Implications of legacy watershed disturbances for channel structure and salmon habitat availability under different low-flow levels: an analysis of 45 years of discharge-habitat relationships at Carnation Creek, B.C.

<table>
<thead>
<tr>
<th>Journal:</th>
<th>Canadian Journal of Fisheries and Aquatic Sciences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manuscript ID</td>
<td>cjfas-2020-0120.R1</td>
</tr>
<tr>
<td>Manuscript Type:</td>
<td>Article</td>
</tr>
<tr>
<td>Date Submitted by the Author:</td>
<td>02-Jul-2020</td>
</tr>
<tr>
<td>Complete List of Authors:</td>
<td>Reid, David; The University of British Columbia Department of Geography, Pike, Robin; British Columbia Ministry of Environment, Watershed Protection and Sustainability Bird, Stephen; Fluvial Systems Research Inc Tschaplinski, Peter; BC Ministry of Environment, Ecosystems Branch; BC Ministry of Environment, Ecosystems Branch Wilford, David; British Columbia Ministry of Forests Lands and Natural Resource Operations</td>
</tr>
<tr>
<td>Keyword:</td>
<td>STREAMS &lt; Environment/Habitat, FORESTRY &lt; General, SEDIMENT TRANSPORT &lt; General, FLOW ASSESSMENT &lt; General, SALMON &lt; Organisms</td>
</tr>
<tr>
<td>Is the invited manuscript for consideration in a Special Issue?:</td>
<td>Not applicable (regular submission)</td>
</tr>
</tbody>
</table>

https://mc06.manuscriptcentral.com/cjfas-pubs
Implications of legacy watershed disturbances for channel structure and salmon habitat availability under different low-flow levels: an analysis of 45 years of discharge-habitat relationships at Carnation Creek, B.C.

David A Reid*, Robin Pike², Stephen Bird³, Peter Tschapinski⁴, David Wilford⁵

*Corresponding author; david.reid@geog.ubc.ca

¹Department of Geography, University of British Columbia. 1984 West Mall Rd, Vancouver B.C. V6T 1Z2

²British Columbia Ministry of Environment and Climate Change Strategy, Watershed Protection and Sustainability. PO Box 9362 Stn. Prov. Govt. Victoria B.C. Canada, V8W 9M2

³Fluvial Systems Research Inc. 501-15216 North Bluff Rd, White Rock B.C., Canada V4B 0A7

⁴British Columbia Ministry of Environment and Climate Change Strategy, Conservation Science Section, PO Box 9338 Stn Prov. Govt. Victoria BC, Canada V8W 9M1

⁵B.C. Ministry of Forests, Lands, Natural Resource Operations and Rural Development, 3333 Tatlow Rd, Smithers, BC V0J 2N5
Abstract

In streams where water availability is limited, conservative flow ranges are often adopted by water managers to ensure that streamflow is available to meet the ecological requirements of aquatic organisms. However, a variety of natural and anthropogenic disturbances can influence stream channel morphology and in-stream wood characteristics through time, potentially altering the availability of habitat at a given flow level. Using a 2D hydrodynamic modeling approach incorporating 45 years of detailed channel morphology data from Carnation Creek, B.C., this paper examines relationships between legacy (forestry-driven) watershed disturbance, changes to channel morphology, and habitat availability for juvenile coho salmon under nine flow levels. Results indicate that substantial variability in the abundance of salmonid habitat is present through time, even when modelled flow levels are held constant. Additionally, trade-offs were observed between availability of habitat types as discharge increased. Finally, modeling results indicate that habitat availability is reduced following historic harvesting. These findings suggest that legacy watershed disturbances affecting stream channel form and function are worth considering when allocating streamflow.

Keywords:

Streams, Forestry, Sediment Transport, Flow Assessment, Salmon
Introduction

The quality and quantity of aquatic habitat supporting juvenile salmonids can be conceptualized as a product of five primary components in stream channels and in the broader surrounding landscape: hydrology, biology, geomorphology, water quality, and connectivity (Annear et al. 2004). These components interact to create temporal variability in habitat through changes in the daily, seasonal, and annual inputs of energy and resources as well as changes in the structural elements provided by the stream channel and adjacent riparian area. A common watershed management priority is to ensure that the quantity and timing of flows required for different aquatic species, their life stages, and varied life histories are maintained (Jowett 1997; Richter et al. 1997; Bradford and Heinonen 2008). However, changes in stream channel morphology and associated structural elements can influence the quantity and quality of suitable habitats available for a given flow level (Fabris et al. 2017; Reid et al. 2020). Similarly, watershed disturbances that alter stream channel form via changes in sediment regimes or riparian function can enact long-lasting disruptions to aquatic habitat conditions, regardless of water availability and timing (Chapman 1962; Murphy et al. 1986; Gregory et al. 1987; Salo and Cundy 1987; Tschaplinski et al. 2004; Tschaplinski and Pike 2010; Moore and Richardson 2012; Tschaplinski and Pike 2017).

Streamflow timing and volume can be affected through land cover changes (Moore and Wondzell 2005), variations in climate (Hodgkins 2009; Wu et al. 2012), flow diversions (Nilsson et al. 2005; Gibeau et al. 2016), and direct stream and aquifer withdrawals (Shank et al. 2015). However, the explicit effects of this variability in streamflow on salmonid habitats depend strongly on many factors including localized physical stream channel characteristics (Cederholm et al. 1997; Hafs et al. 2014), watershed-specific hydrologic storage and release mechanisms, time of year (Tschaplinski and Pike 2017), and importantly, sensitivity of the local aquatic species to flow reductions or consequent water temperature changes (Eliason et al. 2011). Commonly, streams in forested, mountain environments are in a state of adjustment to episodic and spatially discrete formative processes such as landslides and debris flows, which may be a product of both natural and anthropogenic disturbances (Nakamura and Swanson 1993; Hoffman and Gabet, 2007; Reid et al.
2019). In these environments, land surface changes can lead to variation in the abundance and characteristics of in-stream wood (Murphy and Koski 1989; Hassan et al. 2016), and channel stability, geometry, substrate texture, and morphology (Hoffman and Gabet 2007).

To ensure that adequate streamflow is available to maintain functionality of stream habitats, a variety of methods have been developed to estimate the timing and quantity of discharge required (Tharme 2003; Annear et al. 2004; Linnansaari et al. 2013), often termed instream flow needs or requirements (IFN/IFR) and also environmental flow needs (EFN). Common across many of the routine IFN methods is the adoption of a series of conservative flow levels or preferred flow ranges outside of which habitat conditions are considered sub-optimal. Importantly, most of these flow-based approaches assume that the quantity and quality of habitat produced at each flow level is constant through time, regardless of variability in channel form or other elements important for habitat. However, relatively few studies (Thompson and Lee 2000; Rice et al. 2001; Pess et al. 2002; Benda et al. 2004; and Rice 2017) have assessed the relationship between geomorphic variability and habitat availability, providing clues about how channel or watershed disturbance history might affect this interaction with streamflow and habitat availability at a given flow level.

To explore this topic, this study uses a 2D hydrodynamic modeling approach incorporating 45 years of channel bed survey data from Carnation Creek, a small salmon-bearing stream on southwestern Vancouver Island, Canada. This study builds upon two previous papers which have examined (i) long-term change in channel morphology in Carnation Creek (Reid et al. 2019), and (ii) connections between sediment supply conditions, channel morphology, and temporal habitat variability (Reid et al. 2020). The primary focus of the present work is to evaluate the implications of morphology-driven habitat change (via five, flow-based variables) in relation to nine common IFN flow levels, and to explicitly investigate the effect of legacy watershed disturbance on habitat availability at these flow levels. This study concentrates on habitat metrics relevant to juvenile coho salmon (Oncorhynchus kisutch) during summer low-flow conditions from May 1st to September 30th. These metrics include a range of habitat types ranging from low-velocity pool areas...
with wood cover important for juvenile coho rearing to high-velocity flow areas which juveniles tend to avoid (Bjornn and Reiser 1991; Beecher et al. 2002).

This paper has three broad objectives: (i) to briefly describe the Carnation Creek watershed experiment, evolution of stream channel morphology, and disturbance state over the 45-year data record; (ii) to examine the trends and implications of variability across five flow-driven aquatic habitat metrics for nine management flow levels ranging from very low (the lowest seven-day flow occurring once every 10 years – 7Q10) to higher than average (400% of Mean Annual Discharge – MAD); and, (iii) to compare and contrast pre- and post-harvest channel disturbance conditions with focus on relationships between habitat area and streamflow.

This study aims to address the following research questions:

1) Are certain IFN flow levels more sensitive to temporal variability in channel morphology than others?
2) Do higher flow levels always produce improved or increased habitat availability?
3) What are the trade-offs between habitat metrics as flow levels change?
4) Can a channel with legacy watershed disturbances provide similar habitat to an undisturbed channel?

**Study area**

This study uses data collected within the Carnation Creek Experimental Watershed. This research site was established in 1970 to investigate the influence of forest practices of the day on physical and biological watershed processes and salmon populations (Hartman and Scrivener 1990; Tschaplinski and Pike 2017). Component studies of this on-going project include examination of channel morphology, aquatic ecology, and linkages between climate, hydrology, and watershed processes (Tschaplinski and Pike 2017). The 11.2 km² basin (Figure 1) is located on the southern shore of Barkley Sound, on southwestern Vancouver Island, British Columbia. Several anadromous salmon species inhabit Carnation Creek, including chum salmon.
(Oncorhynchus keta), coho salmon, (O. kisutch), steelhead trout (O. mykiss), and sea-run cutthroat trout (O. clarkii) (Tschaplinski and Pike 2017).

The Carnation Creek watershed was glaciated during the most recent glacial maximum, and till varying in depth from 0.15 m to >2 m covers Jurassic volcanic bedrock. Catchment relief exceeds 900 m, and steep gradients greater than 40% are found throughout the watershed (Hartman and Scrivener 1990, Tschaplinski and Pike 2017). This glacial legacy has resulted in a catchment configuration with hillslope-channel coupling (Nakamura and Swanson 1993) and colluvial sediment delivery in headwater regions and in a confined section of channel referred to as the “canyon reach” (see Figure 1) (Zimmermann et al. 2004; Reid et al. 2019). Sediment delivery events have occurred sporadically over the period of record, with the largest debris flows associated with a large storm in 1984 (Hartman and Scrivener 1990; Reid et al. 2019). The lower 2.9 km of stream is generally buffered from direct hillslope processes by a floodplain that is up to 200 m wide.

The climate of the watershed is temperate and humid, and the hydrological regime rain-dominated. Annual precipitation ranges from ~2900 mm near sea level to more than 4800 mm at higher elevations. Most rainfall, occurs during autumn and winter storms, often resulting in flows above 20 m$^3$/s (Reid et al. 2019). Flows during summer months are generally low, usually below 0.1 m$^3$/s (Figure 2). The primary channel morphology is pool-riffle, with gradients typically less than 1%, and active channel width averages approximately 15 m. Numerous wood accumulations (logjams) and individual pieces can be found within the channel and are often associated with both pools and sediment accumulations. Apart from sporadic small sand patches, streambed sediment texture ranges from gravel (median size 20-40 mm) near the river mouth to cobbles and boulders (median size >128 mm) in the canyon reach and headwaters. Large bars spanning over one-half the channel width are common both upstream and downstream of the canyon reach.

The Carnation Creek watershed experiment is a pre- vs. post-harvest observational study design that focusses on both watershed- and channel-scale processes. After 5-6 years of pre-harvest baseline data collection (starting 1970/1971 depending on the variable studied), 41% of the watershed was logged over...
a 6-year period from 1976 to 1981 (Hartman and Scrivener 1990) with the post-logging phase of the experiment extending to present time (Tschaplinski and Pike 2017). Three riparian harvest treatments were included in the study. A riparian buffer varying in width from 1 to 70 m was left along the lowermost 1300 m of stream, followed by two clear-cut treatments each 900 m long. The first clear-cut segment entailed harvesting to the stream’s edge, with cross-stream falling and yarding and limited in-stream salvage of windthrown trees (termed intensive clear-cutting). The second clear cut segment involved harvesting up to the banks, but no cross-stream or in-stream activity was permitted (termed careful clearcutting). Given the complex riparian disturbance history and relatively narrow retention strips, the logging effect along the channel is treated as a binary for this study, with pre-harvest conditions up to 1976, and post-harvest thereafter.

**Methods and data**

**Hydrometric, channel morphology and wood data**

Carnation Creek datasets include detailed information on hydrologic, geomorphic, and in-stream wood. This study uses a portion (45 years, 1971-2015) of the ongoing collected data record. Channel topography surveys have been conducted annually in eight study channel areas (referred to as “SA” hereafter) since 1973, and since 1971 in four of the eight sites (Figure 1, Table 1). Seven of these (SA-2 to SA-8) are spaced 300-500 m apart along the lower 3 km of channel, overlapping with anadromous fish presence. The 8th (SA-9) is located approximately 5.6 km upstream from the river mouth and is upstream of anadromous fish activity. Individual study areas range in length from 5 to 15 bankfull channel width ($w_b$) equivalents, possess gradients of between 0.5 to 1.5 %, and vary in topographic complexity and wood abundance (Reid et al. 2020).

Topographic channel data were collected along cross-sections spaced 1-3 meters apart in each SA until 2008, when the cross-section survey approach was replaced with a feature-based total station survey.
Survey errors are low, typically in the order of 1-2 cm. No data were collected in 2010 in any study area, nor in SA-9 in 1990. Digital elevation models (DEM) of 10-cm resolution were generated from interpolated annual survey data using the R programming language (R Core Team 2019) and the “Raster” package (Hjimans 2019).

Data on wood piece positions and dimensions have also been collected in all SA’s since 1973 (since 1971 in SA-2, SA-3, SA-6 and SA-8). To incorporate wood data into the analysis of the 2D hydrodynamic model output, wood pieces were digitized from annual study area maps. However, it was not possible to locate some original wood piece maps from the mid- and late 1990s for some SAs, and no maps were available for 1999 and 2000. Where wood data are absent, maps before and after the gap were examined for similarity in wood abundance and position, and if similar, the record was filled with the last year of data prior to the gap to approximate the record. Further details of geomorphic and wood data collection can be found in Reid et al. (2019).

Hydrological data have been collected at several locations in the watershed, including from a Water Survey Canada hydrometric station (Station ID WSC-08HB048, Carnation Creek at the Mouth). Discharge data from this station was used to generate flow level statistics. Nine flow levels were calculated as input for the hydrological modeling scenarios, ranging from 7Q10 to 400% MAD or, 6 to 3310 l·s\(^{-1}\) near the river mouth (Table 2). These flow levels encompass nearly the full range of flow conditions typical of the May 1\(^{st}\) to Sept. 30\(^{th}\) period (Figure 2). As flow data were not recorded directly in most study areas, discharge at the WSC hydrometric station was scaled by contributing source area upstream of the midpoint of each study area (Table 2). This relationship was derived by fitting flows from the primary and four secondary hydrometric stations (Figure 1) against contributing area upstream of each station.

**Depth and velocity simulations**

To evaluate the availability of aquatic habitat at different flow levels through time, the Nays2DH hydrodynamic model (Nelson et al. 2016) was used to simulate two-dimensional depths and velocities in...
all study areas. While the input data for this model do not capture details of all structural channel elements relevant to salmonid habitat (e.g., overhanging and undercut banks, grain-scale features), the long temporal record of channel bed topography is valuable for assessing patterns in aquatic habitat. Approximately 2700 individual model simulations were run, incorporating nine flow levels of interest for each SA (Table 2), for each year. As with other two-dimensional hydrodynamic models, boundary conditions include a channel bed DEM and downstream water surface elevation for each flow level, and a roughness value (Manning’s n). All simulations were run through the International Rivers Interface Cooperative (IRIC, Nelson et al. 2016).

Empirical stage-discharge rating curves were generated from historical channel survey and discharge data to obtain downstream water surface elevations for each flow level in each SA. Simulation runtimes ranged between 800-1000 seconds, depending on the specific SA and flow level. Model timestep was 0.01s, the default for the program, and calculation grid with cells of 1 m² were used during simulations. A Manning’s n value of 0.04 is used for all sites and simulations; a typical value for high-roughness gravel bed streams. While Nays2DH has the option to include features such as wood pieces as flow obstacles, uncertainty surrounding wood contact with the channel bed led to the decision to exclude wood from the simulations, and to reincorporate the wood information in the analysis stage. Based on field observations of wood in the SAs, a presumption was made that, at the low modeled flows, wood pieces would have minimal effect on the flow field. Further details of hydrodynamic modelling approach and implementation with Carnation Creek data can be found in Reid et al. (2020).

**Assessment of model performance**

Given the impracticality of calibrating the large number of simulations individually, model output was instead compared with field-measured water depths and velocities. In the summer and fall of 2017, over 60 depth and velocity point measurements were taken in three study areas (SA-2, SA-3, and SA-7) using a SonTek Flow Tracker Acoustic Doppler Velocimeter (ADV) in flow conditions ranging from 12 to 1300 l/s⁻¹. Velocity measurements were taken at 0.6 depth below the water surface. Nays2DH simulations were
run using the same flows and bed surfaces as those present during the field data collection, and results compared. To best capture temporal and spatial variability, reach-averaged widths, depths, and velocities were also checked against 30 DEMs and historical flow conditions sampled from the 45-year record. Width and depths were extracted from the water surface elevations at the times of surveys, and velocities ($V$) calculated as $V = Q/w_b*D$, where $Q$ is study area discharge (scaled), $w_b$ is the bankfull channel width and $D$ is the average depth. In addition, an assessment of model output sensitivity to study area length was performed by duplicating and appending DEMs in SA3, SA-6, and SA-8 to generate double-length segments, and comparing output of simulations in these reaches to simulation results from the regular model output.

Model performance is summarized in Figure 3. Overall, the model performed well when evaluated against field depth and velocity point measurements. Mean prediction error in depth was ± 0.12 m, and velocity ± 0.23 m/s. Nays2DH tends to slightly overpredict low velocities, and underpredict higher velocities. Reach length (Figure 3f) did not have a meaningful effect on model output, with differential results in the order of 1% of channel area. While the model performed well when evaluated against field data, the authors are aware of the limitations of such an approach in small streams with rough boundaries but deem it acceptable for the purposes of exploring the study objectives.

**Model output analysis**

To evaluate temporal and disturbance-driven dynamics in modeled habitat, five flow-based habitat variables were selected: (1) total pool area ($T_p$); (2) pool area with wood cover ($P_{wc}$); (3) high-velocity wetted area ($H_v$); (4) shallow water area ($S_w$); and, (5) mean wetted width ($W_w$) (Table 3). Collectively, these variables capture a range of aquatic conditions, both optimal and sub-optimal, for juvenile coho salmon (see Bjornn and Reiser 1991).

To quantify the availability of habitat for each variable, a depth and velocity rasters of 1 m² resolution were produced from the model output for each simulation. Once generated, raster areas were selected within the
defined value range of each variable, and the area of each variable calculated. To determine the quantity of pool area overlain by wood pieces ($P_{wc}$), areas of flow rasters falling into the pool criteria were cropped by wood piece polygons, and the cropped areas subsequently quantified. The resulting dataset includes time series of each variable, at each flow level, for each study area, over the 45-year record. All analysis was completed with the R programming language using packages "Raster" (Hijmans 2019) and "RGDAL" (Bivand 2019).

In order to evaluate the effect of timber harvesting on habitat availability and to characterise the relationship between discharge and habitat abundance, a non-linear mixed-effects (NLME) modeling approach was used. Mixed-effects models account for both a lack of independence among repeated measures within groups, and for differences in variation due to group characteristics. For the Carnation Creek dataset, the data are grouped by study area; each study area contains 45 observations for each of the nine flow levels, corresponding to a series of annual observations. The “mixed effects” of such models therefore include a combination of fixed and random effects. In this analysis, the fixed effect quantifies habitat area by discharge, while two random effects account for variance attributed to study area and to the harvest state. This structure also allows the entire dataset to be analysed in a single model (per habitat variable), negating the need for multiple comparisons. Following initial analysis, the relationship between discharge and habitat was found to be strongly non-linear, and a logistic-growth function was deemed a more appropriate model. A model of this type will take the form:

$$y = \frac{a}{1 + e^{-(x-b)/c}} \quad \text{Eq. 1}$$
Where $a$ represents the model asymptote, $b$ the sigmoid midpoint, $c$ the logistic growth rate (or scale), and $x$ the independent variable. Additional details of non-linear mixed effects models can be found in Stegmann et al. (2018).

To assess the role of watershed disturbance history on habitat availability at different flow levels, input data were characterised as either pre-harvest (before 1976) or post-harvest (after 1976) time periods, regardless of the specific riparian treatment. To fit the models, the R package “lme4” was used (Bates et al. 2019), and data attributes assigned into fixed (discharge) and random (study area, harvest state) effects. The significance of harvesting on habitat availability was assessed using a likelihood ratio test between a model fit with “harvest state” as a predictor, and a model where “harvest state” was omitted.

Results

Temporal trends and variability of modeled habitat

Overall, channel morphology and in-stream wood at Carnation creek varied through time for all study areas (Figure 4). Normalized bed elevation averaged over all study areas (Figure 4a) increased by approximately 0.2 m between 1978 and the late 1980s, remaining elevated until the late 1990, and then degraded to pre-harvest levels by 2002. Departures in sediment storage (Figure 4b), the combination of change in elevation and width, shows no trend until 1978, when an increase occurred, peaking in 1989. There was a decline in storage from 1997 to 2001, followed by small-scale fluctuation. Channel width (Figure 4c) generally increased to a maximum positive departure of 2.5 m in 1997, followed by a rapid narrowing to 2000, and another reduction near 2005. Finally, departures in wood storage (Figure 4d) show a general increase until 1985, a decline to 1998, and relatively stable values until 2011.

The variation in channel morphology and in-stream wood translates to differences in habitat availability during the study period (Figure 5a to Figure 5d). Total pool area ($T_p$) declined gradually for all flow levels $\geq$5% MAD. From 40-400% MAD, $T_p$ displayed a distinct (decadal) oscillating downward trend. At 400%
MAD, up to 47% of the active channel area can be occupied by pool habitat, while only 2-3% of the study area is occupied at the 7Q10 flow level.

Pool area with wood cover (Pwc) showed a complex temporal pattern (Figure 5b) with two rapid declines. At most flow levels, similar patterns to Tp were detected, with an increase in Pwc through the late 1970s, followed by a period of fluctuating values to the late 1980s, then a rapid decline. Post-1990, Pwc remained relatively constant but declined rapidly (for the highest flow levels) again after 2005 with a slight increase post 2012. Trends at flows less than 10% MAD were relatively subtle, while flow levels from 40% to 400% MAD produced similar Pwc availability. Overall, less than 7% of the active channel area is typically occupied by Pwc at the highest flows.

High-velocity (Hv) wetted areas (i.e., > 0.6 m/s, Figure 5c) displayed a different temporal pattern to the pool-related variables (Tp and Pwc). Below 40% MAD, minimal Hv was present, but occupied up to 43% of channel area at 400% MAD. At 400% MAD, availability of Hv increases to the early 1980s, declined rapidly, then remained similar until the mid-2000s, after which it increased above pre-harvest levels. At 100% MAD, Hv displayed minor fluctuations with no discernable trend through time. From 2000 to 2015, opposite trends are apparent between Tp (Figure 5a) and Hv (Figure 5c) at 400% MAD.

Shallow-water (Sw) habitat area (Figure 5d) displayed the most variable and complex interannual temporal patterns. Flow levels below 20% MAD displayed an oscillating pattern that spiked in the mid- to late-2000s. Flow levels ≥ 40% MAD displayed different long-term patterns, with Sw declining through time at 400% MAD, but increasing slightly after 2000 for 100% MAD. Modeled Sw ranged between 5% and 20% of the active channel area, depending on flow level.

Mean wetted width (Ww) (Figure 5e) displayed the lowest degree of temporal variability. Maximum Ww occurred at the highest flow levels (i.e., 400% MAD). From 40-400% MAD, a minor increase in width occurred to 1980, after which a consistent decline is observed. Flows at 20% and 10% MAD displayed a similar pattern, with minor declines until the late 1990s and then an increase to the mid-2000s. Results for
flows < 5% MAD display little evidence of a long-term trend. At 400% MAD, width averaged up to 15 m. At 7Q10, $W_w$ averages were close to 2 m.

**Relationships between flow level and habitat availability**

Relationships between habitat availability and flow level across the full dataset are shown in Figure 6, with study-area relationships shown in supplementary Figures S1 to S5. Overall, the logistic growth models fit the data well, but the shape of the models differ between variables. For $T_p$, (Figure 6a) values steadily increase from low flows and reach an asymptote (i.e., average maximum habitat provided across study areas) of 372 m$^2$ near 400 ls$^{-1}$ (50% MAD) near the river mouth. The most rapid increase in habitat with added flow is between 60 and 120 ls$^{-1}$, approximately 7% and 15% MAD near the river mouth.

The model fit for $P_{wc}$ (Figure 6b) illustrates a similar steady increase from low flows from a site-average minimum near 15 m$^2$, but reaches the asymptote sooner, close to 190 ls$^{-1}$ with a value of 52 m$^2$. This corresponds to a maximum occurring between 20% and 40% MAD, depending on position along the channel. The most rapid increase in $P_{wc}$ with added flow is between 20 and 70 ls$^{-1}$ or approximately 3% to just below 10% MAD.

The model for $H_v$ (Figure 6c) displays a distinct shape from the pool-based variables. Very little $H_v$ is present at flows below 200 ls$^{-1}$ (~25% MAD) but area increases rapidly between 600 and 1100 ls$^{-1}$ (~75% to 130% MAD) and reaches the site-mean asymptote of 383 m$^2$ near 2000 ls$^{-1}$, or ~240% MAD, again depending on location along the channel.

The relationship between flow level and $S_w$ habitat area (Figure 6d) shows an elevated minimum near 75 m$^2$ at the lowest flows and a rapid increase to the asymptote. The most rapid gains in $S_w$ area are at the lowest flows, with continually diminishing returns at higher discharges. The asymptote of 171 m$^2$ is reached at approximately 100 ls$^{-1}$, slightly above 10% MAD.

For mean wetted width ($W_w$, Figure 6e), the logistic shape of the model fit is more subtle, approaching a log-linear form. $W_w$ increases most rapidly between 60 and 180 ls$^{-1}$, or between 10% and slightly more than...
20% MAD. The $W_w$ model asymptote is reached near 700 ls$^{-1}$ (85% MAD near the river mouth) with a SA-averaged value of 11.1 m.

While the logistic growth model fits the data well, in some cases a decrease in habitat area is apparent at higher flows. This is apparent in several individual study areas for $Pwc$ (Figure 6b) but is more pronounced for $Sw$ (Figure 6d, also see Figure 7d), where most study areas display some degree of reduction in $Sw$ area.

**Habitat response to historic forest harvesting**

The significance of legacy forestry disturbances in affecting habitat was examined using a likelihood ratio test, with discharge and study area as the control variables and harvesting state as the test variable (Table 4). For all variables, the non-linear mixed effects models fit with ‘harvest state’ as a predictor yielded significantly different predictions from models fit without ‘harvest state’ as an explicit variable. Generally, the fixed effects show that harvesting reduced the asymptote or the stable amount of habitat area reached once flow exceeded a given threshold. This difference in habitat availability following harvesting is further summarized in Figure 7. In the case of $Tp$ (Figure 7a), pre-harvest values are elevated above post-harvest values at all flow levels and with little overlap, suggesting a consistent reduction in available habitat post-harvesting. Of all variables, $Pwc$ (Figure 7b) displays the greatest difference between pre and post-harvest habitat availability, with a substantial reduction in post-harvest area, and little overlap between pre- and post-harvest data. $Hv$ area (Figure 7c) shows much subtler differences pre- and post harvest, with slightly greater areas post-harvest for 20-100% MAD. $Sw$ area (Figure 7d) again shows a general reduction in habitat area after harvesting, but the post-harvest difference is less pronounced at flows below 20% MAD. $W_w$ (Figure 7e) also shows greatest differences at flows above 5% MAD, where pre-harvest wetted width for a given flow is elevated notably above post-harvest width.
The effect of legacy watershed disturbances on habitat availability can be further examined through a comparison of asymptotes from the NLME model (Figure 8). For $T_p$ (Figure 8a), pre-harvest asymptotes are greater than post-harvest in all cases except for SA-8, which changes very little over time. $P_{wc}$ asymptotes (Figure 8b) are greater pre-harvest in all sites but SA-3 and SA-8, with the largest reductions in SA-2 and SA-7. $H_v$ (Figure 8c) asymptotes show both increases and decreases, with greater high-velocity area post-harvest in SA-7, SA-8, and slightly more in SA-2. Asymptotes for $S_w$ models (Figure 8d) are similar before and after harvesting for four of eight sites, with notable increase in post-harvest asymptotes for SA8 and decreases in SA5-SA7. Finally, asymptotes for $W_w$ (Figure 8e) are greater pre-harvest with the exception of SA-8.

To determine if legacy forest practice disturbances have a detectable effect on habitat availability when real hydrological data are considered, the pre- and post-harvest logistic growth models were used to predict habitat at the study area level using the full hydrological record (May through September, 1972-2015). For each variable, this analysis results in two predicted time series: one series predicted from the pre-harvest, and one from the post-harvest flow-habitat relationship (Figure 9). For $T_p$ (Figure 9a), the average post-harvest reduction in daily average habitat area is 16.5% but ranges from 14% to 23% depending on the flow characteristics of a given season. For $P_{wc}$ (Figure 9b), a more dramatic reduction of 31.3% occurs, but ranges from 28% to 38% year to year. For daily mean $H_v$ (Figure 9c), there is little difference between pre- and post harvest values, with an average increase of 3.3%, ranging from an increase of less than 1% to 8%. For $S_w$ area (Figure 9d), post-harvest models resulted in a reduction of 7.7%, and ranges from 7% to 8.5%. Finally, $W_w$ (Figure 9e) was reduced by 12.5% on average, ranging from 11% to 15%.

For all variables, the effect of legacy watershed disturbances on habitat availability over a given season is strongly related to the mean flow conditions for that season (Figure 10). In the cases of $T_p$, $P_{wc}$, and $W_w$ (Figure 10 a, b, and e, respectively), the effects are most pronounced during the driest seasons, and least pronounced during the wettest. For $S_w$ (Figure 10d), there is a high degree of scatter in the data, but the wettest seasons consistently experience lower potential losses from harvesting. For $H_v$ (Figure 10c), the
overall effect of legacy harvesting disturbance at Carnation creek is low, but a significant positive relationship is found between average daily flow and change in available habitat.

Discussion

Temporal patterns in channel form and habitat availability

Field and model data presented in Figures 4 and 5 illustrate that neither channel morphology, instream wood, nor modeled habitat variables remain static through time. Given that flow levels are held constant throughout the simulations, temporal variability in habitat is therefore driven by direct changes to channel morphology, and in the case of $P_{wc}$, also from changes in wood abundance (see Figure 4). Therefore, the adoption of static threshold IFN standards in these instances is likely to yield differing quantities of habitat through time. The sensitivity of modeled aquatic habitat to channel morphology change is, however, variable dependent. For instance, $Sw$ is most sensitive to changes in channel shape and structure, while $Ww$ and $Hv$ was found to be comparatively stable through time (Figure 5).

The declining pattern of wetted width (Figure 5e) is likely a product of instream wood loss, associated reduction in sediment storage, and reduction in sediment supply after a period of elevated input in the early to mid-1980s (Reid et al. 2019). Reduced supply and abundance of wood will often lead to a simplified channel which may incise and lead to reduced topographic relief (Nakamura and Swanson 1993). The cascading morphological effects of wood loss may also explain the overall reduction in several habitat variables with time, (particularly $Tp$) as wood is often associated with pool areas (Abbe and Montgomery 1996).

With the exception of $Sw$, temporal patterns in all habitat variables display a partial dependency on flow level, with habitat availability at lower flows (<10% MAD) generally fluctuating less through time. While basic principles of hydraulic geometry (e.g., Leopold 1953) will dictate the relationships between discharge and specific channel hydraulics, changes to smaller-scale and transient features, such as bars and pools, appear to exert a strong influence on the temporal patterns of modeled habitat. Given that the abundance
of $T_p$, $P_{wc}$ and $H_v$ area is very low at the lowest flows (<5% MAD), changes in morphology appear to have comparatively little effect on small scale variation, but longer-term trends are still apparent. While few studies (e.g., Lapointe 2012; Rice 2017) have examined connections between geomorphic variability and habitat availability, results from Carnation Creek further support the finding that changes in channel morphology are important factors in regulating habitat availability through time.

The habitat variables selected for this study represent ranges of hydraulic conditions for juvenile coho. While the specific criteria for these variables are based largely on published literature for the species (e.g. Bjornn and Reiser 1991; Beecher et al. 2002), definitions for what constitutes optimal and marginal habitat will vary by species, and details of patterns in habitat will vary as a function of the habitat variable definition. For instance, the definition for $S_w$, chosen to illustrate patterns in shallow water areas, is relatively subjective, but the consequence of a different threshold can be inferred in part from the patterns observed in the other variables. Future work could consider flow-based definitions of morphological units (e.g., Wyrick and Pasternack 2014) as an alternative approach to characterising hydraulic variability over time.

**Relationships between flow level and habitat availability**

Differing shapes of the habitat-discharge relationships for each variable (Figures 6 and 7) demonstrate that all modelled variables are maximized at different flow levels, and therefore singular IFN levels do not yield optimal availability for all variables. The logistic growth form of the flow-habitat relationships (Figure 6) indicates that additional streamflow generally increases habitat quantity rapidly at flow levels equal to and lower than 20% MAD, with the exception of $H_v$, which increases most above 20% MAD.

Evidence of trade-offs in habitat availability between variables is observable as discharge increases (Figures 6 and 7). In general, the primary trade-off is between the pool-based variables ($T_p$ and $P_{wc}$, which contain a velocity component), and $S_w$ and $H_v$. For instance, maximizing the area of suitable $T_p$ (Figure 6a and 7a) may result in an unacceptable quantity of $H_v$ (Figure 6c and 7c). Given that many natural channels in
mountainous environments have steep banks, once the bed area has been mostly wetted, it is likely that
additional discharge will primarily increase depths and velocities, reducing $Sw$ area and increasing $Hv$ area.
$Pwc$ displays diminishing returns with added streamflow beginning near 10% MAD, as most wood appears
to be within the wetted channel at this flow level, and additional streamflow does not create pool areas in
the vicinity of wood. Therefore, as discharge increases, flow in pool areas becomes too swift and falls
outside of the $Tp$ criteria, thus leading to few additional gains, and in some cases (Figure 6b and 7b)
reductions in rearing habitat with preferred velocities (Bjornn and Reiser 1991; Beecher et al. 2002). While
clear inflection points in the flow-habitat relationships are not always obvious, the rapid increase in $Hv$
above 20% MAD, combined with the relatively minor increases in $Tp$ above 20%-40% MAD indicate that
targets between 10% to 20% MAD are producing at least a moderate quantity of suitable habitat, and that
below 10% MAD sharp losses in habitat availability will occur in Carnation Creek. In Carnation Creek and
many other streams in seasonally dry climates, streamflow may drop to very low levels even in the absence
of any direct withdrawals (Reid et al. 2020). Though streamflow may naturally drop below 10% MAD,
these results support the conservation of streamflow for aquatic habitat below this level where possible, in
order to limit major declines in habitat availability.

**Legacy watershed disturbances and habitat availability**

In Carnation Creek, the legacy of watershed and riparian disturbance from historical timber harvesting
appears to have significantly influenced the availability of aquatic habitat through time, and this effect is
likely persisting even 30 years after the disturbance has occurred. A combination of removal of vegetation
in the riparian zone and colluvial processes following harvesting appears to be associated with a general
reduction in the availability of $Tp$, $Pwc$, $Sw$, and $Ww$, with a slight increase in $Hv$. While our selection of
variables represents a subset of hydraulic conditions relevant for juvenile coho, the changes to the pool-
based variables imply a reduction in low-velocity rearing habitat, while high-velocity areas avoided by
juveniles (Beecher et al. 2002) are comparatively less affected.
The relative reduction in habitat is most pronounced during drier than average low-flow seasons (Figure 10), suggesting that the effect of legacy harvesting may be exacerbated at lower flows (<10% MAD), though the greatest absolute differences between pre- and post-harvest habitat production occur at the highest flow levels (Figure 7). These findings are important for water management considerations, suggesting that maintenance and conservation efforts at the lowest of flows (< 10% MAD) ensure consistent habitat provision regardless of channel condition. Collectively, these results highlight the importance of channel status evaluation as part of the process of defining critical and optimal environmental flow levels. These findings have direct implications for the establishment of presumptive flow standards in regions with a history of timber harvesting or other watershed disturbances that affect fluvial processes, suggesting that evaluation of channel status may be required to periodically adjust target flow levels to maintain constant habitat availability while providing water for societal use.

The primary mechanisms through which historical logging influenced habitat in Carnation Creek are likely tied to the reduction in wood supply through riparian harvesting, and changes to sediment and debris delivery from hillslopes. In addition to providing direct cover, wood pieces (particularly logjams) serve to retain sediment (Hogan 1998; Wohl and Scott 2017) and increase the topographic complexity of stream channels through the creation of pools and sediment wedges (Abbe and Montgomery 1996, Montgomery et al. 2003). As riparian forests are often a dominant source of wood to streams, their removal can have a substantial and long-lasting effect on in-stream wood loads (Murphy and Koski 1989; Stout et al. 2018). The loss of wood could also explain why a slight increase in $H_v$ was observed, as a reduction in channel roughness could lead to elevated velocities at a given flow level (Davidson et al. 2015).

A number of debris flows occurring on previously harvested hillslopes delivered sediment and logging slash to the channel in the mid-1980s. Previous work focussing on the watershed (Hartman and Scrivener 1990; Reid et al. 2019) suggests that sediment delivered from these debris flows had an effect on sediment storage in certain locations along the channel, and at least one major logjam was formed from slash and debris near SA-8 (see Figure 1). The sediment supplied from these events and evidence of channel widening was also
found to propagate downstream over time (Reid et al. 2019). Numerous studies have documented the role of legacy forest practices on slope destabilization and delivery of sediment to streams and resulting consequences for channel morphology (e.g., Roberts and Church 1986; Gomi and Sidle 2003; Jordan 2006). It is likely that some of the temporal variability in habitat observed in Carnation Creek is also related to variation in sediment supply, which is often tied to morphological change (e.g. Hoffman and Gabet 2007). Given the association between channel morphology, in-stream wood and diverse habitat for a variety of aquatic organisms (e.g. Cederholm et al. 1997; Hafs et al. 2014), this legacy harvesting effect may be a helpful factor for assessing whether a disturbed watershed is likely to have a reduction in habitat area at a given flow level.

While legacy harvest-related disturbances appear to be associated with a reduction in habitat availability, it may be possible to partially compensate by increasing streamflow at the lowest flow levels, should water supplies exist. However, given the downward shift in model asymptotes during post-harvest conditions (Figure 8), additional streamflow will not be able to compensate for the harvest effect at higher (generally > 40% MAD) flows. This issue of compensatory flows is, however, further complicated by potential trade-offs between low-velocity pool area and higher-velocity regions that would naturally be observed as streamflow increases.

In Carnation Creek, historical riparian and hillslope harvesting has likely led to changes in the supply of wood and sediment to the channel, affecting channel morphology and flow hydraulics. However, the habitat response to disturbance in other channels will strongly depend on the nature of the disturbance, the background process rates in the channel, and the mechanisms through which the disturbance can lead to changes. Given that specific channel morphology has bearing on the relationship between habitat availability and discharge, it is therefore not only important to understand the likelihood of morphological change occurring from watershed and riparian disturbance, but also the mechanisms behind the change.

**Summary and conclusions**
Using a 2D hydrodynamic modeling approach incorporating a 45-year dataset of channel morphology and in-stream wood, this paper has characterised the variability in habitat-discharge relationships in Carnation Creek, B.C., a small salmon-bearing gravel bed stream in coastal British Columbia. This study demonstrates the magnitude of variability through time in five flow-based habitat variables. This variability is driven both by changes to channel morphology and wood loads in the system. Collectively, these findings highlight the importance of channel morphology as co-control on the provision of aquatic habitat along with discharge and have implications worthy of consideration when estimating and setting presumptive flow standards for a variety of management purposes.

When flow level is held constant, changes in channel morphology appear to have a smaller influence on modeled habitat at the lowest of flow levels (< 3% MAD and less) than for higher flows with four of five studied variables, though low flow variability is still apparent. Trade-offs were observed between pool-based and high-velocity habitat metrics as flow level increases, where low-velocity channel areas are replaced with greater areas of higher flow velocities. The habitat-discharge relationships are strongly non-linear, with rapid gains in habitat at low and intermediate flow levels but diminishing returns at higher flows.

In four of the five habitat variables studied (total pool area, pool area with wood cover, shallow wetted area, and mean wetted width), a reduction was found after widespread watershed disturbance (including riparian area harvesting) occurred in the watershed during the mid- to late 1970s. The exception was for high-velocity (> 0.6 m/s) flow areas which increased slightly in the post-harvest channel state, with the likely change mechanism being a reduction in wood delivered to the stream channel.

These findings support the notion that adding more water to the channel can potentially compensate for variability in habitat or habitat losses through disturbance at very low flows (< 10% MAD), but less so at higher flows (≥ 40% MAD). However, it is not feasible in many cases, especially for flows ≥ 20% MAD, to rely on water conservation to overcome losses in disturbance-driven habitat availability, particularly in...
regions with seasonally dry conditions. A combination of careful flow allocation, habitat management or channel restoration may be required to recover pre-disturbance habitat production of the channel.

This paper has focused on hydraulic components of aquatic habitat for juvenile coho salmon. It is important to note that other variables such as stream temperature, nutrient and food availability, rates of predation, and water quality could also be affected by watershed and riparian disturbance. These factors have bearing on the availability and quality of habitat over time and across space, and future work should aim to incorporate other variables into consideration of streamflow allocations in regions affected by disturbances.

Acknowledgements

We acknowledge the thoughtful and expert input of the following individuals: Dan Hogan (general project guidance, field data), Tobias Mueller (AutoHotkey, Nays2dh automation), Carina Helm (wood piece digitizing, field velocity measurements), Dave Spittlehouse (precipitation data), Matt Sakals (project discussions), and Steve Voller and Andrew Westerhof (photos and field data collection logistics). Two anonymous reviewers provided comments which improved the paper.

References


Kawamura, I. Kimura, T. Kyuka, R. R. McDonald, M. Nabi, M. Nakatsugawa, F. R. Simoes, H.
Takebayashi, and Y. Watanabe (2016). The international river interface cooperative: Public domain flow
and morphodynamics software for education and applications, *Advances in Water Resources*, 93, 62–74,


Pess, G.R., D.R. Montgomery, E.A. Steel, R.E. Bilby, B.E. Feist, and H.M. Greenberg (2002), Landscape characteristics, land use, and Coho salmon (Oncorhynchus
kisutch) abundance, Snohomish River, Wash., U.S.A., *Canadian Journal of Fisheries and Aquatic

Computing.

storage over 45 years in Carnation Creek, BC, a previously glaciated mountain catchment. *Earth Surf.


Rice, S.P. (2017), Tributary connectivity, confluence aggradation and network bio- diversity,


https://mc06.manuscriptcentral.com/cjas-pubs


Table 1: Study Area Characteristics (1971-2015 average values)

<table>
<thead>
<tr>
<th>Study Area</th>
<th>Length (m)</th>
<th>Average Channel Width (m)</th>
<th>Average Bank-Full Depth (m)</th>
<th>Slope (%)</th>
<th>Wood Pieces</th>
<th>Wood Vol. (m$^3$/m$^2$)</th>
<th>Treatment</th>
<th>Riparian</th>
<th>Surveyed Since</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA-2</td>
<td>82</td>
<td>13.8</td>
<td>0.99</td>
<td>0.73</td>
<td>35</td>
<td>0.03</td>
<td>Buffer</td>
<td>1976$^d$</td>
<td>1971</td>
</tr>
<tr>
<td>SA-3</td>
<td>68</td>
<td>19.6</td>
<td>0.97</td>
<td>0.36</td>
<td>40</td>
<td>0.07</td>
<td>Buffer</td>
<td>1978$^d$</td>
<td>1971</td>
</tr>
<tr>
<td>SA-4</td>
<td>62</td>
<td>21.2</td>
<td>0.42</td>
<td>1.35</td>
<td>44</td>
<td>0.04</td>
<td>Buffer</td>
<td>1978$^d$</td>
<td>1973</td>
</tr>
<tr>
<td>SA-5</td>
<td>75</td>
<td>13.7</td>
<td>0.61</td>
<td>0.91</td>
<td>47</td>
<td>0.04</td>
<td>Intensive</td>
<td>1976$^e$</td>
<td>1973</td>
</tr>
<tr>
<td>SA-6</td>
<td>70</td>
<td>14.9</td>
<td>0.74</td>
<td>0.53</td>
<td>24</td>
<td>0.01</td>
<td>Intensive</td>
<td>1976$^e$</td>
<td>1971</td>
</tr>
<tr>
<td>SA-7</td>
<td>51</td>
<td>19.6</td>
<td>0.77</td>
<td>0.86</td>
<td>23</td>
<td>0.01</td>
<td>Intensive</td>
<td>1976$^e$</td>
<td>1973</td>
</tr>
<tr>
<td>SA-8</td>
<td>58</td>
<td>16.9</td>
<td>0.87</td>
<td>0.95</td>
<td>39</td>
<td>0.05</td>
<td>Careful</td>
<td>1978$^f$</td>
<td>1971</td>
</tr>
<tr>
<td>SA-9</td>
<td>148</td>
<td>11.0</td>
<td>0.59</td>
<td>1.90</td>
<td>95</td>
<td>0.08</td>
<td>Careful</td>
<td>N/A$^g$</td>
<td>1973</td>
</tr>
</tbody>
</table>

$^a$ Average channel width (m).

$^b$ Average bank-full depth (m).

$^c$ Slope calculated from fit line along thalweg.

$^d$ Variable riparian buffer strip left (2-70 m).

$^e$ Intensive harvesting treatment: all riparian vegetation removed in and outside of stream channel.

$^f$ Careful harvesting treatment: woody riparian vegetation removed, no instream activities or yarding.

$^g$ No riparian harvesting occurred along SA-9.
### Table 2: Flow Level Parameters

Discharge (liters per second)

<table>
<thead>
<tr>
<th>Study Area</th>
<th>Area(^a) (km(^2))</th>
<th>7Q10</th>
<th>95(^{b}) MAD</th>
<th>MAD</th>
<th>MAD</th>
<th>MAD</th>
<th>MAD</th>
<th>MAD</th>
<th>MAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA-2</td>
<td>10.1</td>
<td>6.0</td>
<td>19.0</td>
<td>24.8</td>
<td>41.4</td>
<td>82.8</td>
<td>165.5</td>
<td>331.0</td>
<td>827.5</td>
</tr>
<tr>
<td>SA-3</td>
<td>9.3</td>
<td>5.9</td>
<td>18.8</td>
<td>23.1</td>
<td>38.5</td>
<td>77.0</td>
<td>153.9</td>
<td>307.8</td>
<td>769.6</td>
</tr>
<tr>
<td>SA-4</td>
<td>8.7</td>
<td>5.8</td>
<td>18.6</td>
<td>21.8</td>
<td>36.3</td>
<td>72.7</td>
<td>145.3</td>
<td>290.6</td>
<td>726.5</td>
</tr>
<tr>
<td>SA-5</td>
<td>8.1</td>
<td>5.7</td>
<td>18.1</td>
<td>20.1</td>
<td>33.5</td>
<td>66.9</td>
<td>133.9</td>
<td>267.8</td>
<td>669.4</td>
</tr>
<tr>
<td>SA-6</td>
<td>7.8</td>
<td>5.7</td>
<td>17.8</td>
<td>19.5</td>
<td>32.4</td>
<td>64.9</td>
<td>129.7</td>
<td>259.5</td>
<td>648.7</td>
</tr>
<tr>
<td>SA-7</td>
<td>7.6</td>
<td>5.7</td>
<td>17.6</td>
<td>18.9</td>
<td>31.5</td>
<td>63.1</td>
<td>126.1</td>
<td>252.2</td>
<td>630.5</td>
</tr>
<tr>
<td>SA-8</td>
<td>7.4</td>
<td>5.6</td>
<td>17.4</td>
<td>18.3</td>
<td>30.5</td>
<td>61.0</td>
<td>122.0</td>
<td>243.9</td>
<td>609.8</td>
</tr>
<tr>
<td>SA-9</td>
<td>3.8</td>
<td>5.1</td>
<td>11.3</td>
<td>9.5</td>
<td>15.8</td>
<td>31.5</td>
<td>63.0</td>
<td>126.1</td>
<td>315.2</td>
</tr>
</tbody>
</table>

\(^a\) Contributing area to centre of the study area

\(^{b}\) 95\(^{th}\) Percentile flow represents a flow that is equal to or exceeded 95% of the time in May to September flow record.
Table 3: Habitat Variables and Definitions

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total pool area</td>
<td>Tp</td>
<td>All wetted area of depth &gt;0.1 m and velocities &lt;0.6 m/s</td>
</tr>
<tr>
<td>Pool area with wood cover</td>
<td>Pwc</td>
<td>Tp overlain by wood pieces</td>
</tr>
<tr>
<td>High-velocity water areas</td>
<td>Hv</td>
<td>All wetted area of velocities &gt;0.6 m/s</td>
</tr>
<tr>
<td>Shallow water area</td>
<td>Sw</td>
<td>All wetted area &lt;0.1 m depth</td>
</tr>
<tr>
<td>Mean wetted width</td>
<td>Ww</td>
<td>Modeled wetted area &gt; 0.02m depth / reach length</td>
</tr>
</tbody>
</table>
### Table 4: Logistic Growth Model Parameters for the Fixed Effect– With and Without Harvesting

<table>
<thead>
<tr>
<th>Variable</th>
<th>Full model</th>
<th>Reduced(^a) model</th>
<th>Anova</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Asymptote</td>
<td>Mid</td>
<td>Scale</td>
</tr>
<tr>
<td><strong>Tp</strong></td>
<td>372</td>
<td>89.3</td>
<td>46.9</td>
</tr>
<tr>
<td><strong>Pwc</strong></td>
<td>51.8</td>
<td>34.5</td>
<td>29.3</td>
</tr>
<tr>
<td><strong>Hv</strong></td>
<td>384</td>
<td>805</td>
<td>166</td>
</tr>
<tr>
<td><strong>Sw</strong></td>
<td>171</td>
<td>9.07</td>
<td>12.2</td>
</tr>
<tr>
<td><strong>Ww</strong></td>
<td>11.1</td>
<td>122</td>
<td>107</td>
</tr>
</tbody>
</table>

\(^a\) harvesting omitted as a predictor variable
Figure 1: Carnation Creek watershed and location of hydrometric stations and eight channel morphology study areas. Maps shown correspond to 2015 channel survey at approximately 200% MAD (1655 ts⁻¹). The confined canyon reach is illustrated as a red line. Maps were created using the R programming language and ArgGIS 10.6, and map data were collected by the authors.
Figure 2: Daily average flows over the 45-year period of record collected at the primary hydrometric station between SA-2 and SA-3 (see Figure 1). Note the period of low flows from May 1st to September 30th.
Figure 3: Evaluation of model performance. (a) modeled vs. measured depth, point measurements; (b) modeled vs. measured velocity, point measurements; (c) modeled vs. measured depth, SA-averaged; (d) modeled vs. measured velocity, SA-averaged; (e) modeled vs. measured wetted width, SA averaged; (f) model performance comparing areas extended vs. regular reaches.
Figure 4: Plots of departures in (a) bed elevation, (b) sediment storage (scaled to channel area), (c) channel width, and (d) wood volume. All panels show results grouped across all study areas. The dashed line corresponds to the start of timber harvesting activities in the Carnation Creek watershed.
Figure 5: Time series of modeled habitat for the five variables of interest. Note: plots have been smoothed with a loess function of span 1.7 for ease of interpretation. Vertical dashed line corresponds to beginning of harvesting period at Carnation Creek. Results are grouped across all study areas.
Figure 6: Raw data from Nays2DH model output with logistic growth model fit overlaid for (a) pool area; (b) pool area with wood cover; (c) high-velocity wetted area; (d) shallow water areas; and (e) mean wetted width. Each colored point corresponds to a single year of data for each study area and flow level. Colors correspond to data for individual study areas. Model fit includes all data; individual study-area models can be found in supporting information Figures S1 to S5.
Figure 7: Boxplots of habitat availability pre- and post-harvesting for the average habitat availability in all study areas, for (a) total pool area; (b) pool area with wood cover; (c) high-velocity wetted area; (d) shallow water areas; and (e) mean wetted width. Note that a direct test for significance between pre- and post harvest periods is not possible with a non-linear mixed effects model. See Table 4 for an evaluation of significance.
Figure 8: Asymptotes (i.e., maximum attainable habitat) fit for pre- and post-harvest data periods for each study area. (a) Total pool; (b) pool area with wood cover; (c) high-velocity wetted area; (d) shallow water area; and (e) mean wetted width. Values below the 1:1 line indicate greater maximum habitat under pre-harvest conditions.
Figure 9: Mean daily habitat values across May 1st to Sept 30th over the 45-year period of record, for (a) total pool area; (b) pool area with wood cover; (c) high-velocity wetted area; (d) shallow-water area; and (e) mean wetted width. Daily habitat values are predicted using pre- and post-harvest logistic growth models for individual study areas, and the results summed across all study areas, with the exception of mean wetted width (e), which was calculated as the average across the study areas.
Figure 10: Relationships between change in habitat availability predicted from the pre- and post-harvest logistic growth models, and mean daily flow level over each May 1st to Sept 30th season from 1972-2015, for (a) total pool; (b) pool area with wood cover; (c) high-velocity wetted area; (d) shallow-water area; and (e) mean wetted width. Relationships are significant with $p < 0.05$ in all panels.