RIVER RESEARCH AND APPLICATIONS

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EFFECTS OF DAM REMOVAL ON TULE FALL CHINOOK SALMON SPAWNING HABITAT IN THE WHITE SALMON RIVER, WASHINGTON

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ABSTRACT

Condit Dam is one of the largest hydroelectric dams ever removed in the USA. Breached in a single explosive event in October 2011, hundreds-of-thousands of cubic metres of sediment washed down the White Salmon River onto spawning grounds of a threatened species, Columbia River tule fall Chinook salmon *Oncorhynchus tshawytscha*. We investigated over a 3-year period (2010–2012) how dam breaching affected channel morphology, river hydraulics, sediment composition and tule fall Chinook salmon (hereafter 'tule salmon') spawning habitat in the lower 1.7 km of the White Salmon River (project area). As expected, dam breaching dramatically affected channel morphology and spawning habitat due to a large load of sediment released from Northwestern Lake. Forty-two per cent of the project area that was previously covered in water was converted into islands or new shoreline, while a large pool near the mouth filled with sediments and a delta formed at the mouth. A two-dimensional hydrodynamic model revealed that pool area decreased 68.7% in the project area, while glides and riffles increased 659% and 530%, respectively. A spatially explicit habitat model found the mean probability of spawning habitat increased 46.2% after dam breaching due to an increase in glides and riffles. Shifting channels and bank instability continue to negatively affect some spawning habitat as sediments continue to wash downstream from former Northwestern Lake, but 300 m of new spawning habitat (river kilometre 0.6 to 0.9) that formed immediately post-breach has persisted into 2015. Less than 10% of tule salmon have spawned upstream of the former dam site to date, but the run sizes appear healthy and stable. Published 2015. This article is a U.S. Government work and is in the public domain in the USA.

KEY WORDS: dam breach; Chinook salmon; White Salmon River; GIS; habitat

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INTRODUCTION

Dams and hydropower operations in the Columbia River Basin negatively affect rearing and spawning habitats, migration rates and populations of Chinook salmon *Oncorhynchus tshawytscha* and steelhead *O. mykiss* (Tiffan *et al*., 2002; Keefer *et al*., 2004; Hatten *et al*., 2009; Harnish *et al*., 2014). On the White Salmon River, Condit Dam blocked 53 km of steelhead habitat and 23 km of salmon habitat for almost 100 years [Washington Department of Ecology (WDOE), 2007]. A perceived benefit of Condit Dam removal was access to spawning and rearing areas upstream of the dam by steelhead (*O. mykiss*) and spring Chinook salmon (*O. tshawytscha)*). Federal and state agencies determined that Condit Dam removal would not have significant adverse impacts on bull trout (*Salvelinus confluentus*), federally listed lower Columbia River (tule) Chinook salmon, lower Columbia coho salmon (*O. kisutch*), Columbia River chum salmon (*O. keta*), or mid-Columbia River steelhead [Federal Energy Regulatory Commission (FERC), 2002; U.S. Fish and Wildlife Service (USFWS), 2002; National Marine Fisheries Service (NMFS), 2006; U.S. Fish and Wildlife Service (USFWS), 2005a; U.S. Fish and Wildlife Service (USFWS), 2005b; Washington Department of Ecology (WDOE), 2007].

The Washington Department of Fish and Wildlife (WDFW) conducted spawning-ground surveys between Condit Dam powerhouse, located at river kilometre (rkm) 3.7 and the mouth of the White Salmon River (rkm 0) since 1965, assessing the health of tule fall Chinook salmon (hereafter 'tule salmon'). The tule salmon population, which spawns in the fall (Sept–Oct), is a federally listed threatened species with a spawning population fluctuating from 32 to 11 480 between 1992 and 2015 [Washington Department of Fish and Wildlife (WDFW), 2015]. Prior to dam removal, tule salmon spawned near the confluence with the Columbia River from rkm 0.96 to 3.37, with over half spawning between rkm 1.4 and 1.7. This spawning area is partially backwatered by the Columbia River where significant fine-grained reservoir sediment deposition was predicted to accumulate within the existing spawning habitat after breaching [Washington Department of Ecology (WDOE), 2007]. The amount of time that undesirable sediments might remain in

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the lower river was a key question because the longer they persisted the greater the perceived impacts on tule salmon spawning habitat downstream of Condit Dam. Other unknowns included how far upstream tule salmon would spawn, the rate of upstream colonization, and the stability and quality of spawning habitat downstream of the dam. Would tule salmon abandon their favoured downstream location after dam breaching and head upstream or would some fraction continue to spawn in the lower river?

The depressed status of tule salmon and opportunities to learn about dam breaching and its effects on salmonid habitats were the impetus for our study. Our primary goal was to quantify the effects of Condit Dam removal on tule salmon spawning habitat in the project area (rkm 0–1.7) because this was the primary spawning reach over the last century. A secondary goal was to assess tule salmon spawning activities both inside and upstream of the project area after dam breaching. We used quantitative modelling and intensive field work to assess the first goal. Specific objectives inside the project area before and after dam breaching (2010–2012) included (1) characterize bathymetry and substrate; (2) characterize the hydraulics with a two-dimensional (2D) hydrodynamic model; (3) create a habitat suitability (probability) model of tule salmon spawning habitat and (4) assess ecohydraulic impacts of dam breaching on tule salmon spawning habitat. Accomplishment of the second goal required on-the-ground surveys of tule salmon spawning activities September and October, 2010–2014. Our combined approach of fine-scale modelling on a reach scale, and tule salmon spawner-ground surveys river-wide, allowed us to focus small and large, maximize our financial resources and to vertically integrate across each scale. Our findings should help fill in some of the knowledge gaps related to dam removal and biological responses.

STUDY AREA

Originating from Mount Adams, the White Salmon River drains a 1036 km^2 basin (Figure 1). Major tributaries upstream of former Northwestern Lake, formed by Condit Dam (rkm 5.3), include Rattlesnake, Buck and Mill Creeks, with no major tributaries downstream of the dam. The topography surrounding the lower White Salmon River is varied, with channel confinement and riverbed slopes increasing substantially upstream of rkm 3.2 (Colaiacomo, 2014; Hardiman and Allen, 2015). Since 1938, when Bonneville Dam was created, backwater conditions on the Columbia River (rkm 234) inundated the lower 1.5 km of the White Salmon River. The mean annual streamflow downstream of Condit Dam is approximately 30.07 m^3 s^{-1}, with a mean annual velocity of 0.64 metres per second (m s^{-1}) upstream of the gauge, and 0.37 m s^{-1} downstream of the gauge [U.S. Geological Survey (USGS), 2010]. The surrounding landscape is composed of a mixture of conifer and oak woodlands.

The focus of our study was Condit Dam, constructed in 1912 on the White Salmon River (45°46′02″N 121°32′16″W). Built for hydropower generation without functional fish ladders, it measured 144-m wide by 38-m tall, and created a 3-km reservoir (Northwestern Lake). A settlement agreement was signed in 1999 to remove Condit Dam and reopen the upper White Salmon River to fish passage (PacifiCorp, 1999). On 26 October 2011, Condit Dam was breached after a drain tunnel was excavated at the base of the downstream side (Figure 2A). The drain tunnel was designed to allow a maximum flow of 293.2 m^3 s^{-1} to pass through and drain in approximately 6 h but it drained in less than two hours, exceeding 400 m^3 s^{-1} (Wilcox *et al*., 2014). The concrete dam and hydroelectric accessories were subsequently removed the following year (Figure 2B–2F).

Hydraulic and geomorphic features inside the project area were very different between rkm 0.0–0.9 and 0.9–1.7, due to a rapid transition in water depth. Water depths between rkm 0.0 and 0.9 averaged approximately 5 m compared with 1.5 m between rkm 0.9 and 1.7. Water velocities between rkm 0.0 and 0.9 averaged approximately 0.1 m s^{-1}, compared with 0.6 m s^{-1} between rkm 0.9 and 1.7. Fine sediments dominated downstream of rkm 0.9, while gravel and cobble dominated upstream (rkm 0.9–1.7). The average water-surface gradient in the project area was 0.2%, compared with 0.7%–1.2% between rkm 1.7 and 7.9 (Hardiman and Allen, 2015), and 2–11% upstream of former Northwestern Lake Bridge (Haring, 2003). Husum Falls (rkm 12.6) is believed to be a barrier to upstream migration of tule salmon, although steelhead can get above it (Engle *et al*., 2013).

METHODS

Spawning-ground surveys

Tule salmon spawning-ground (redd) surveys have been conducted each year in the White Salmon River during September and October since 1965 (Figure 3). In recent years, those surveys are conducted by the State of Washington and Pacific State Marine Fisheries Commission staff for population level monitoring. In 2010 and 2012, USFWS surveyors specifically performed tule salmon redd (nest) surveys from rafts, on a boat or on foot to identify redd locations within the study area downstream of Condit Dam with established protocols (Engle and Skalicky, 2009; Skalicky, 2009). In 2011, the USFWS captured and translocated 679 tule salmon (554 were natural origin) from the Lower White Salmon River to several locations

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upstream of Condit Dam before it was breached (Engle *et al*., 2013). Spawning-ground surveys did not occur in 2011 in the project area due to the capture and translocation efforts as well as water clarity from upstream dam-breaching activities. Redd surveys were conducted on multiple occasions in late September to coincide with normal tule salmon peak spawning. Individual redds were documented using a handheld Global Positioning System (GPS) or were marked on detailed field maps for later digitizing and enumeration in a geographic information system (GIS) during 2012. In 2010, 148 tule salmon redds were located on their spawning grounds, of which 82 redds occurred in the project area. A year after the dam was breached, surveyors located 28 tule salmon redds in the same project area in 2012 (Engle *et al*., 2013). The spatial locations of redds recorded by the GPS were imported into a GIS for modelling and accuracy assessment. State and Federal agencies continued to conduct spawning ground surveys in 2013 and 2014, which we incorporated into our discussion.

Substrate mapping and bathymetric surveys

We created substrate maps of the project area in 2011 and 2012 with a composite of methods, utilizing GIS technology, Real-time Kinetic (RTK) GPS, underwater videography, still imagery and sketch maps (Warrick *et al*., 2008; Hatten *et al*., 2013). In 2011, the water was too deep to wade in most locations, so an underwater-video camera system was utilized with two lasers spaced 10-cm apart to determine substrate size in each video frame: RTK–GPS position

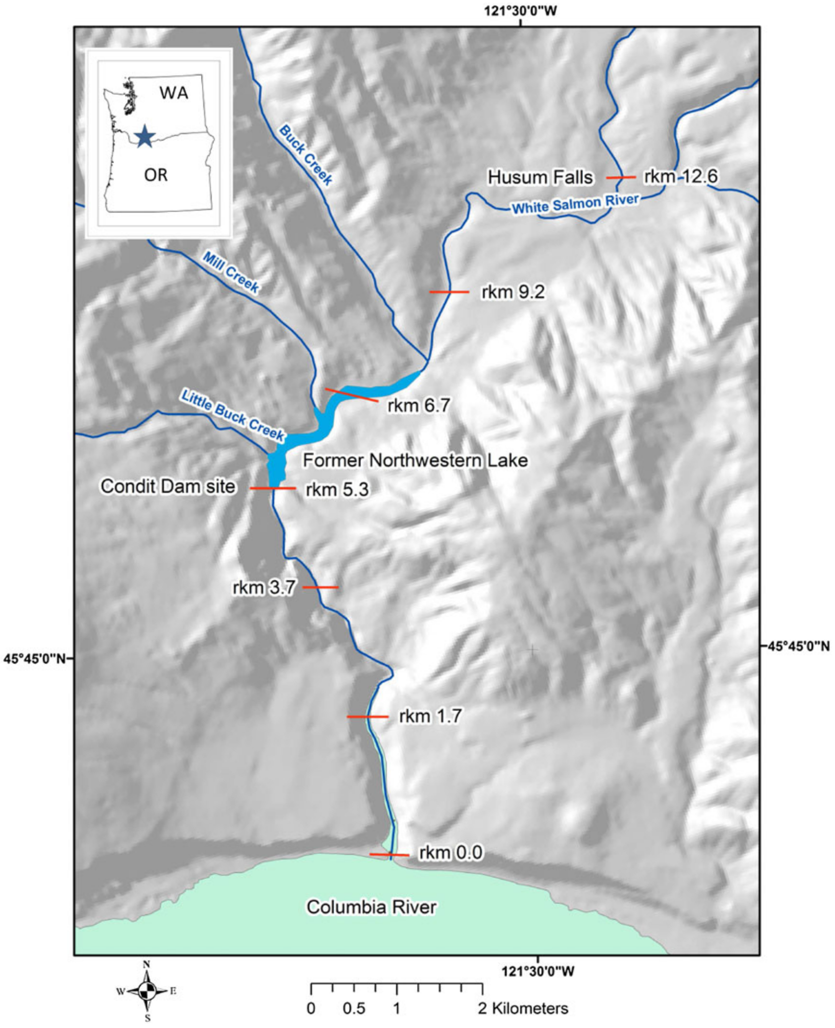

Figure 1. A map of the White Salmon River from the confluence of the Columbia River (river kilometre [rkm] 0.0) upriver to Husum Falls, an anadromous barrier to tule fall Chinook salmon (rkm 12.6). The project area (rkm 0.0 to 1.7) is where hydrodynamic modelling occurred from 2010 to 2012. Tule salmon spawned up to rkm 3.7 prior to dam breaching; after dam breaching, tule salmon also spawned between rkm 6.7 and 9.2.

Figure 2. Decommissioning photos of Condit Dam as shown by photos taken by time-lapse cameras by Steve Stampfli of White Salmon, Washington. (A) The initiation of dam removal before the reservoir was drained, (B) approximately 75% decommissioned, (C) approximately 90% decommissioned, (D) 100% decommissioned. Photos (E) and (F) were taken by PacifiCorp staff on the day the reservoir was drained on 26 October 2011.

was recorded and embedded within the video. Several hundred georeferenced still images were post-processed from the underwater video. In locations that were too shallow for the boat to operate safely (<1 m), personnel waded on foot, creating sketch maps of substrate on detailed field maps, noting dominant and subdominant particle sizes. We divided substrate into six dominant and sub-dominant particle sizes according to a modified Wentworth scale (Wentworth, 1922); boulder (>256 mm), cobble (>64–256 mm), coarse gravel (>16–64 mm), medium gravel (4–16 mm), fine gravel (2–4 mm) and fines (sand/silt/mud, <2 mm). In 2012, the average water depth in the project area was significantly reduced because of dam breaching, sediment aggregation and pool filling, so we waded and mapped (sketched) the substrates with the aid of detailed GIS maps. Key personnel involved in the first substrate survey participated in the second survey to ensure consistency in mapping and substrate characterization.

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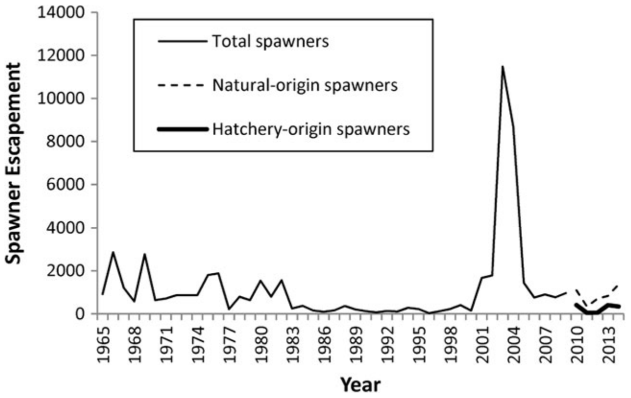

Figure 3. Tule fall Chinook salmon spawning escapement estimates in the White Salmon River, WA (1965 through 2014, WDFW 2015). Spawning data are total escapement estimates based on peak live plus dead spawner counts from the Condit Dam powerhouse (river kilometre 3.7) downstream to the confluence with the Columbia River (through 2011) when Condit Dam was in operation. From 2012 through 2014, escapement estimates represent the lower White Salmon River from Husum Falls (river kilometre 12.6) downstream to the confluence.

Two-dimensional hydrodynamic simulations (2010–2012)

We simulated hydraulic conditions in the lower 1.7 km of White Salmon River before and after Condit Dam removal (2010–2012) with a 2D hydrodynamic model [River2D (Steffler and Blackburn, 2002)]. River2D is a transient finite-element model that can be set to obtain a steady-state based upon the 2D, depth-averaged St. Venant equations. Developed for use in streams and rivers, River2D has been verified with theoretical and field results (Ghanem *et al*., 1995; Waddle *et al*., 1996). To ensure confidence in the predictability of our 2D hydrodynamic model, we followed the methodology and steps in the online manual (http://www.river2d.ualberta.ca), and from previous applications (Tiffan *et al*., 2002; Hatten *et al*., 2009). A three-dimensional mesh with 3-m resolution was produced from the 2D hydrodynamic model for subsequent habitat simulations.

Spawning-habitat model

We developed a binary logistic-regression model (Hosmer and Lemeshow, 2000) to characterize and map the probability of tule salmon spawning habitat in the project area pre-breach at a spawning-season median flow ($16.99\,\mathrm{m^3\,s^{-1}}$) (Hatten *et al*., 2009). We trained the habitat model with 82 redd locations from 2010, along with a complimentary set of absence locations (459) obtained with a random point generator in GIS. To avoid spatial confusion between presence and absence locations, we buffered each location by 10 m (Anglin *et al*., 2006). Following model development, we reapplied the spawning model to a wide range of discharges commonly observed during the spawning period (14.15–$24.92\,\mathrm{m^3\,s^{-1}}$), at two water-surface elevations that commonly occur because of backwatering from the Columbia River (Table I). This approach resulted in eight spawning-habitat maps that represented a wide range of flow conditions that can occur on the spawning grounds, at 3 × 3-m resolution. We reapplied the 2010 spawning-habitat model to the 2012 post-breach conditions (altered bathymetry, substrate and hydraulics) using the same range of flows (Table I).

Logistic regression is ideal for evaluating relationships between predictor variables and a species' location because presence-absence data are binary (Keating and Cherry, 2004). We used Arc/Info® GRID [ESRI (Environmental Systems Research Institute), 1992] to calculate and map the probability that a salmon would be present within 3 × 3-m (9-m^2) cells. We calculated the relative probability (P) with the following equation:

$$P = e^{g(x)} / 1 + e^{g(x)} \tag{1}$$

where *g(x)* is the linear combination of parameter estimates obtained from the logistic regression (Hosmer and Lemeshow, 2000). In Eq. (1), the relative suitability of an area is linked (indexed) to the probability of spawning activity, with the model assigning each cell a probability between 0 and 99% (Hatten *et al*., 2009). We evaluated the significance of the associations between spawning activity and substrate class, depth-averaged velocity and water depth. We screened variables for collinearity, examined their significance with backwards stepping, checked for linearity with higher-order terms (i.e. quadratic, cubic) and examined

Table I. Pre-breach (2011) and post-breach (2012) River2D boundary conditions

Flow ($\mathrm{m^3\,s^{-1}}$	Flow ($\mathrm{ft^3\,s^{-1}}$)	Downstream elevation Normal pool (m)	Downstream elevation Low pool (m)
14.158[a]	500	23.98	23.65
16.99 [a]	600	23.98	23.65
19.821 [a]	700	23.98	23.65
22.653[a]	800	23.98	23.65
24.9188[a,c]	880	23.98	23.65
14.158[b]	500	23.709	23.509
15.574[b,d]	550	23.714	23.514
16.99[b]	600	23.722	23.522
19.821[b,c]	700	23.729	23.529
22.653[b]	800	23.741	23.541
24.9188[b]	880	23.749	23.549

[a]pre-breach
[b]post-breach
[c]calibration
[d]validation

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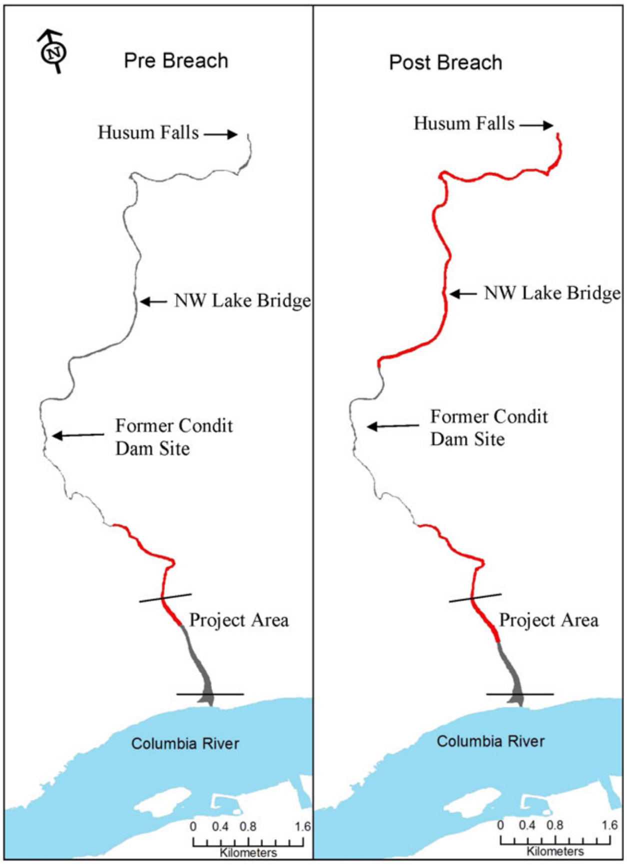

Figure 4. Spawning distribution (red line) of tule fall Chinook salmon in the White Salmon River before (left panel) and after (right panel) dam removal. Distribution was determined from spawning surveys and redd mapping conducted by multiple agencies (Engle *et al*., 2013).

model fit and accuracy with a Receiver Operating Characteristic area-under-the-curve (AUC; Egan, 1975) and a classification table (Story and Congalton, 1986).

Accuracy assessment

We assessed the accuracy of our 2D hydrodynamic model by comparing simulated velocities and depths to field measurements obtained with a flowmeter at two different transects (~ rkm 0.5 and 0.6), at 15.57 $m^3 s^{-1}$ (Tiffan *et al*., 2002). We assessed the accuracy of our post-breach logistic model with an independent dataset composed of 28 tule salmon redd locations collected in 2012 inside the project area. We used a GIS to randomly generate 125 absence locations after buffering the presence locations by 10 m. We did not assess accuracy in 2011 because approximately 23% of tule salmon escapement to the lower White Salmon River were trapped and relocated upstream of Condit Dam prior to breaching (Engle *et al*., 2013). Model accuracy depends upon a movable probability cutpoint used to delineate (extract) suitable versus unsuitable spawning locations (cells) from the probability grid (Hatten *et al*., 2009). For this analysis, we selected a probability cutpoint (threshold) that balanced commission and omission errors (Story and Congalton, 1986). Cells (3 × 3-m) that were predicted to be occupied but found to be empty were counted as a commission error.

Change detection

Post-breach changes (2012) in substrate and hydraulics within the project area were summarized in several ways to define the spawning habitat at a given streamflow and tail-water elevation. First, we tabulated the amount of area found within each class (e.g. substrate and pool/riffle/glide) and created bar graphs. Second, we created maps that displayed the two surfaces side-by-side before and after

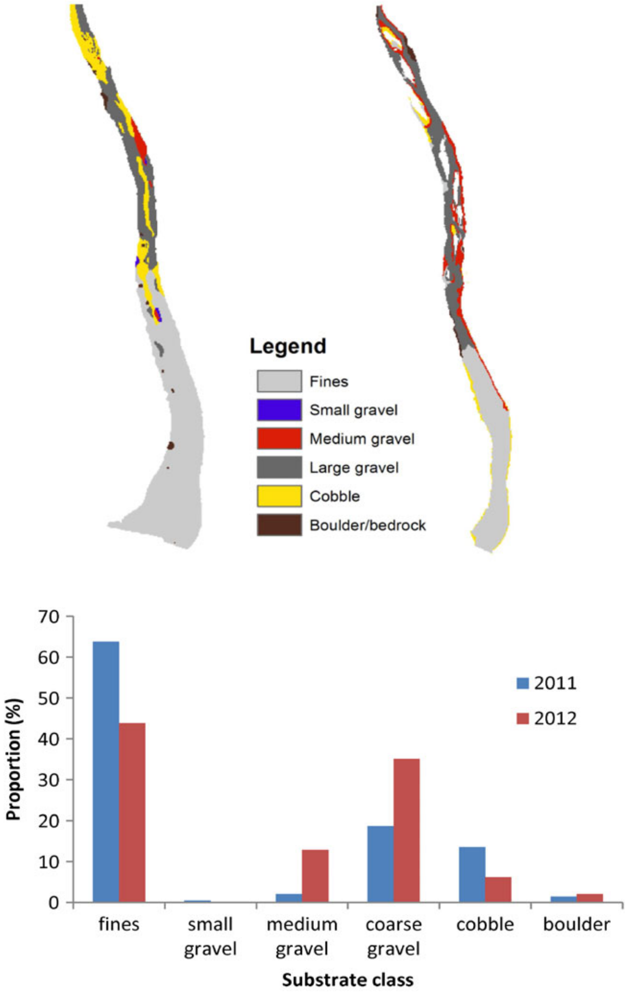

Figure 5. Substrate maps before (top left) and after (top right) dam breaching, and area (proportion of study area) of substrate classes before (2011) and after (2012) dam breaching.

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dam removal. Third, we used GIS to graphically show where changes occurred. The probability of tule salmon spawning habitat was examined both as a continuous surface and as a discrete, binary map after applying a probability threshold that achieved the greatest overall accuracy.

RESULTS

Spawning-ground surveys

Total escapement of tule salmon was 379 in 2011, and 755 in 2012 (Figure 3), with the majority being natural origin, non-hatchery fish [Washington Department of Fish and Wildlife (WDFW), 2015]. Almost 10% (18 redds) of the 194 tule salmon redds observed in 2012 surveys occurred upstream of the former dam site, from ~ rkm 6.7 to 9.2, which represents a large range expansion post-breach (Figure 4). The remainder of tule salmon redds (~90%) occurred downstream of rkm 3.7. Total escapement of tule salmon in 2013 was 1232 (829 natural), with only 1% upstream of the former dam site, and 1704 in 2014 (1366 natural), with none upstream of the former dam. The overall escapement of natural spawners post-breach has been increasing (Figure 3), with the majority (~90%) spawning between rkm 0.6 and 3.7 [Washington Department of Fish and Wildlife (WDFW), 2015].

Substrate mapping and bathymetric surveys

There were large changes in the White Salmon's channel morphology post-breach, with the formation of numerous islands and a new sinuous channel. Fine grained sediments (silt, clay and sand) were heavily deposited between the mouth and rkm 0.6, while coarse grained sediments (gravel and cobbles) were deposited between rkm 0.61 and 1.7 (Figure 5, top panel). Within the post-breach wetted

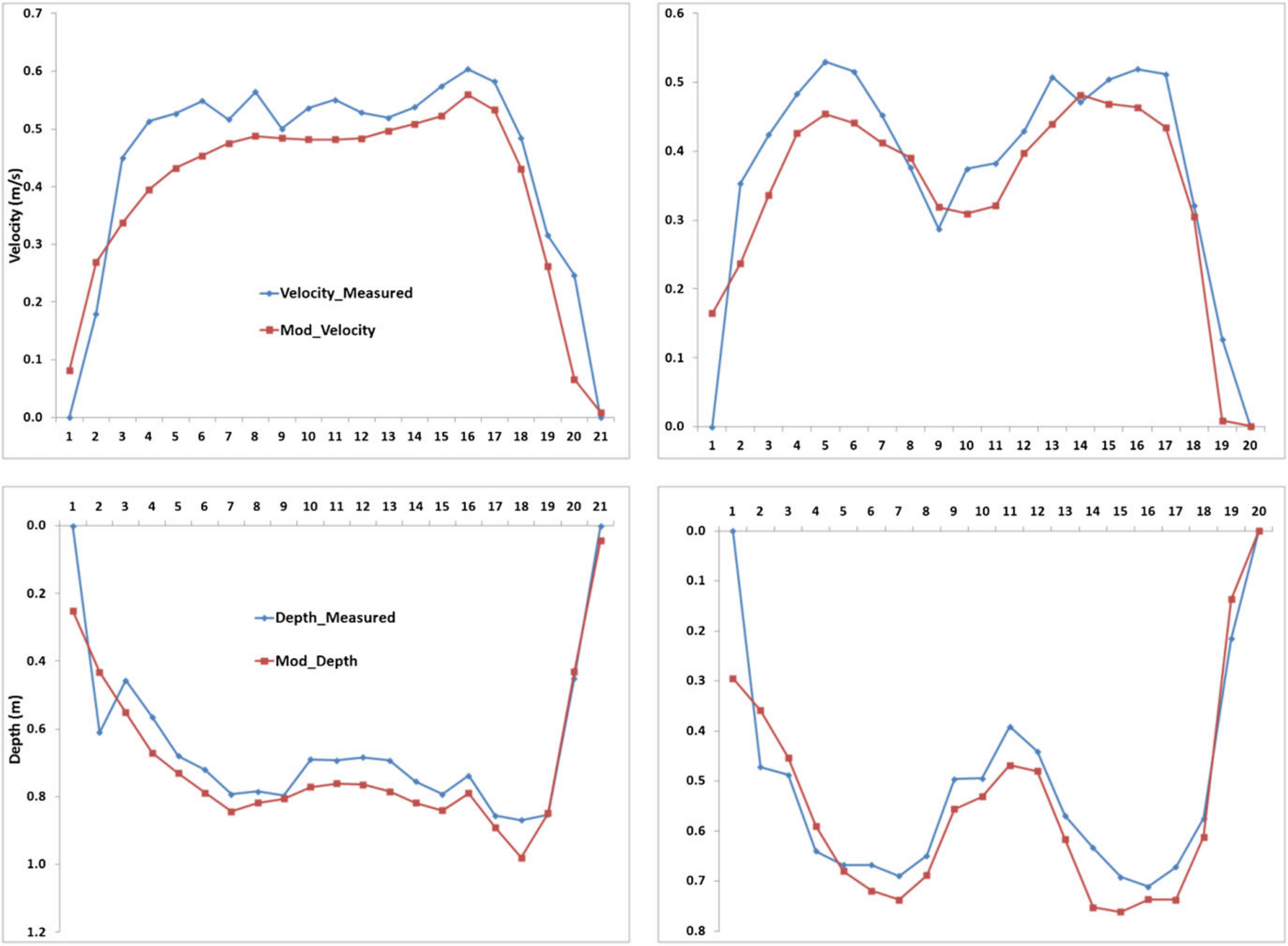

Figure 6. Comparison of water velocities and depths obtained with a flowmeter (Velocity_Measured, Depth_Measured) and hydrodynamic simulations (Mod_Velocity, Mod_Depth) at a 15.57 $m^3 s^{-1}$ (550cfs) flow, at 0.5 (left panel) and river kilometre 0.6 (right panel).

channel, fine grained sediments decreased approximately 34% following dam removal—due to a narrower, faster channel, while courser grained sediments increased 125% (Figure 5, bottom panel). Much more apparent than substrate composition was the rearrangement of the channel, with islands filling in pools, and a new channel meandering through the project area. Much of the pool that backwatered the lower White Salmon River filled in with reservoir sediment, resulting in a 42% reduction in the wetted channel, and an increase in the bed elevation of the entire project area. Specifically, the White Salmon's mouth was 9.36-m deep in 2011 before dam breaching but only 2.03-m deep after dam breaching.

Two-dimensional hydraulic simulations

The River2D model achieved 86% depth accuracies and 83% velocity accuracies when compared with the data obtained with a flowmeter along two transects (~ rkm 0.5 and 0.6), at 15.57 $m^3 s^{-1}$ (Figure 6). The 2D model closely matched the shape of the channel's bottom, while the depth-averaged velocities closely matched flowmeter readings in both deep and shallow waters. The close agreement between simulated and measured flows demonstrated the River2D model accurately captured the hydraulic conditions in the project area.

Dramatic differences in bed elevation, water depth and water velocities along the entire project area occurred as a result of dam breaching (Figure 7). Mean depth decreased from 3.2 to 0.6 m after dam removal (16.99 $m^3 s^{-1}$), maximum depth decreased from 9.4 to 2.0 m, while variability (SD) decreased from 2.0 to 0.4 (Figure 8, top panel). The mean velocity in the project area increased from 0.1 to 0.5 $m s^{-1}$ post-breach (16.99 $m^3 s^{-1}$), maximum velocity increased from 2.6 to 3.4 $m s^{-1}$, while variability (SD) doubled (Figure 8, bottom panel). Froude number thresholds (pool: $Fr < 0.18$; riffle > 0.41; with glide intermediate (Jowett, 1993) revealed that the total pool area inside the project area decreased after dam removal 68.7% (16.99 $m^3 s^{-1}$), glides increased 659%, while riffles increased 530% (Figure 9, top panel). These patterns changed little at higher or lower flows, or at different tail-water elevations, with the overall patterns mirroring each other, so we focused on 16.99 $m^3 s^{-1}$ for the habitat analysis.

Spawning habitat model

The following binary logistic regression model (Eq. 2) characterized tule salmon spawning habitat:

$$\begin{aligned} Logit = & -17.686 + (5.755 * VEL) \\ & - \left(5.455 * VEL^2\right) - (0.896 * DEP) \\ & + (7.169 * SUB) - \left(0.709 * SUB^2\right), \end{aligned} \tag{2}$$

where VEL = velocity ($m s^{-1}$), DEP = water depth (m), and SUB = six substrate classes. For modelling purposes,

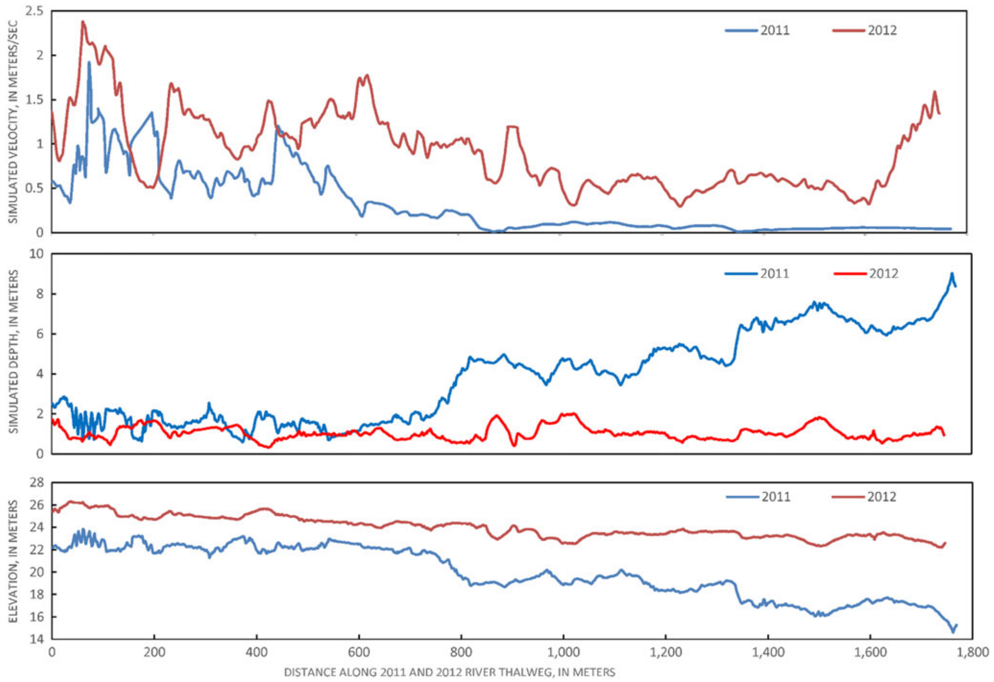

Figure 7. Changes is bed elevations, velocities and depths, along the pre-breach (2011) and post-breach (2012) thalweg inside the project area. Distance 0.0 is at the confluence of the Columbia River

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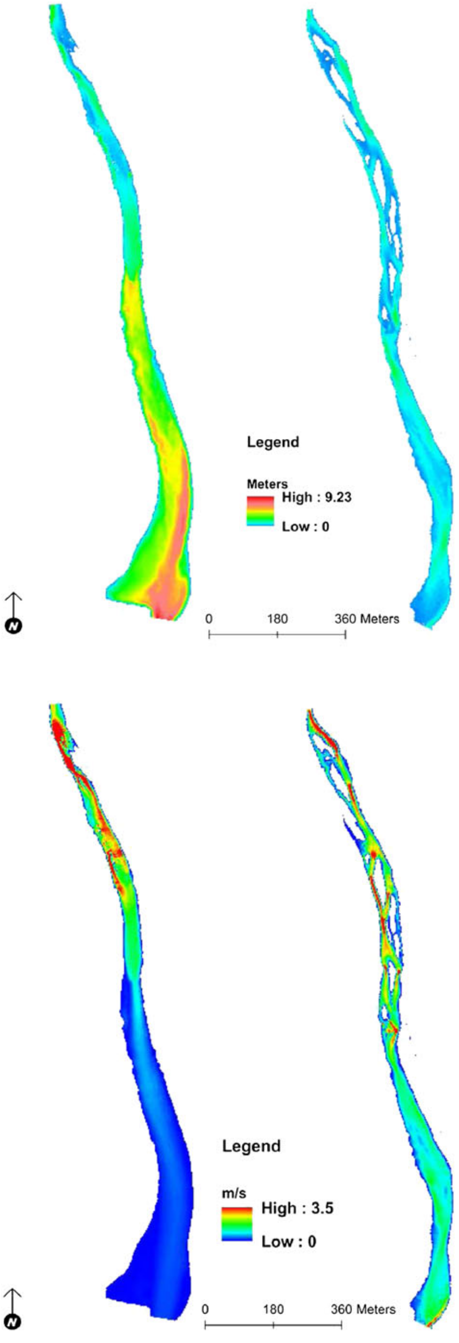

Figure 8. Simulated depths (top panel) and velocities (bottom panel) obtained from a 2D hydrodynamic model before (left side) and after (right side) dam removal.

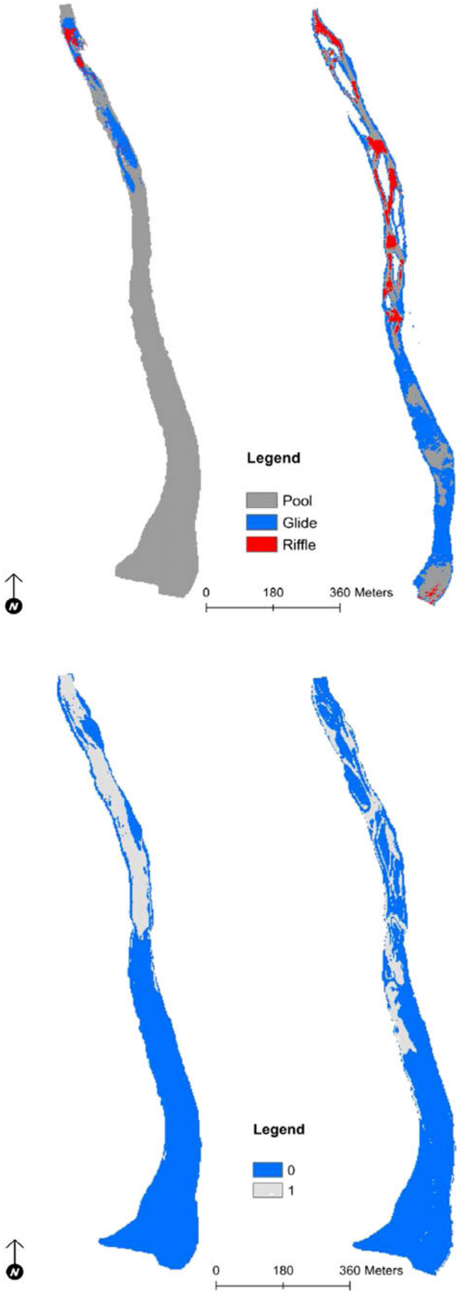

Figure 9. Simulated pool/riffle/glides (top panel) and predicted tule fall Chinook salmon spawning habitat (bottom panel) before (left side) and after (right side) dam breaching (0 = predicted unsuitable; 1 = predicted habitat)

substrate classes were ranked from one to six, with the smallest diameter (fines) set at one, and the largest (boulder) set at six (see Methods for size classes). Backward stepping revealed that water depth had the largest effect on the model's log-likelihood, followed by velocity and substrate, respectively. The mean probability of spawning habitat was 0.13 in 2010, with a maximum value of 0.87. A probability threshold (cutpoint) of 0.3 provided the best discrimination in the training data between presence and absence locations (AUC = 0.94), with 2.7 ha of the project area predicted suitable. Ninety-nine per cent of the 82 training redds occurred inside or within one cell (3 m) of predicted habitat (99% sensitivity and 1% omission). The mean probability of spawning habitat increased after dam removal

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in the project area from 0.13 to 0.19 (46.2%), but the maximum probabilities (0.87 to 0.86) and predicted habitat (2.7 to 2.6 ha) remained almost unchanged (Figure 9, bottom panel). An additional 300 m of habitat was created as a result of pool filling and increased hydraulics, between rkm 0.6 and 0.9, while a variable-length delta formed at the river's mouth, depending on the Columbia River's pool elevation.

Accuracy assessment

The GIS-based habitat model post-breach (2012) found 26 out of 28 tule salmon redd locations in the project area occurred inside or within 1 m of predicted habitat (92.8% sensitivity). However, the AUC was only 0.65, compared with 0.94 in 2010, due to high commission error (areas predicted suitable did not contain redds). For example, at an 80% sensitivity level (20% omission), the model produced 50% commission error, while a 70% sensitivity level produced 45% commission error. This contrasts with the habitat model's performance in 2010 when it achieved 15% commission error at an 80% sensitivity level, and 10% commission at 70% sensitivity.

DISCUSSION

Over 500 dams have been removed in the USA since 2006, but studies that integrate biological and physical responses are rare (O'Connor *et al.*, 2015). Of the 798 dams in Washington state, 70 have been completed since 2000, but only 12 have been removed [American Rivers, 2015; United States Army Corps of Engineers (USACE), 2015]. Notable dams removed in the last decade in the Pacific Northwest include Marmot Dam (Major *et al.*, 2012), Hemlock Dam (Magirl *et al.*, 2010), Condit Dam (Wilcox *et al.*, 2014), and Elwha and Glines Canyon dams (East *et al.*, 2015). Two common approaches to dam removal are explosive dam breaches, called blow-and-go or slower, notch-it-down (phased) methods (Magirl *et al.*, 2010; Lovett, 2014). To our knowledge, Condit Dam is the largest dam in the USA breached in a single explosive event, while Glines Canyon Dam, located on the Elwha River, is the largest dam removed with a phased approach. If the goal is to remove sediment quickly from the system, blow-and-go is very efficient (Wilcox *et al.*, 2014), while a phased approach is appropriate when downstream resources are vulnerable (Warrick *et al.*, 2015). Which method is used depends on a thoughtful approach to each dam and potential downstream effects, but both methods have produced immediate benefits to migratory and anadromous fishes (O'Connor *et al.*, 2015).

Our spawning-habitat model revealed that dam breaching had little effect on the net amount of tule salmon spawning habitat in the project area in 2012, even though 42% of the project area was displaced above the new waterline (island and bar formation). Overall habitat quality, as determined by model probabilities, actually increased 46% because of improved hydraulic conditions. The fines and alluvium trapped in Northwestern Lake quickly distributed downstream where they filled a deep pre-breach pool (rkm 0.0–0.9), resulting in approximately 300 m of new spawning habitat (rkm 0.6 to 0.9), or were transported into the Columbia River (Colaiacomo, 2014; Wilcox *et al.*, 2014).

The habitat model could not assess the stability of the river channel, which became very unstable after Condit Dam was breached due to large quantities of sediment washing downstream from the former Northwestern Lake. Aerial photography, lidar and visual observations indicate that the lower White Salmon River continues to be in a state of flux, with new gravel bars, islands and riffles forming after major flow events (Hardiman and Allen, 2015). A large wedge of sediment continues to work its way through the project area toward the confluence of the Columbia River. In spite of changes in the river channel annually, the new spawning reach (rkm 0.6 to 0.9) has persisted and appears relatively stable. However, we are uncertain on how the new White Salmon River delta at the confluence with the Columbia River will impact the project area in the future, but it could affect channel morphology and water quality (Foley *et al.*, 2015), especially if the Yakima tribe's in-lieu fishing site is dredged and armoured.

To date, less than 10% of tule salmon have spawned upstream of the former dam site, but benefits to other salmonids, including steelhead and coho, are just being realized as they normally utilize habitat further upstream (Engle *et al.*, 2013; Hardiman and Allen, 2015). Several factors appear to be limiting more tule salmon from spawning upstream (Haring, 2003; Colaiacomo, 2014; Hardiman and Allen, 2015). First, most spawning areas upstream of rkm 3.7 have a confined floodplain, limited large woody debris and high gradients that produce large velocities and substrates typically not used by tule salmon. Second, many upstream areas are confined by bedrock that limits large riffle/pool sequences that facilitate upwelling and downwelling favoured by tule salmon. Third, a partial blockage to tule salmon is occurring at Steelhead Falls (rkm 4.2), which appears to be limiting upstream access in some years—but note that tule salmon did spawn at rkm 9.2 in 2012 (Engle *et al.*, 2013). The tule salmon total escapement has increased each year post-breach, but it remains to be seen if this trend will continue, or whether we are just observing the natural fluctuations that have been observed since 1965 (Figure 3). Despite the uncertainties, we remain confident that tule salmon will prosper with the removal of Condit Dam.

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