life-stage under the given simulated conditions.

The following table summarizes the findings of the current project as well as findings previously reported and organized by the management questions formulated in the Terms of Reference.

Management Question	Associated Hypotheses	Summary of Key Monitoring Results
MQ-1: Did the physical flow model developed prior to the DDM WUP accurately predict floodplain inundation levels and extent in Lower Duncan River mainstem and side channel areas?	$H_0$1: The quantity and quality of fish habitat for the Lower Duncan River floodplain over the range of flows influenced by Duncan Dam operations predicted by the existing HEC-RAS model (2003) does not significantly differ from those predicted in a more comprehensive and updated 2-dimensional flow model.	No. MQ -1 was addressed in Years 1 and 2 of the DDMMON-3 program (NHC, 2010). The 2D modelling and simulation of habitat provided more representative estimates of wetted (flooded) area and WUA, than the 1D physical flow model developed prior to the DDM WUP. The 2D model incorporated depth, velocity and substrate compared to depth alone in the 1D model. In addition, bathymetric surveys were undertaken with a broader mandate and scope and encompassed the entirety of the LDR to Kootenay Lake and most side channels (NHC, 2010). Whereas earlier DDM WUP surveys did not account for side channels or the full length of the LDR. For comparison, the 1D Model was 7.5 km long and had only 12 cross sections, while the 2D model covered the entire river with a 5 m grid coverage (NHC, 2010). The 2D Model captures a greater length of the LDR and utilizes a much greater resolution of channels and surveyed bed elevations. Long profiles of the LDR from the 1D and 2D models illustrate the differences in resolution between the two models. The coarseness of the 1D Model is also evident when overlaying a discharge of 75 m^3/s predicted by the 1D Model with the surveyed bed elevation used in the 2D model. It shows water elevations that are less than the surveyed bed elevation, putting into question the accuracy of the mainstem flows used in the 1D Model. Based on these findings, NHC concluded that the physical flow model developed prior to the DDM WUP, ***did not*** accurately predict floodplain inundation levels or the extent of the LDR mainstem and side channel areas (NHC, 2010). Rather, the 2D Model was much more accurate at predicting water elevations. After the current 2020 model update, we can further confirm that improved habitat and physical data, as well as numerical and computational models lead to models that better represent the extent of inundation levels for both, the mainstem and side channels.

Management Question	Associated Hypotheses	Summary of Key Monitoring Results
MQ-2: Were the habitat-flow relationships for fish species of interest incorporated into DDM WUP performance measures accurate for the range of operations licensed for the Lower Duncan River?	$H_0$2: Areas of habitat use predicted by the updated 2-D flow model do not accurately reflect those observed in habitat use studies included in the DDM WUP monitoring program (i.e., DDMMON#2). $H_0$3: The transient nature of the LDR floodplain morphology does not significantly change the flow-habitat relationships that are predicted by the 2-D flow model.	No. MQ-2 was addressed in 2010 by comparing the habitat-flow relationships of spawning and rearing for Rainbow Trout, Kokanee and Whitefish. The original 1D Model overestimated habitat compared to the 2D Models. The current model update does reflect areas fish use as observed in other programs, therefore we can be confident that the relationships are appropriately captured in the 2020 model and use them to redefine the assumptions made in the WUP. $H_0$2 was rejected. By further refining the flow-habitat relationships, including alternative scenarios of discharge for the Lardeau River, we can verify that the relationships with the performance measures were not accurate for the 3 species and their corresponding life stages. Improvements in the Habitat Use curves and the floodplain bathymetry show that, in previous models, habitat was overestimated for the 3 species, especially at low discharge levels. The transient nature of the floodplain highlights the dynamics of the flow habitat availability relationships and the need to review the predictive models and results periodically. $H_0$3 is rejected, except for Mountain Whitefish, whose flow habitat relationship seems more stable that for the other species.

Management Question	Associated Hypotheses	Summary of Key Monitoring Results
MQ-3: Given the criteria for operating recommendations made during the DDM WUP, would a more extensive and validated modeling effort result in revised recommendations? Will future model revisions result in revised recommendations?	$H_0$4: Fish stranding risk predicted by the 2-D model of LDR floodplain for operating scenarios evaluated and/or considered in the Adaptive Stranding Protocol Development plan provides a reasonable surrogate for empirical observations made prior to and during the DDM WUP monitoring review period (i.e., the two approaches do not differ).	Even though data were available from complementary projects, previous reports and model versions did not provide evidence for updating or revising WUP recommendations or reach conclusive statements. Kokanee habitat was modelled as optimal at around 73 m^3/s in the 1-D model, and subsequent results were considerable different. Also, in previous models, both Whitefish spawning and Rainbow Trout rearing habitat were predicted as increasing with discharge, but this does not fit with the Habitat Use Curve responses associated with both species. This more comprehensive model update, together with the additional data provided by DDMMON-2, 4 and 16, shows that some of the original recommendations included in the WUP should be revised. For instance, a minimum discharge of 3 m^3/s puts tailout Rainbow Trout redds at risk of either dewatering or backwatering (depending on the discharge from Lardeau River). On the other hand, we observed that the simulated WUP minimum flow of 73 m^3/s does not support activation of all side channels. Rather, the simulated minimum flow for all side channels to be active is around 150 m^3/s. This matches the zone of maximum Weighted Usable Area for Kokanee and Whitefish spawning, but not necessarily for Rainbow Trout rearing. $H_0$4 is not rejected, as model results represent a reasonable surrogate to assess stranding risk. The results show that higher flows (>250 m^3/s) to prevent Kokanee spawning on side channels at risk might not be having the desired effect.

ACKNOWLEDGEMENTS

Ecoscape would like to express our appreciation and acknowledge BC Hydro Project Manager Teri Neighbour who has overseen DDMMON-3 during our brief contract. Dr. Guy Martel of BC Hydro has provided scientific oversight; his supportive suggestions and discussion have aided in our understanding of the complexities of DDMMON-3. Northwest Hydraulic Consultants Ltd. completed Years 1, 2 and 5 of the DDMMON-3 contract. While Narges Sadat and Morgan Garrett, Senior Engineers with BC Hydro provided modelling updates in 2017 and 2019, respectively.

External data associated with DDMMON-2 was provided by Joseph Thorley of Poisson Consulting.

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1 INTRODUCTION

1.1 Background

The Lower Duncan River (LDR) Hydraulic Model Development Program (DDMMON-3) is one of several programs associated with the Duncan Dam Water Use Plan (DDM WUP) (BC Hydro, 2007) to address two objectives:

1. *Support the Adaptive Stranding Protocol Development Program (ASDP).* This program seeks to answer the following management question: *what are the optimal operating strategies considering both the benefits for fish populations and costs/forgone revenues at Duncan Dam to reduce fish stranding in the LDR?* and,
2. *Improve Performance Measure Accuracy.* This objective aims to address data gaps in the flow-habitat relationships used in the DDM WUP. While ensuring that habitat changes in the channel related to ongoing instability in the floodplain are captured in a dynamic hydraulic response model.

DDMMON-3 was expected to be implemented over a 10-year period, from 2009 to 2018, with works occurring in Years 1, 2, 5 & 10. The scope of the program included surveying, hydraulic and habitat modelling of the LDR to assess channel change and operation impacts on fisheries habitat, for consideration in future flow planning processes and to help define ramping rate protocols (BC Hydro, 2008).

The first stage of the program was to update survey data to use more sophisticated modelling tools to evaluate the habitat flow relationships of concern under the WUP (NHC, 2009). It followed the development of a comprehensive 2-D hydrologic model to contrast the results with the 1-D used in the initial WUP (NHC, 2010). Subsequently, the River2D model (Steffler & Blackburn, 2002) was migrated to the Telemac 2D platform (Hervouet, 2007; Hervouet & Ata, 2017) to take advantage of modelling capabilities and computational power, using the more recent bathymetric data (NHC, 2013).In 2015, this model was updated to reflect changes to river conditions caused by 2012 flood events (BC Hydro, 2015). In 2017, BC Hydro translated the bathymetric data used in the 2010 model to use it with the Telemac 2D version and assess changes in riverbed as captured by the 2012 data and Lidar data available in 2015 (BC Hydro, 2017). Additional bathymetric data updates were undertaken in 2018 leading to the current version of the Telemac 2D model (BC Hydro, 2020). All these models are summarized in
Table 1-1 , with additional details in Appendix 1.

1.2 Report Scope

The scope of this report (Year 10) involves the integration of the habitat use data from DDMMON-2, 4 and 16 into the 2020 hydraulic model and a re-assessment of the performance measures (Table 1-2) (hereafter referred to as the T2D_2020 model). Generally, performance measures include flow-habitat relationships, transient habitat distribution analysis, and stranding risk assessment. This final report includes habitat and performance measure updates and analyses and addresses the outstanding management questions and hypotheses. These program results will be incorporated into the Adaptive Stranding Protocol and inform decision making during the Water Use Plan Order Review process.

Table 1-1: Summary of models developed before and during the DDMMON-3 program

Year - Model platform	Bathymetric Survey Data	Hydraulic Model Characteristics	Habitat Use Analysis Data
2003 - HEC-RAS	1-D cross-sections along mainstem (1996)	1 dimensional (1D)	Assumed wetted side channel area as usable habitat
2010 - River 2D	2008 bathymetric survey	2-Dimensional (2D) Mesh resolution limited to 100000 nodes Steady state modelling	DDMON programs preliminary habitat use areas
2013 - Telemac 2D	2008 bathymetric survey with updated DEM model (2012)	2D Steady and unsteady state modelling	DDMMON-2 updated, and modelled habitat use
2015 - Telemac 2D	2012 bathymetric survey with LiDAR update	Improved side-channel alignment	No habitat use analysis
2017 - Telemac 2D	2008 bathymetric Survey converted	2-D 2008 Mesh converted for Telemac 2D	No habitat use analysis
2020 - Telemac 2D	2018 bathymetric survey update	2-D Steady and unsteady models Additional scenarios	DDMMON-2, DDMMON-4, and DDMMON-16 habitat and stranding data

Table 1-2: Performance measures developed for the DDM WUP (BC Hydro, 2008).

Location	Performance Measure
LDR Mainstem	Whitefish effective spawning habitat area
	Whitefish effective spawning habitat area lost
	Kokanee effective spawning habitat area
	Rainbow effective rearing habitat area lost
	# of days TGP >115%
	# of events TGP >115%
	# of significant operational changes >0.20 m
	# of significant operational changes >0.45 m
LDR Side channels	Kokanee effective spawning area lost
	Kokanee effective spawning area
	Kokanee effective rearing area lost
	Rainbow effective rearing area
	Rainbow effective rearing area lost

2 STUDY AREA

The study area corresponds to the extent of the LDR floodplain that is covered by the model mesh. This includes the mainstem, side channels and backwatered areas at the Lardeau River confluence between Duncan Dam's low level outlet tailrace and the river's outlet with Kootenay Lake at the low pool level (Figure 2-1). The area used in the 2020 model differs slightly from previous study areas as the mesh boundaries were defined differently. The area covered by the 2008 – 2013 mesh was 10.65 km^2 while the area covered by the 2020 mesh is 16.58 km^2. To reduce the impact of this difference in the analysis of the results, the 2020 mesh was clipped to the extent of the wetted area of a discharge equivalent to 400 m^3/s. The results are still affected by an additional area in the confluence of the LDR and Kootenay Lake. Therefore, it is important to analyze the results in relative terms or compare for the same year across discharge levels.

2.1 Hydrology

The study area floodplain is dominated by the operation of the Duncan Dam**.** Figure 2-2 shows the hydrograph of the LDR before and after the construction of the Duncan Dam in 1969. The regulated flows follow a similar pattern, but with reduced peaks and valleys (i.e., ~40-400 m^3/s before 1969, compared to 75-250 m^3/s after). The study area is also influenced by the Lardeau River which is located approximately 1.3 km downstream of Duncan Dam. The Lardeau River is an unregulated system, and substantially influences LDR during spring freshet when mean peak flows approach 200 m^3/s (Figure 2-3).

2.2 Morphology

The LDR floodplain is dynamic; the ongoing morphological changes have been captured with riverbed surveys and updates to the bathymetric datasets in 2013 and 2019. The extent of wetted areas for equivalent discharge, highlights the effect of bathymetric changes over time. We quantified these changes by comparing bathymetric data across three years: 2008, 2013, and 2019. Major changes to the floodplain are associated with sediment transport, flood events, and log jams. The 2020 model bathymetry data represent, on average, a deeper riverbed with shallower edges and adjacent areas.

2.2.1 Side Channels

Channelization is a major dynamic in the LDR. The nine side channels of interest are shown in Figure 2-1. They are consistent with the side channels defined in the first year of the study (NHC, 2010). An analysis of habitat suitability on the side channels was not undertaken in 2013 (NHC, 2013), but it is included herein.

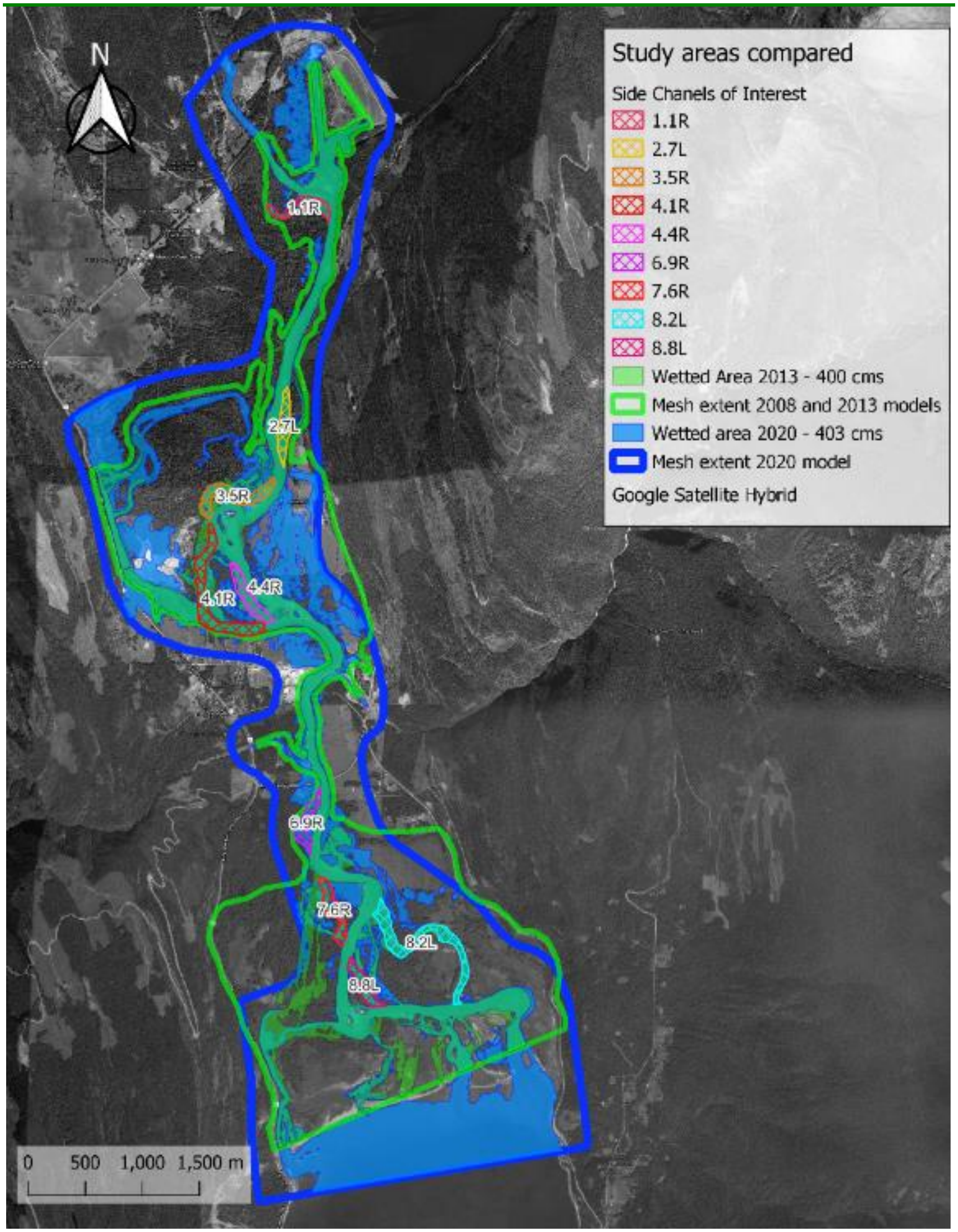


Figure 2-1: Study area location and model extents (mesh areas).

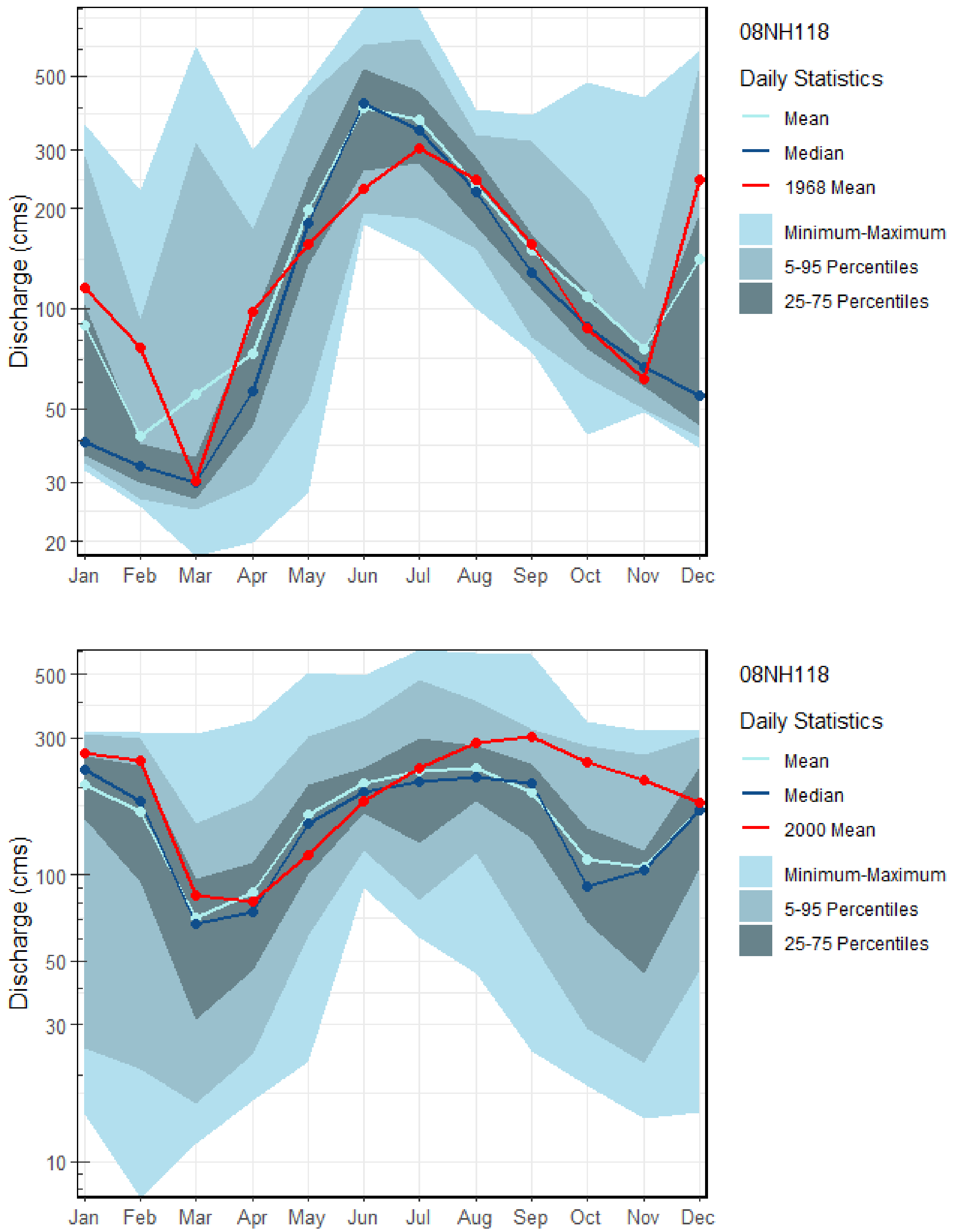


Figure 2-2: Lower Duncan River hydrograph depicting mean daily flows. Top: before, and bottom: after the construction of the Duncan Dam (1969).

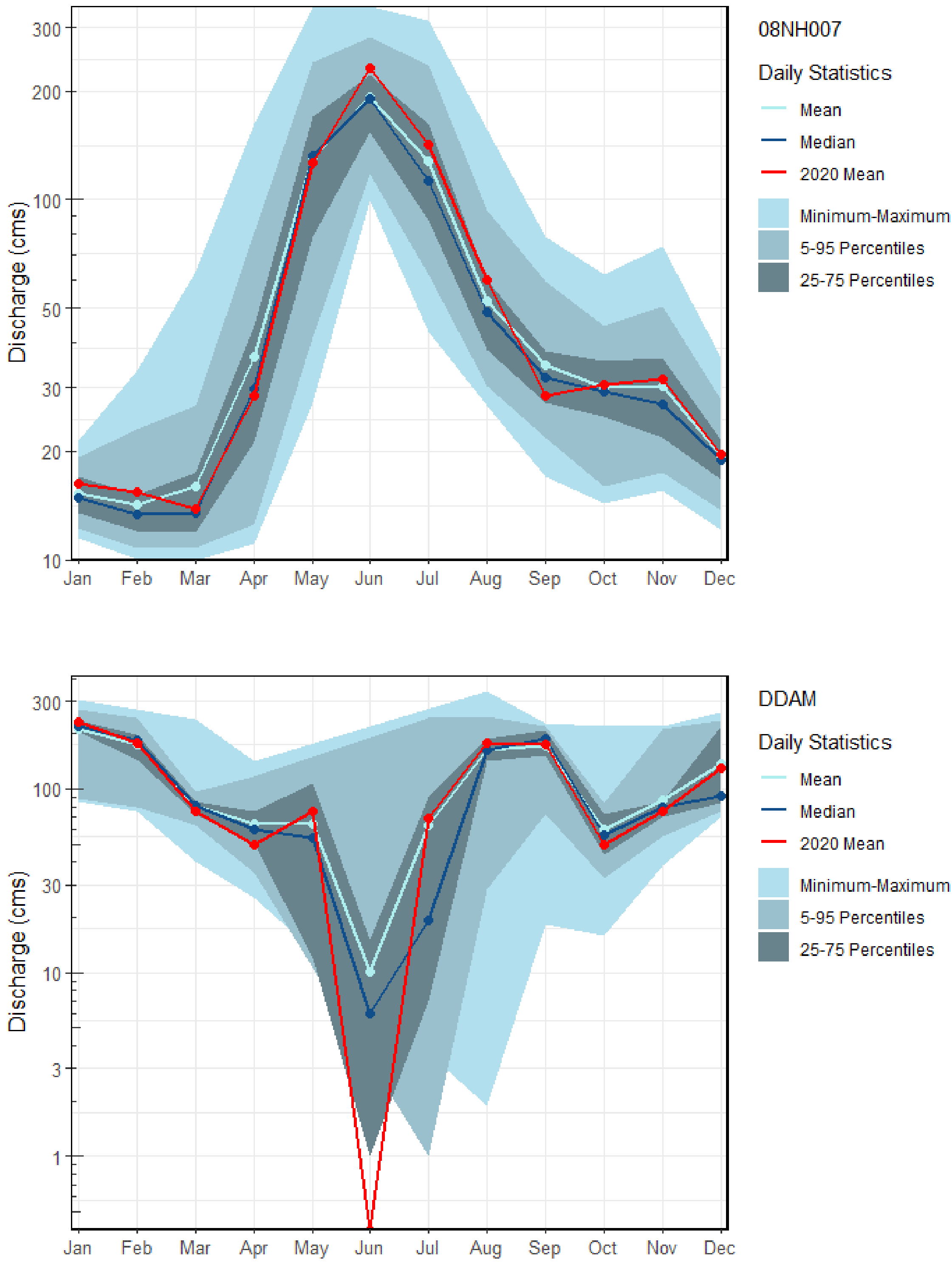


Figure 2-3: Mean daily flow from: Top: Lardeau River; and bottom: Duncan Dam (2008 to 2020).

3 METHODS

3.1 Hydraulic Modelling

The re-assessment of the Performance Metrics for DDMMON-3 was carried out using an updated version of the 2019 two-dimensional hydraulic model of LDR developed by BC Hydro (BC Hydro, 2020). The model is programmed as a Telemac2D model, and it is the third update of the LDR hydraulic models. This version incorporates more recent bathymetric and environmental data. Appendix 2 provides an example of a Telemac 2D model configuration.

The model was used to simulate steady state conditions under different discharge levels. This led to the production of 48 scenarios as a combination of 16 discharge levels from the Duncan Dam and three levels from the Lardeau River. Additionally, seven down ramping scenarios were simulated to study dewatering and stranding risk. This expands the scenarios from previous studies that fixed the Lardeau River discharge at 20 m^3/s (NHC, 2010, 2013). The discharge from the other tributaries: Meadow, Cooper, and Hamill creeks, was set at the same levels as previous reports, 5, 1, and 1 m^3/s, respectively. Table 3-1 summarizes the flow and time settings for the simulations.

Depth and velocity conditions were extracted from the steady state simulation results along the LDR mainstem and side channels. Depth and velocity, in conjunction with substrate data, were used to estimate habitat suitability for the three fish species of interest.

3.2 Floodplain Morphology and Wetted Area

Morphology is captured in the bathymetric data of the floodplain. We computed the difference in the elevation of the collected floodplain points to estimate the changes in morphology captured by the bathymetric data.

The wetted area corresponds to the extent of the sections of the floodplain where the free surface has a depth greater than zero when the model reaches a steady state (i.e., the inflowing and outflowing water amounts are balanced, and the flooded area is unchanged). These data are extracted directly from the simulation results, and it can be verified by the difference between free surface and bathymetric (bottom) elevations. Flooded area was computed for each of the simulated discharges and compared to results of the previous models.

3.3 Habitat Suitability and Usable Area

Following Lewis *et. al.* (2004, p. 37) the Continued Product Method (CPM) is used to estimate Habitat Suitability Indices (HSI). Species specific HSIs were derived with Habitat Use Curves (HUC) data for Gerrard Rainbow Trout (*Oncorhynchus mykiss*) and Mountain Whitefish (*Prosopium williamsoni*) provided by DDMMON-2 (Thorley et al., 2012), while habitat use for Kokanee (*Oncorhynchus nerka*) was derived from DDMMON-4 data (Plate et al., 2018). HSI data are combined with simulation mesh parameters to estimate the Weighted Usable Area (WUA) for each species and life stage. WUAs provide an indicator of the suitable habitat available for a species at a given life-stage under the given simulated conditions. WUAs are the basis for the computation of the fish habitat performance metrics summarized in Table 1-2. Additional details on HSI and WUA computation are provided in Appendix 3. These areas are independent of time, therefore, if habitat needs to be quantified for a specific life-stage/time of the year combination, the time of the year must match the life cycle stage indicated in the curve with the discharge levels assessed.

Table 3-1: Hydrologic model factors for the 2020 2-D model update.

Model/Sub-model	Variable	Values
Steady state	Duncan Dam Discharge	(0, 25, 50, 75, 100, 125, 150, 175, 200, 225, 250, 275, 300, 325, 350, 375) cms
	Lardeau River	(20, 65, 165) cms
	Hamill, Meadow, and Cooper Creeks	1, 5, 1 cms, respectively.
	Simulation length to reach steady state	24 hrs
Down ramping		
Winter 1	DAM (Initial – Final) Duration	196 – 140 cms 2 months
Winter 2	DAM (Initial – Final) Duration	140 – 80 cms 2 months
Spring 1	DAM (Initial – Final) Duration	80 – 45 cms 1 months
Spring 2	DAM (Initial – Final) Duration	45 – 10 cms 1 months
Summer (B. trout)	DAM (Initial – Final) Duration	24 – 3 cms 3 hrs
Fall	DAM (Initial – Final) Duration	150 – 50 cms 1 months

3.4 Dewatering

Dewatering happens when a section of the floodplain stops receiving water inflow and gets disconnected from the streamflow. In the model, the isolated section might fully lose the water cover or, for the lack of an evaporation mechanism, remain flooded but stranded. Simulated dewatering was computed to inform stranding risk in key sites of interest, mainly side channels. Steady-state simulations inform the status of side channels when steady state is reached and can be used to inform management scenarios involving down-ramping. To have a more detailed view of the status of each side channel, we split them in three sections, namely: Inflow, Middle, and Outflow. This allowed us to evaluate and provide the status of each section, which, depending on the discharge level, might differ substantially.

Dewatering from down-ramping simulations scenarios was assessed by extracting velocity and depth data from areas of interest at points along centerlines of side channels. Velocity was used as a proxy for detecting when the channel is no longer receiving inflow or outflow. Depth change allows to verify such states. This method is heuristic and could be improved by including an additional parameter to remove stranded water from the floodplain to better reflect depth of 0 m when slope generates stranded pools. For simplicity, we used a 10-hour time window and a 0.1 m minimum depth as thresholds.

Stranding risk is not directly assessed, instead side-channel status is provided to inform risk. Stranding risk was then assessed using a combination of operational and life-history factors, following the Adaptive Stranding Protocol for the LDR (Westcott et al., 2013). Stranding risk will depend on other factors including species, life-stage, and travel thresholds. Risk can be assessed by estimating the probability of stranding (Irvine et al., 2015).

3.5 Datasets

The primary datasets utilized for DDMMON-3 are separated as physical and ecological data and are summarized in Table 3-2.

Table 3-2: Physical and ecological datasets used for the modelling and reassessment of DDMMON-3.

Name/Description	Source	Period covered
Physical Datasets		
LDR Bathymetry	BCH	2009/2012/2019
LDR Substrate survey	NHC	2013
LDR Hydrological data	WSC HYDAT	1969-2020
Ecological Datasets		
Kokanee HUC	DDMMON-3/DDMMON-4	2008-2016
Rainbow Trout HUC	DDMMON-2	2009-2011
Mountain Whitefish	DDMMON-2	2009-2011
Fish Stranding	DDMMON -16	
Models and Results		
R2D_2010	DDMMON-3	2010
T2D_2013	DDMMON-3	2013
T2D_2020	BCH	2019

4 RESULTS

4.1 Floodplain Morphology

We assessed morphological changes based on the differences in elevation of the riverbed as represented by the bathymetric data (Table 4-1). We limited the computation of differences to the maximum overlapping floodplain area. A positive difference indicates the point was higher in the first year of the bathymetric data. This can be used to approximate depth, although actual depth would be a function of the surrounding points.

Table 4-1: Point by point aggregated differences in bathymetric data for each pair of years.

	Difference Statistic					
Compared data	**Min**	**Max**	**Sum**	**Median**	**Mean**	**SD**
2008 – 2013	-4.019	9.554	2921.271	-0.001	0.003	0.236
2008 – 2020	-19.876	10.890	-20552.903	-0.029	-0.019	0.795
2013 – 2020	-19.723	10.402	-23474.174	-0.030	-0.022	0.773

Appendix 5 contains additional details on the frequency of bathymetric differences and their spatial distribution.

4.2 Wetted Area

The total wetted or flooded area predicted by each model was compared to complement the assessment of morphological differences. Figure 4-1 shows the extension of wetted area predicted by the corresponding models, both nominally (m^2) and relative (%) to the study area for the range of discharge levels simulated. The three model versions predict different amounts of wetted areas for the same discharge levels. The differences are relativized when considered with respect to the simulated area. The differences in proportion of predicted wetted areas for the three models (2010, 2013 & 2020) were all statistically significant. These differences can be explained by variability in bathymetry (morphology). The modelled riverbed for the 2020 hydrologic model is shallower and therefore a similar quantity of water covers a larger area in the floodplain.

4.3 Weighted Usable Area

Using the specific Habitat Use Curves (see Figure 4-2), data on substrate (S) types (Table 4-2), and simulated results for depth (D) and velocity (V), we determined the WUA for each combination of species and life stage. Comparisons with previous models, where data was available, were performed by species/life stage and are summarized in Figure 4-3. Rainbow Trout rearing habitat was split for fry and parr. Parr habitat was not reported in the 2013 report, neither was Whitefish spawning habitat.

This last model update (T2D_2020) includes additional scenarios to account for the different discharge levels from the Lardeau River (20, 75, 165 m3/s). We also simulated higher total discharges to reflect levels recorded in previous years.

WUA results are presented in nominal area amounts (m^2) (Figure 4-3), and relative (%) to the total area of the corresponding model (Figure 4-4).

Table 4-2: Substrate characterization and type codes.

Substrate	Size (mm)	Type Code
Fines (silt-clay, sand, org.)	< 2	1
Small to Medium gravel	2 – 16	2
Coarse gravel	16 - 64	3
Small cobble	64 – 128	4
Large cobble	128 – 256	5
Small boulder/ Bed Rock	762 - 256	6
Large boulder	> 762	7
Rock, Rip-Rap	n.a.	8

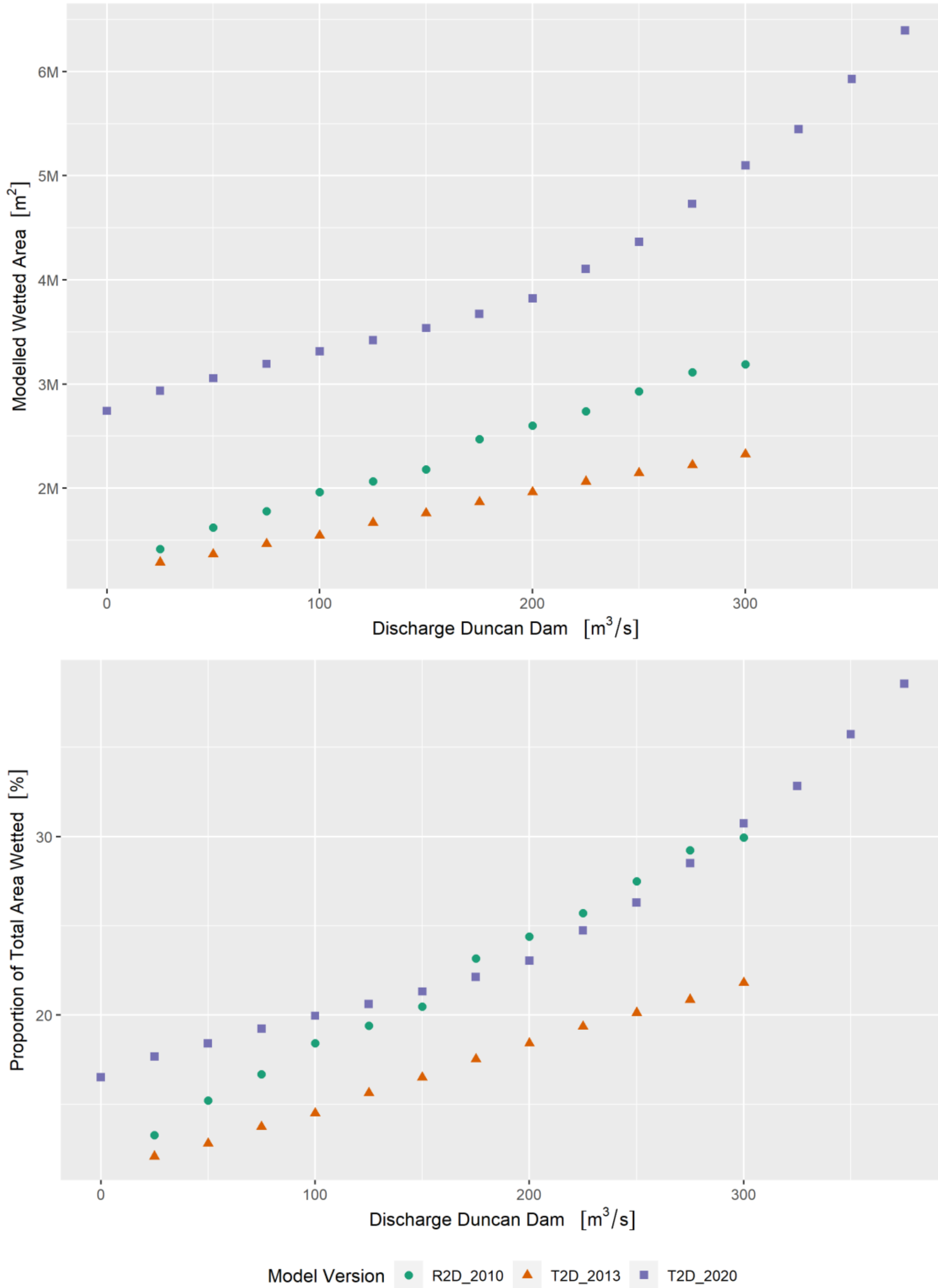


Figure 4-1: Simulated Wetted Area: nominal (top) and relative to the extent of modelled area (bottom); predicted by the corresponding model version, for a 20 m^3/s discharge from the Lardeau River.

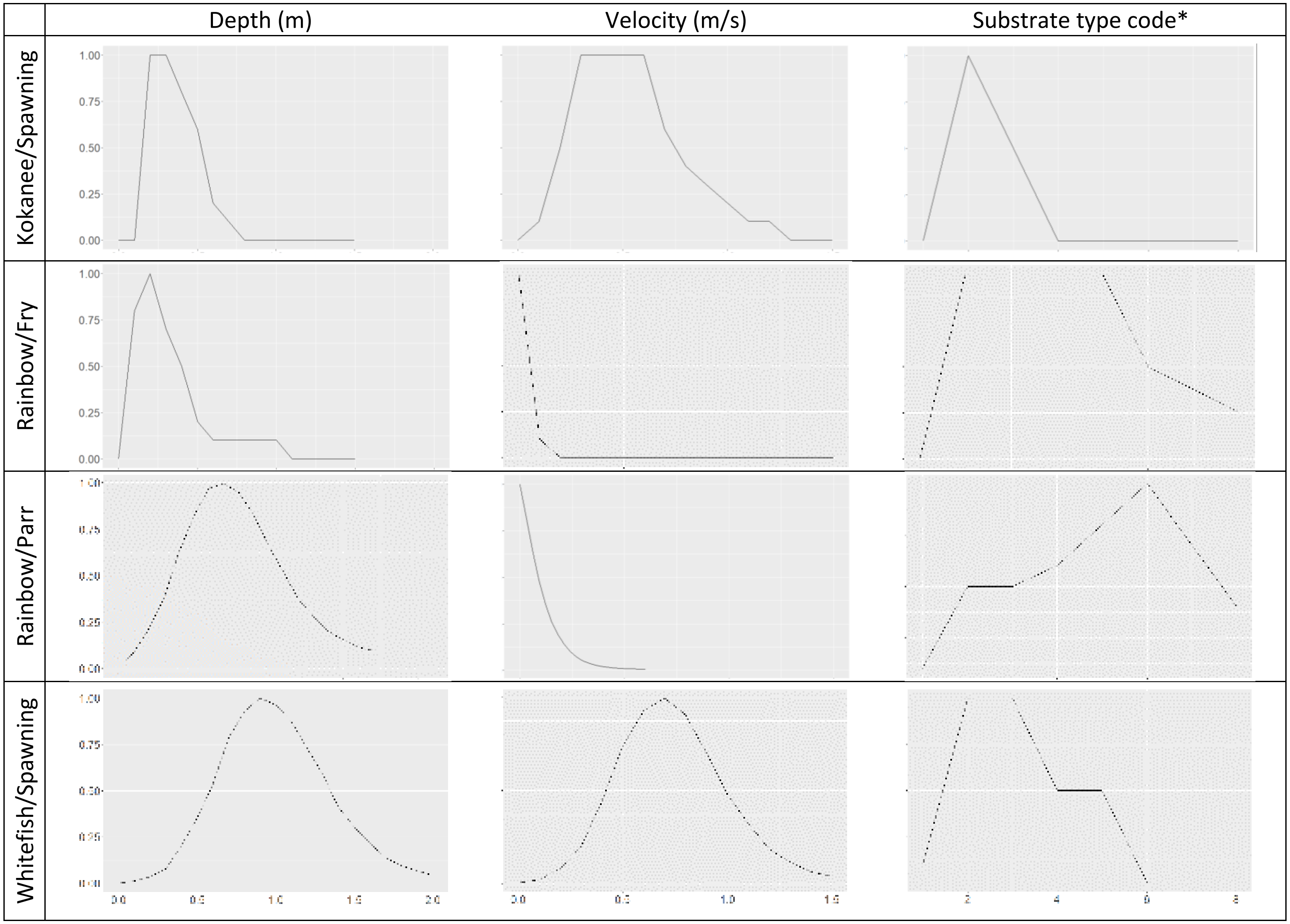


Figure 4-2: Habitat Use Curves (HUC) used in model T2D_2020 to compute Habitat Suitability Index (HSI) and Weighted Usable Area for each species/life stage. Data from the corresponding project (DDMMON-2 for RT and MW, and DDMMON-4 for KO). * See Table 4-2 for details on substrate type codes.

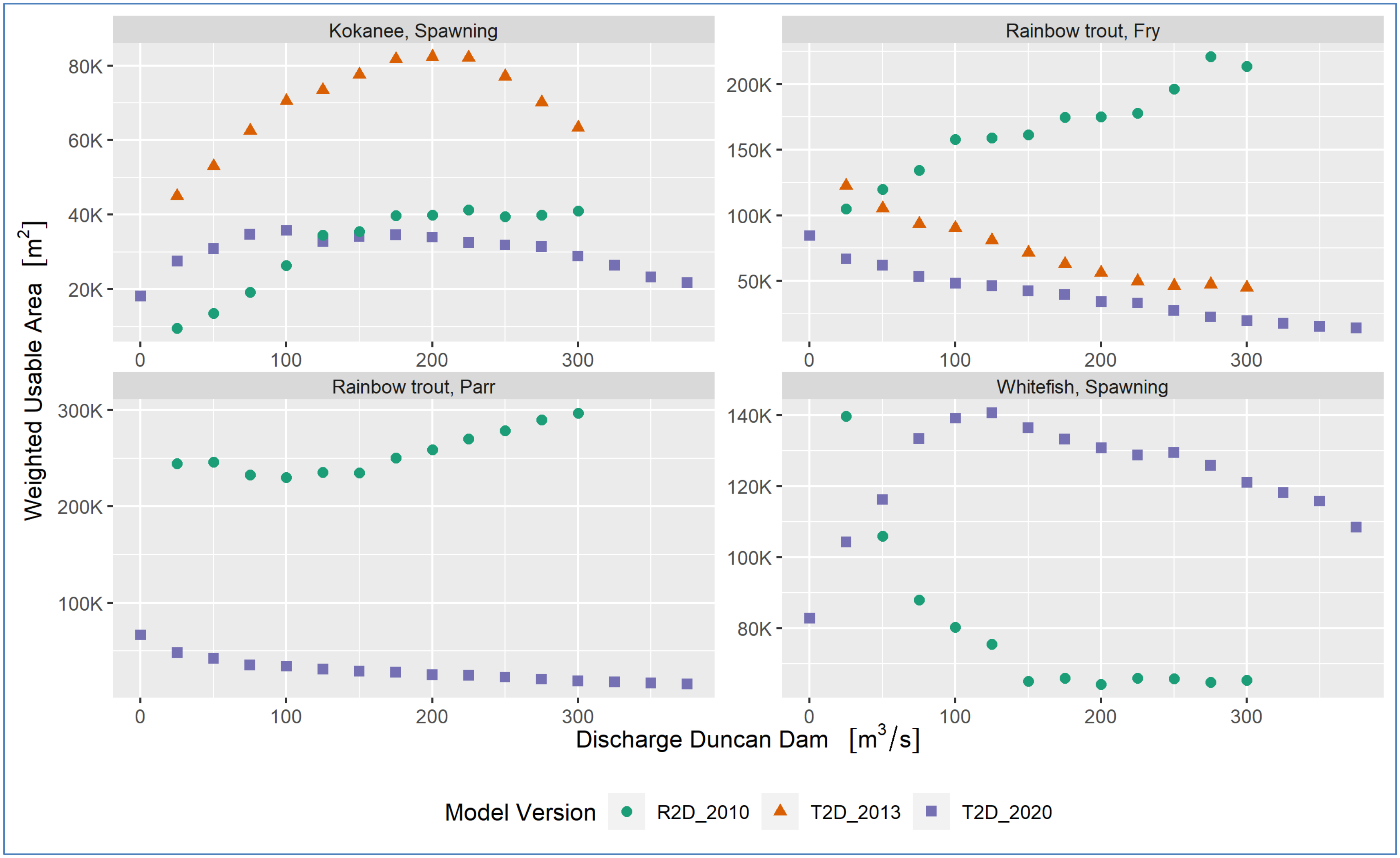


Figure 4-3: Weighted Usable Area (WUA in m^2) for each species/life stage derived from the simulated results for depth and velocity, substrate size, and HUC. Note Y axis scale is different for each species/life-stage.

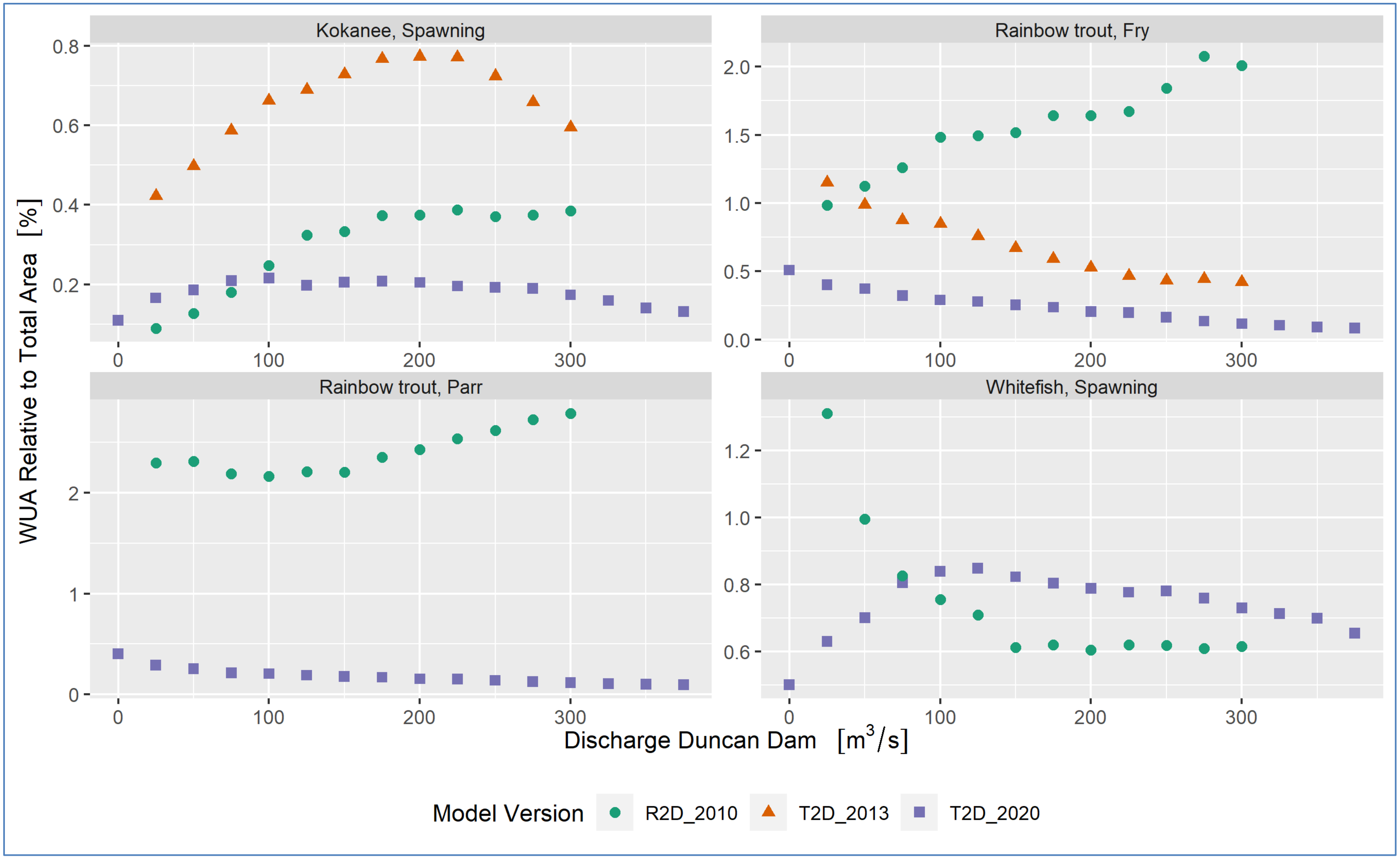


Figure 4-4: Relative WUA with respect to simulated total area for each species/life stage derived from the simulated results for depth, velocity, substrate size, and HUC. Note Y axis scale is different in each plot.

4.4 Dewatering

We extracted side channel's status for both steady-state and down ramping scenarios described in Table 3-1. In this case, we divided each side channel into: Inflow, Middle, and Outflow sections. This allowed for a further differentiation and detail of channel status, defined as:

- Active (ON): Water flowing in the dominant stream direction,
- Backwatering (BW): Water mainly flowing from the outflow towards inflow,
- Dewatered (OFF): Water present but not flowing, or Depth = 0.

We observed that the simulated WUP minimum flow of 73 m^3/s does not support activation of all side channels. Rather, the simulated minimum flow for all side channels to be active is around 150 m^3/s. This matches the zone of maximum WUA for Kokanee and Whitefish spawning, but not necessarily for Rainbow Trout rearing (see Figure 4-4). For the simulated transient scenarios, and considering no other external factors, some side channels experience dewatering, either completely or partially (see Table 4-4).

Table 4-3: Side channel status (Inflow/Middle/Outflow) for steady-state flow simulations. The number in parentheses is the actual simulated total discharge closest to the flow constraint.

Side Channel	Flow constraint Total (m^3/s)					
	73 (75)	110	120 (128)	130 (133)	190 (203)	250 (253)
1.1R	DW/DW/DW	ON/DW/ON	ON/DW/ON	ON/DW/ON	ON/DW/ON	ON/ON/ON
2.7L	DW/ON/ON[1]	ON/ON/ON	ON/ON/ON	ON/ON/ON	ON/ON/ON	ON/ON/ON
3.5R	**DW/DW/ON**	**ON/ON/ON**	**ON/ON/ON**	**ON/ON/ON**	**ON/ON/ON**	**ON/ON/ON**
4.1R	ON/ON/ON	ON/ON/ON	ON/ON/ON	ON/ON/ON	ON/ON/ON	ON/ON/ON
4.4R	ON/ON/ON	ON/ON/ON	ON/ON/ON	ON/ON/ON	ON/ON/ON	ON/ON/ON
6.9R	**DW/DW/DW**	**DW/DW/DW**	**DW/DW/DW**	**DW/DW/DW**	**ON/ON/ON**	**ON/ON/ON**
7.6R	**DW/DW/DW**	**DW/DW/DW**	**ON/ON/ON**	**DW/DW/DW[3]**	**ON/ON/ON**	**ON/ON/ON**
8.2L	**ON/ON/ON**	**ON/ON/ON**	**ON/ON/ON**	**ON/ON/ON**	**ON/ON/ON**	**ON/ON/ON**
8.8L	ON/DW[2]/ON	ON/DW[2]/ON	ON/DW[2]/ON	ON/DW[2]/ON	ON/ON/ON	ON/ON/ON

1: Additional Inflow
2: Biggest Middle Section
3: To review

Table 4-4: Side channels status under different down ramping scenarios. Channels that switch status are underlined.

Side Channel	Down Ramping scenario (Start/End) (m^3/s)					
	24-3-24*	45-10	80-45	150-50	140-80	196-140
1.1R	ON[1]/OFF/OFF	ON/ON[1]	ON/ON[1]	ON/ON[1]	ON/ON[1]	ON/ON[1]
2.7L	ON/OFF/OFF	ON/ON	ON/ON	ON/ON[1]	ON/ON[1]	ON/ON
3.5R	**ON/OFF/OFF**	**ON/ON[1]**	**ON/ON[1]**	**ON/OFF**	**ON/ON[1]**	**ON/ON**
4.1R	ON/ON/ON[1]	ON/ON[1]	ON/ON[1]	ON/ON[1]	ON/ON[1]	ON/ON[1]
4.4R	ON/ON/ON	ON/ON	ON/ON	ON/ON	ON/ON	ON/ON
6.9R	**OFF/OFF/OFF**	**ON/ON[1]**	**ON/ON**	**ON/OFF**	**ON/OFF**	**ON/ON[1]**
7.6R	**OFF/OFF/OFF**	**ON/ON**	**ON/ON**	**ON/OFF**	**ON/OFF**	**ON/ON**
8.2L	**ON/ON/ON[1]**	**ON/ON**	**ON/ON**	**ON/ON**	**ON/ON**	**ON/ON**
8.8L	ON/ON/ON[1]	ON/ON[1]	ON/ON	ON/ON[1]	ON/ON[1]	ON/ON[1]

*: Start/Half/End of the simulated scenario.
1: Partially active

5 HYPOTHESIS TESTING

5.1 Flow Habitat Relationships

$H_0$1: *The quantity and quality of fish habitat for the Lower Duncan River floodplain over the range of flows influenced by Duncan Dam operations predicted by the existing HEC-RAS model (2003) does not significantly differ from those predicted in a more comprehensive and updated 2-dimensional flow model.*

WUA summarize the quantity and quality of predicted habitat. As expected in the TOR, *$H_0$1* was rejected in the Year 2 Report using a qualitative approach (NHC, 2010). Here, we compare the results from the two previous models: 2010 (R2D_2010) and 2013 (T2D_2013), with the results obtained with the current model (T2D_2020). Because of the different areas considered in each model, comparisons are based on the relative WUA. These results should be combined with a comparison of the predicted wetted areas (see section 5.3). Given the differences in predicted wetted areas, we should also expect to see differences in predicted habitat (WUA), accentuated by the different Habitat Use Curves employed in each model.

For Kokanee and Rainbow Trout, we observed that the extent of habitat areas predicted by the 2010 and 2013 model versions are higher than the amounts predicted by the 2020 update of the Telemac 2D model (Figure 4-3), even though the study and wetted areas were smaller in the earlier models (see Figure 4-1). On the other hand, for Mountain Whitefish, we see that the differences are reduced when using the WUA relative to the total area modelled.

The general shapes of the predicted habitat curves are also different. Kokanee spawning predicted habitat follows a parabolic trajectory with maximum WUA around 100 m^3/s in the 2020 model and near 200 m^3/s in the previous model versions. Rainbow Trout WUA patterns are somehow contradictory. Fry WUA decreases with increased discharge, driven by the decrease in preference for increased velocity. The pattern was similar in the 2013 T2D model, however, the 2010 R2D model predicted WUA increased with discharge (see Figure 4-3 and Figure 4-4), which does not correspond with the asymptotic shape of depth and velocity use curves.

The pair-wise t-test results (Figure 5-1) show that, except for whitefish habitat predictions, all pairwise model differences are statistically significant. In the case of Kokanee and Rainbow Trout fry, the 2013 and 2020 model used the same HUC, therefore these results are to be driven by the morphological riverbed differences. From the test results we can confirm that *$H_0$1* can be rejected, the differences in the amounts of habitat predicted by the different model updates are statistically significant, except for whitefish spawning.

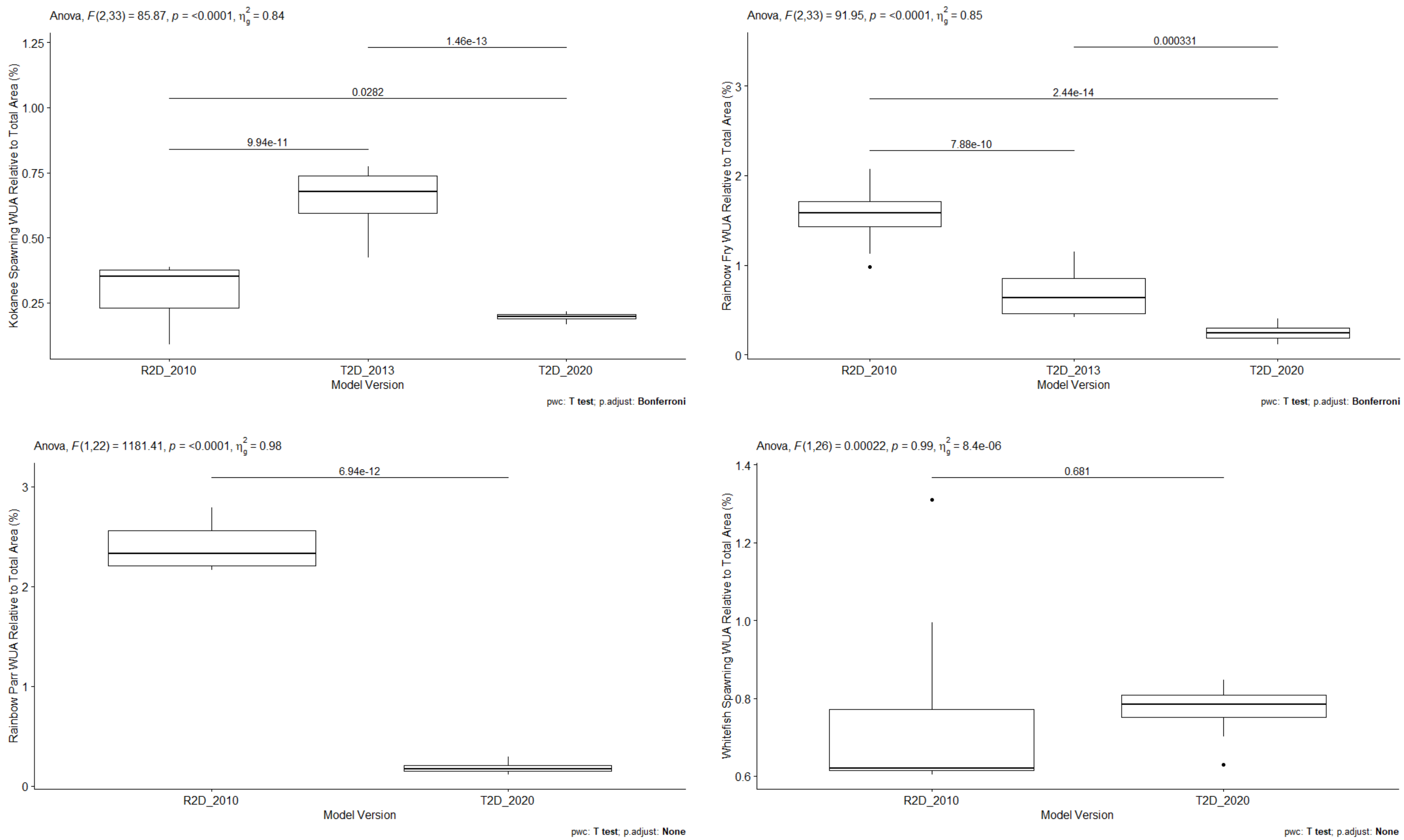


Figure 5-1: Box plots, ANOVA, and pairwise t-tests results for relative WUA (WUA/Total model area) for each species- life stage.

5.2 Modelled and Observed Fish Habitat Areas

$H_0$2: *Areas of habitat use predicted by the updated 2-D flow model do not accurately reflect those observed in habitat use studies included in the DDM WUP monitoring program (i.e., DDMMON#2).*

This hypothesis was not assessed in previous reports. Now that the associated studies, DDMMON-2, DDMMON-4, and DDMMON-16 have produced additional results, a more informed assessment can be undertaken. However, the coverage of observed occurrences remains limited, therefore comparisons are qualitative and combined with professional opinion. To support this comparison, we recommend using a mapping interface.

Because the CPM method for computing HSI gives equal importance to each habitat attribute, predicted habitat is heavily affected when information is incomplete or by one very restrictive attribute value (for which HSI = 0). This requires having the same level of confidence on the data quality for each habitat factor (Depth, Velocity, Substrate type). In this case, substrate data (from 2008) seems to be off with substrate observed. Nevertheless, for the four species/life stages considered, the overlap of suitable habitat with observed presence varies around 50%, considering only points with some degree of suitability. This result leads us to qualitatively reject $H_0$2, because this version of the model does reflect observed habitat use from observational studies. In the following sections we present some of this evidence.

5.2.1 Kokanee Spawning Habitat Use

Kokanee spawning has been observed under a wide range of discharge levels (min = 70, max = 254 m^3/s, median = 92 m^3/s), during the months of September and October (see Figure 5-2). Modelled habitat availability, in terms of velocity and depth, corresponds with this wide range of discharge levels. The main disagreement between modelled and observed data occurs over side channel S6.9R. This channel is modelled as inactive under 130 m3/s, but some aggregations of spawning Kokanee have been recorded below that discharge level. Another disagreement is produced when considering the available substrate data for channel 2.7L. Given the type of HSI method used, habitat in that channel drops to 0 in most of the channel as it was recorded has having fines as dominant substrate (fine substrate is not used by Kokanee spawning).

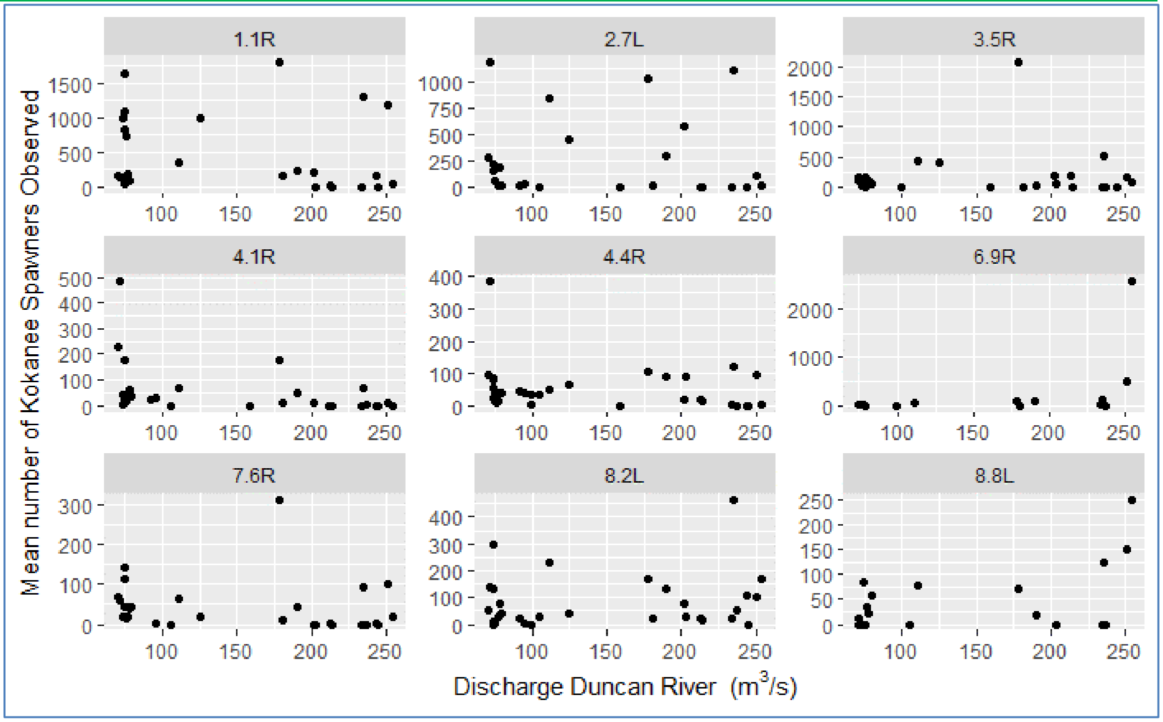


Figure 5-2: Observed use of side channel by Kokanee spawners for the period 2008 - 2016. Refer to Figure 2-1 for locations of channels.

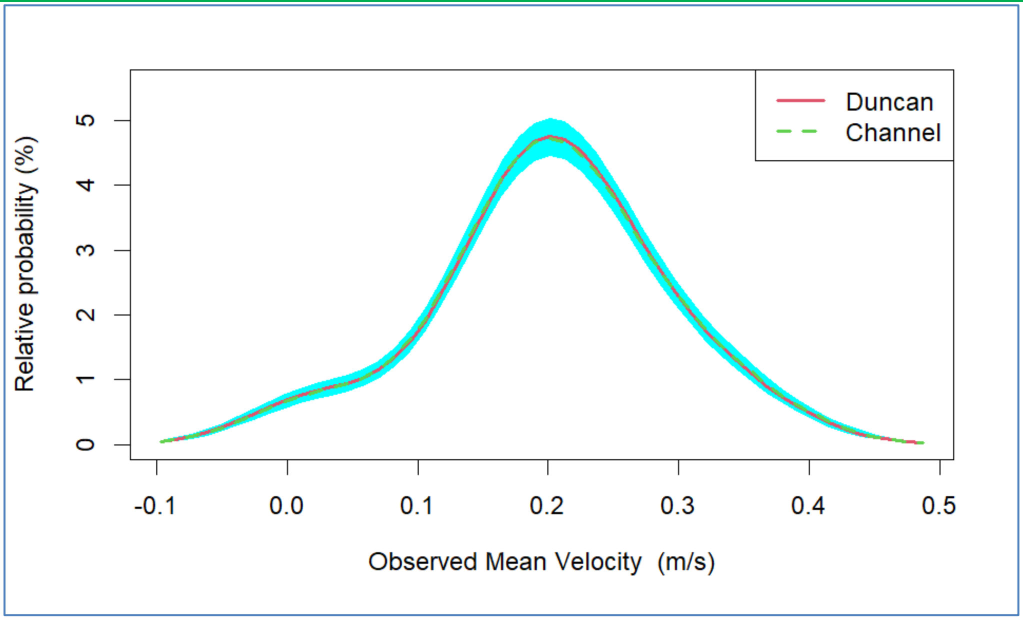
5.2.2 Gerrard Rainbow Trout Fry Habitat Use

Rainbow Trout fry observation data were collected under DDMMON-2. Comparing field habitat use and abundance data with the modelled habitat quality we observe a good overlap. Habitat is concentrated on the shores of the mainstem and side channels. This might also be an artifact from the sampling design, but it corresponds with general Rainbow Trout habitat preferences. The range of modelled discharges capture the observed pattern for overall WUA distribution along the riverbed, especially on the edges where velocity is reduced.

The velocity and depth preference curves used in this model update (see Figure 4-2) came from the Bayesian model results of DDMMON-2. However, as depicted in Figure 5-3 the observed mean velocity and depth describe different distributions and point out the need to improve the preference curves used for habitat modelling. And although there is no significant difference between velocity preference between mainstem and side channels (p-value = 0.9), an increase range of velocity and depth preference would increase the potential WUA.

5.2.3 Gerrard Rainbow Trout Parr Habitat Use

Following DDMMON-2, Rainbow Trout parr are juveniles whose length is greater than 100 mm. There were 695 of such observations. Their habitat use is similar to that of Rainbow fry, but with a slightly wider range for depth preference. All sample points overlap habitat points modelled as suitable. When considering the location accuracy, at least 50 % of the points fall in a zone with modelled suitable habitat.



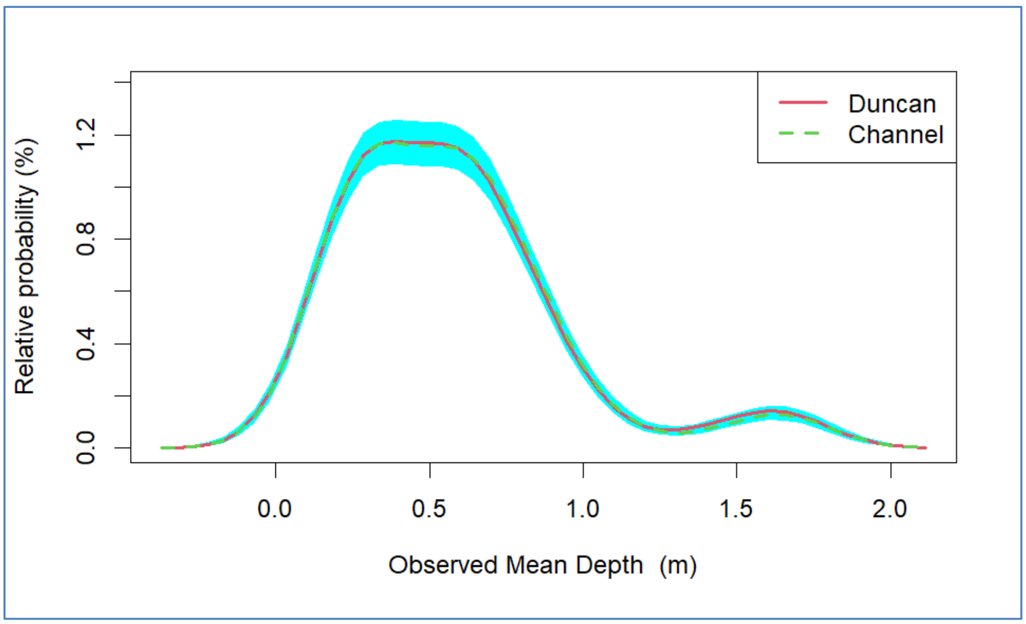


Figure 5-3: Observed density distribution for mean velocity (top) and mean depth (bottom) for Rainbow Trout fry derived from observed data in DDMMON-2. The density estimates for the mainstem (Duncan) and side channels overlap.

5.2.4 Mountain Whitefish Spawning Habitat Use

Spawning Mountain Whitefish exhibit the widest range of habitat preferences. Consequently, the modelled habitat in terms of WUA is the larger of the species considered. Observed data includes 1150 records. Figure 5-4 depicts an example comparing observed records with modelled HSI. The observed spawning individuals are found in areas where the current mode update (T2D_2020) predicted suitable habitat. However, some areas with high HSI have a lower density of observed individuals.

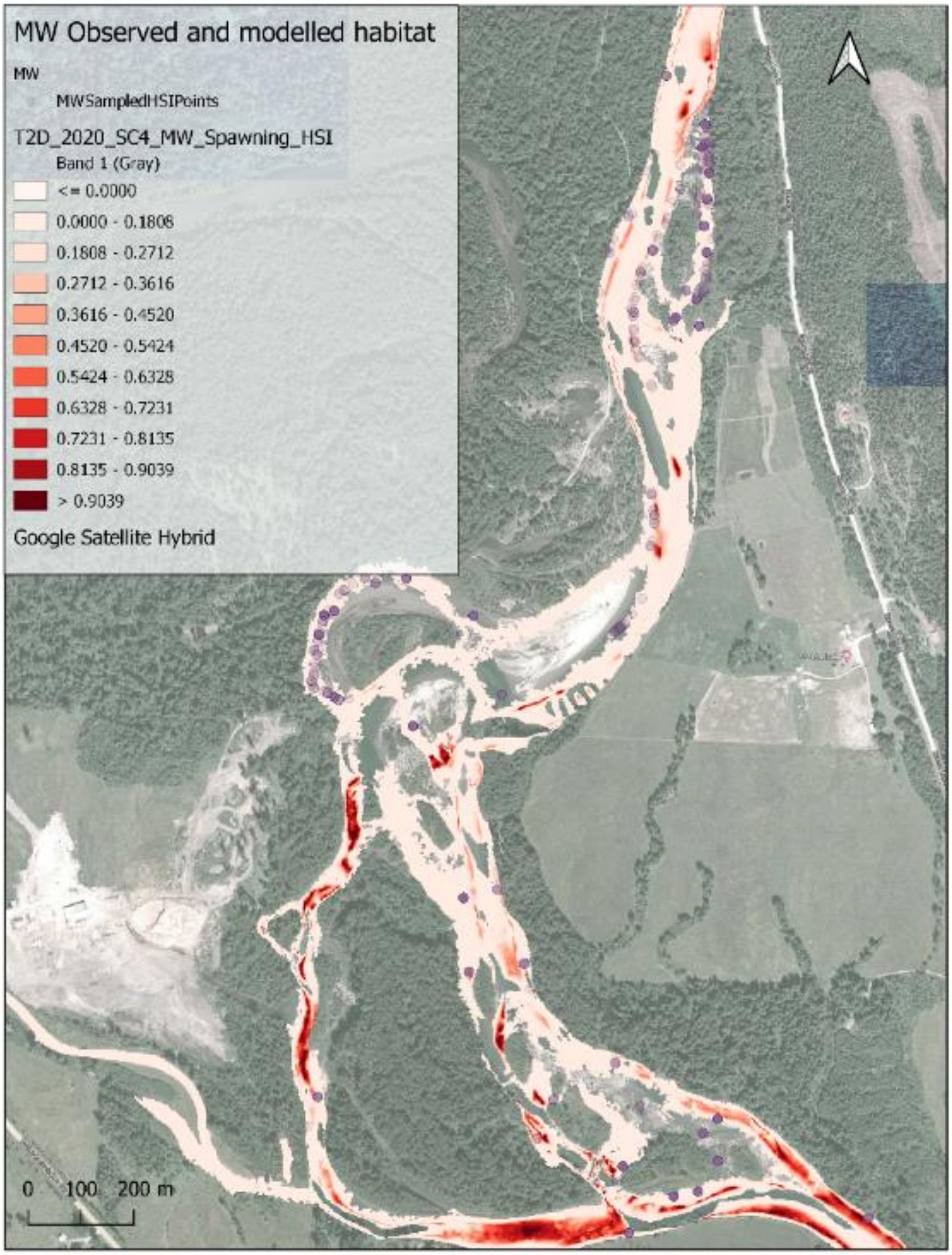


Figure 5-4: Example of observed Whitefish spawning records overlapping predicted HSI for a single modelling scenario (SC4 = 103 m^3/s total LDR discharge). The darker the red tone, the higher the HSI. Purple dots represent observed Mountain Whitefish across discharge levels.

5.3 Flow-Habitat Relationship Stability

$H_0$3: *The transient nature of the Lower Duncan River floodplain morphology does not significantly change the flow-habitat relationships that are predicted by the 2-D flow model.*

Figure 5-5 shows the ANOVA and pair-wise t-test comparisons for the predicted proportion of total area wetted by the three models. Only the differences for the 2010 – 2013 and 2013 – 2020 models are statistically significant (α = 0.05). These differences can be explained by the differences in bathymetry (morphology). As indicated in the morphological comparison results, the modelled riverbed for the 2013 hydrological model represented, in general, higher bed edges. This might cause that a similar amount of water spreads less in the floodplain compared to 2020, where a slightly deeper riverbed with lower edges might induce a greater spread of the wetted area.

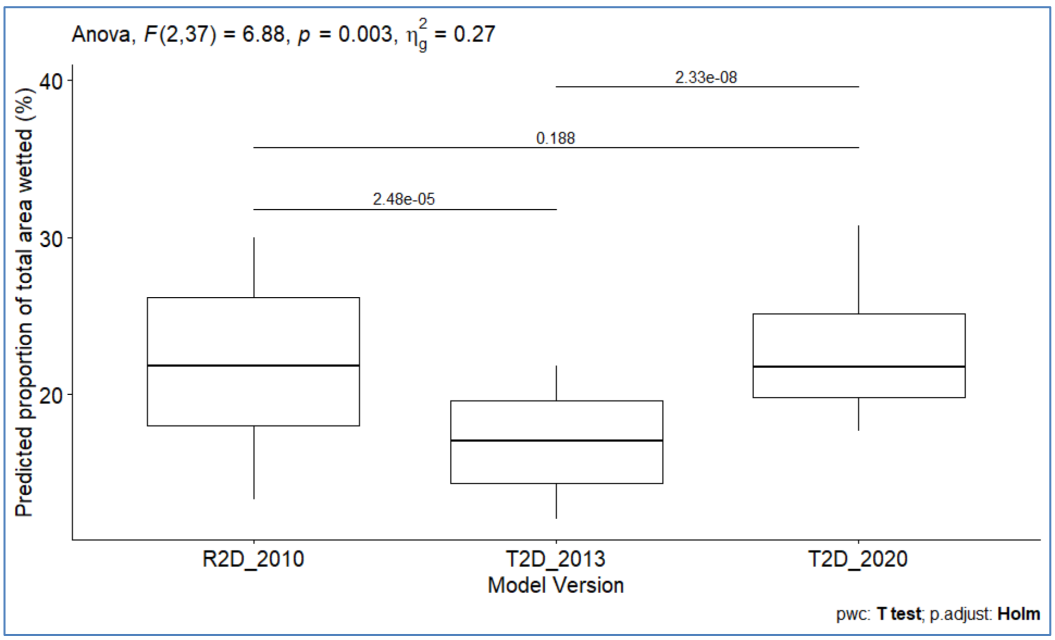


Figure 5-5: Boxplot comparing F-Test results for the predicted proportion of wetted area by model. T2D_2020 = 2020 Telemac 2D Update; T2D_2013 = 2013 T2D Model; R2D_2010 = River 2D 2010 Model.

Fitting a simple linear model to the predicted relative wetted area (*Proportion of Total Area Wetted = a*DAM + Intercept*), we can observe small differences in the estimated Flow – Wetted Area relationship between models (see Table 5-1). This indicates that the shape of the relationship between flow and wetted area (a general proxy for habitat) differs across models. Because the general structure of the simulation models is similar and the main difference lies in the bathymetric data used, we would reject $H_0$3, changes in morphology do seem to change flow-habitat relationships.

In particular, if we observe the relationship between discharge and the amount of habitat (relative to the area modelled) for Kokanee spawning, we can see, a similar shape, the relationship is better represented by a quadratic polynomial (the curve describes an inverse parabola), but different equations for the Habitat - Flow relationship (see Figure 5-6).

Table 5-1: Fitted linear models summary for Proportion of Total Area Wetted by Discharge level (DAM).

Model	Term	Estimate	R squared	Std Error	F-statistic	p-value
R2D_2010	(Intercept)	11.577	0.993	0.2746	42.16029	1.63e-13
	DAM	0.0633		0.0016	40.76344	2.35e-13
T2D_2013	(Intercept)	11.014	0.999	0.0727	151.46927	1.30e-19
	DAM	0.0364		0.0004	88.60246	4.72e-17
T2D_2020	(Intercept)	17.291	0.801	0.9251	18.68937	4.06e-23
	DAM	0.0571		0.0042	13.59251	1.01e-17

Table 5-2: Fitted linear models summary for Kokanee Spawning Relative WUA by Discharge level (DAM).

Model	Term	Estimate	Std Error	F-statistic	p-value
R2D_2010	(Intercept)	-0.0033	0.0178	-0.1839	0.8582
	DAM	0.0323	0.0025	12.8036	0.0000
	$(DAM/10)^2$	-0.0007	0.0001	-8.7611	0.0000
T2D_2013	(Intercept)	0.2896	0.0149	19.4083	0.0000
	DAM	0.0500	0.0021	23.6979	0.0000
	$(DAM/10)^2$	-0.0013	0.0001	-20.8405	0.0000
T2D_2020	(Intercept)	0.1616	0.0084	19.2683	0.0000
	DAM	0.0060	0.0012	5.0360	0.0007
	$(DAM/10)^2$	-0.0002	0.0000	-5.2674	0.0005

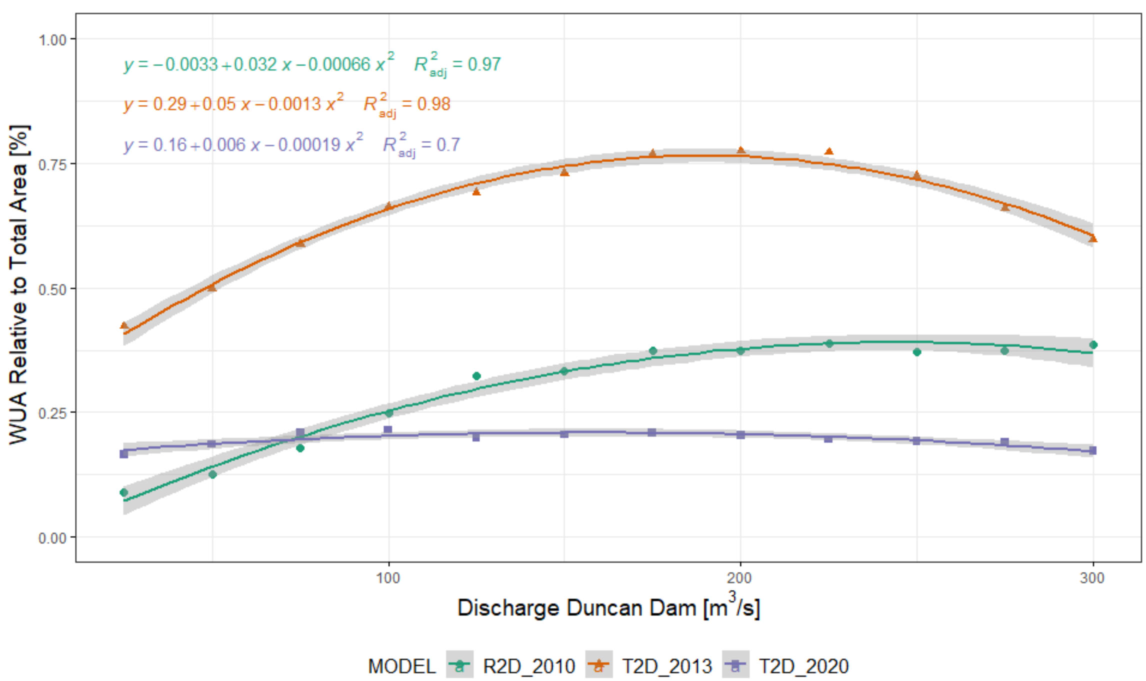


Figure 5-6: Fitted models for Kokanee Spawning Relative WUA by Duncan Dam Discharge level. In the model, x = DAM/10 (m^3/s).

5.4 Dewatering and Fish Stranding Risk

$H_0$4: *Fish stranding risk predicted by the 2-D model of the Lower Duncan River floodplain for operating scenarios evaluated and/or considered in the Adaptive Stranding Protocol Development plan provides a reasonable surrogate for empirical observations made prior to and during the DDM WUP monitoring review period (i.e., the two approaches do not differ).*

Previous reports partially assessed dewatering from wetted areas using the down-ramping rate as a measure of risk (NHC, 2013). However, according to Irvine et al. (2015), dewatering rate (Rate of reduction) is a poor measure of stranding probability (risk).

Over the years of reported stranding data (2008 – 2020), the side channel sites with highest incidence of stranded individuals have been S3.5R, S4.1R, and S6.9R (see Table 5-3). Moreover, the observed stranding impact seems insensitive to the size of the discharge down-ramp, although a higher incidence is concentrated around a decrease of 50 m^3/s (see Figure 5-7). Additionally, YOY and Juvenile individuals tend to be the most impacted by dewatering (see Table 5-4). These results partially correspond with the loss of usable habitat predicted in the down ramping scenarios (see Table 5-5).

Status of the area of interest or loss of usable habitat could be used to inform stranding risk assessment and would need to be combined with other criteria to get an appropriate measure of risk. However, further investigation is needed to identify why those channels concentrate the observed stranding occurrences, even though the impact of down-ramping is similar in other sites. The modelling results can be used as a basic proxy (surrogate) to assess stranding risk; therefore, we do not reject $H_0$4. Predicted dewatering of side-channels can be used in the application of the Adaptive Stranding Protocol. Notwithstanding further improvement of habitat use curves and substrate survey should be provided.

Table 5-3: Reported count of stranded individuals for the species of interest from 2002 to 2020. Data from DDMMON-16.

	Species		
Side Channel	**Kokanee**	**Whitefish**	**Rainbow**
S2.7L	10		27
S3.5R	3112	125	1193
S4.1R	654	190	208
S6.9R	515	115	440
S8.2L	8	3	53

Table 5-4: Percentage distribution of stranded individuals by life stage.

Species	Stranding Life Stage			
	Other	**YOY**	**Juvenile**	**Adult**
Kokanee	5	60	14	21
Rainbow Trout	25*	7	68	0.1
Whitefish	8.4	3	88	0.6

*: 24 % did not have a life-stage specified.

Figure 5-7: Incidence of stranded individuals by side channel for species of interest over the years of DDMMON-16 recorded data (2002 - 2020). The discharge ramp-down represents the difference between the discharge at the beginning and at the end of the event. Notice the different scale for each plot. Refer to Figure 2-1 for locations of channels.

Table 5-5: Predicted amount of WUA at the start of the down ramping and percentage of change at the end of the event.

Side channel	Down-Ramping Scenario (Initial WUA / Final WUA) (m²) - Risk Approximation (as % area lost)										
	196-140		140-80		150-50		80-45		45-10		24-3-24
1.1R	476.04	18%	563.55	-78%	465.63	-72%	123.77	4%	129.14	-100%	0.37
2.7L	320.79	136%	756.26	-71%	766.27	-53%	216.93	66%	359.85	-90%	71.64
3.5R	**1353.43**	**112%**	**2867.07**	**-100%**	**1720.10**	**-100%**	**10.78**	**-92%**	**0.86**	**-100%**	**0.00**
4.1R	522.28	318%	2182.42	85%	1140.32	245%	4047.54	-3%	3933.26	-67%	2579.46
4.4R	29.13	822%	268.44	128%	161.83	421%	611.40	38%	842.93	-46%	903.14
6.9R	**2558.63**	**-99%**	**27.57**	**-100%**	**576.97**	**-100%**	**0.00**	**---**	**0.00**	**---**	**0.00**
7.6R	**205.58**	**-64%**	**74.48**	**-99%**	**261.28**	**-100%**	**0.41**	**-100%**	**0.00**	**---**	**0.00**
8.2L	**2097.49**	**-32%**	**1429.62**	**-69%**	**1471.80**	**-98%**	**443.84**	**-94%**	**27.00**	**-32%**	**36.60**
8.8L	894.99	-25%	666.88	-64%	787.70	-91%	242.43	-70%	73.87	-81%	28.48

Note: The positive values are due to the parabolic type of response for the WUA for Kokanee causing that flow decreases produce an increase in usable habitat.

6 DISCUSSION

6.1 Overall Modelling Results

Bathymetric differences indicate that, on average, riverbeds were modelled with similar morphologies with differences limited to specific sections. However, these differences are enough to predict different wetted (flooded) areas for similar discharge levels. Given the added quality of the data for the 2020 model, we can assume the morphological changes due to sediment transport and other processes were adequately captured. Therefore, differences in wetted area can be attributed to the differences in the underlying bathymetry (i.e., morphology), and, in lesser terms, to different algorithms/models used. Given the difference in extent of study areas, the relative wetted areas provide additional information when comparing predicted habitat amounts (WUA).

As expected, the extents of wetted areas for the different discharge levels are bigger in the 2020 model update. This is consistent with the bigger mesh extent. However, when normalized with the extent of the modelled area, we observe that the 2020 (Telemac2D) and 2010 (River2D) models are equivalent for similar discharge levels. However, the predicted wetted areas for the 2013 (Telemac2D) model update are proportionally smaller. This might be due to the observed differences in bathymetry, where the 2013 riverbed elevation is, on average, lower than the 2008 and 2020 elevations.

Management questions are addressed in the following sections with various degrees of depth dependent on the question. Ecoscape does not have access to the physical flow model (1D) developed prior to the DDM WUP, therefore questions directly pertaining to this model have been addressed with graphics from previous DDMMON-3 annual reports.

The performance measures including habitat distribution and stranding risk are also addressed in the following sections. Some operational changes were considered in the down ramping modelling. For the relationship between TGP and discharge, the reader can consult DDMMON-7.

6.2 Management Question 1

MQ -1 *Did the physical flow model developed prior to the DDM WUP accurately predict floodplain inundation levels and extent in Lower Duncan River mainstem and side channel areas?*

MQ -1 was addressed in years 1 and 2 of the DDMMON-3 program ((NHC, 2010)). The 2D modelling and simulation of habitat provided more representative estimates of WUA, than the 1D physical flow model developed prior to the DDM WUP. The 2D model incorporated depth, velocity and substrate compared to depth alone in the 1D model. In addition, survey data was undertaken with a broader mandate and scope. Bathymetric surveys encompassed the entirety of the LDR to Kootenay Lake and included most side channels (NHC, 2010). Whereas earlier DDM WUP surveys did not account for side channels or the full length of the LDR. For comparison, the

1D Model was 7.5 km long and had only 12 cross sections, while the 2D model covered the entire river with a 5 m grid coverage (NHC, 2010).

Figure 6-1 depicts the long profiles of the LDR and illustrates the differences between the 1D (blue and red lines) and 2D Models. In addition to the 2D Model capturing a greater length of the LDR, there is also much greater resolution of channels and surveyed bed elevations. The coarseness of the 1D Model is also evident when overlaying a discharge of 75 m^3/s with the surveyed bed elevation of the 2D model (black line). It shows flow elevations that are less than the surveyed bed elevation, putting into question the accuracy of the mainstem flows used in the 1D Model.

Based on these findings, NHC concluded that the physical flow model developed prior to the DDM WUP, ***did not*** accurately predict floodplain inundation levels or the extent of the LDR mainstem and side channel areas (NHC, 2010) . Rather, the 2D Model was much more accurate at predicting water elevations.

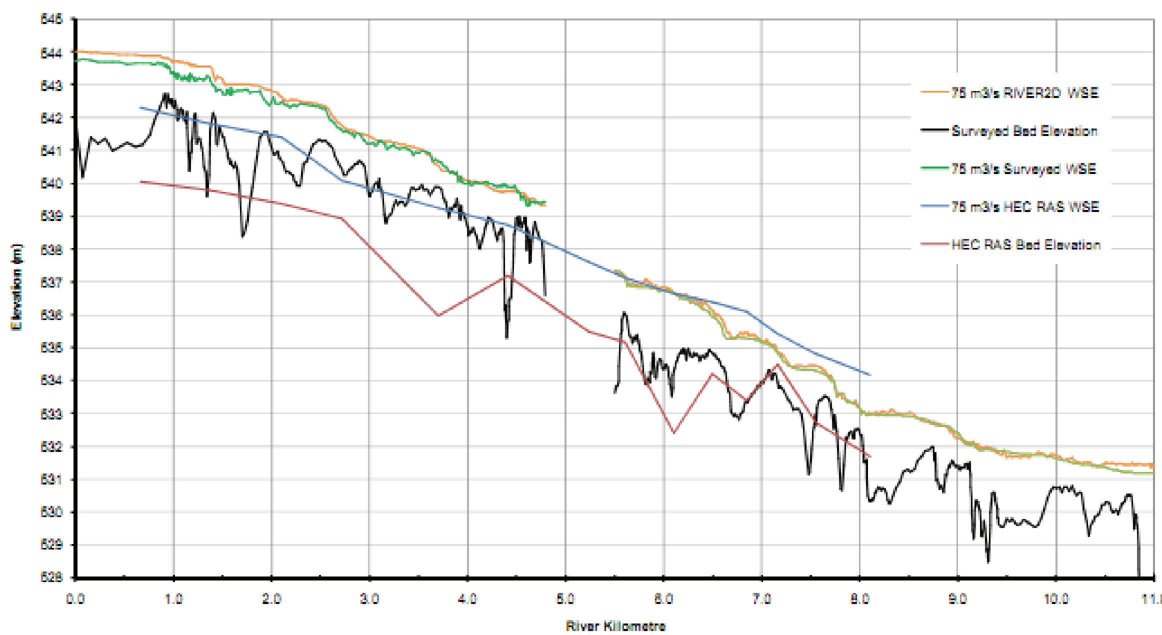


Figure 6-1: Long Profiles of the Lower Duncan River (NHC, 2010). 1D Model profiles are blue and red lines, all others relate to the 2D Model.

6.3 Management Question 2

MQ-2 — *Were the habitat-flow relationships for fish species of interest incorporated into DDM WUP performance measures accurate for the range of operations licensed for the Lower Duncan River?*

The modelling that has been undertaken during this program has shown that the habitat-flow relationships for Whitefish, Kokanee and Rainbow Trout, that were incorporated into DDM WUP performance measures, were not accurate in most cases. For example, the 1D Model over estimated Kokanee spawning habitat compared to the 2D Model (Figure 6-2) (NHC, 2010). It was suspiciously inaccurate, as the Kokanee spawning habitat estimated by this model approached 10% of the riverbed at flows of approximately 50 m^3/s. Whereas the 2D Models estimated spawning habitat for Kokanee from less than one percent of the riverbed (2020 model) to about 4.5% (2013 model) (Figure 4-4).

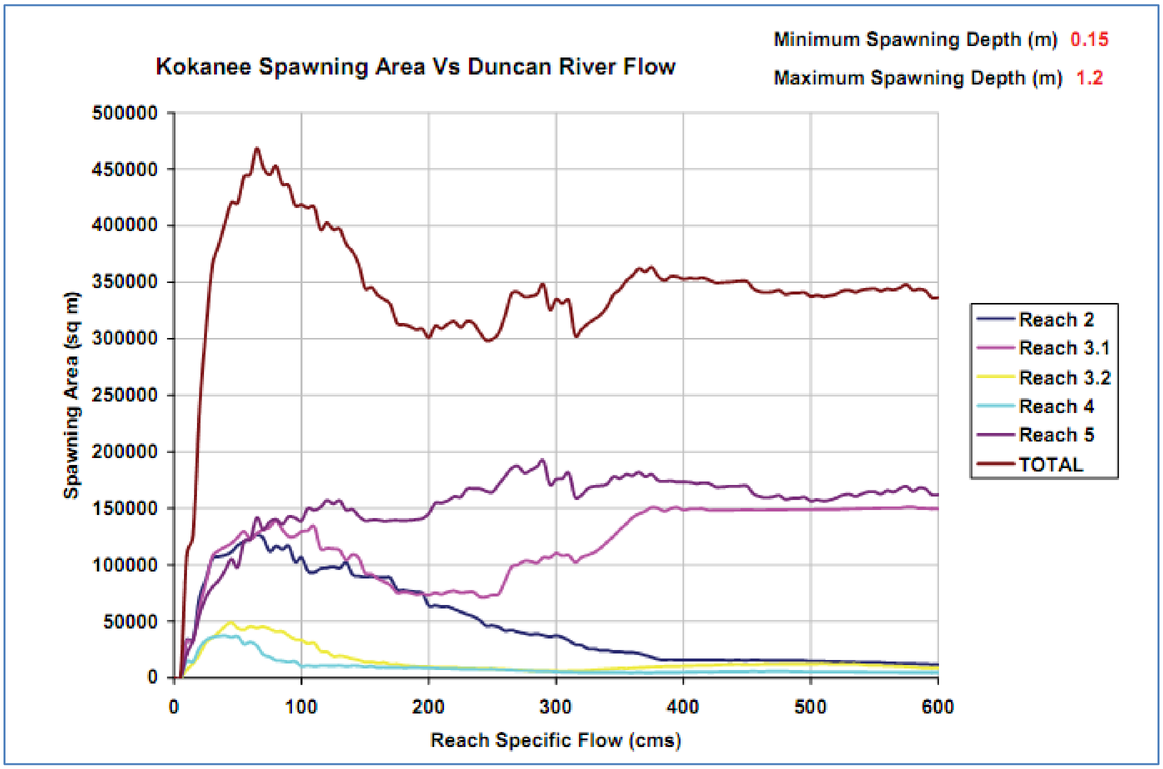


Figure 6-2: Duncan Dam Water Use Plan 1D Modelled Kokanee Spawning WUA (NHC, 2010, fig. 34).

NHC (2010) originally reported that spawning area for Mountain Whitefish increased with increasing flows likely due to the broad range of substrates utilized by Whitefish. The magnitude and relationship to flows was similar for both the 1D and 2D Models (NHC, 2010, figs. 35 and 36). However, in the raw data, that result was corrected to a decreasing trend. The results that we generated for 2010, from the raw data, showed this decreasing trend, more consistent with the 2020 results (Figure 4-4).

Rainbow Trout rearing habitat that was generated with the 1D and River-2D models exhibited similar increasing trends with increasing flows. It is worth noticing that RBT fry WUA in the DDM WUP HEC-RAS 1D model were solely based on wetted area (NHC, 2010, p. 58). On the other hand, the 2013 and 2020 2D models, produce different results from the 1D and River 2D models, but with similar patterns. In these updates WUA decreases as discharge increases, consistent with juvenile Rainbow Trout's preference for low water velocity. According to the 2020 model results, the flow - habitat relationships derived from the 1D HEC-RAS model and incorporated in the DDM WUP were not accurate.

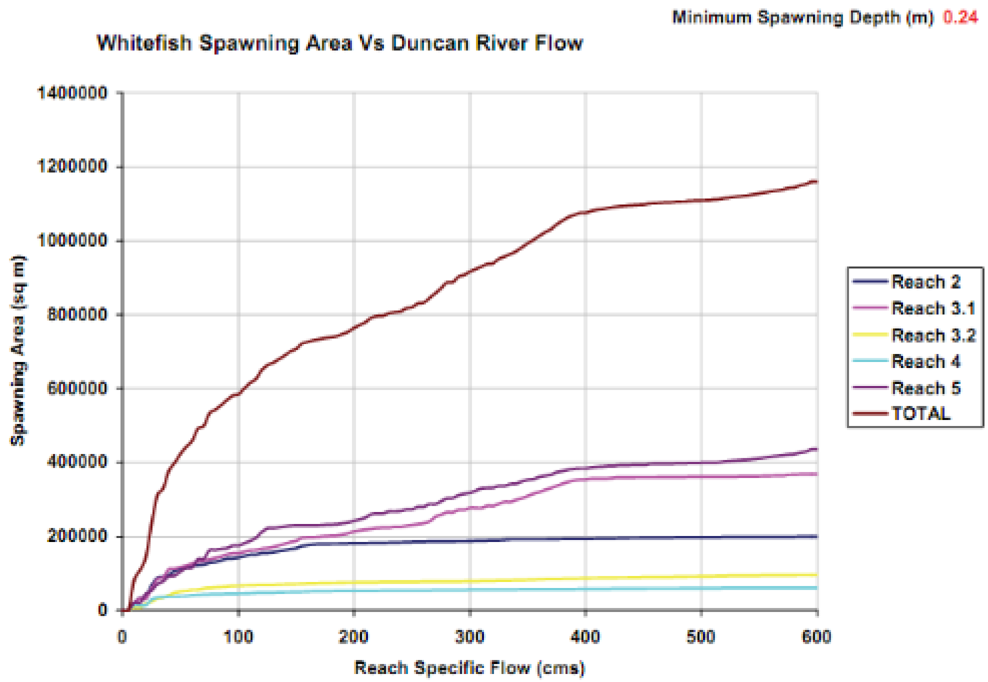


Figure 6-3: Duncan Dam Water Use Plan 1D Model Mountain Whitefish Spawning Weighted Usable Area (NHC, 2010, fig. 36).

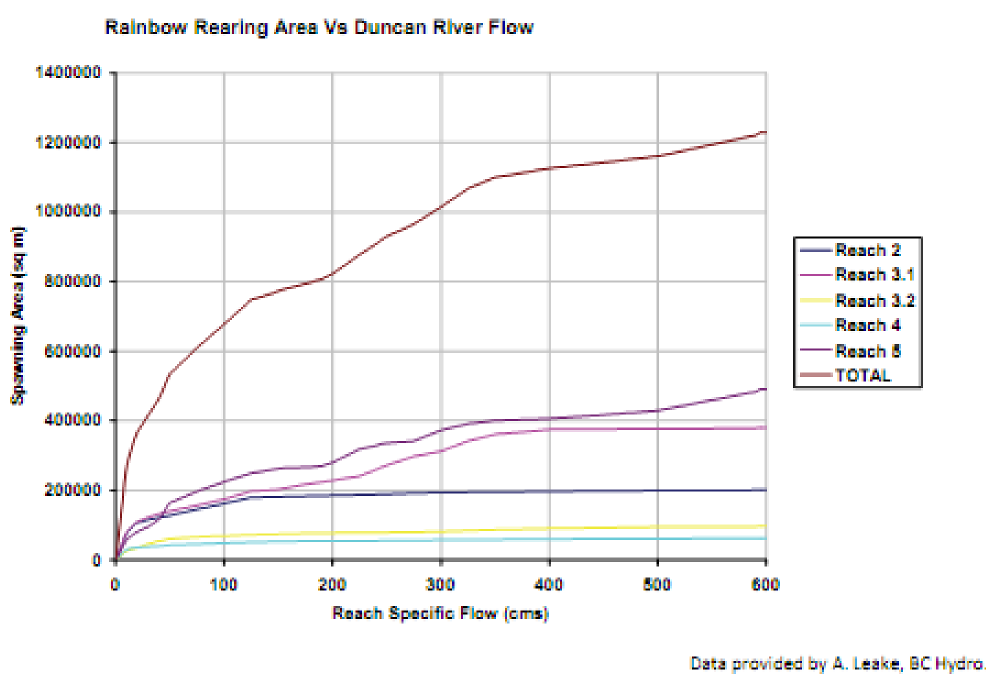


Figure 6-4: Duncan Dam Water Use Plan 1D Model Mountain Whitefish Spawning Weighted Usable Area (NHC, 2010, fig. 38).

6.4 Management Question 3

MQ-3 *Given the criteria for operating recommendations made during the DDM WUP, would a more extensive and validated modeling effort result in revised recommendations? Will future model revisions result in revised recommendations?*

We can see that the minimum monthly discharge level of 3.0 m^3/s (BC Hydro, 2007, p. 11) provides very limited habitat, regardless of the discharge levels of the Lardeau River. 3 m^3/s for more than 1 h will entail the dewatering of most side-channels (see Table 1-1) and edges of the riverbed (refer to flooded areas and HSI maps). On the other hand, 73 m^3/s after the confluence with the Lardeau River, to maintain and enhance fisheries habitat in the Duncan River (BC Hydro, 2007, p. 12), does not provide the amount of habitat for all the species of interest as previously assessed. A minimum flow of 73 m^3/s could generate backwatering and dewatering of tailout area redds. However, while the amount of habitat is lower than what previous models indicated (Table 6-1, this flow level is close to the optimal of 100 m^3/s where most habitat levels peak (see Figure 4-4). These recommended minimum discharge and flow levels could be reviewed.

Table 6-1: Estimated total (m^2) / relative (%) Wetted Area and habitat (WUA) for the species of interest as predicted by the corresponding model at flow level of ~ 73 m^3/s.

Species/Life-stage	2010 River 2D	2013 T2D	2020 T2D
Wetted area	1,619,992 / (15.2)	1,363,921 / (12.8)	3,055,138 / (18.4)
Kokanee / Spawning	13,514.21 / (0.13)	52,983.00 / (0.50)	30,900.30 / (0.19)
Rainbow Trout Fry	119,898.08 / (1.13)	105,239.00 / (1.00)	61,984.45 / (0.37)
Rainbow Trout Parr	246,132.40 / (2.30)	---	42,334.51 / (0.26)
Whitefish Spawning	106,017.42 / (1.00)	---	116,232.71 / (0.70)

Regarding maximum flows (BC Hydro, 2007, p. 13), the effects seem to be limited as habitat plateaus for some species/life-stages (Figure 4-3). Additionally, Kokanee spawning occurs across a wide range of flows (Figure 5-2). The challenge remains in the combination of initial flow, time of the year, and ramping rate. With the data generated in our simulations, a more dynamic interface could be built to assess the combined effects for a given species/life-stage.

6.5 Challenges in Addressing Management Questions

Ecoscape experienced several challenges in addressing the management questions, largely due to our limited history and knowledge of the DDMMON-3 program. We had to rely heavily on earlier reports to determine specific modelling approaches and evaluation criteria. Report inconsistencies led to several interim questions and divergent paths. For example, we had to make several assumptions pertaining to the habitat use and suitability models, as the annual reports used different analytical approaches (i.e., Geometric Mean Method (GMM) versus Continued Product Method (CPM) for evaluating HSI and WUA.

We also had difficulty addressing several of the performance metrics, including those relating to total gas pressure (TGP) and the significance of operational changes, due to a lack of available data or variables that were not reported in previous updates. The variability in the various model outputs also led to confusion and questioning of accuracy.

The incompleteness of previous models created gaps in the capacity to address the different hypothesis and questions. We had to mine additional steps to be able to compile the necessary data to generate a more cohesive result.

This is, of course, a modelling effort, and results are valid under the assumptions and for the range of data and scenario considered. Data limitations or simple model parsimony make the model as good as the data and assumptions included in the effort to keep it simple but informative. The diversity of data sources with little or no overlap in protocols for metadata and storage posed an additional challenge to a project with such a wide requirement of data.

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8 APPENDICES

Appendix 1. Timeline and Milestones of DDMMON-3

Table A1. Timeline and Milestones of DDMMON-3.

Year	Milestones
(Year 1) Jul 2008 - Jan 2009	Contract awarded to NHC. Works completed in Year 1 included: hydrographic survey of wetted portions of the LDR from the tailrace of DDM to Kootenay Lake, including wetted side channels; terrestrial / ground survey of dry portions of the channel – including lateral and mid channel bars, top-of-bank and bank areas assessable via foot along LDR; sediment surveys of the LDR, including classification and mapping of substrate size within the channel; and installation of remote water level recorders at key side channel locations to document water level fluctuations and provide a continuous record of water levels along the LDR.
(Year 2) Feb 2009 – Mar 2010	Works completed in Year 2 included: integration of DEM data with collected survey data; continued monitoring of water levels and hydraulic variables throughout the floodplain to calibrate and update the model; River2D model development, calibration and verification; development of hydraulic habitat relationship for species and habitat; and analyses using historical time series flow and habitat relationships to determine habitat duration curves, critical flow habitat relationships for key life stages and species. In 2010, a 2D numerical hydraulic model was created to reflect the 2008 LDR conditions using the software River2D (Steffler & Blackburn, 2002). Compared to the original model from Year 1, the River2D model improved the resolution and quantification of modeled hydraulic habitats. NHC concluded that the physical flow model developed prior to the DDM WUP did not accurately predict floodplain inundation levels or the extent of the LDR mainstem and side channel areas (NHC, 2010). Rather, the River2D model was much more accurate at predicting water elevations. A preliminary assessment of habitat-flow relationships was completed by modelling Weighted Usable Area (WUA) for species and life stages in the LDR (i.e., habitat suitability). However, comparison of the areas of habitat use predicted by River2D was deferred to Years 5 and 10 of the study when data from other programs would be available.
(Year 5) Feb 2012 – Jul 2013	In Year 5, recent morphological changes in the LDR were incorporated into the hydrodynamic model; the habitat modelling methodology was updated to reflect improvements in analytical ability; and data collected from other programs was utilized. Specific tasks included: • Updating the DEM; • Upgrading the hydraulic model from a steady-state simulation using RIVER2D to and unsteady simulation using TELEMAC2D; • Implementing refined analytical tools for analyzing flow ramping effects; and • Comparing the weighted usable area (WUA) derived from the updated TELEMAC2D model to the results obtained in the Year 2 RIVER2D model.
2015	BC Hydro updates the Year 5 (NHC 2013) model to better capture the effects of the 2012 flooding events. Since high flows in July 2012 changed the morphology of the study area, BC Hydro updated the Telemac2D model developed by NHC using LiDAR data that was collected after 2012. The LiDAR data provided improved geometric representation of side channel alignments and shallow areas.
2017	BC Hydro also converted NHC's River2D model to Telemac2D, with similar mesh characteristics so that comparisons of the 2008 and 2013 channel conditions could be made.

Year	Milestones
2020	BC Hydro updated the LDR modelling to represent 2019 conditions. Significant topographical and bathymetric data were collected to update the LDR hydraulic model to reflect 2019 conditions. Information used to update the ground elevations included: • July 5, 2018 Orthophotos • 2021 LiDAR data • Manual DEM – With LiDAR DEM data vulnerable to elevation errors due to thick vegetation, DEM data was removed from the LiDAR set near areas of interest and replaced with elevation data extracted from the 2018 orthophotos • River and island edges – Elevation information along the water edges were extracted from the 2018 orthophotos • Bathymetry data for LDR was collected on September 21 – 26, 2019, where boat access was not feasible, data points were manually collected • Underwater DEM – To augment boat-based bathymetric data collected in the main Duncan River channel as well as provide bathymetric data for numerous side channels, bathymetric data was extracted from the 2018 orthophotos. Due to the low flow at the time of the photo collection and the clarity of the water in the photos, underwater bathymetry data was able to be extracted. • Standing water edge was extracted from the latest orthophotos.
(Year 10) 2021	Quantitative data from the following programs were integrated into the hydraulic model: • DDMMON-2 the Lower Duncan River Fish Habitat Use Monitoring program – the habitat use preferences of Rainbow Trout and Mountain Whitefish and their associated timing and population data (Thorley et al., 2012); • DDMMON-4 Lower Duncan River Kokanee Spawning Monitoring program – the annual Kokanee (*Oncorhynchus nerka*) escapement in the LDR, spawning data in the LDR within and outside of operational constraints and their spawning habitat preferences, timing and differences in morphology between different runs' (Plate et al., 2017); and, • DDMMON-16 Lower Duncan River Fish Stranding Impact Monitoring program – the abundances estimations and fish stranding observed by Rainbow Trout and Mountain Whitefish (Golder Associates Ltd., 2018). Management questions and hypotheses addressed.

Appendix 2. Steady State Modeling and Simulation Methods

We updated the Telemac 2D model files provided by BCH to run the model in the current version of Telemac 2D (Version 8). The updated model and configuration files are provided as accompanying data files. Example configuration file:

```
TITLE                                                     :
'LDR_M2019_SC1_LR20_DAM0'
TIME STEP                                                 :   2
DURATION                                                  :   86400
ORIGINAL DATE OF TIME                                     :   2019;01;01
ORIGINAL HOUR OF TIME                                     :   00;00;00
COMPUTATION CONTINUED                                     :   YES
INITIAL TIME SET TO ZERO                                  :   YES
PARALLEL PROCESSORS                                       :   4
STEERING FILE                                             :   M2019_SC1.cas
BOUNDARY CONDITIONS FILE                                  :   LDR_BC_2020.cli
GEOMETRY FILE                                             :   Geom-f-29May2020.slf
PREVIOUS COMPUTATION FILE                                 :   Ini-f-29May2020.slf
PRESCRIBED ELEVATIONS                                     :   531.62;0
PRESCRIBED FLOWRATES                                      :   0;0
VELOCITY PROFILES                                         :   4;4
WATER DISCHARGE OF SOURCES                                :
1;0;0;0;0;5;5;5;5;1;5;1
LISTING PRINTOUT PERIOD                                   :   1800
VARIABLES FOR GRAPHIC PRINTOUTS                           :   'U; V; M; S; H'
GRAPHIC PRINTOUT PERIOD                                   :   1800
RESULTS FILE                                              :   M2019_SC1_Results.slf
LAW OF BOTTOM FRICTION                                    :   4
FRICTION COEFFICIENT                                      :   0.03
TIDAL FLATS                                               :   YES
OPTION FOR THE TREATMENT OF TIDAL FLATS                   :   1
TURBULENCE MODEL                                          :   1
VELOCITY DIFFUSIVITY                                      :   10E-2
MASS-BALANCE                                              :   YES
CONTINUITY CORRECTION                                     :   YES
SOLVER                                                    :   7
SOLVER OPTION                                             :   4
INFORMATION ABOUT SOLVER                                  :   YES
SOLVER ACCURACY                                           :   1.E-5
MAXIMUM NUMBER OF ITERATIONS FOR SOLVER                   :   100
NUMBER OF SUB-ITERATIONS FOR NON-LINEARITIES              :   1
TYPE OF ADVECTION                                         :   14;5;14
SUPG OPTION                                               :   0;0;1;1
TREATMENT OF NEGATIVE DEPTHS                              :   2
TREATMENT OF THE LINEAR SYSTEM                            :   2
FREE SURFACE GRADIENT COMPATIBILITY                       :   0.9
MATRIX STORAGE                                            :   3
MASS-LUMPING ON H                                         :   1
ABSCISSAE OF SOURCES                    =   503802.8125;
                                            503384.4375; 503372.53125; 503360.46875; 503344.625;
                                            502585.9375; 502580.78125; 502573.750; 502566.0625;
                                            503800.90625;
                                            501397.25; 502807.875
ORDINATES OF SOURCES                    =   5566237.5;
                                            5566849; 5566857; 5566864.5; 5566849.5;
                                            5566450; 5566443; 5566439.5; 5566434.5;
                                            5561111;
                                            5563543; 5560770.5
```

Figure A - 1: Telemac 2D configuration file example for simulation scenario.

Appendix 3. Wetted Area, HSI and WUA Computations

Wetted Area

Estimated as the total area of non-zero depth. Since the areas are projected, we can use the cell resolution times the total wetted cells. This will include a section of the riverbed overlapping Kootenay Lake, but since this happens for all the areas, its effect gets cancelled. Consider frequency with 1 significant digit to include shallow waters (> 0.1 m deep).

Habitat Suitability Index

In previous studies, the Habitat Suitability Index (HSI) has been the indicator of choice to assess available habitat for each fish species at different life stages. To compute the HSI, habitat use curves (HUC) for Depth, Velocity, and Substrate are used. Afterwards, Weighted Usable Area (WUA) is derived for the different scenarios as a product of the HSI and the associated cell area.

According to NHC (2010) the approach used to compute the HSI corresponds to a composite suitability index (CSI), using a product of the individual preference values for the habitat variables (Depth, Velocity, and Substrate) normalized over the range [0,1] (which correspond to the CSI-Combined Suitability Index- method used in River2D). This index is more restrictive than an additive model. However, in Year 5, with the Telemac2D version of the 2010 model, they indicate that the method used is an aggregate, which we would understand as the additive version of HSI. Considering Lewis et al. (2004, p. 37), the Continued Product Method (CPM) for HSI is retained.

$$HSI = DP * VP * SP$$

where:

HSI = Habitat Suitability Index,
DP = Species life stage specific Depth preference,
VP = Species life stage specific Velocity preference,
SP = Species life stage specific Substrate preference.

For a given cell i, the Habitat Suitability Index (HSI):

$$HSI_i = \prod_j HP_j$$

This approach assumes that the j habitat variable preferences (selected/available) are independent and non-spatially auto correlated. As a caveat, these preference values represent habitat use curves, not necessarily habitat preference.

> *It is important to be aware that habitat use does not necessarily indicate habitat preference and that preference does not in turn necessarily indicate requirement (Rosenfeld 2003). For example, spawning fish may utilize slow water because the preferred faster water is not available as appears to be the case at Gerrard in recent years (Thorley and Bowers 2006, Thorley 2006). Thus, in order to interpret a habitat use curve as a suitability curve, it is necessary to establish that the full range of habitats are available.(Thorley et al., 2012)*

Depth and velocity microhabitat use for Rainbow Trout and Mountain Whitefish spawning and rearing were estimated from sample data using a Bayesian model (Thorley et al., 2012).

Depth Preference

Simulated depth corresponds to the steady state difference between the free surface and the bottom geometry.

Velocity Preference

Simulated velocity is computed as a depth averaged velocity (scalar dimension of velocity vector). This is assumed to be equivalent to monitoring reported mean column velocity (Vel40).

Substrate Preference

Substrate was not modified during simulations (no sedimentation process) and it corresponds to the substrate data reported by NHC (NHC, 2013). Additionally, data was lacking for substrate preferences of some species/life stages.

Substrate classification

```
substrate_class <- read_csv(r"(C:\DDMMON3\SubstrateClass.csv)")

substrate_class
```

Species Preference curves

Species specific habitat preference curves were derived in the linked DDMMON programs

- Kokanee (DDMMon-3)
  - Depth
  - Velocity
  - Substrate
- Rainbow Trout Rearing (DDMMON -2)
  - Depth
  - Velocity
  - Substrate
- Mountain Whitefish
  - Depth
  - Velocity
  - Substrate

Read Habitat Preference Data

Habitat Preference Curves were compiled into a single table.

```
path_to_fhp <- r"(C:\DDMMON3\FishHabitatPreference.csv)"

fish_hab_pref <- read_csv(path_to_fhp, lazy = FALSE)
```

```
fish_hab_pref
```

HSI Computation Method

1. For each species
    1. For each life stage
        1. For each variable
            1. Read Preference table
            2. For each discharge scenario
                1. Read simulated variable(s) raster files,
            3. Calculate habitat raster (classify)
                1. Export habitat raster
                2. Compute weighted area

Simulation Results

Previously, the discharge from Lardeau River was fixed at 20 m^3/s. This level corresponds to less than 10% of the flow conditions for Lardeau River. Therefore, to produce more representative scenarios, while still being able to compare to previous reports, we included additional discharge levels for Lardeau River. A total of 48 water discharge scenarios were simulated using the adapted 2019 Telemac 2D model version provided by BC Hydro.

Telemac2D results were clipped to the last iteration, and the mesh data exported to raster format. We simplified raster files using a contour mask to focus on maximum flooded area, have a comparable extent with previous models, and reduce computing times. As reference area, we used the total area flooded by a 403 cms total discharge as determined by scenario 16 (6470741.855 m^2), the closest to the maximum flooded area produced in previous iterations (4258094.070 m^2).

Read Experiments/Results table

```
ss_scen_files <- read_csv("M:/GIS/Projects/2021/21-3728 - DDMMON3 - Hyd
raulic Model Finalization - BC Hydro/R_Analysis/WD03_Telemac_extract_re
sults/tables/ss_results_files_index.csv")
ss_scenarios <- ss_scen_files %>%
  dplyr::select(SCENARIO, DAM,LARDEAU, TOTAL)
ss_scenarios
```

Read simulation results

```
path_to_simResults <- r"(C:\DDMMON3\Model2019\Simulations\varResutls)"
```

Depth

R snippet to import data and create a raster stack to compute depth preference maps from simulated depth results.

```
library(raster)
depth_raster_data_files <- list.files(path = path_to_simResults, pattern = "*depth_clipped.tif$", full.names = TRUE)
depth_rs <- stack(depth_raster_data_files)
NAvalue(depth_rs) <- -999
depth_rs
```

Velocity

R snippet to import data and create a raster stack to compute velocity preference maps from simulated velocity results.

```
library(raster)
vel_raster_data_files <- list.files(path=path_to_simResults, pattern = "*vel_clipped.tif$", full.names = TRUE)
vel_rs <- stack(vel_raster_data_files)
NAvalue(vel_rs) <- -999

names(vel_rs)
vel_rs
```

Weighted Usable Area (WUA)

To estimate habitat changes, the research program used the weighted usable area (WUA) approach. WUA corresponds to the aggregated product of a spatial unit (cell) Habitat Suitability Index (HSI) and the cell's area.

For a given discharge scenario k:

$$WUA_k = \sum_i [HSI_i * Area_i]$$

WUA can also be expressed as a normalized ratio ($nWUA = WUA/TotalArea$).

Appendix 4. HSI Map Example

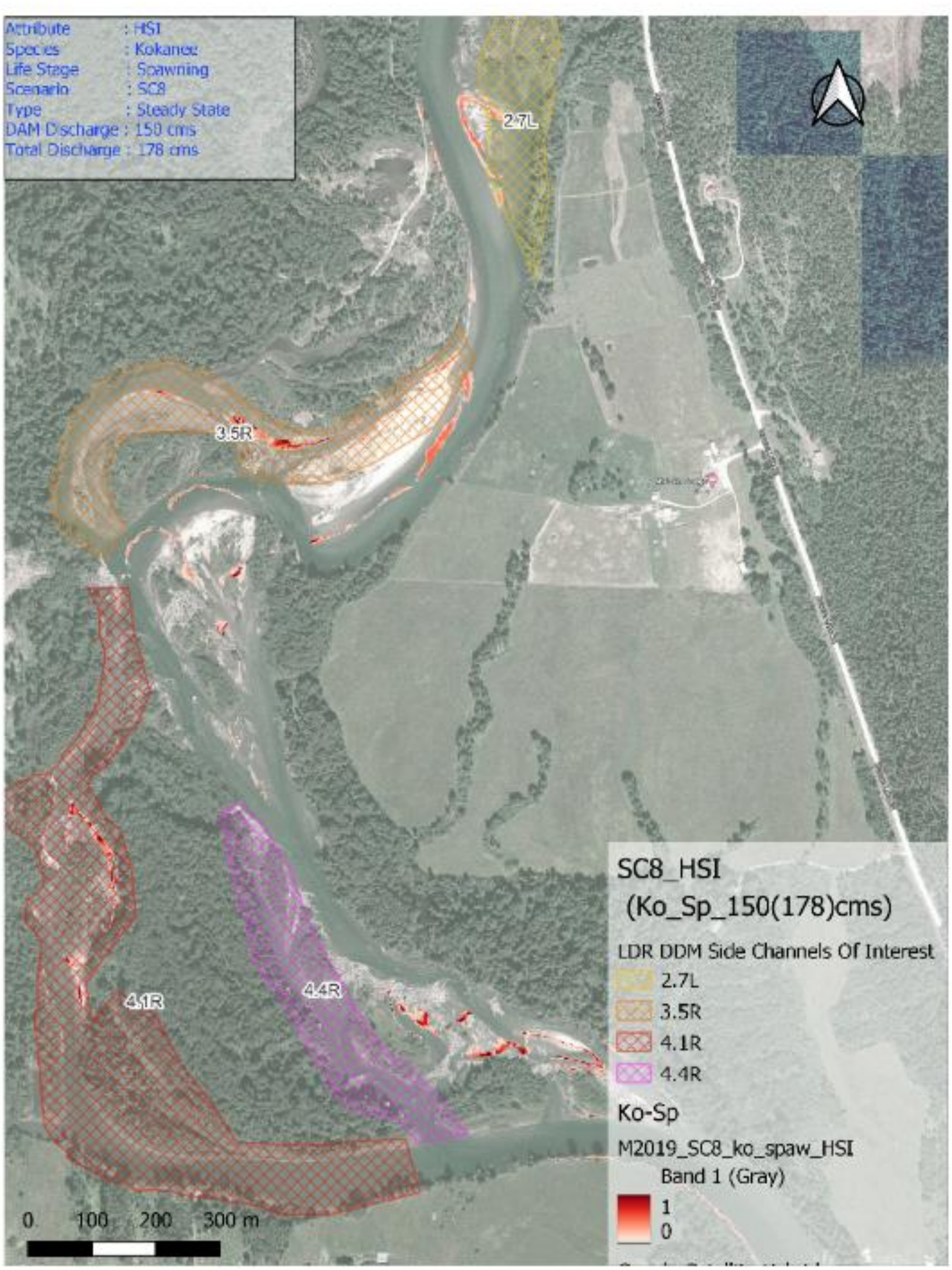

Figure A - 2: Excerpt of map of Habitat Suitability Index for Kokanee Spawning from simulated flow at 178 m3/s in the 2020 T2D model. Darker red indicates better habitat.

Appendix 5. Morphological Differences

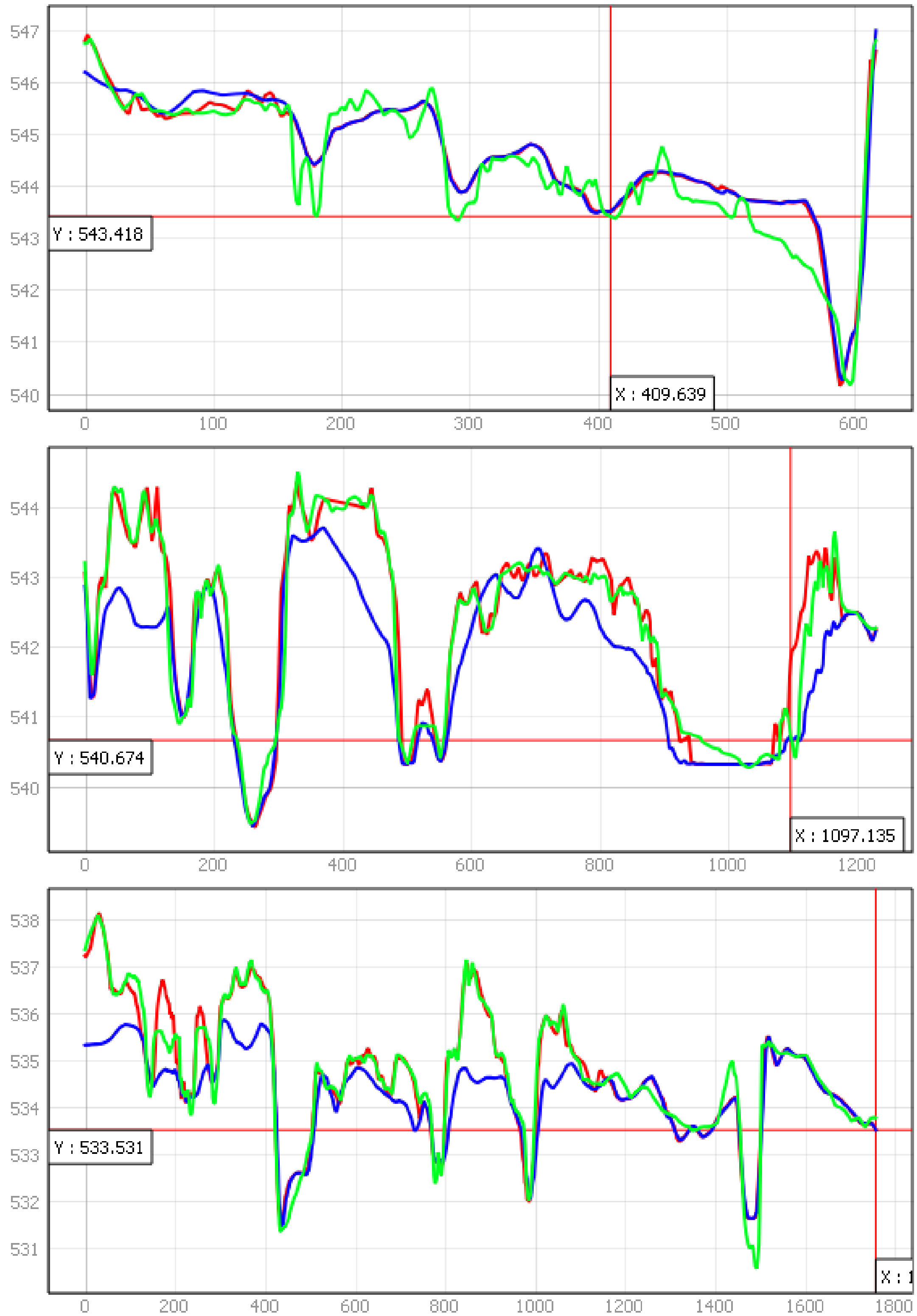

Figure A - 3: Elevation profile comparison, in m, for bathymetric data sets. 2008 (Red), 2013 (Blue), 2020 (green). Along Side Channel 1.1R (Top), across 2.7L (Middle), and across 7.1R (Bottom). X axis represents the cross-section, in m.

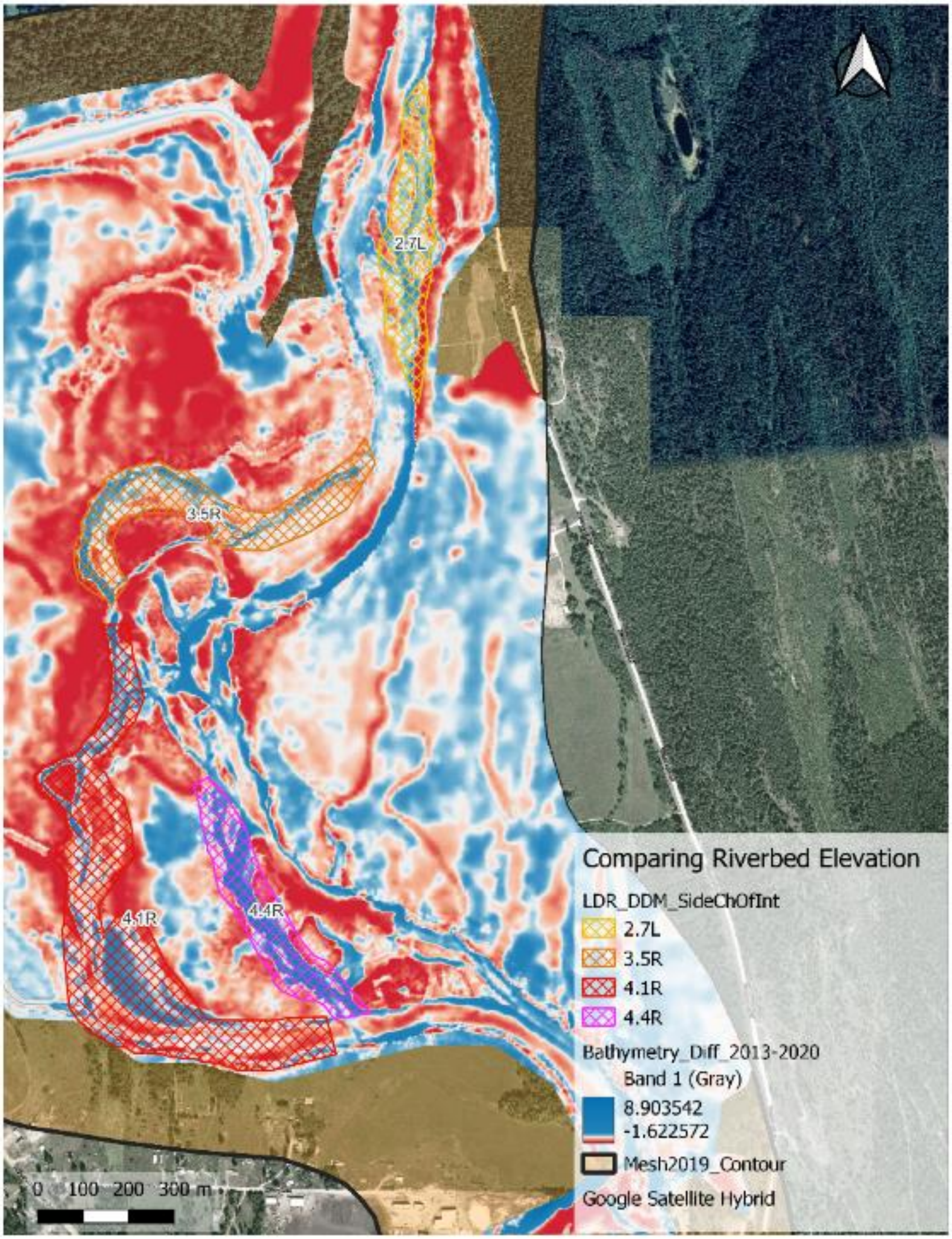

Figure A - 4: Detail of bathymetric differences (m) between 2013 and 2020 riverbeds. Blue indicates a positive difference, meaning the elevation at that coordinate was higher in 2013. Red indicates the coordinate's elevation was higher in 2020. Most of the river mainstem is blue, meaning the 2020 bathymetric data represents, in general, a deeper mainstem in this section.

Appendix 6. WUA Results Kokanee Spawning

Spatial results are provided as digital files

Table A2. Predicted habitat for Kokanee spawning (Relative WUA averaged over simulated DAM discharge levels).

Discharge Scenario	Dam Discharge (m³/s)	Total discharge (m³/s)	Wetted Area (m²)	Total WUA (m²)	WUA Relative (%)	Side Channels WUA (m²)
LARDEAU: 20.0						
M2019_SC1	0	28	2,742,242	18,098.07	0.66	3,648.22
M2019_SC2	25	53	2,934,404	27,505.30	0.94	5,278.00
M2019_SC3	50	78	3,055,138	30,900.30	1.01	5,594.29
M2019_SC4	75	103	3,193,018	34,683.06	1.09	6,922.87
M2019_SC5	100	128	3,312,284	35,756.68	1.08	8,564.85
M2019_SC6	125	153	3,421,517	32,830.73	0.96	7,017.75
M2019_SC7	150	178	3,537,619	34,096.23	0.96	8,185.35
M2019_SC8	175	203	3,673,771	34,582.23	0.94	8,643.08
M2019_SC9	200	228	3,822,944	33,962.29	0.89	7,755.95
M2019_SC10	225	253	4,104,181	32,469.44	0.79	7,775.71
M2019_SC11	250	278	4,364,400	31,872.81	0.73	8,299.71
M2019_SC12	275	303	4,730,619	31,424.02	0.66	7,678.68
M2019_SC13	300	328	5,098,706	28,832.80	0.57	5,205.97
M2019_SC14	325	353	5,446,927	26,424.22	0.49	3,768.90
M2019_SC15	350	378	5,929,427	23,292.31	0.39	2,435.10
M2019_SC16	375	403	6,396,894	21,765.39	0.34	1,831.17
LARDEAU: 75.0						
M2019_SC17	0	83	3,083,430	29,163.13	0.95	5,909.87
M2019_SC18	25	108	3,221,978	36,292.05	1.13	8,309.68
M2019_SC19	50	133	3,328,198	35,351.68	1.06	8,253.52
M2019_SC20	75	158	3,441,332	32,775.42	0.95	7,208.56
M2019_SC21	100	183	3,561,774	33,372.84	0.94	8,305.58
M2019_SC22	125	208	3,699,710	34,005.60	0.92	8,543.15
M2019_SC23	150	233	3,846,615	33,218.91	0.86	7,631.09
M2019_SC24	175	258	4,122,443	32,706.88	0.79	7,608.09
M2019_SC25	200	283	4,376,781	32,985.42	0.75	8,747.37
M2019_SC26	225	308	4,730,559	31,773.38	0.67	7,181.78
M2019_SC27	250	333	5,096,878	28,238.32	0.55	4,967.67
M2019_SC28	275	358	5,497,433	24,875.98	0.45	3,360.74

Discharge Scenario	Dam Discharge (m^3/s)	Total discharge (m^3/s)	Wetted Area (m^2)	Total WUA (m^2)	WUA Relative (%)	Side Channels WUA (m^2)
M2019_SC29	300	383	5,990,379	23,255.51	0.39	2,548.87
M2019_SC30	325	408	6,355,301	21,193.77	0.33	1,766.13
M2019_SC31	350	433	6,411,776	17,655.73	0.28	1,127.27
M2019_SC32	375	458	6,437,107	13,983.82	0.22	797.74
LARDEAU: 165.0						
M2019_SC33	0	173	3,513,552	32,581.89	0.93	8,047.68
M2019_SC34	25	198	3,639,399	32,431.95	0.89	8,418.97
M2019_SC35	50	223	3,774,671	32,241.33	0.85	8,564.08
M2019_SC36	75	248	4,020,015	31,578.74	0.79	7,626.00
M2019_SC37	100	273	4,258,639	31,117.21	0.73	8,091.91
M2019_SC38	125	298	4,559,043	31,902.05	0.70	7,919.86
M2019_SC39	150	323	4,896,270	29,760.77	0.61	5,729.96
M2019_SC40	175	348	5,222,629	26,183.05	0.50	3,981.69
M2019_SC41	200	373	5,649,195	23,682.55	0.42	2,671.22
M2019_SC42	225	398	6,168,463	21,569.54	0.35	1,826.66
M2019_SC43	250	423	6,300,079	18,713.87	0.30	1,434.64
M2019_SC44	275	448	6,356,882	15,043.71	0.24	918.15
M2019_SC45	300	473	6,390,321	12,354.97	0.19	577.77
M2019_SC46	325	498	6,404,679	9,515.95	0.15	387.40
M2019_SC47	350	523	6,438,091	7,752.40	0.12	278.84
M2019_SC48	375	548	6,447,080	5,667.30	0.09	175.87

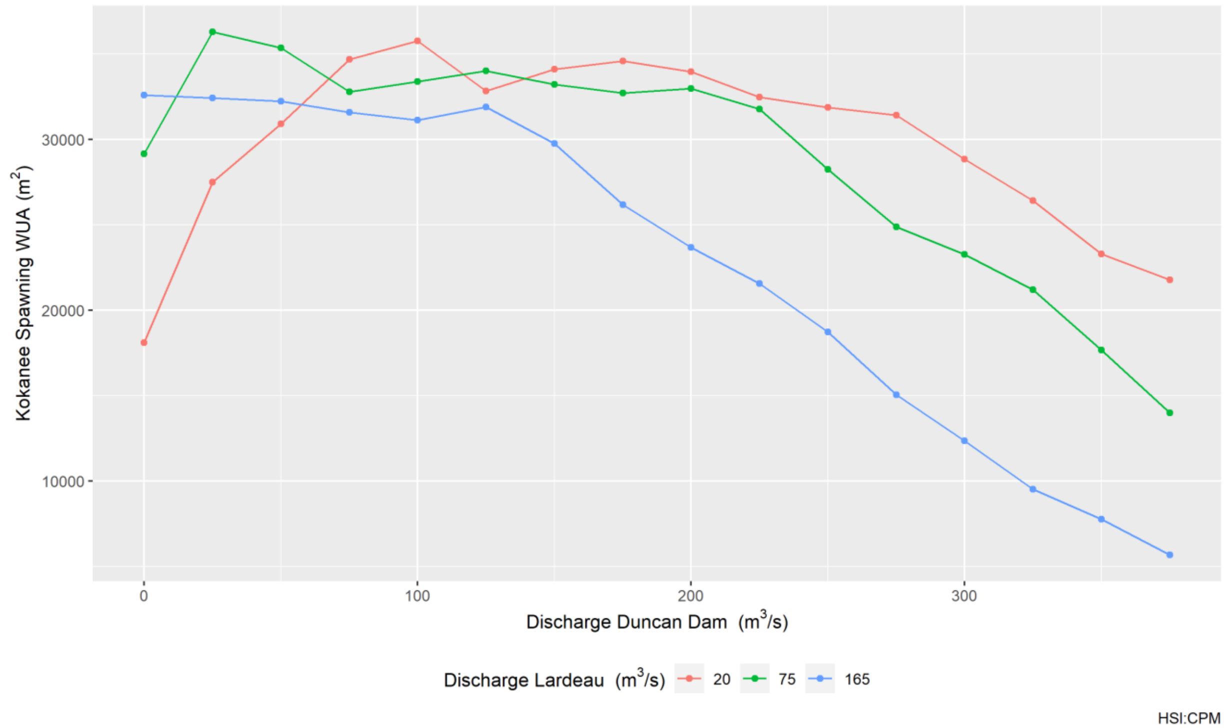

Figure A - 5: Kokanee spawning WUA estimated by the 2020 T2D Model.

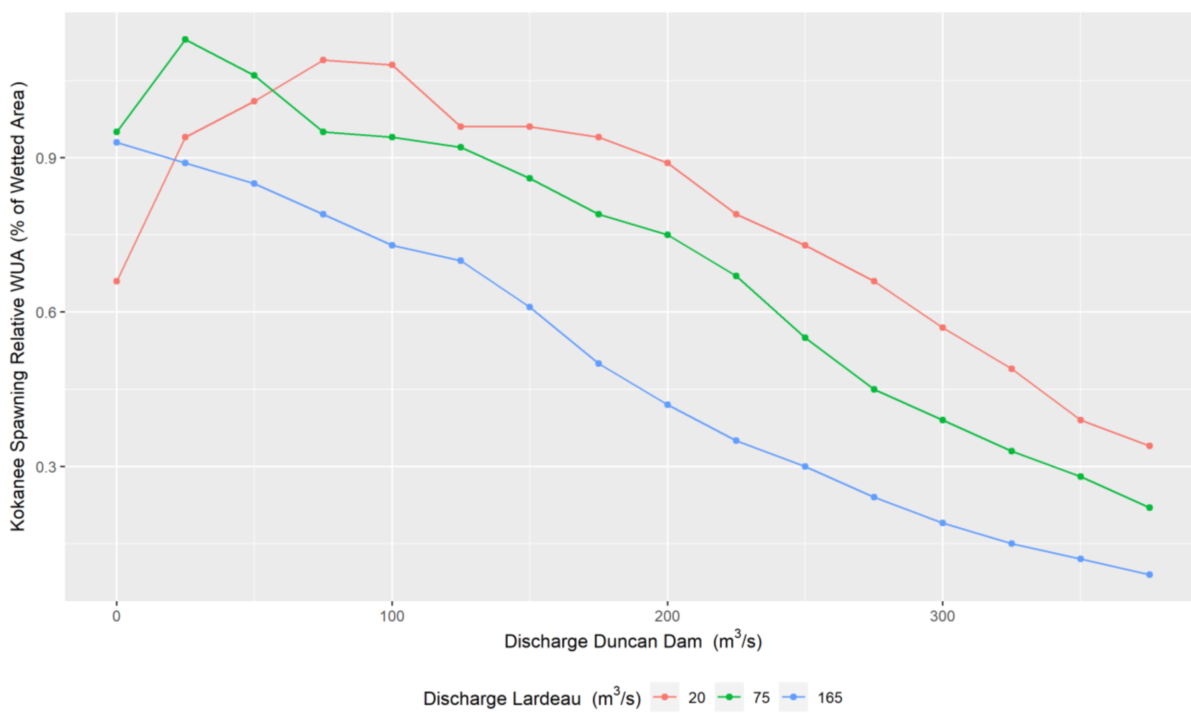

Figure A - 6: Kokanee spawning relative WUA estimated by the 2020 T2D model.

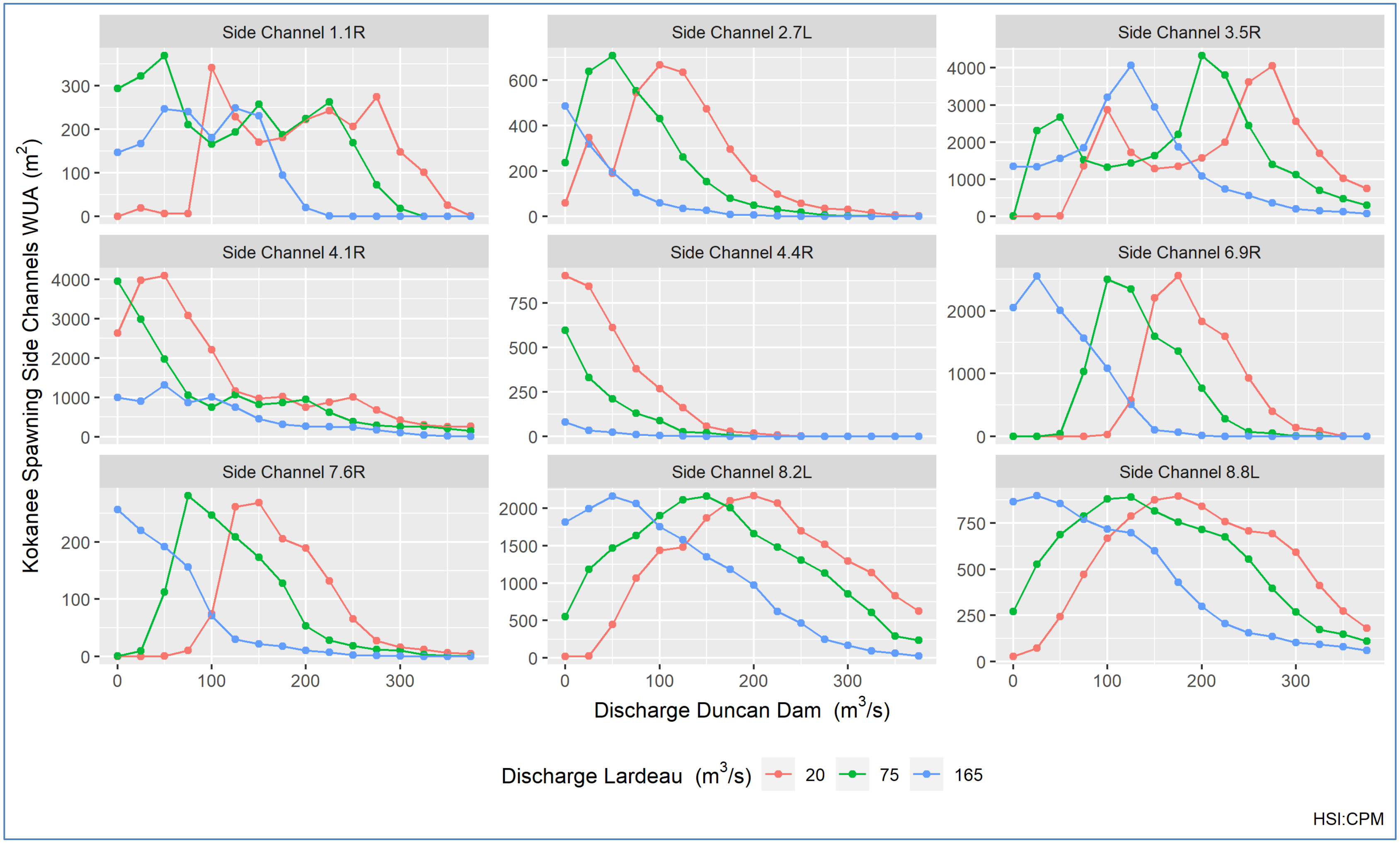

Figure A - 7: Kokanee spawning WUA by side channel estimated by the 2020 T2D Model (notice different y axis scale)

Appendix 7. WUA Results Rainbow Trout Fry

Spatial results are provided as digital files.

Table A3. Predicted habitat for Rainbow Trout fry (Relative as a percentage of wetted area). Side Channel WUA is total area of side channels.

Discharge Scenario	Dam Discharge (m^3/s)	Total discharge (m^3/s)	Wetted Area (m^2)	Total WUA (m^2)	WUA Relative (%)	Side Channels WUA (m^2)
LARDEAU: 20						
M2019_SC1	0	28	2,742,242	84,513.90	3.08	7,792.07
M2019_SC2	25	53	2,934,404	66,819.13	2.28	4,294.98
M2019_SC3	50	78	3,055,138	61,984.45	2.03	2,599.91
M2019_SC4	75	103	3,193,018	53,299.47	1.67	1,822.58
M2019_SC5	100	128	3,312,284	48,254.81	1.46	1,402.22
M2019_SC6	125	153	3,421,517	46,318.85	1.35	1,061.52
M2019_SC7	150	178	3,537,619	42,304.40	1.20	842.02
M2019_SC8	175	203	3,673,771	39,454.10	1.07	644.11
M2019_SC9	200	228	3,822,944	34,176.26	0.89	7,492.20
M2019_SC10	225	253	4,104,181	33,048.17	0.81	6,270.77
M2019_SC11	250	278	4,364,400	27,324.35	0.63	4,862.11
M2019_SC12	275	303	4,730,619	22,444.58	0.47	9,331.92
M2019_SC13	300	328	5,098,706	19,425.74	0.38	5,721.37
M2019_SC14	325	353	5,446,927	17,506.73	0.32	5,106.12
M2019_SC15	350	378	5,929,427	15,354.38	0.26	4,392.94
M2019_SC16	375	403	6,396,894	14,047.03	0.22	4,731.43
LARDEAU: 75						
M2019_SC17	0	83	3,083,430	69,062.73	2.24	3,713.79
M2019_SC18	25	108	3,221,978	54,614.33	1.70	2,324.43
M2019_SC19	50	133	3,328,198	49,370.66	1.48	1,678.08
M2019_SC20	75	158	3,441,332	45,405.92	1.32	1,296.87
M2019_SC21	100	183	3,561,774	43,215.23	1.21	971.63
M2019_SC22	125	208	3,699,710	38,430.71	1.04	785.58
M2019_SC23	150	233	3,846,615	34,549.96	0.90	7,867.92
M2019_SC24	175	258	4,122,443	31,313.23	0.76	591.68
M2019_SC25	200	283	4,376,781	24,878.14	0.57	399.93
M2019_SC26	225	308	4,730,559	21,229.21	0.45	272.50
M2019_SC27	250	333	5,096,878	19,058.88	0.37	5,211.92

Discharge Scenario	Dam Discharge (m^3/s)	Total discharge (m^3/s)	Wetted Area (m^2)	Total WUA (m^2)	WUA Relative (%)	Side Channels WUA (m^2)
M2019_SC28	275	358	5,497,433	16,982.71	0.31	4,724.10
M2019_SC29	300	383	5,990,379	15,599.28	0.26	4,189.81
M2019_SC30	325	408	6,355,301	13,837.99	0.22	4,673.29
M2019_SC31	350	433	6,411,776	11,715.22	0.18	2,875.28
M2019_SC32	375	458	6,437,107	9,661.44	0.15	1,880.32
LARDEAU: 165.0						
M2019_SC33	0	173	3,513,552	48,902.30	1.39	1,431.90
M2019_SC34	25	198	3,639,399	43,177.98	1.19	7,425.25
M2019_SC35	50	223	3,774,671	38,023.30	1.01	1,129.87
M2019_SC36	75	248	4,020,015	34,324.90	0.85	862.04
M2019_SC37	100	273	4,258,639	29,711.95	0.70	657.66
M2019_SC38	125	298	4,559,043	23,447.43	0.51	456.84
M2019_SC39	150	323	4,896,270	19,976.61	0.41	305.07
M2019_SC40	175	348	5,222,629	18,001.22	0.34	199.59
M2019_SC41	200	373	5,649,195	15,640.00	0.28	147.43
M2019_SC42	225	398	6,168,463	14,614.18	0.24	102.10
M2019_SC43	250	423	6,300,079	12,305.68	0.20	72.11
M2019_SC44	275	448	6,356,882	10,278.65	0.16	4,968.12
M2019_SC45	300	473	6,390,321	8,923.87	0.14	6,031.00
M2019_SC46	325	498	6,404,679	7,865.02	0.12	5,164.61
M2019_SC47	350	523	6,438,091	6,890.72	0.11	4,577.90
M2019_SC48	375	548	6,447,080	6,398.68	0.10	4,363.74

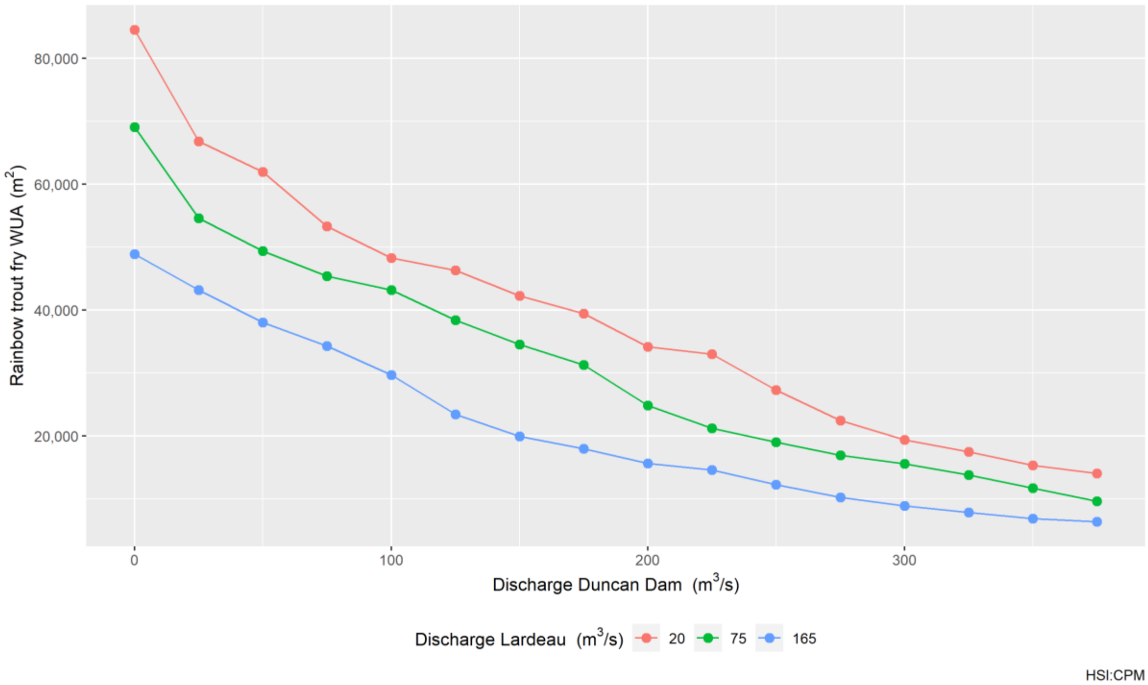

Figure A - 8: Rainbow Trout fry WUA for the combination of discharges defined in the simulation scenarios.

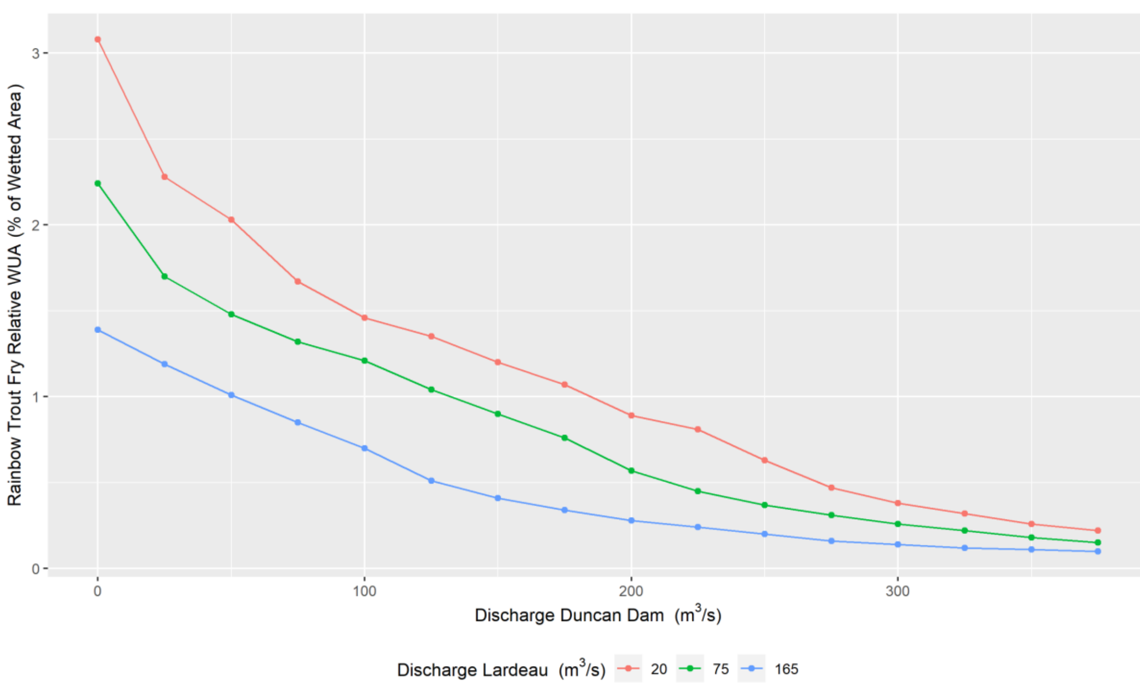

Figure A - 9: Rainbow Trout fry relative WUA estimated by the 2020 T2D Model.

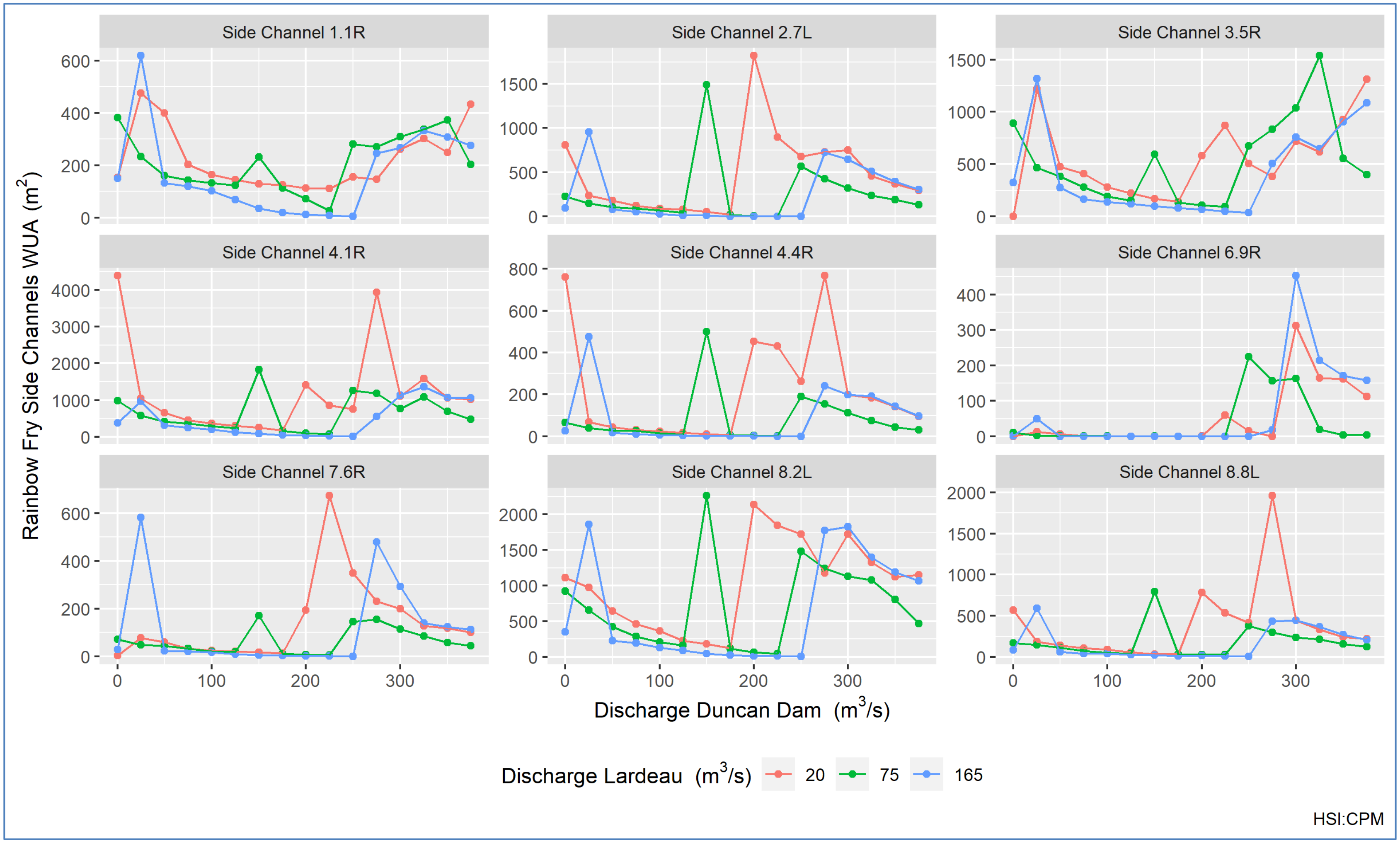

Figure A - 10: Rainbow Trout fry WUA by side channel as estimated by the 2020 T2D Model (notice different y axis scale).

Appendix 8. WUA Results Rainbow Trout Parr

Spatial results are provided as digital files.

Table A4. Predicted habitat for Rainbow Trout parr. WUA relative to wetted area. Side Channel WUA is total area of side channels.

Discharge Scenario	Dam Discharge (m^3/s)	Total discharge (m^3/s)	Wetted Area (m^2)	Total WUA (m^2)	WUA Relative (%)	Side Channels WUA (m^2)
LARDEAU: 20						
M2019_SC1	0	28	2,742,242	66,781.82	2.44	6,623.68
M2019_SC2	25	53	2,934,404	48,373.50	1.65	2,439.90
M2019_SC3	50	78	3,055,138	42,334.51	1.39	2,263.98
M2019_SC4	75	103	3,193,018	35,467.27	1.11	2,029.87
M2019_SC5	100	128	3,312,284	34,175.87	1.03	1,723.45
M2019_SC6	125	153	3,421,517	31,483.56	0.92	1,471.03
M2019_SC7	150	178	3,537,619	29,155.43	0.82	1,210.43
M2019_SC8	175	203	3,673,771	28,108.16	0.77	1,102.48
M2019_SC9	200	228	3,822,944	25,555.14	0.67	4,992.17
M2019_SC10	225	253	4,104,181	24,993.33	0.61	4,190.24
M2019_SC11	250	278	4,364,400	23,078.66	0.53	3,039.01
M2019_SC12	275	303	4,730,619	20,885.93	0.44	7,161.06
M2019_SC13	300	328	5,098,706	19,070.92	0.37	2,788.53
M2019_SC14	325	353	5,446,927	17,819.94	0.33	2,372.74
M2019_SC15	350	378	5,929,427	16,842.69	0.28	2,433.97
M2019_SC16	375	403	6,396,894	15,732.94	0.25	2,481.86
LARDEAU: 75						
M2019_SC17	0	83	3,083,430	47,223.26	1.53	2,414.49
M2019_SC18	25	108	3,221,978	38,224.96	1.19	2,151.71
M2019_SC19	50	133	3,328,198	34,151.90	1.03	1,859.56
M2019_SC20	75	158	3,441,332	29,490.04	0.86	1,623.77
M2019_SC21	100	183	3,561,774	29,446.02	0.83	1,343.52
M2019_SC22	125	208	3,699,710	27,470.65	0.74	1,129.84
M2019_SC23	150	233	3,846,615	25,124.75	0.65	5,595.33
M2019_SC24	175	258	4,122,443	23,249.29	0.56	995.17
M2019_SC25	200	283	4,376,781	21,953.12	0.50	841.35
M2019_SC26	225	308	4,730,559	19,948.30	0.42	681.26
M2019_SC27	250	333	5,096,878	18,692.33	0.37	2,556.25

Discharge Scenario	Dam Discharge (m^3/s)	Total discharge (m^3/s)	Wetted Area (m^2)	Total WUA (m^2)	WUA Relative (%)	Side Channels WUA (m^2)
M2019_SC28	275	358	5,497,433	17,443.05	0.32	2,488.60
M2019_SC29	300	383	5,990,379	16,693.65	0.28	2,328.77
M2019_SC30	325	408	6,355,301	15,432.37	0.24	2,546.57
M2019_SC31	350	433	6,411,776	14,018.25	0.22	2,235.11
M2019_SC32	375	458	6,437,107	12,634.76	0.20	2,004.27
LARDEAU: 165.0						
M2019_SC33	0	173	3,513,552	39,715.39	1.13	1,674.68
M2019_SC34	25	198	3,639,399	32,427.93	0.89	4,861.44
M2019_SC35	50	223	3,774,671	29,371.74	0.78	1,485.93
M2019_SC36	75	248	4,020,015	26,237.95	0.65	1,202.52
M2019_SC37	100	273	4,258,639	24,637.12	0.58	1,005.08
M2019_SC38	125	298	4,559,043	21,789.53	0.48	882.92
M2019_SC39	150	323	4,896,270	19,545.17	0.40	719.86
M2019_SC40	175	348	5,222,629	17,992.11	0.34	603.14
M2019_SC41	200	373	5,649,195	16,593.33	0.29	526.53
M2019_SC42	225	398	6,168,463	16,032.39	0.26	469.11
M2019_SC43	250	423	6,300,079	14,108.61	0.22	402.75
M2019_SC44	275	448	6,356,882	13,065.04	0.21	3,161.71
M2019_SC45	300	473	6,390,321	12,244.26	0.19	2,914.89
M2019_SC46	325	498	6,404,679	11,547.14	0.18	2,518.01
M2019_SC47	350	523	6,438,091	10,435.62	0.16	2,486.78
M2019_SC48	375	548	6,447,080	9,780.23	0.15	2,352.26

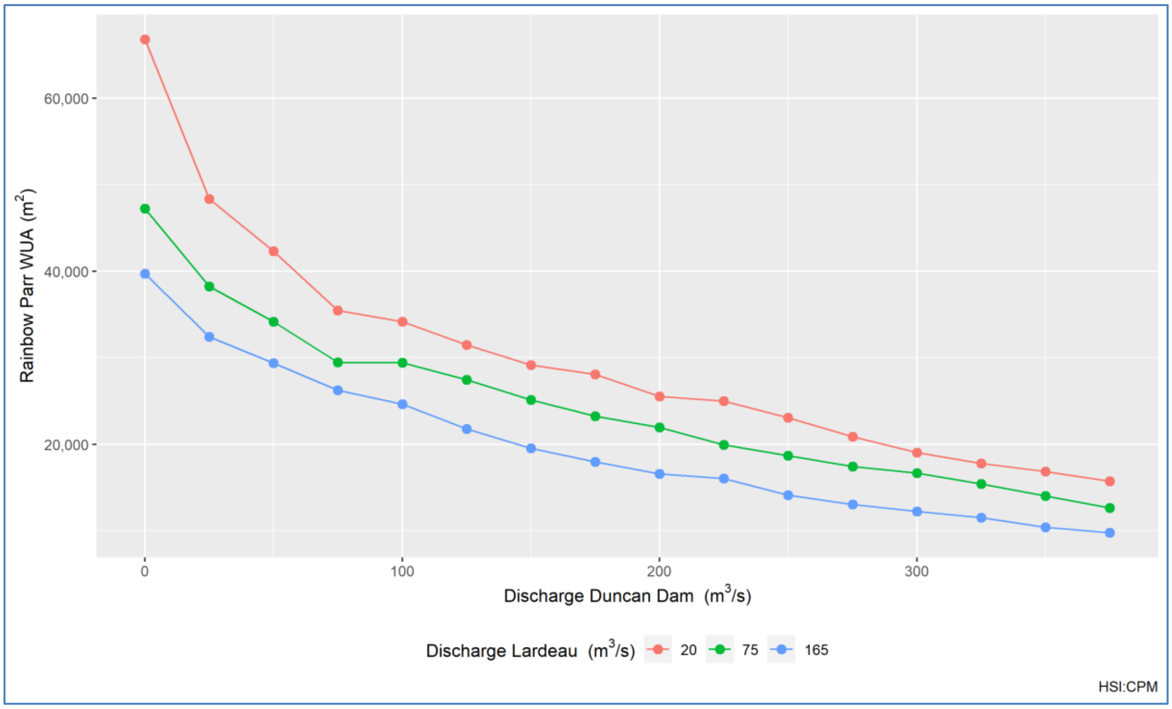

Figure A - 11: Rainbow Trout parr WUA for the combination of discharges defined in the simulation scenarios.

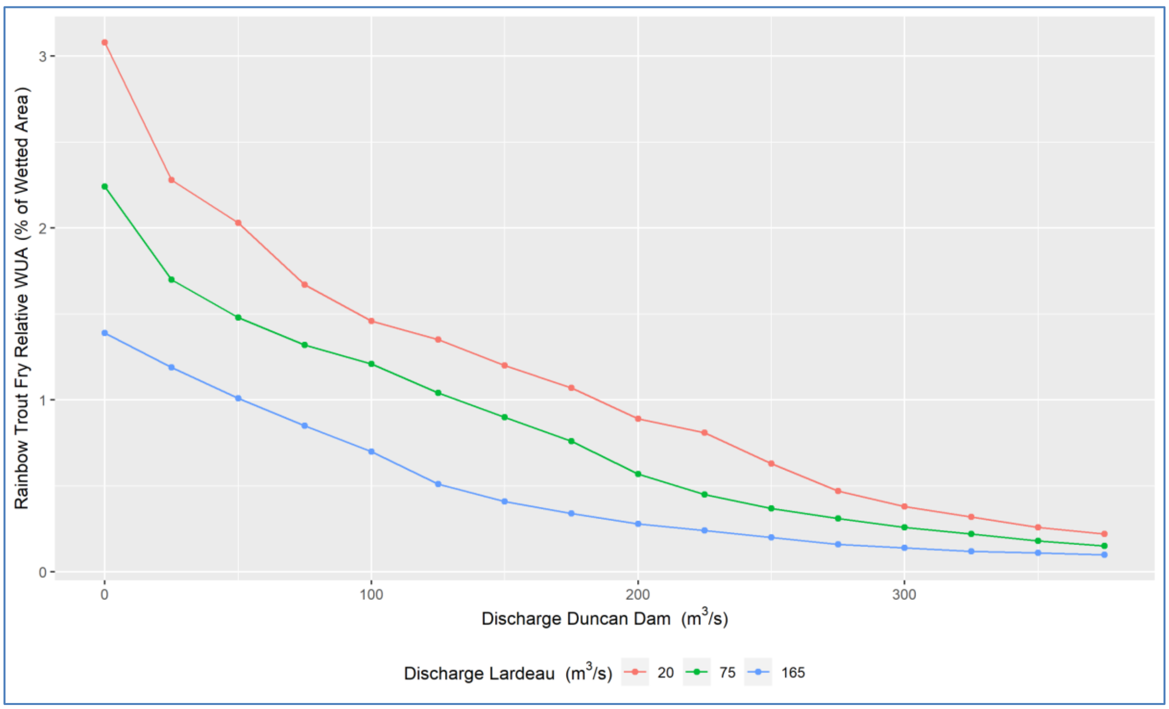

Figure A - 12: Rainbow Trout parr relative WUA as estimated by the 2020 T2D Model.

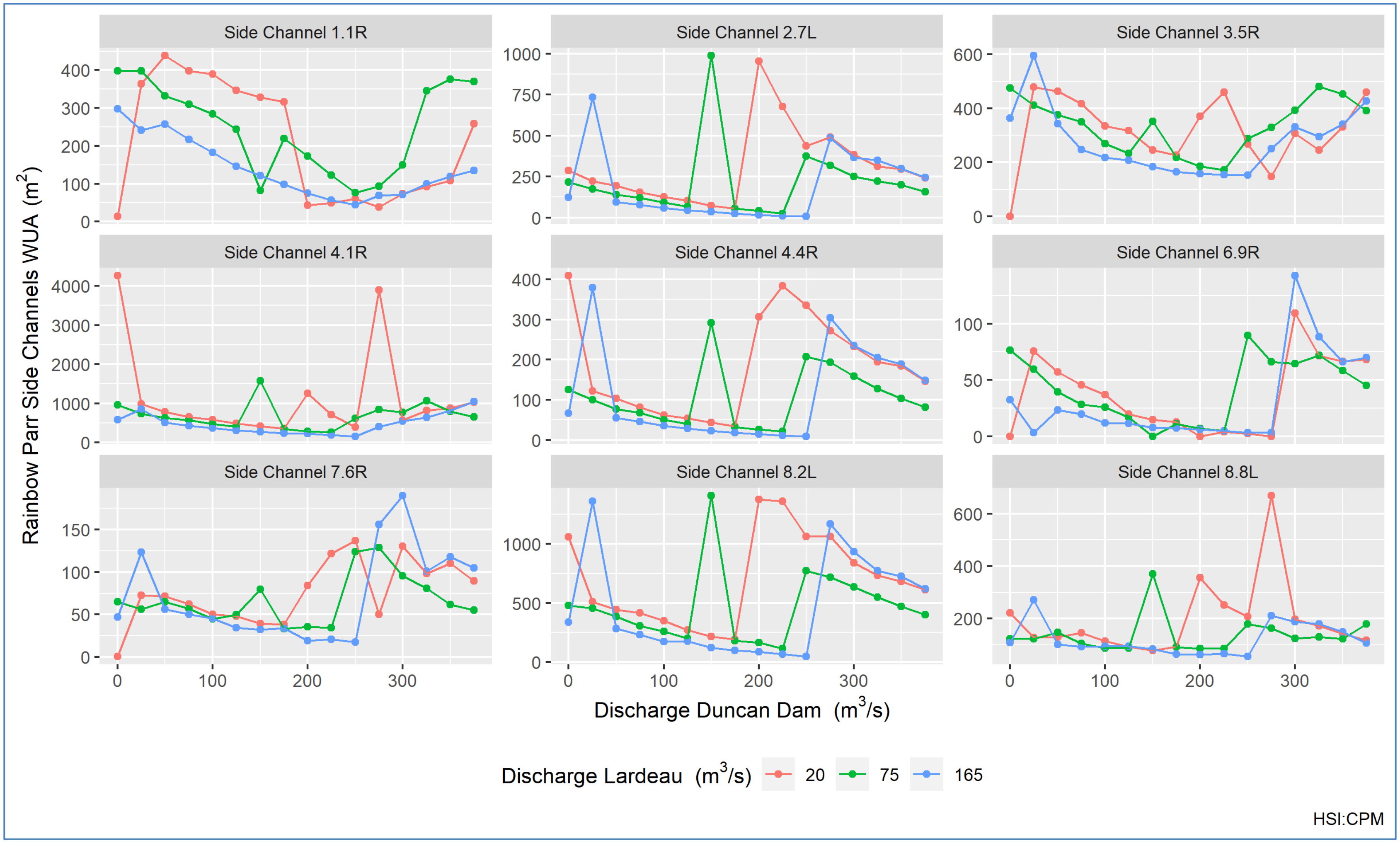

Figure A - 13: Rainbow Trout parr WUA by side channel as estimated by the 2020 T2D Model (notice different y axis scale).

Appendix 9. WUA Results Mountain Whitefish Spawning

Spatial results are provided as digital files.

Table A5. Predicted habitat for Mountain Whitefish spawning. WUA relative to wetted area. Side Channel WUA is total area of side channels.

Discharge Scenario	Dam Discharge (m^3/s)	Total discharge (m^3/s)	Wetted Area (m^2)	Total WUA (m^2)	WUA Relative (%)	Side Channels WUA (m^2)
LARDEAU: 20						
M2019_SC1	0	28	2,742,242	82,915.02	3.02	6,169.52
M2019_SC2	25	53	2,934,404	104,334.83	3.56	28,655.99
M2019_SC3	50	78	3,055,138	116,232.71	3.80	29,062.17
M2019_SC4	75	103	3,193,018	133,371.81	4.18	28,391.78
M2019_SC5	100	128	3,312,284	139,090.27	4.20	27,803.12
M2019_SC6	125	153	3,421,517	140,592.86	4.11	26,596.71
M2019_SC7	150	178	3,537,619	136,425.06	3.86	25,497.85
M2019_SC8	175	203	3,673,771	133,226.51	3.63	23,006.31
M2019_SC9	200	228	3,822,944	130,781.14	3.42	15,462.60
M2019_SC10	225	253	4,104,181	128,766.94	3.14	23,388.70
M2019_SC11	250	278	4,364,400	129,514.87	2.97	28,356.51
M2019_SC12	275	303	4,730,619	125,878.24	2.66	6,667.29
M2019_SC13	300	328	5,098,706	121,065.19	2.37	29,892.93
M2019_SC14	325	353	5,446,927	118,227.18	2.17	30,707.90
M2019_SC15	350	378	5,929,427	115,798.21	1.95	29,284.74
M2019_SC16	375	403	6,396,894	108,519.34	1.70	29,126.12
LARDEAU: 75						
M2019_SC17	0	83	3,083,430	111,808.78	3.63	29,100.07
M2019_SC18	25	108	3,221,978	128,588.76	3.99	28,901.56
M2019_SC19	50	133	3,328,198	140,974.58	4.24	28,946.13
M2019_SC20	75	158	3,441,332	144,734.18	4.21	27,976.43
M2019_SC21	100	183	3,561,774	139,740.80	3.92	26,916.20
M2019_SC22	125	208	3,699,710	134,318.41	3.63	25,653.22
M2019_SC23	150	233	3,846,615	132,786.21	3.45	12,989.93
M2019_SC24	175	258	4,122,443	131,483.42	3.19	22,615.84
M2019_SC25	200	283	4,376,781	130,150.72	2.97	20,521.55
M2019_SC26	225	308	4,730,559	127,284.88	2.69	18,962.70
M2019_SC27	250	333	5,096,878	123,548.91	2.42	29,280.45

Discharge Scenario	Dam Discharge (m^3/s)	Total discharge (m^3/s)	Wetted Area (m^2)	Total WUA (m^2)	WUA Relative (%)	Side Channels WUA (m^2)
M2019_SC28	275	358	5,497,433	119,836.59	2.18	29,151.70
M2019_SC29	300	383	5,990,379	116,402.46	1.94	29,209.19
M2019_SC30	325	408	6,355,301	107,449.33	1.69	28,471.02
M2019_SC31	350	433	6,411,776	101,834.18	1.59	28,922.48
M2019_SC32	375	458	6,437,107	92,747.34	1.44	28,825.69
LARDEAU: 165.0						
M2019_SC33	0	173	3,513,552	130,225.95	3.71	28,691.09
M2019_SC34	25	198	3,639,399	127,974.01	3.52	21,802.94
M2019_SC35	50	223	3,774,671	125,943.33	3.34	27,481.39
M2019_SC36	75	248	4,020,015	125,543.80	3.12	26,237.70
M2019_SC37	100	273	4,258,639	126,073.78	2.96	24,197.61
M2019_SC38	125	298	4,559,043	125,579.28	2.75	22,220.59
M2019_SC39	150	323	4,896,270	123,269.83	2.52	19,565.67
M2019_SC40	175	348	5,222,629	120,422.23	2.31	17,809.95
M2019_SC41	200	373	5,649,195	117,766.52	2.08	16,837.42
M2019_SC42	225	398	6,168,463	111,800.71	1.81	15,673.50
M2019_SC43	250	423	6,300,079	103,350.90	1.64	14,344.48
M2019_SC44	275	448	6,356,882	96,713.35	1.52	27,811.12
M2019_SC45	300	473	6,390,321	88,838.25	1.39	29,949.05
M2019_SC46	325	498	6,404,679	84,491.82	1.32	29,493.28
M2019_SC47	350	523	6,438,091	80,645.05	1.25	29,203.56
M2019_SC48	375	548	6,447,080	77,975.39	1.21	28,917.16

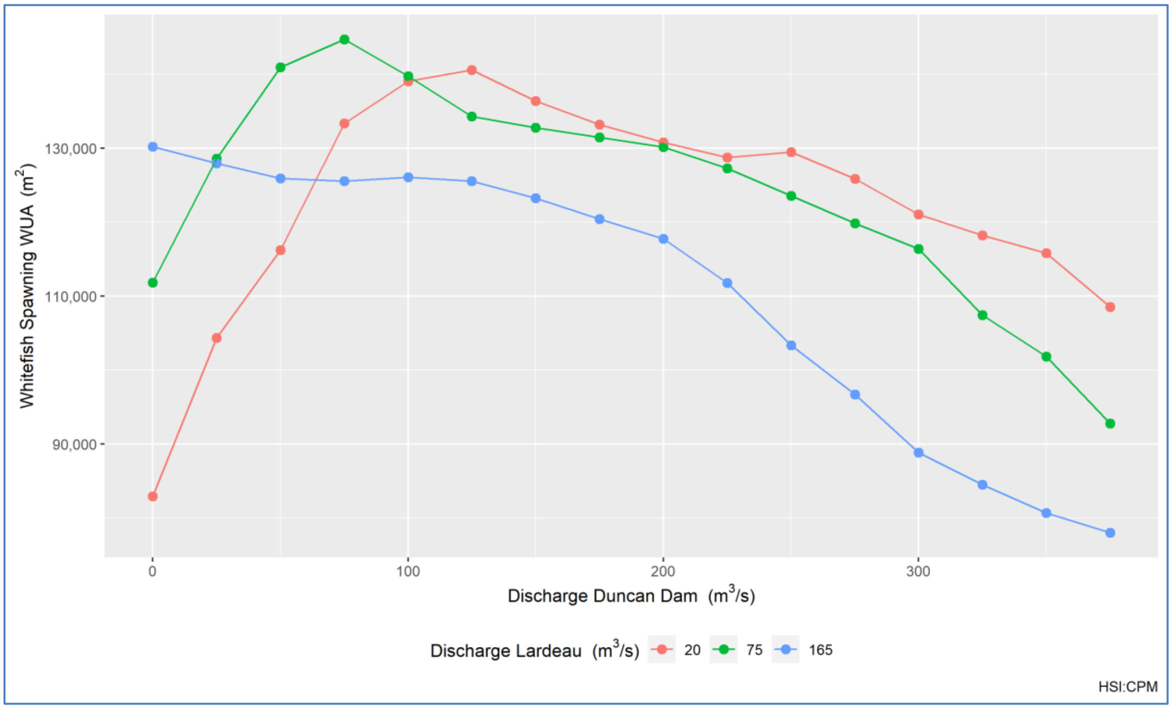

Figure A - 14: Mountain Whitefish WUA for the combination of discharges defined in the simulation scenarios.

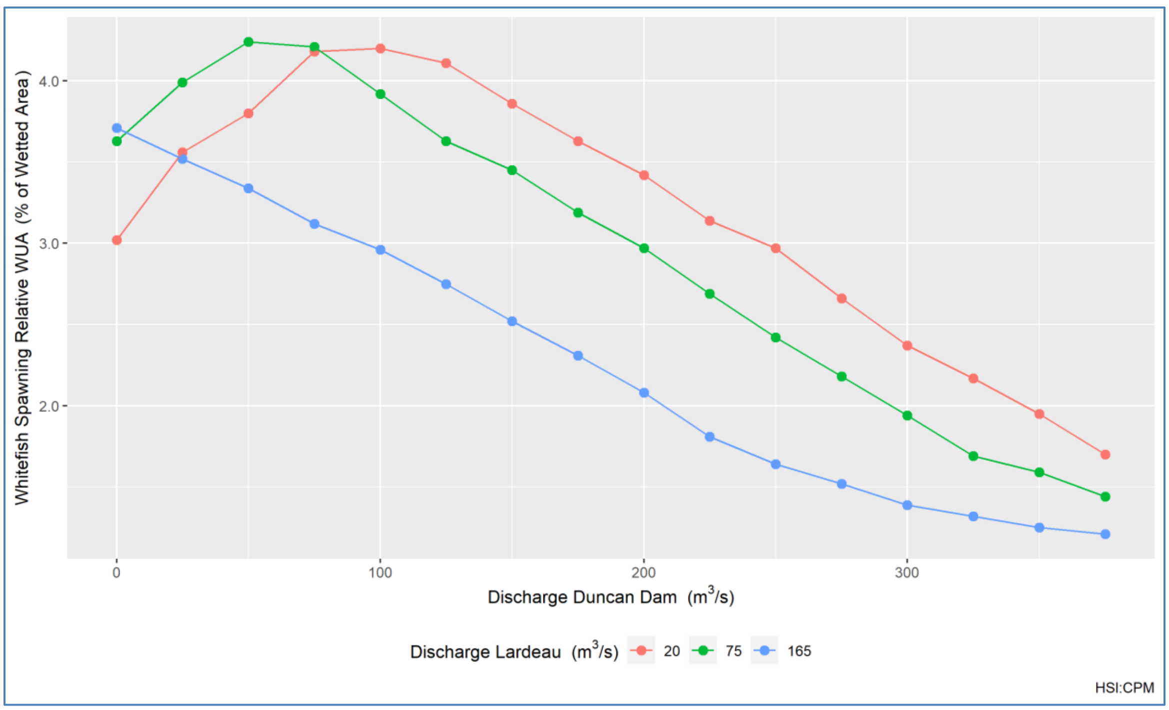

Figure A - 15: Whitefish spawning relative WUA for the range of simulated discharge levels.

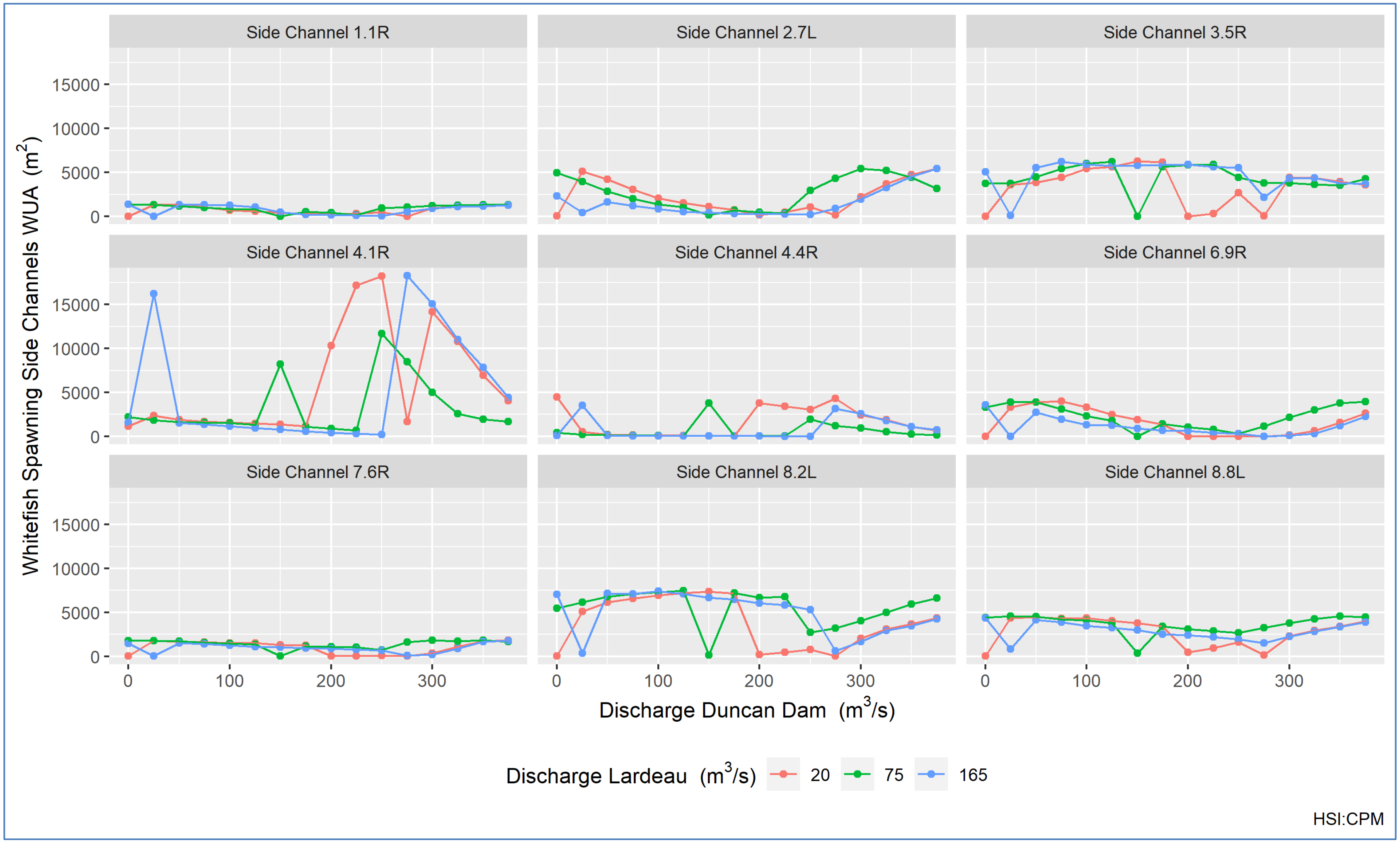

Figure A - 16: Mountain Whitefish spawning WUA by side channel as estimated by the 2020 T2D Model (notice different y axis scale).