2015 Deschutes River Fisheries Monitoring Report:

Assessing Redband Trout status in the middle and upper Deschutes River basin using young-of-the-year occupancy surveys in lateral habitats

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Abstract

The Deschutes River, from Big Falls upstream to Wickiup Dam, has experienced dramatic alterations to its flow regime, habitat quality and connectivity, ecological processes, and fish community, including a perceived decline in the distribution and abundance of Redband Trout. Concern for the status of this species in this river and some of its tributaries led to a research effort to gain a better understanding of the distribution and abundance of Redband Trout and other salmonids and test the feasibility and effectiveness of different monitoring protocols. Fish distribution and abundance surveys are particularly challenging in large rivers like the Deschutes River. To avoid some of these challenges, this study used an occupancy survey design targeting young-of-the-year (YOY) trout in the river margins and other lateral habitats to accomplish the following four objectives: 1) determine YOY Redband Trout and Brown Trout occupancy and density patterns, 2) evaluate how different variables influence these patterns, 3) assess how occupancy and habitat change under the managed flow regime, and 4) assess the feasibility and effectiveness of this monitoring protocol. Additionally, tissue samples from the YOY cohort were collected for genetic analysis.

YOY of both species were detected throughout the study area and study period (i.e., July 2015 – March 2016). High occupancy probabilities ($\psi \geq 0.87$) of YOY Redband Trout were observed in the tributary Tumalo Creek and the following Deschutes River segments: 1) from Steelhead Falls to Benham Falls, 2) between the confluences of the Little Deschutes River and Fall River, and 3) near Wickiup Dam. High density reaches (i.e., containing multiple sites with > 5 YOY 100-m^{-1}) were detected in the Deschutes River from Awbrey Falls to Lava Island Falls and in Tumalo Creek. For YOY Brown Trout, high occupancy probabilities ($\psi \geq 0.86$) and multiple high density sites were observed throughout the middle Deschutes River downstream of North Canal Dam, in Spring River and Fall River, and in the Deschutes River reaches adjacent to those tributaries. Maximum summer temperatures and other habitat variables did not significantly influence YOY occupancy, suggesting these patterns may be reflecting spawning distribution and densities rather than the quality, quantity, or spatial distribution of YOY habitat. Channel and lateral habitat changed dramatically when the managed flow regime abruptly transitioned from irrigation season (i.e., April to October) to water storage season. Naïve site occupancy decreased seasonally for YOY of both species, which may signal a response to lateral habitat changes or an ontogenetic shift away from lateral habitat use. Genetic analyses of the YOY cohort revealed population structure and localized introgression with hatchery-stocked trout and, using sibling frequency analysis, produced relatively precise estimates of the effective number of breeders (N_b).

Overall, the monitoring protocol was highly feasible because of the ease of accessing and surveying in lateral habitats, how readily YOY were captured using backpack or raft

electrofishers, and the minimal time and crew size needed for surveying in these shallow narrow bands along the river margin. The protocol was effective because it provided precise, high-resolution estimates of YOY occupancy probabilities and yielded information about the breeding population, including precise estimates of N_b. The range in capture methods used, stream sizes surveyed, and native and nonnative YOY salmonids and other fishes captured suggests that this monitoring protocol could be useful in a wide range of research and monitoring contexts.

Introduction

An understanding of the distribution and abundance of animal populations is fundamental to assessing conservation status and conducting sound resource management. Many sampling models have been developed to estimate these population characteristics, assess factors that influence status, and track population trends (e.g., capture-mark-recapture [CMR] models, Seber 1982; occupancy models, MacKenzie et al. 2006; DNA-based models, Liukart et al. 2010). Each model has particular assumptions to meet and sampling challenges to ameliorate in order to obtain accurate and precise estimates of population status needed for effective management (Gwinn et al. 2008).

Estimation accuracy and precision often varies with the spatial scale, habitat, and animal species under study. Estimating fish distribution and abundance is particularly challenging in large rivers (Murphy et al. 1989, Beechie et al. 2005, Gwinn et al. 2011). Some of the sampling challenges include deep water that is difficult to sample with traditional sampling methods, wide channels and large habitat volume that take longer to survey, and flow velocities that can reduce sampling effectiveness and limit the use of some gear types; in addition, fish usually are difficult to see from above the water surface and are capable of moving in and out of sample sites during the study period. These challenges contribute uncertainty about whether sampling assumptions are met and cast doubt on the accuracy of the estimates (Gwinn et al. 2011). Even though ecological processes, fish habitat, and flow regimes in many large rivers have been altered for human use (Bednarek 2001, Tockner and Stanford 2002) and fish populations and species diversity have been negatively affected (Bunn and Arthington 2002), including potamodromous salmonid populations (Wenger et al. 2011), the sampling challenges have limited the number of fish distribution and abundance studies in large rivers (Beechie et al. 2005).

Potamodromous Rainbow Trout *Oncorhynchus mykiss* populations that occur on the east side of the Cascade Mountain range, commonly known as Redband Trout *O. mykiss* ssp. (Behnke 1992, Currens et al. 2009), have received recent conservation attention because of concern about their status (i.e., mainly distribution and abundance; Muhlfeld et al. 2015), the effect of human land and water use on habitat, and how projected climate warming is likely to adversely affect habitat (Penaluna et al. 2016). Although Redband Trout have declined an estimated 58% from their historical range, this polyphyletic group is still widely distributed, with many populations not subject to main threats or protected by active conservation measures, and is considered not to be at imminent risk of extinction (Muhlfeld et al. 2015). In the middle and upper Deschutes River, management concern for the status of native Redband Trout *O. m. gairdneri* and the recreational fishery has increased as this river has been harnessed for human use (Fies et al. 1996, NPCC 2004). This large spring-fed river has experienced dramatic alterations to its flow regime, habitat quality and connectivity, and ecological processes (see Starcevich et al. 2015 for a more detailed summary). This coincided with changes to the fish community: native Bull Trout *Salvelinus confluentus* were extirpated; Brown Trout *Salmo trutta*, Brook Trout *S. fontinalis*, and other fish species were introduced; and there has been a perceived decline in Redband Trout population status (Fies et al. 1996, NPCC 2004). From 2012 to 2014, occupancy and CMR sampling designs were used with boat-electrofishing in the mid-channel of this river to gain a more rigorous understanding of the distribution and abundance of native Redband Trout and other salmonids and to test monitoring protocols for feasibility and effectiveness in tracking change in population status (Starcevich et al. 2015, Starcevich 2016). This large river sampling was useful for estimating the distribution and relative abundance of some size classes of Redband Trout, but the study was hampered by many of the challenges noted above and resulted in low capture and detection probabilities for some species and size classes, imprecise abundance estimates, and uncertainty about adherence to sampling assumptions.

To avoid some of these sampling challenges and relax model assumptions, this study used an occupancy design that focused on capturing age-0 salmonids (hereafter, young-of-the-year [YOY]) in low-velocity, shallow lateral habitats (*sensu* Moore and Gregory 1988, Beechie et al. 2005) in the middle and upper Deschutes River. The objectives were to 1) determine the spatial patterns of occupancy and density of YOY Redband Trout and Brown Trout, 2) evaluate the influence of spatial factors, lateral habitat covariates, and summer stream temperature on detection and occupancy of YOY trout, 3) investigate seasonal changes in lateral habitat characteristics and occupancy, and 4) assess this sampling design for feasibility and effectiveness as a long-term monitoring protocol. Additionally, this sampling design provided an opportunity to collect Redband Trout tissue samples from the YOY cohort for genetic analysis (see Bohling et al. 2017).

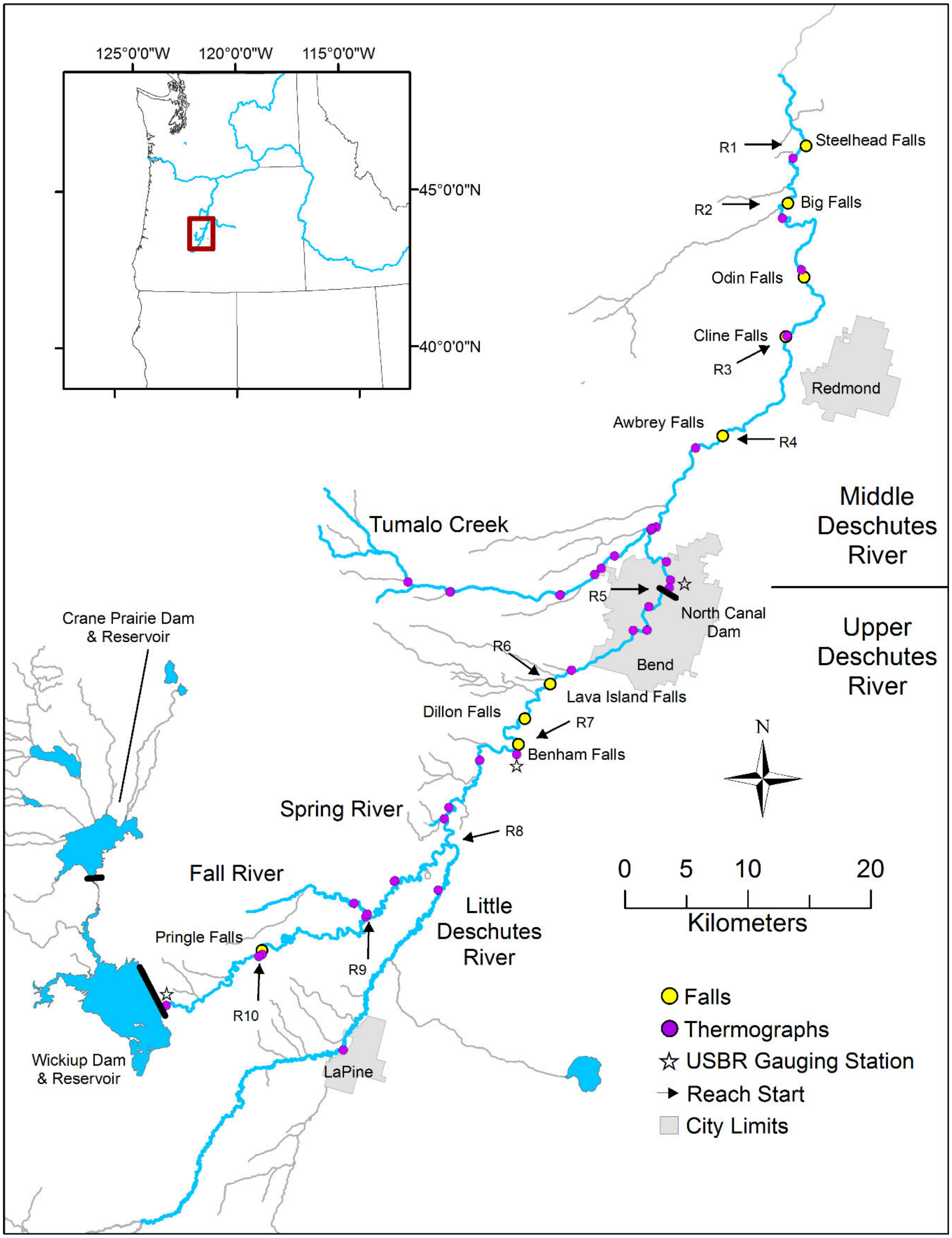


Figure 1. Study area and several features, including U.S. Bureau of Reclamation (USBR) discharge gauging stations, in the middle and upper Deschutes River.

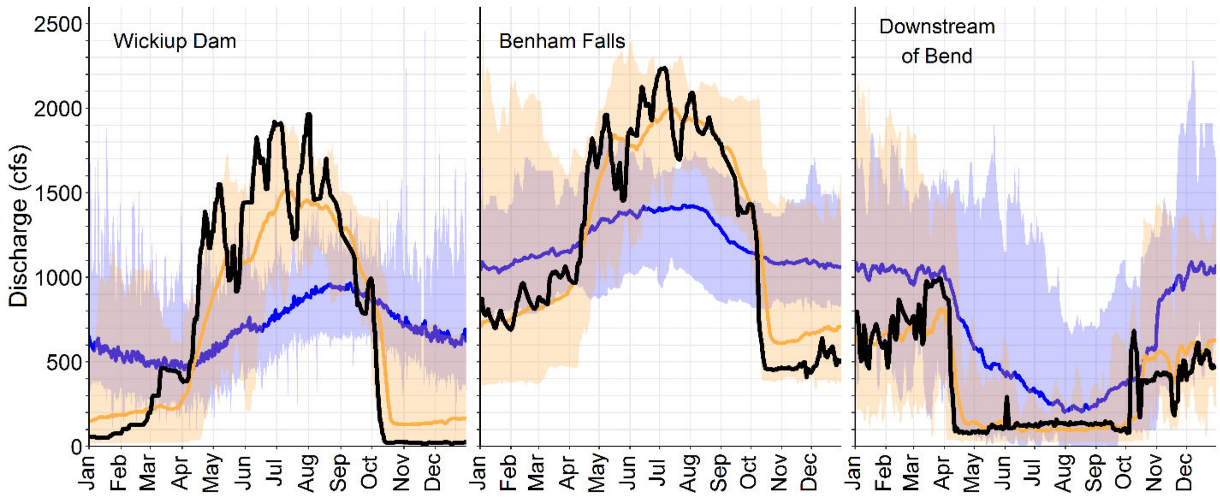


Figure 2. Hydrographs of mean daily discharge (cfs, cubic feet per second) from three BOR Hydromet gauging stations on the Deschutes River (panels). Each panel is composed of hydrographs for the study year (2015, black line), average pre-dam (blue) and dam-regulated discharge (orange), and daily maximum and minimum (shaded ribbons). At the Wickiup Dam station, pre-dam discharge was summarized from estimates based on a BOR hydrological equation for the period from 1983 to 2017. At the Benham Falls and Bend stations, pre-dam discharge was summarized from actual discharge records from 1924 to 1939 (i.e., prior to the construction of Wickiup and Crane Prairie dams); pre-dam discharge downstream of Bend was already influenced by large irrigation diversions. Regulated discharge was summarized from actual records from 1990 to 2016. All hydrograph data were obtained from the BOR Hydromet website (www.usbr.gov/pn/hydromet/).

Study Area

The Deschutes River in central Oregon flows north along the Cascade Mountain range to the Columbia River (Figure 1, inset). The study area is commonly described as two segments, the middle and upper Deschutes River, which differ substantially in their fluvial geomorphology and managed flow regime. The study area was further divided into 14 sampling reaches delineated by falls, dams, tributaries, and confluences (Figure 1). The middle Deschutes River was defined as extending from Steelhead Falls (river kilometer [rkm] 206) to the North Canal Dam (rkm 265) in Bend. This segment is characterized by relatively high channel slope (median, 0.9) and the river channel is largely constrained by canyon geology. Maximum water temperatures range from 13.0-27.2˚C during the summer. Tumalo Creek is the only major tributary in this segment, with annual mean daily discharge of 67 cubic feet per second [cfs] and mean daily summer flow reduced to 10-20 cfs by diversions for drinking water and irrigation. Artificial and natural barriers in this segment that affect upstream movement of fishes include Steelhead Falls, Big Falls (rkm 213), Odin Falls (rkm 225), Cline Falls (rkm 233), Awbrey Falls (rkm 246), and the North Canal Dam (rkm 265) in the city of Bend.

The upper Deschutes River was defined as extending from the North Canal Dam (rkm 265) to Wickiup Dam (rkm 365) (Figure 1). From Bend upstream to the Little Deschutes River confluence, the river flows through basalt formations that result in a series of falls and cascades. From the Little Deschutes River upstream to Wickiup Dam, the river is sinuous and low gradient (channel slope, 0.0-0.1), except at Pringle Falls (rkm 349), which may pose some upstream passage difficulties. Maximum daily stream temperatures range from 14-18 ˚C in summer. Lava Island Falls (rkm 281), Dillon Falls (rkm 286), and Benham Falls (rkm 291) may be barriers to upstream movement by fish during certain flows. Three major tributaries enter the Deschutes River in this segment: Spring River (annual mean daily discharge, 150 cfs, rkm 306), Little Deschutes River (365 cfs; rkm 311), and Fall River (150 cfs; rkm 330).

The flow regime of the middle Deschutes River changed dramatically (Figure 2) with the construction of the North Canal Dam and Pilot Butte Canal in 1900; this irrigation project was capable of diverting the entire flow of the Deschutes River (up to 1400 cfs; Golden and Alyward 2006). The natural flow regime would have varied annually between a mean daily discharge of 1000-1400 cfs. Under the current managed flow regime, mean daily discharge ranges from 500-800 cfs in winter and (as of 2016) a median protected flow of 127 cfs in summer. The construction of Crane Prairie Dam and Reservoir (55,300 acre feet [af] of storage) in 1940 and Wickiup Dam and Reservoir (200,000 af) in 1949 marked the start of a managed flow regime in the upper Deschutes River (Figure 2). The natural flow regime ranged in daily mean discharge between 450-965 cfs (estimated near the Wickiup Dam location). Currently, mean daily discharge averages 140 cfs in winter, often dropping below 50 cfs as Wickiup Reservoir refills during the storage season, and a mean of 1500 cfs, at times peaking at 2000 cfs, in the summer as water is released for downriver irrigation diversions.

Methods

Sample sites

The study area was divided into 500-m long sites using a geographical information system (ArcGIS) and 14 reaches marked by falls, dam, or major tributaries (Table 1). Sample sites were selected using the general random-tessellation stratified (GRTS) sampling design (Stevens and Olsen 2004) stratified by reach and the GRTS draw sample order was followed. Sample sites were added near the ends of each reach and near the confluence of tributaries when there was poor sampling coverage for these areas in the GRTS draw. The sampling schedule rotated through survey reaches to temporally distribute site visits during the 3.5 month summer and fall study period (i.e., July-October, 2015). Within each 500-m sample site, fish and habitat surveys were conducted in the lateral habitat in the first, third, and fifth 100-m subsections (hereafter, replicates). Site surveys were conducted on only one side of the river. The survey side was determined systematically by odd or even site number. If there was an access problem, the survey side was chosen by the easiest access or to avoid private landownership. Survey start and end points were determined by global positioning system (GPS).

Table 1. Sample reach description and sampling rate from July through October, 2015, in the middle and upper Deschutes River basin. Within the 500-m sample sites, 2-4 100-m long replicates were surveyed. The fraction of the sampling frame surveyed was based on the number of sample sites visited.

Deschutes Reach/Trib	Reach breaks	Sampling frame extent (km)	Sites (N)	Replicates (N)	Surveyed (%)
1	Steelhead Fall - Big Falls	6.8	6	19	44
2	Big Falls - Cline Falls	19.6	15	38	38
3	Cline Falls - Awbrey Falls	12.6	8	29	32
4	Awbrey Falls - N. Canal Dam	19.0	11	34	29
Trib	Tumalo Creek	12.5	5	15	20
5	N. Canal Dam - Lava Island Falls	15.1	9	27	30
6	Lava Island Falls - Benham Falls	10.1	12	46	59
7	Benham Falls - Little Deschutes R.	18.3	12	43	33
Trib	Spring River	0.5	1	3	100
Trib	Little Deschutes River	33.5	14	69	21
8	Little Deschutes River - Fall River	18.4	11	41	30
Trib	Fall River	8.0	9	32	56
9	Fall River - Pringle Falls	19.1	14	49	37
10	Pringle Falls - Wickiup Dam	15.4	12	42	39

Fish and habitat surveys

Fish surveys were conducted by two 2-person crews using either backpack or raft electrofishers. The backpack electrofisher (Smith-Root, model LR-24, Vancouver, WA; and Electrofishing Systems LLC, model ABP-3, Madison, WI) was used in sites without safe boating access, steep channel slope, and in areas too shallow for raft access; mainly in the middle Deschutes River, Tumalo Creek, and Fall River. The raft electrofisher was used in sites that were often too deep for wading or where silt substrate prevented walking in the lateral habitats. Prior to backpack electrofishing, sample site length was measured with a rangefinder and flagged at both ends without disturbing lateral habitat. When using the backpack electrofisher, one crewmember operated the electrofisher and netted, the other netted and monitored the condition of captured fish. All backpack electrofishing surveys were done moving upstream. The 4.3 m cataraft was outfitted with an electrofishing system (Smith-Root 2.5 Streambank Generator Powered Pulsator, Vancouver, WA) with one anode (0.8 m diameter array dropper) located between the two pontoons of the boat. On the raft, one crewmember operated the gas-powered generator and pulse box electrofishing system (Kohler Power Systems, Kohler, WI) while rowing. The raft was positioned perpendicular to the bank, keeping the anode in the lateral habitat and working downstream through the replicate. The other raft crew member operated a foot pedal, which powered the electrical current, and netted fish from the bow. The rower used a GPS during the survey to find the end point of the replicate about 100 m from the start. For both raft and backpack surveys, the actual replicate length was measured after the fish survey. Photos were taken at the beginning and end of each replicate. Coordinates, time, and photo number were recorded at the start and end of each replicate; stream temperature and electrofishing seconds were recorded at the end. Fish surveys were conducted in low velocity and relatively shallow lateral habitat from the edge of the river (i.e., the riverbank) to a visible current shear line, defined as the line on the water surface created where low and higher velocity water intersect (Beechie et al. 2005). Surveys were conducted a minimum width (perpendicular to the river bank) of 0.5 m in edge areas with no lateral habitat (i.e., no slow water, no current shear line) and a maximum width of 3 m in wide lateral habitats. Captured fish were placed in aerated buckets filled with stream water. Small fish (<40 mm total length [TL]) were kept separate from large fish to prevent predation.

Table 2. Total catch of salmonid species during electrofishing surveys in the Deschutes River study area.

Species	Deschutes Reach & Tributary	Count	Total Length (mm)			
			Mean	SD	Min	Max
Redband Trout	1	276	59	26	24	197
	2	100	105	61	30	260
	3	83	69	30	26	204
	4	168	84	44	23	246
	Tumalo Cr.	170	58	33	23	175
	5	386	92	38	45	259
	6	121	72	32	31	350
	7	20	44	22	26	111
	L. Deschutes R.	50	160	56	77	298
	8	28	51	10	32	76
	Fall R.	53	74	38	25	215
	9	40	105	67	48	440
	10	86	80	42	19	299
Brown Trout	1	151	111	49	45	350
	2	166	161	77	53	400
	3	49	131	66	49	375
	4	207	148	90	51	500
	Tumalo Cr.	41	97	53	31	273
	5	13	110	13	84	130
	6	30	155	111	70	425
	7	154	71	29	41	285
	Spring R.	107	74	10	56	126
	L. Deschutes R.	24	213	71	77	315
	8	58	117	82	57	470
	Fall R.	298	86	53	31	559
	9	68	138	62	60	380
	10	18	186	154	70	700
Mountain Whitefish	2	7	244	87	146	408
	3	5	170	85	115	320
	4	18	204	81	102	392
	Fall R.	1	123	NA	123	123
	6	10	147	52	110	247
	7	8	142	85	81	320
	L. Deschutes R.	63	214	65	110	314
	8	59	126	45	64	321
	9	127	137	46	90	330
	10	19	143	69	87	353
Brook Trout	Fall R.	346	93	33	43	220
	Spring R	2	51	0	51	51
	Tumalo Cr.	46	99	36	25	191
Kokanee (*O. nerka*)	2	1	101	NA	101	101
	3	1	110	NA	110	110
	4	1	75	NA	75	75
	5	2	105	13	96	114
	6	2	63	24	46	80
	7	2	85	11	77	92
	L. Deschutes R.	1	101	NA	101	101
	9	3	90	10	81	101
	10	2	92	38	65	118

Table 3. Total catch of non-salmonid species during electrofishing surveys in the study area.

Species	Deschutes Reach/Trib	Count	Total Length (mm)			
			Mean	SD	Min	Max
Brown Bullhead (*Ameirus nebulosus*)	7	6	93	68	50	230
	L. Deschutes R.	256	117	52	51	220
	8	1	NA	NA	NA	NA
	9	1	118	NA	NA	NA
	10	9	283	11	270	300
Chiselmouth (*Acrocheilus alutaceus*)	1	423	NA	NA	NA	NA
Dace (*Rhinichthys spp*)	1	498	NA	NA	NA	NA
Largemouth Bass (*Micropterus salmoides*)	2	2	82	12	73	90
	3	25	NA	NA	NA	NA
	9	4	69	12	55	84
	10	7	66	18	36	82
Peamouth (*Mylocheilus caurinus*)	1	5	NA	NA	NA	NA
	2	1	NA	NA	NA	NA
	10	3	NA	NA	NA	NA
Sculpin (*Cottus* spp.)	4	82	NA	NA	NA	NA
	Tumalo Cr.	1	NA	NA	NA	NA
	5	2020	NA	NA	NA	NA
	6	1508	NA	NA	NA	NA
	7	1260	NA	NA	NA	NA
	Spring R.	1	NA	NA	NA	NA
	L. Deschutes R.	8350	NA	NA	NA	NA
	8	460	NA	NA	NA	NA
	Fall R.	387	NA	NA	NA	NA
	9	343	NA	NA	NA	NA
	10	26	NA	NA	NA	NA
Sucker (*Catostomus* spp.)	1	308	NA	NA	NA	NA
	10	2	NA	NA	NA	NA
Threespine Stickleback (*Gasterosteus aculeatus*)	1	4	NA	NA	NA	NA
	2	44	NA	NA	NA	NA
	3	7	NA	NA	NA	NA
	4	7	NA	NA	NA	NA
	5	411	NA	NA	NA	NA
	6	846	NA	NA	NA	NA
	7	1426	NA	NA	NA	NA
	Spring R.	2	NA	NA	NA	NA
	L. Deschutes R.	375	NA	NA	NA	NA
	8	1195	NA	NA	NA	NA
	9	326	NA	NA	NA	NA
	10	166	NA	NA	NA	NA
Tui Chub (*Gila bicolor*)	2	18	111	31	58	182
	6	5	55	6	48	62
	7	8	46	7	36	57
	L. Deschutes R.	117	71	33	31	169

At the end of each replicate, fish species and TL were recorded for all individual salmonids captured. For other fishes captured during the survey, species and total count for each species were recorded. Because of their frequent high abundance, sculpins *Cottus* spp., Threespine Stickleback *Gasterosteus aculeatus,* and juvenile Brown Bullhead *Ameirus nebulosus* were usually not netted or counted individually; instead, their abundance was visually estimated, often in batches (e.g., >10 individuals). Tissue samples (minimum size, 25 mm^2) were collected for genetic analysis from all captured Redband Trout. Samples were placed in a plastic vial filled with ethanol. Vial number was recorded with the fish data. Redband Trout <30 mm TL were killed and the whole fish was collected. To maximize survey efficiency, tissue samples were taken from a maximum of 25 YOY Redband Trout per replicate. No anesthetic was used on fish during brief handling (i.e., 5-15 s). Fish recovered in an aerated bucket filled with stream water for at least five minutes and until they could swim against a current, then were returned to their replicate and spread throughout the lateral habitat.

A habitat survey of the replicate was conducted after the fish survey. Replicate location within the river channel was characterized by channel unit type (i.e., pool, glide, or fastwater unit; *sensu* Moore et al. 2010), channel width (measured with a rangefinder), and survey side orientation on a straight channel or river bend (i.e., inside or outside edge of the bend). Lateral habitat characteristics were recorded at habitat transects perpendicular from the riverbank to the current shear line and spaced at 5-m intervals. Only habitat characteristics that intersected the transect line were recorded. At each transect, the lateral habitat type was recorded, consisting of bar, bank, alcove-backwater, or marsh. Banks (*sensu* Beechie et al. 2005) were characterized by a steep (> 45 degree angle) step along the shoreline. Bars (*sensu* Beechie et al. 2005) displayed a shallow, low gradient interface at the shoreline. Alcoves and backwaters (*sensu* Moore et al. 2010) were lumped into a single category because of their similarities and rarity in the study area. Alcoves were the most protected lateral habitat type, at least partially displaced from the active channel, not scoured by high flows, and contained fine sediment and organic matter as the dominant substrate types. Backwaters were defined as eddying habitat created by obstructions that were part of the active channel during all flows and had substrate types from sand to cobble. Marsh was a relatively shallow area with emergent vegetation extending a substantial distance from the shear line. The marsh habitat type was prevalent from Benham Falls to Wickiup Dam in the upper Deschutes River. Marsh habitat in this area usually was created by artificially high flows that inundated riparian areas during the irrigation season and dewatered them during the water storage season. Transect width was measured from the water's edge to the current shear line. Transect depth was measured along each transect at 0, 50, and 100% of the distance from the from the river edge. Dominant and subdominant substrate were measured using modified Wentworth classification types (see Bain 1999). Cover types measured were aquatic vegetation, instream wood, overhead vegetation, and undercut bank. Aquatic vegetation included live, non-woody plants (emergent or submerged) such as algae, sedge, cattails, grass, and forbs. Instream wood included live woody plants and dead wood in the water and potentially creating instream cover. Overhanging vegetation included live or dead vegetation within 0.5 m of the water surface. Presence of undercut bank at individual transects was recorded if the bank was undercut at least 0.1 m.

When there was more than one channel in a site, fish and habitat surveys were conducted in the main and secondary channels. The GPS start point for a replicate was used to draw a line perpendicular to the main flow across all channels. The location where this line intersected a secondary channel acted as the survey start point. The end point and replicate length was determined as stated above. In sites with multiple channels, two main channel sites and two secondary channel sites were surveyed. For replicates in short secondary channels and small off-channel habitats (<100m long), at least 10 habitat transects were surveyed.

Temperature and Discharge

Stream temperature was recorded during the study period at 38 observation sites by digital temperature loggers (Minilog-II-T, Vemco, Nova Scotia, Canada, accuracy ±0.1 °C; and Hobo Water Temp Pro v2, Onset, MA, U.S.A, ±0.5 °C), henceforth referred to as thermographs, and placed in locations spread throughout the study area (Figure 1). Thermographs were managed by several different agencies and placed in accordance with agency-specific study objectives. Those agencies were Oregon Department of Fish and Wildlife (ODFW), City of Bend (COB), U.S. Bureau of Reclamation (USBR), and the Upper Deschutes Watershed Council (UDWC). Depending on the agency, stream temperature was recorded every 30 or 60 minutes. In mid-July, 2015, ODFW thermographs were placed in a way to maximize coverage of the study area and aid in creating a geostatistical stream-temperature model. This model, built from these observed temperature locations and site covariates, was used to estimate maximum seven-day moving average of the daily maximum temperature in the summer period ($7DADM_s$) of June 15 to August 31, 2015, for a set of prediction sites spaced in 500-m intervals throughout the study area. Maximum $7DADM_s$ was calculated at the observation sites by the following equation:

$$7DADM_s = max_{t,s}\left\{\frac{(T_{t-3} + T_{t-2} + + \cdots T_{t+3})}{7}\right\},$$

where T is the maximum temperature at day t during the summer period s. There are a number of stream temperature descriptors useful in predicting distribution patterns of salmonids (see Benjamin et al. 2016), including maximum summer 7DADM (e.g., Isaak et al. 2010), which can be used as an indicator of both acute and chronic thermal conditions of a study area during summer (Falke et al. 2016). Seven of the ODFW thermographs were placed in the river too late to capture the early-July maxima in stream temperature, but they recorded a secondary peak in mid-July. To estimate the early-July maximum $7DADM_S$ at these seven late sites, the difference between early-July and mid-July maximum $7DADM_S$ was calculated for each pair of thermographs bracketing (i.e., upstream and downstream) a late site and the mean difference was added to the mid-July maximum $7DADM_S$ of the bracketed late site.

Daily discharge has been recorded at three USBR Hydromet Stations on the Deschutes River (Figure 1), beginning in 1916 at the station near Bend, 1924 at the Benham Falls station, and 1983 at Wickiup Dam station. After Wickiup and Crane Prairie dams were built and discharge became regulated for storage and irrigation, unregulated discharge was estimated using a USBR hydrological equation beginning in 1990 for the Benham Falls station and 1983 at the Wickiup Dam station. Mean daily discharge data were downloaded from the USBR Hydromet website (https://www.usbr.gov/pn/hydromet/).

Seasonal habitat comparison

Seasonal change in lateral habitat characteristics and YOY trout use was investigated by revisiting a subset of sample sites, which were surveyed during the irrigation season from upper Deschutes River dams (i.e., mid-April to mid-October), and repeating fish and habitat surveys during the water-storage season (late October to early April). The subset was selected from three reach-stratified lists: 1) sites with a high density of YOY Redband Trout (i.e., >5 YOY per 100-m), 2) sites with secondary channel habitat, and 3) all other sites. For each reach, high-density sites were selected in order of density (with highest first), multi-channel sites and all other sites were selected randomly.

Data analysis

Fish and habitat surveys

Replicate survey time was standardized to a survey length of 100-m by calculating the quotient of the survey minutes and the measured length of a replicate and then multiplying the quotient by 100 for each replicate. Standardized survey time was averaged for both backpack and raft electrofishing and for habitat surveys in general. Capture method duration was compared using a t-test of backpack and raft electrofishing seconds. Density of YOY trout was summarized at the site level and displayed as the mean number of YOY captured per 100-m surveyed. Habitat surveys were summarized at the levels of reach and lateral habitat type, using proportions for variables that were counted and means for measured variables.

Occupancy

A single-season occupancy model (MacKenzie et al. 2006) with a spatial revisit design was used for estimating detection (p) and occupancy (ψ) probabilities of YOY Redband Trout and Brown Trout and for evaluating the influence of sampling and habitat factors and covariates on p and ψ; each species was modeled separately. YOY age-class was determined by visual evaluation of length-frequency histograms of all captured trout. To account for growth over the sampling period and by reaches with different stream temperatures, histograms were evaluated by month and reach or tributary for each species (Appendix 1). To reduce the number of candidate covariates, logistic generalized linear mixed modeling with a site-level random intercept was used to evaluate the influence of continuous covariates individually on detection (using only known occupied sites) and univariate logistic regression modeling to evaluate occupancy (using all sites) (Wenger et al. 2008). Plots of these comparisons were visually inspected for non-linear relationships. Covariates from models with *P*-value < 0.1 were evaluated in the occupancy modeling (see Appendix 2 for results). Multicollinearity among the candidate covariates was evaluated using Pearson product moment correlations of all pairwise combinations (Wenger et al. 2008). Covariates that were statistically significant and strongly correlated (defined as *P*-value < 0.05 and the absolute value of the correlation coefficient [*R*] > 0.5) were evaluated individually in the detection and occupancy modeling. The detection model was built by first evaluating a set of time models to determine if detection varied among replicate visits, and then candidate covariates and factors were evaluated with the top-ranked time model fixed (Appendix 3). The top-ranked detection model was used as the baseline for modeling occupancy. A spatial factor, with levels based on different groupings of reaches and tributaries, was evaluated first in occupancy modeling, and other covariates were evaluated with the top-ranked spatial model fixed (Appendix 4). Akaike information criterion model selection procedures, with a correction for small sample size [AIC_c], were used to select the model that best approximated the data (Burnham and Anderson 2002). Models were ranked by AIC_c values and evaluated using the ΔAIC_c (i.e., the difference in AIC_c values between a given model and the highest ranked model; only models with $\Delta AIC_c < 7$ are shown) and Akaike weight (w_i), which is a relative measure of the weight of evidence for a model given the data. The best approximating model had the lowest AIC_c value and the greatest w_i. R statistical software 3.3.2 (R Core Team 2016) was used for all data analysis and in conjunction with Program MARK (White and Burnham 1999) through the package RMark (Laake 2013). Naïve detection was calculated, for known occupied sites, as the ratio of the number of replicates with YOY detected and the total number of replicates surveyed. Naïve occupancy was calculated as the ratio of the number of sites occupied by YOY and the total number of sites surveyed. Coefficient of variation (CV), a measure of estimate precision, was calculated as the ratio of the standard error (SE) and the modeled estimate of detection and occupancy probabilities (Conroy and Carroll 2009).

Stream temperature model

A stream-temperature model was built using a geostatistical method designed to represent the spatial autocorrelation inherent in stream networks (see Peterson and Ver Hoef 2010, Ver Hoef and Peterson 2010). Generalized linear modeling was used to evaluate several temperature models for their ability to predict stream temperature (i.e., maximum $7DADM_S$) at prediction sites spaced at 500-m intervals throughout the study area. The predictor variables evaluated were mean elevation and separate indicator variables for the Deschutes River, a cold tributary group (i.e., Fall River, Spring River, and Tumalo Creek), and the Little Deschutes River. Mean elevation for a 500-m prediction site was calculated by averaging the elevation of the upstream and downstream site endpoints. Elevation was derived using a 10-m Digital Elevation Model (DEM) layer in ArcGIS ArcMap 10.4.1 (Environmental Systems Research Institute, Redlands, California, USA). The Spatial Tools for the Analysis of River Systems (STARS) ArcGIS custom toolset was used to calculate the spatial information needed to fit geostatistical models (Peterson and Ver Hoef 2014). Several spatial and non-spatial models were fit using the Spatial Stream Network (SSN) package (Ver Hoef et al. 2014) for R statistical software (Appendix 5). Also using the SSN package, universal kriging (Le and Zidek 2006) was used to predict maximum $7DADM_S$ for prediction sites and leave-one-out cross validation [LOOCV] was used to evaluate each model for its predictive performance at observation sites (Ver Hoef et al. 2014). The best approximating model of maximum $7DADM_S$ for this study area was selected using a combination of low AIC value; model fit of the data, using the coefficient of multiple determination (r^2); and best predictive ability, using the lowest root-mean-squared prediction error [RMSPE] from the LOOCV.

Seasonal habitat and occupancy comparison

Paired t-tests were used to compare differences between habitat variables for Deschutes River sites that were sampled during the irrigation season and again during the water-storage season. Sites were pooled into three different river segments to represent the distinct flow characteristics; and comparisons were done separately by segment, which were defined by the following landmarks: 1) Steelhead Falls to North Canal Dam, 2) North Canal Dam to Benham Falls, and 3) Benham Falls to Wickiup Dam. Seasonal photo points were also displayed for a visual comparison of habitat changes. Seasonal site occupancy by YOY Redband and Brown Trout was evaluated with a simple comparison of change in naïve occupancy.

Results

Fish and habitat surveys

Fish surveys were conducted from July 8 to October 8, 2015, in 139 sites and 467 replicates; proportionally by site, this covered 33% of the 209 km sampling frame (Table 1). Standardized for a 100-m replicate, the mean replicate survey time was 41 minutes (range, 19-119) for backpack electrofishing surveys, 14 minutes (range, 4-100) for raft electrofishing surveys, and 32 minutes (range, 12-67) for habitat surveys. Mean electrofishing seconds per replicate was significantly greater using the backpack electrofisher (669 s) than it was using the raft electrofisher (408 s) (95% confidence interval of difference = 203-320 s, t = -8.83, df = 214, *P*-

value <0.001). Four species of salmonid (Table 2) and ten other fish species (Table 3) were captured during fish surveys. By sampling in the lateral habitat, most of the salmonids captured were YOY: 88% of Redband Trout, 82% of Brown Trout, and 74% of Mountain Whitefish (Table 2, Figure 3). Among salmonids, Redband Trout and Brown Trout comprised 79% of the catch (Table 2). Sculpin and Threespine Stickleback were highly abundant, mainly in the upper Deschutes (Table 3).

YOY densities at the replicate level (standardized for a replicate length of 100 m) ranged from 0 (N=102 replicates) to 67 Redband Trout and from 0 (N=127) to 45 Brown Trout (Figure 4). YOY Redband Trout and Brown Trout were distributed in all the Deschutes River reaches and tributaries, except YOY Redband Trout were not detected in Spring Creek (Table 2, Figure 5). Sites with high densities of Redband Trout (i.e., >5 YOY per 100-m) were detected in all reaches in the middle Deschutes River, Tumalo Creek, and only Reach 5 of the upper Deschutes River. Multiple high density sites of YOY Redband Trout were only detected in Reach 1, Reach 4, and Reach 5 of the Deschutes River and Tumalo Creek. High densities of YOY Brown Trout were detected in Reach 1, Reach 2, and Reach 4 of the Deschutes River; Spring River and two Deschutes River sites (in Reach 7) just downstream of the Spring River confluence; and Fall River.

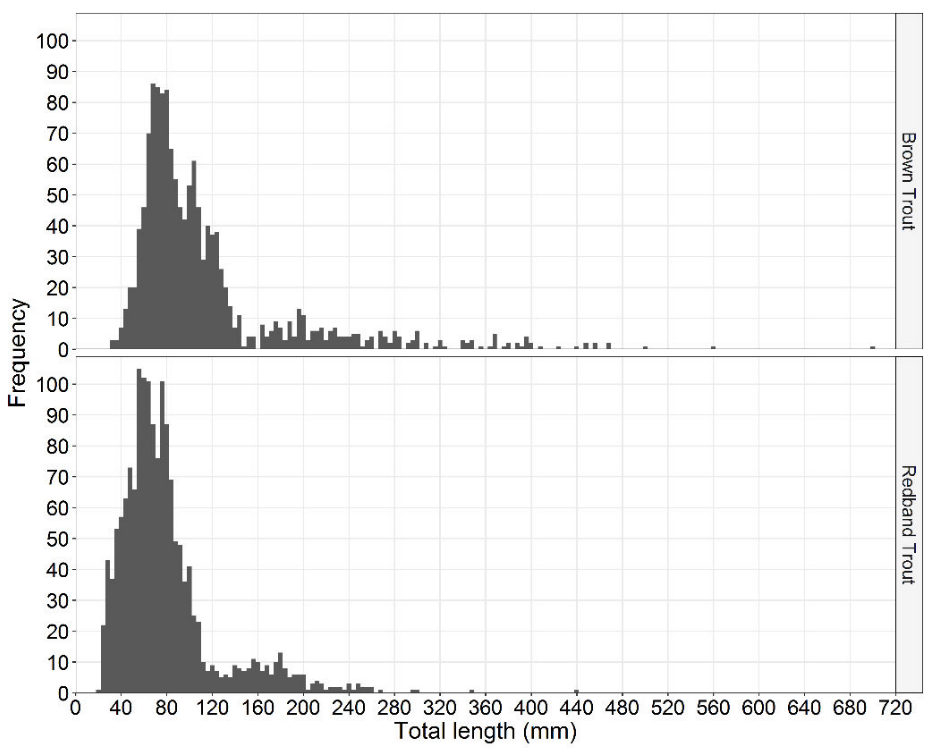


Figure 3. Frequency distributions of the total body length of Brown Trout and Redband Trout captured during fish surveys in the study area. Bars represent 4-mm bins.

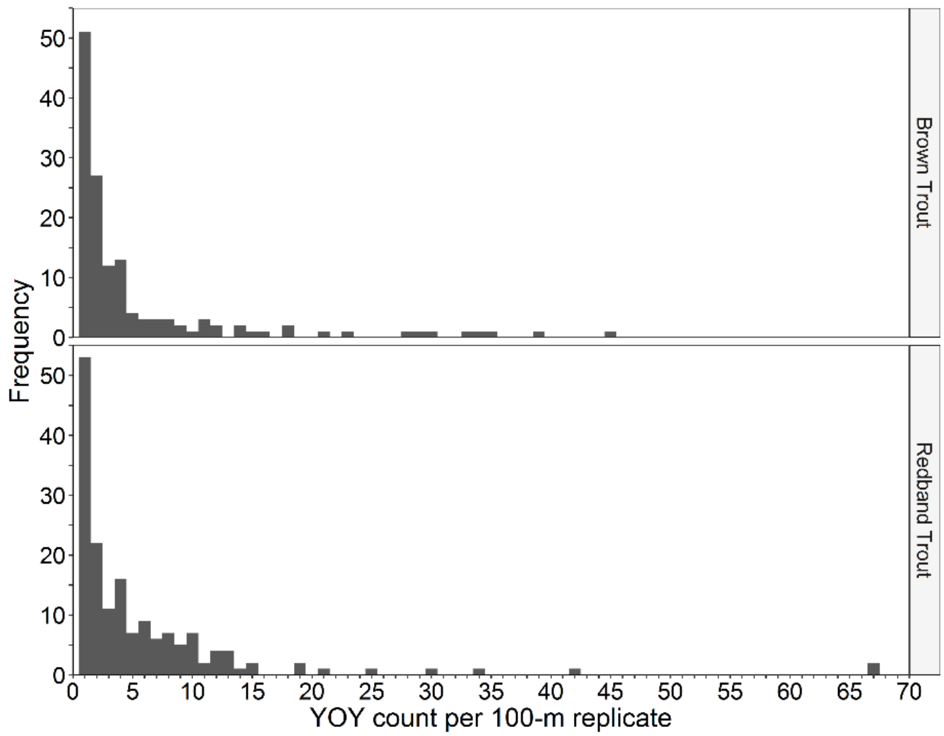


Figure 4. Frequency distributions of the number of young-of-the-year (YOY) captured at individual replicates standardized for 100-m fish survey length. No YOY Brown Trout were captured in 127 replicates and no YOY Redband Trout were captured in 102 replicates; however, these bars are not shown in this figure.

Habitat surveys were conducted in 87 sites and 267 replicates; as a proportion of the total number of sites, this equaled 21% of the sampling frame. Fewer habitat surveys than fish surveys were completed because the focus at the end of the field season shifted to fish surveys only and increasing the sample size of YOY Redband Trout tissue samples for genetic analysis. Habitat surveys were not conducted in the Little Deschutes River and these fish survey sites were not included in the occupancy modeling. Habitat characteristics varied by reach (Appendix 6). Compared to the upper Deschutes River reaches, the middle Deschutes River reaches (i.e., Reach 1-4) contained a higher proportion of fastwater and pool habitat units, bank lateral habitats, coarse sediments, and overhanging vegetation; and greater mean channel slope and warmer maximum $7DADM_S$. Relative to the middle Deschutes River, the upper Deschutes River reaches had a higher proportion of glide and marsh habitats, fine sediment, and emergent vegetation; as well as lower mean channel slope and maximum $7DADM_S$. Relative to the Deschutes River reaches, the cold tributaries (i.e., Tumalo Creek, Spring River, and Fall River) had the highest proportion of gravel, greatest mean slope, and the lowest mean summer stream temperature (Appendix 6). Off-channel and secondary channel habitat was relatively rare throughout the study area. Lateral habitat characteristics varied by type (Appendix 7). Alcove-Backwaters were rarely encountered and had the greatest mean lateral habitat volume. Bars were associated with greater channel slope and most prevalent in fastwater habitat units. Banks were the most common type encountered and most prevalent in glides. Marshes were most prevalent in glides and had a high proportion of silt sediment and low mean channel slope.

Occupancy modeling

The best approximating occupancy models for YOY trout showed some differences and similarities between the two species. For YOY Redband Trout, the probability of detection varied by capture method and replicate visit (Table 4, Table 5). Detection probability for Redband Trout varied from 0.21 to 0.84, with greater detection using the backpack electrofisher and during the first two replicates surveyed at a site (Table 6). The occupancy probability of YOY Redband Trout varied by spatial group and survey side orientation (Table 6, Table 7). YOY Redband Trout occupied all sites surveyed in Deschutes River reaches 3, 4, and 6, and in Tumalo Creek (i.e., ψ=1.00). There was a high probability of occupancy (ψ=0.87) in reaches 1, 2, 5, 8, and 10 and a moderate occupancy probability (ψ=0.62) in reaches 7 and 9, Spring River, and Fall River. YOY Redband Trout occupancy was negatively associated with the outside bend of the river. There was high precision in the detection probability and occupancy probability estimates at the reach level (CV range, 0.07-0.18).

For YOY Brown Trout, detection probability did not vary by replicate visit but was positively associated with electrofishing seconds (which was related to capture method) and negatively associated with mean lateral habitat width (i.e., poorer detection with greater width) (Table 4, Table 5). Detection probability for YOY Brown Trout was 0.68 (Table 6). Similar to Redband Trout, YOY Brown Trout occupancy probability varied by a spatial group factor; however, they differed in the specific spatial group. Brown Trout occupied all sites surveyed in Deschutes River reaches 2, 8, and 9, and Spring River (ψ=1.00). There was a high probability of occupancy (ψ=0.86) in reaches 1, 3, 4, 6, 7, and Fall River and a moderate occupancy probability (ψ=0.53) in reaches 5 and 10, and in Tumalo Creek. Detection and occupancy probability estimates were highly precise at the reach level (CV range, 0.08-0.25).

Temperature modeling

The temperature model that was most strongly supported by the data included mean elevation and a tributary factor variable, which consisted of indicators for the Deschutes River (acting as the reference), cold tributary, and the Little Deschutes River; the linear model was as follows (Table 7):

$$7DMAM_S = 34.09 - 0.01(Elevation) - 2.59(Cold\ Trib) + 9.35(Little\ Deschutes) + z + \varepsilon,$$

where z contains the spatially autocorrelated variance components and ε contains random error. The top candidate model results and comparisons are presented in Appendix 5. All explanatory variables were statistically significant. The linear model explained 80% of the variation in the data and had a RMSPE of 1.53 (Figure 6). Summer stream temperature generally decreased in the upstream direction in the Deschutes River, with reach means of maximum 7DMAMs ranging from 21.4^o to 24.9^o C in the middle segment and 17.2^o to 19.4^o C in the upper segment (Figure 7). Mean 7DMAM$_s$ was 16.4^o C for Tumalo Creek, 14.0^o C for Spring Creek, 27.0^o C for the Little Deschutes River, and 14.5^o C for Fall River (Figure 7).

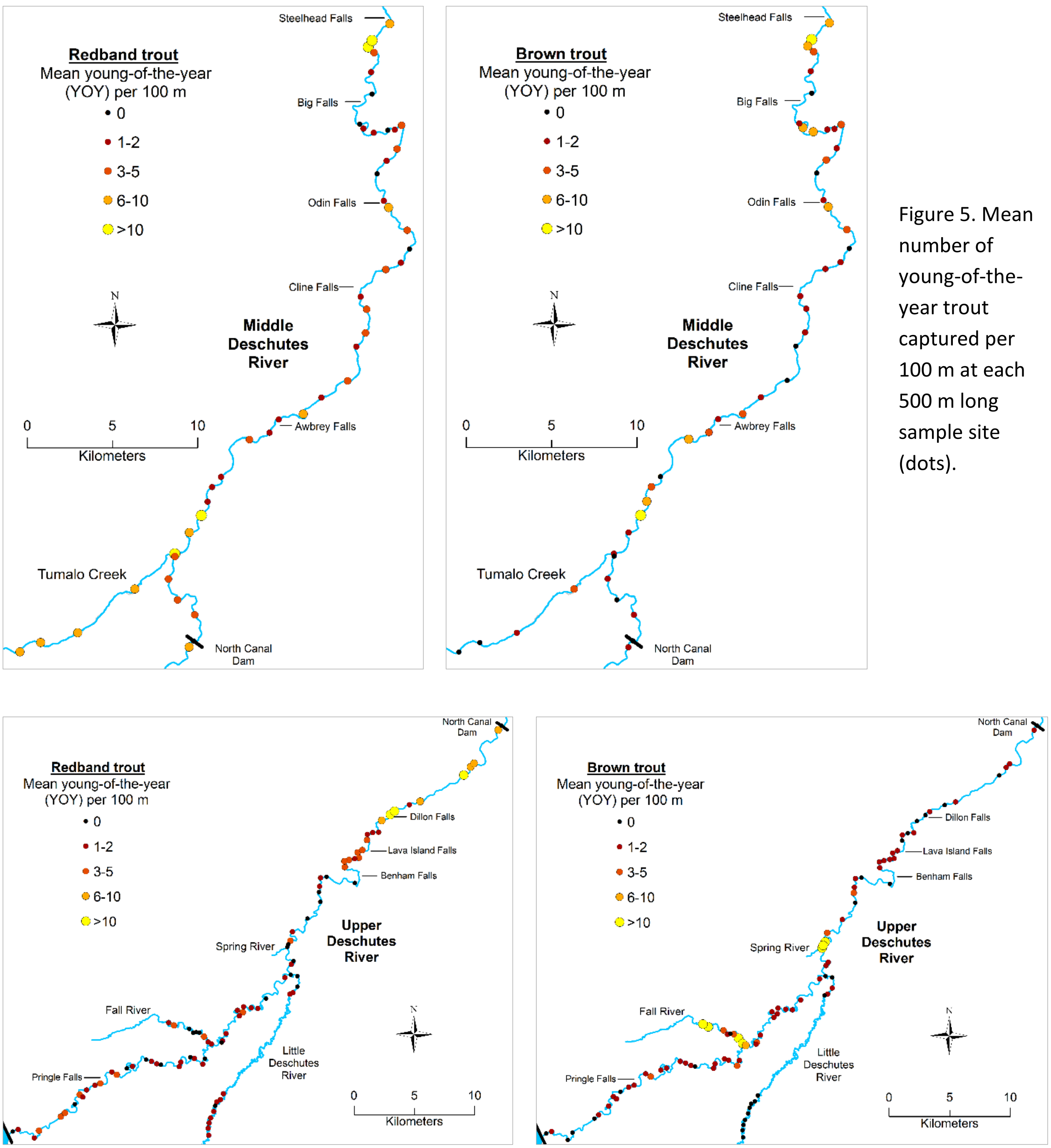


Figure 5. Mean number of young-of-the-year trout captured per 100 m at each 500 m long sample site (dots).

Table 4. Occupancy modeling results for YOY trout evaluated using Akaike Information Criterion with a correction for small sample size (AICc). The best approximating model was determined by the lowest AICc value and the greatest Akaike weight (w_i).

Redband trout					
p model	ψ model	Parameters	AICc	ΔAICc	w_i
~pG2 (p1=p2, p3=p4) + capture method	~sgG + outside bend	7	299.22	0.00	0.46
	~sgG + outside bend + overhanging veg.	8	300.74	1.53	0.22
	~sgG + outside bend + fastwater unit	8	301.64	2.42	0.14
	~sgG + overhanging vegetation	7	302.81	3.60	0.08
	~sgG	6	303.02	3.80	0.07
	~sgG + fastwater unit	7	305.03	5.81	0.03

Brown trout					
p model	ψ model	Parameters	AICc	ΔAICc	w_i
~efishing seconds + mean lateral width	~sgJ	6	336.50	1.42	0.61
	~sgJ + channel slope	7	337.36	2.28	0.39

Table 5. Linear model results for the top models for detection and occupancy of YOY trout in the Deschutes River basin study area. Spatial group "G" and "J" (sgG and sgJ) were factors with three indicator variables; all sites surveyed in sgG3 and sgJ3 were occupied (ψ =1) so betas (β) were not estimable. β represents the slope of the linear relationship of individual covariates and is considered significant if their confidence interval (CI) does not overlap zero.

Redband Trout					Brown Trout				
β	Estimate	SE	CI: Lower	CI: Upper	β	Estimate	SE	CI: Lower	CI: Upper
p: intercept	1.7	0.2	1.2	2.2	*p*: intercept	1.4	0.3	0.7	2.1
p: pG2 (p3=p4)	-2.1	0.7	-3.4	-0.8	*p*: efishing seconds	0.4	0.2	0.1	0.7
p: boat capture	-0.9	0.3	-1.6	-0.3	*p*: mean lateral wd.	-0.5	0.2	-1.0	-0.1
ψ: intercept	0.8	0.5	-0.1	1.8	ψ: intercept	-0.4	0.6	-1.6	0.8
ψ: outside bend	-3.7	1.5	-6.7	-0.6	ψ: sgJ2	1.7	0.7	0.2	3.1
ψ: sgG2	1.4	0.7	0.1	2.8	ψ: sgJ3	NA	NA	NA	NA
ψ: sgG3	NA	NA	NA	NA					

Seasonal comparison

Twenty sites and 58 replicates were revisited among all 10 reaches of the Deschutes River for habitat and fish surveys during the water storage season from October 23, 2015, to March 24, 2016. Five replicates (9%) were not surveyable because the channel was covered in ice, dewatered, or both, mainly upstream of Pringle Falls (i.e., Reach 10). There were significant seasonal differences in channel and lateral habitat characteristics in the revisited replicates (Table 8). In the segment from Steelhead Falls to North Canal Dam, mean daily discharge averaged 360 cfs higher during revisits and channel width increased by 7.9 m. Lateral habitats in this segment increased in several habitat dimensions, including habitat volume in general; sediment size shifted from coarse to fine; and emergent vegetation increased because some vegetated riverbanks were inundated by the increased discharge. In the segment from North

Canal Dam to Benham Falls, discharge decreased by a mean of 1083 cfs; silt sediment, emergent and overhanging vegetation, and water depth decreased; and bars were more prevalent. In the segment from Benham Falls to Wickiup Dam, discharge was 1309 cfs lower during revisits and mean channel width decreased by 14.8 m. Later habitats in this segment decreased in width and depth; bank and marsh type habitat declined and bars increased; sediments shifted toward gravel and away from silt; emergent and overhanging vegetation and undercut banks decreased. Naïve YOY occupancy decreased from 80% (16 of 20 sites) for Redband Trout and 75% (15 of 20 sites) and for Brown Trout during the irrigation season to 60% for both species during the water storage season (Table 9).

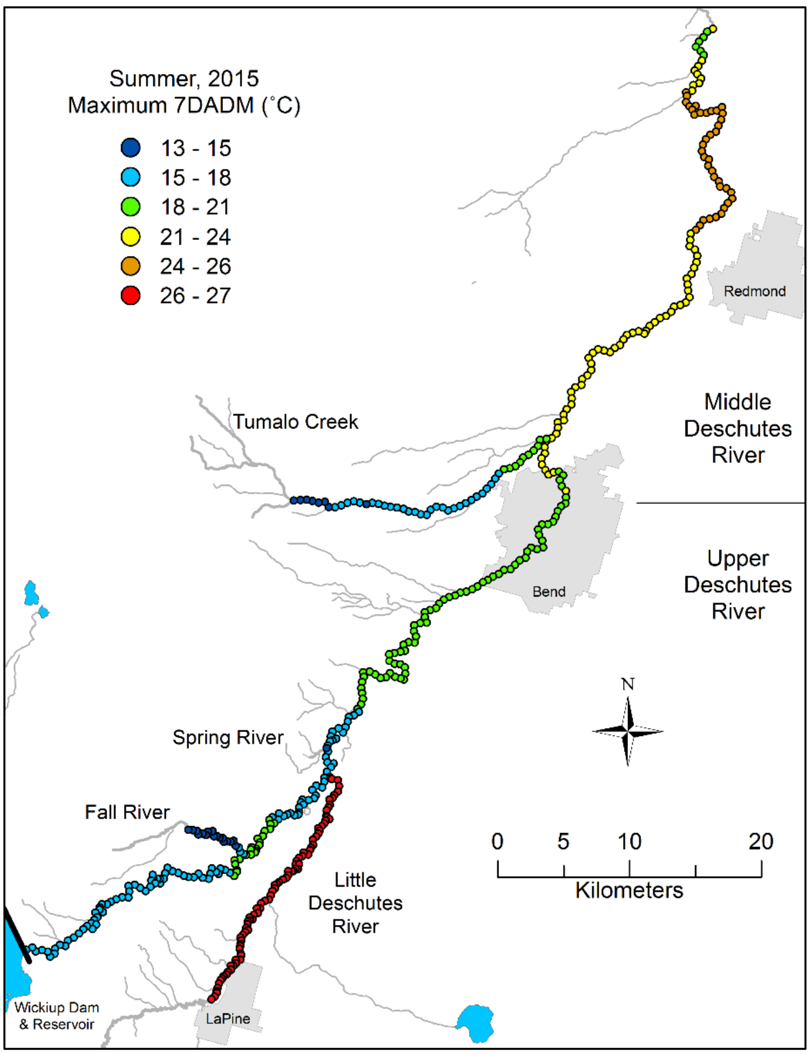
Table 6. Modeled detection (p) and occupancy (ψ) probabilities and 95% confidence intervals (CI) for YOY trout in the Deschutes River study area. Capture method consisted of two types of electrofishing. Naïve detection was calculated, for known occupied sites, as the ratio of the number of replicates with YOY detected and the total number of replicates surveyed. Naïve occupancy was calculated as the ratio of the number of sites occupied by YOY and the total number of sites surveyed. Coefficient of variation (CV), a measure of estimate precision, was calculated as the ratio of the standard error (SE) and the modeled estimate of detection and occupancy probabilities.

	Redband Trout								Brown Trout						
Detection: Visit	Capture method	Naïve *p*	Modeled *p*	SE	CI: Lower	CI: Upper	CV	Detection: Visit		Naïve *p*	Modeled *p*	SE	CI: Lower	CI: Upper	CV
p1, p2	backpack	0.86	0.84	0.03	0.77	0.90	0.04	p1, p2, p3, p4		0.68	0.65	0.04	0.58	0.72	0.05
p3, p4	backpack	0.75	0.40	0.15	0.16	0.70	0.38								
p1, p2	raft	0.75	0.68	0.05	0.56	0.77	0.08								
p3, p4	raft	0.62	0.21	0.11	0.06	0.50	0.56								

Occupancy: Deschutes Reach/Trib	Spatial group (G)	Naïve ψ	Modeled ψ	SE	CI: Lower	CI: Upper	CV	Occupancy: Deschutes Reach/Trib	Spatial group (J)	Naïve ψ	Modeled ψ	SE	CI: Lower	CI: Upper	CV
1	2	0.83	0.87	0.06	0.70	0.95	0.07	1	2	0.83	0.86	0.07	0.67	0.94	0.08
2	2	0.78	0.87	0.06	0.70	0.95	0.07	2	3	1.00	1.00	NA	NA	NA	NA
3	3	1.00	1.00	NA	NA	NA	NA	3	2	0.71	0.86	0.07	0.67	0.94	0.08
4	3	1.00	1.00	NA	NA	NA	NA	4	2	0.75	0.86	0.07	0.67	0.94	0.08
Tumalo Creek	3	1.00	1.00	NA	NA	NA	NA	Tumalo Creek	1	0.50	0.53	0.13	0.28	0.76	0.25
5	2	0.86	0.87	0.06	0.70	0.95	0.07	5	1	0.57	0.53	0.13	0.28	0.76	0.25
6	3	1.00	1.00	NA	NA	NA	NA	6	2	0.71	0.86	0.07	0.67	0.94	0.08
7	1	0.50	0.62	0.11	0.40	0.80	0.18	7	2	0.75	0.86	0.07	0.67	0.94	0.08
Spring River	1	0.00	0.62	0.11	0.40	0.80	0.18	Spring River	3	1.00	1.00	NA	NA	NA	NA
8	2	0.86	0.87	0.06	0.70	0.95	0.07	8	3	1.00	1.00	NA	NA	NA	NA
Fall River	1	0.57	0.62	0.11	0.40	0.80	0.18	Fall River	2	0.86	0.86	0.07	0.67	0.94	0.08
9	1	0.67	0.62	0.11	0.40	0.80	0.18	9	3	0.89	1.00	NA	NA	NA	NA
10	2	0.86	0.87	0.06	0.70	0.95	0.07	10	1	0.43	0.53	0.13	0.28	0.76	0.25

Table 7. Parameter estimates and summary statistics for the final temperature model used to predict the maximum 7-day moving average maximum daily stream temperature in summer (7DADM$_S$) at 500-m intervals throughout the study area. Root mean square prediction error (RMSPE) is presented and "Cold tribs" consisted of Tumalo Creek, Spring River, and Fall River.

Predictor							Variance component	
fixed effects	β	SE	t	*P*-value	RMSPE	r^2	Fixed effect (%)	Spatial error (%)
Intercept	34.09	2.44	14.0	<0.001	1.53	0.80	80.2	19.8
Elevation	-0.01	0.002	-6.0	<0.001				
Trib1 – Cold tribs	-2.59	0.93	-2.8	0.008				
Trib2 – L. Deschutes	9.35	1.38	6.8	<0.001				



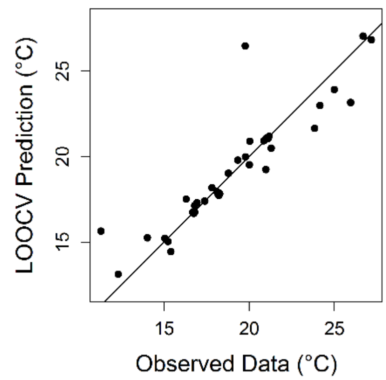


Figure 6. Accuracy comparison (above), using leave-one-out cross validation (LOOCV), of the observed summer stream temperature at 38 thermograph locations and stream temperature predictions from the best fitting geostatistical model (r^2=0.80).

Figure 7. Stream temperature predictions (left) of the seven-day moving average maximum daily temperature in summer (7DADM$_S$), 2015, at 500 m intervals based on a geostatistical temperature model built from continuous water temperature records at 38 thermograph locations.

Table 8. Paired t-test results comparing lateral and channel (italicised) habitat characteristics during the irrigation season (April-October, 2015) and the water storage season (November 2015 to March 2016).

Deschutes Segments	Variable	*t*	DF	*P*-value	Seasonal change	CI: Lower	CI: Upper
Steelhead Falls to North Canal Dam	Emergent vegetation (%)	5.4	21	<0.001	0.29	0.18	0.40
	Discharge (cfs)	-7.8	7	<0.001	361.13	471.10	251.16
	Boulder (%)	-3.4	21	0.003	-0.13	-0.21	-0.05
	Cobble (%)	-3.2	21	0.005	-0.16	-0.27	-0.06
	Lat. hab. mean width (m)	3.1	21	0.006	0.71	0.23	1.18
	Sand (%)	2.9	21	0.009	0.22	0.06	0.37
	Silt/Organic (%)	2.8	21	0.011	0.16	0.04	0.29
	Channel width (m)	2.7	21	0.013	7.89	1.84	13.95
	Pebble (%)	-2.6	21	0.016	-0.06	-0.11	-0.01
	Lat. hab. max depth (m)	2.6	21	0.017	0.29	0.06	0.52
	Lat. hab. mean depth (m)	2.4	21	0.025	0.05	0.01	0.10
	Large wood (%)	2.3	21	0.035	0.04	0.00	0.08
	Lat. hab. volume (m^3)	2.2	21	0.041	22.66	1.04	44.28
	Overhanging veg. (%)	-2.1	21	0.044	-0.13	-0.25	0.00
North Canal Dam to Benham Falls	*Discharge (cfs)*	15.2	5	<0.001	-1082.90	-899.84	-1265.89
	Silt/Organic (%)	-4.3	16	0.001	-0.47	-0.70	-0.23
	Emergent veg. (%)	-3.6	16	0.002	-0.43	-0.68	-0.18
	Sand (%)	3.5	16	0.003	0.27	0.11	0.44
	Lat. hab. mean depth (m)	-3.1	16	0.008	-0.14	-0.24	-0.04
	Lat. hab. max depth (m)	-2.5	16	0.022	-0.38	-0.70	-0.06
	Bar (%)	2.4	16	0.028	0.23	0.03	0.43
	Overhanging veg. (%)	-2.3	16	0.036	-0.06	-0.12	0.00
Benham Falls to Wickiup Dam	Bar (%)	8.5	15	<0.001	0.73	0.55	0.91
	Channel width (%)	-7.6	15	<0.001	-14.80	-18.97	-10.63
	Discharge (cfs)	14.1	5	<0.001	-1308.50	-1070.50	-1546.40
	Mean depth (%)	-5.2	15	<0.001	-0.28	-0.39	-0.16
	Emergent veg. (%)	-4.7	15	<0.001	-0.44	-0.64	-0.24
	Silt/Organic (%)	-4.4	15	<0.001	-0.46	-0.68	-0.24
	Marsh (%)	-4.0	15	0.001	-0.45	-0.69	-0.21
	Gravel (%)	3.8	15	0.002	0.23	0.10	0.36
	Mean width (%)	3.5	15	0.003	1.19	0.47	1.92
	Bank (%)	-3.2	15	0.006	-0.31	-0.52	-0.10
	Electrofishing (sec)	3.1	15	0.008	202.12	61.31	342.94
	Overhanging veg. (%)	-3.1	15	0.008	-0.06	-0.11	-0.02
	Lat. hab. max depth (m)	-2.9	15	0.011	-0.55	-0.96	-0.14
	Transects (N)	2.8	15	0.013	1.56	0.38	2.75
	Undercut banks (%)	-2.6	15	0.022	-0.11	-0.20	-0.02

Table 9. Seasonal change in naïve occupancy of 20 sample sites surveyed during the irrigation and water storage seasons.

	Irrigation season				Water storage season			
	Occupied		Not detected		Occupied		Not detected	
Species	%	N	%	N	%	N	%	N
Redband trout	80	16	20	4	60	12	40	8
Brown trout	75	15	25	5	60	12	40	8

Discussion

YOY Redband Trout and Brown Trout occupancy and density patterns

Young-of-the-year (YOY) Redband Trout and Brown Trout were widely distributed throughout the study area and detected in all sampling reaches of the Deschutes River and most of its tributaries. Although there was much spatial overlap in the distribution of the two species, there were differences in the spatial pattern of occupancy probabilities and relative densities of YOY. For YOY Brown Trout, there was a high probability of occupancy throughout the middle Deschutes River, in Spring River and Fall River, and in the Deschutes River reaches adjacent to those tributaries. For YOY Redband Trout, there was a high probability of occupancy and densities from Steelhead Falls upstream to Benham Falls in the Deschutes River and in Tumalo Creek. From Benham Falls upstream to Wickiup Dam, including Spring River and Fall River, there was a moderate probability of Redband Trout occupancy and YOY densities were relatively low.

Effective number of breeders (N_b) was estimated for Redband Trout at the reach and local population levels based on sibling frequency analysis of tissue samples obtained during this study (Bohling et al. 2017). The spatial pattern of N_b estimates at both the reach and local population levels corresponded to the spatial pattern of YOY occupancy and density, with lower N_b in the river reaches above Benham Falls and high relative N_b in the reaches downstream. This correspondence suggests that YOY occupancy and density alone may be a useful proxy for assessing the status of Redband Trout local populations. Furthermore, occupancy surveys focused on capturing YOY in lateral habitats may provide an alternative to mid-channel sampling methods for assessing status of breeding populations of salmonids in large rivers.

Although capturing YOY Redband Trout was the primary interest, this study also provided information about the distribution and density of nonnative fishes, including the influence of hatchery-reared trout. Nonnative Brown Trout are of management concern because previous studies have shown their wide distribution in the study area and greater relative abundance in the upper Deschutes River (Starcevich et al. 2015, Starcevich 2016) and multiple studies have shown that introduced Brown Trout tend to have competitive advantages over native trout species (Fausch and White 1981, Shirvell and Dungey 1983, Gatz et al. 1987, Wang and White 1994, McHugh and Budy 2005). One area of high relative concern for Redband Trout was the section of the study area that includes Fall River, Spring River, and Reach 7 and Reach 8 of the Deschutes River. In this section, YOY Brown Trout have a higher probability of occupancy and greater densities relative to YOY Redband Trout. Furthermore, the Redband Trout in this section have a high degree of introgression with hatchery-stocked trout, especially in Fall River where hatchery Redband Trout have largely displaced the native Redband Trout (Bohling et al. 2017). Nonnative YOY Brook Trout were also prevalent in the cold tributaries of Tumalo Creek, Spring River, and Fall River. Nonnative Threespine Stickleback, which are likely competitors of YOY trout (Maitland 1965), were present in high relative abundance in the lateral habitats of the upper Deschutes River. This study confirms the wide distribution of Brown Trout and provides sampling reach level resolution on occupancy and density of nonnative fishes, which can aid in the identification of areas of greater relative management concern.

Variables influencing occupancy and density patterns

Despite differences in lateral habitat characteristics by reach and by lateral habitat type, most habitat variables measured in this study were not useful in explaining the variation in the probability of site occupancy for YOY Redband Trout and Brown Trout. The only significant factors explaining variation in the site occupancy probability of YOY trout were spatial group factor and survey side orientation of the river. Several spatial groupings of Deschutes River sampling reaches were evaluated and the top-ranked spatial group model suggested that there were three probability levels of occupancy among the reaches. Because most other habitat variables measured in this study were not useful in explaining variation in site occupancy, these occupancy levels likely did not reflect the spatial availability or quality of lateral habitats in those sampling reaches and tributaries. Rather, it suggests these YOY spatial patterns were more likely reflecting the distribution of spawning and breeding densities, with high YOY occupancy and density reflecting high breeding occupancy and density.

There is some evidence that suggests YOY salmonids have relatively short dispersal distances from their respective redd and families tend to be spatially clumped for an extended period after emergence. For example, in relatively small streams, YOY Brook Trout (Hudy et al. 2010) and Brown Trout (Andersson 2016) tended to be within 300 m of their inferred redd location 8 and 16 months, respectively, after emergence; and YOY Atlantic salmon (*Salmo salar*) remained within 100 m of their redd in an experimental stream at least 2 months after emergence regardless of YOY densities (Einum and Nislow 2005). Since Redband Trout and Brown Trout spawn in different seasons (spring and fall, respectively), the two species experience different seasonal and managed flow regime conditions during spawning and egg development, which may account for some of the interspecific differences in YOY spatial distribution. There is an apparent lack of dispersal studies in rivers the size of the Deschutes River, but our knowledge of

YOY dispersal is likely to increase as new molecular methods are employed to track YOY and family dispersal in a greater range of watersheds (Broquet and Petit 2009, Hudy et al. 2010).

Survey side orientation was the only other explanatory variable in the top occupancy model for YOY Redband Trout. YOY Redband Trout had a significantly higher probability of occupying the lateral habitat of straight channels and in the inside bend of a river relative to lateral habitat in the outside bend of the river. This is not surprising given that, within a river channel, the outside bend is the erosive side and generally has higher relative flow velocities and greater depth and the inside of a bend tends to be depositional with lower flow velocities and more shallow habitat (Knighton 1998). Future studies with the principal focus on maximizing capture of YOY salmonids could minimize sampling effort by avoiding conducting fish surveys in lateral habitats on the outside bend of the river.

The maximum seven-day moving average maximum daily water temperature in summer ($7DADM_S$) was not a significant explanatory variable for YOY Redband Trout and Brown Trout occupancy probabilities even though the maximum $7DADM_S$ exceeded the state water quality standard for trout rearing habitat (7DADM<18 °C; OAR 340-041-0028) in most of the study area. The entire middle Deschutes River segment exceeded the state temperature standard, including the lower portion of Tumalo Creek. In 2015, the standard was exceeded in the upper Deschutes River from North Canal Dam upstream to Benham Falls in the Little Deschutes River. In this study, however, YOY Redband Trout occupied the warmest reaches of the Deschutes River and the lower Little Deschutes River, with maximum $7DADM_S$ temperatures approaching 27 °C. The simplest explanation for this apparent contradiction may be that Redband Trout have a thermal range and temperature tolerance that exceed the state standard. In a laboratory study of YOY Redband Trout response to fluctuating diel temperatures over a wide range of temperatures (8-16 °C, mimicking diel temperatures in montane habitat; and 18-26 °C, for desert habitat), there was high survival and continuous growth under all conditions for fish taken from both montane and desert environments in the Snake River basin, Idaho (Cassinelli and Moffitt 2010). The critical thermal maximum for Redband Trout is 29.4 °C (Rodnick et al. 2004), which exceeds any maximum 7DADM observed in the study area in 2015. Additionally, juvenile Redband Trout have been observed feeding at water temperatures between 26-28 °C (Behnke 1992, Zoellick 1999).

While the current temperature regime may not be measurably affecting Redband Trout distribution and occupancy in this study area, it may be a limiting factor in other ways where the standard is exceeded. The optimum range for growth for Rainbow Trout (*O. mykiss*) in a laboratory setting with fluctuating diel temperatures designed to mimic a more natural thermal regime is between 15.5-17.3 °C (Hokanen et al. 1977, Myrick and Cech 2000). It is not clear that

Redband Trout share the same temperature optima as their conspecifics since intraspecific studies have shown both close similarities (Myrick and Cech 2000) and some differences (Rodnick et al. 2004, Hartman and Porto 2014), and intraspecific temperature-growth relationships for Redband Trout are generally not known (Hartman and Porto 2014). Juvenile Redband Trout collected from both warm and cold streams in Idaho selected a temperature of 13 °C when exposed to a thermal gradient of 8-30 °C in a laboratory environment (Gamperl et al. 2002). In the field, stream temperatures exceeding 18 °C have been shown to slow growth of juvenile Redband Trout (Kammerer and Hepell 2010) and cause a stress response in the form of elevated heat shock protein levels (Kammerer and Hepell 2010); at temperatures greater than 23 °C, Redband Trout lipid storage ability was reduced (Kammerer and Hepell 2010), which can negatively affect growth and survival (McMillan et al. 2011). This suggests that optimal temperature preferences of Redband Trout, similar to Rainbow Trout, are below the 18 °C state standard. Exceeding this state standard may also differentially benefit nonnative Brown Trout, which have been shown to have a higher occurrence probability than Redband Trout in warmer stream temperatures (Wenger et al. 2011).

It is currently unclear how this temperature exceedance affects Redband Trout growth, productivity, occupancy, and population abundance in this study area since pre-development population and thermal regime data for the study area were not found, and there are several confounding factors (e.g., modified flow regime, nonnative species interactions, reduced migratory connectivity, etc.) that may also influence current Redband Trout status. However, exceedance of optimal Redband Trout water temperature and state water quality standards are likely to worsen throughout the region as the regional human population continues to grow (PRC 2015), with a concomitant increase expected in human demands for water (Newton et al. 2006), and the climate warms from greenhouse gas emissions that are projected to continue to accumulate in the atmosphere throughout this century by a range of emissions scenarios used for climate modeling (IPCC 2014). Stream temperatures are projected to increase based on climate warming models and trout of all species in this region are projected to lose thermally suitable habitat and negative interspecific interactions may be exacerbated (Wenger et al. 2012). To accurately predict the status of Redband Trout populations in this study area and the region in general, a more thorough understanding of inter- and intra-specific population response to elevated water temperature is needed and a statistically rigorous temperature model should be built to predict stream temperatures under different managed discharge regimes and climate warming scenarios for this study area.

Seasonal change in lateral habitat and fish occupancy

Seasonal change in channel and lateral habitat characteristics was documented throughout the Deschutes River. The greatest number of significant habitat characteristic changes occurred in the first segment (i.e., Steelhead Falls to North Canal Dam) and third segment (i.e., Fall River to Wickiup Dam), both of which experienced the greatest relative change in discharge from irrigation season to water storage season. In the abrupt transition from irrigation to water storage season, discharge increased four-fold in the first segment, decreased by 98% in the third segment, and dropped by 61% in the second segment (i.e., North Canal Dam to Fall River). It is difficult to interpret the changes in lateral habitat characteristics and how they might affect YOY Redband Trout given that none of the characteristics measured significantly influenced the probability of YOY occupying a site. Dramatic and abrupt changes to channel characteristics in the first and third segments, namely discharge and channel width (see selected photos in Appendix 8), likely led to large changes in habitat volume. The abrupt reduction in discharge can directly affect trout populations by stranding and killing large numbers of fish, especially juvenile trout in lateral habitats, which occurs annually in the secondary channel along Lava Island in the Deschutes River (see Starcevich et al. 2015). Abrupt changes in discharge and dewatering of lateral habitats can also adversely affect fish populations through the extirpation of aquatic insects whose larval stages depend on the river margins (Kennedy et al. 2016). Since these aquatic insects are important prey of fish and other predators (Baxter et al. 2005), this extirpation of or reduction in insect diversity and density undermines river food webs, which has been documented in other managed river systems (Kennedy et al. 2016).

Time constraints and lack of winter access to the river resulted in a small sample size of revisited sites so the effect of the large and abrupt changes in discharge of the managed flow regime on habitat were not well quantified in this study. An early study measured the effect of flow management on upper Deschutes River habitat and found that lowering discharge from 650 cfs to 50 cfs at Wickiup Dam exposed 36% of the stream bottom and would lead to a substantial reduction in the aquatic prey base and trout production (Dimick et al 1947). To our knowledge, no contemporary study has attempted to quantify the effect of the managed flow regime on the aquatic prey base in this study area. To improve our understanding of how the Deschutes River habitat and aquatic prey base are affected by the managed flow regime, we suggest using remote sensing tools (see Whited et al. 2013, Gilvear and Bryant 2016) to efficiently and extensively quantify channel habitat characteristics by season or at different levels of discharge and implement studies designed to quantify aquatic insect diversity, density, and lateral habitat use in relation to the flow regime.

Feasibility and effectiveness of the monitoring protocol

The protocol of conducting occupancy surveys with a spatial revisit design in lateral habitats focused on capturing YOY trout was more feasible when compared to previous raft electrofishing surveys in the large river habitats of the Deschutes River (see Starcevich et al. 2015, Starcevich 2016). Relative to raft electrofishing in large river habitat, person-hours per site was reduced because there was less habitat volume to survey, each site was sampled in less than a day and did not require repeat visits to the same site, and smaller crews were required since surveys were conducted in relatively shallow and narrow bands along the river margin. The reduction in person-hours per site allowed for a greater sample size per unit time.

Relatively equal effort (i.e., similar electrofishing seconds) was used at each replicate, whether discharge was 14 cfs or 2090 cfs, which made fish density comparisons more reasonable than those from previous studies. Using a backpack electrofisher to survey a replicate took 64% more time (in electrofishing seconds) than boat electrofishing, and capture method was included (in some form) in the detection models of both species. This difference in electrofishing seconds between the two capture methods may have been caused by flow velocity pushing the boat downstream faster through the replicate compared to walking upstream with the backpack electrofisher. Relatively low densities of juvenile trout in some of the upper Deschutes River reaches, where boat electrofishing was used exclusively, may have contributed to lower detection and a faster pace through the replicate. This result suggests that future studies interested in maximizing detection probabilities and capture of YOY trout should consider using the backpack electrofisher whenever lateral habitat depth is shallow enough for wading or testing the effectiveness of different capture methods in a range of lateral habitats and YOY densities prior to the field season.

The lateral habitat survey protocol was also more effective compared to the previous surveys in the mid-channel habitat. In this study, there was wider access to the river because lateral habitats could be surveyed using a backpack electrofisher when there was no boat access, which resulted in a greater percentage and presumably more representative sample of the study area. In the lateral habitat fish surveys, a large majority of the salmonids captured were the targeted species and age-class. In the large river fish surveys, non-target Mountain Whitefish composed high percentages of the total catch in the middle (e.g., 60-69%) and upper (e.g., 69-94%) Deschutes River (Starcevich et al. 2015, Starcevich 2016). Relative to past studies (e.g., Starcevich et al. 2015, Starcevich 2016) occupancy probability estimates in this study were similarly precise, with CVs that suggest they would have reasonable power to detect trends in YOY occupancy; however, this study produced relatively precise estimates at a higher spatial resolution, which would be capable of tracking trend in YOY occupancy at the reach or local population level.

Sampling focused on capturing YOY also yielded information related to breeding adults. The spatial patterns of YOY occupancy and density likely relates directly to spawning distribution and density as discussed above. By focusing on a single cohort (i.e., YOY), genetic monitoring analyses can be used to gain information about genetic diversity, introgression, population structure, and effective number of breeders (N_b). In a separate study (see Bohling et al. 2017), tissue sampled from YOY Redband Trout during this study was used to determine population structure and estimate N_b using sibship frequency analysis on genetic marker data (Wang 2016). The genetic analysis found introgression with hatchery-stocked redband trout in Fall River and nearby Deschutes River reaches as mentioned above, it also found population substructure and produced varying N_b estimates for the three populations (Table 12). These N_b values likely are lower than the actual number of reproductively mature adults in each population (N_C) because these estimates represent only those adults that contributed to producing this specific YOY cohort but not the adults that did not spawn this year (Palstra and Fraser 2012). N_b estimates are not yet directly useful to assessing short-term or long-term population extinction risks or minimum viable population thresholds because those are based on estimates of effective population size (N_e, Jamieson and Allendorf 2012) and it is not yet understood how N_b reflects N_e (Palstra and Fraser 2012). N_b is useful as a measure of relative abundance within this study area and these estimates suggest that the number of breeders in 2015 between Fall River and Wickiup Dam in the upper Deschutes River was substantially smaller than the breeding population downstream of Benham Falls. Furthermore, annual estimates of N_b can be used to track this population trend and assess population response to a management action or interannual environmental variation (Whiteley et al. 2015, Bernos and Fraser 2016).

These N_b estimates were more precise than Redband Trout abundance estimates derived from closed capture modeling (CV=0.85; Starcevich 2016) and N-mixture modeling (CV=0.29-1.2; Carrasco and Moberly 2014, Starcevich et al. 2015) in previous studies surveying in the mid-channel of the Deschutes River. The N_b estimates also provide a direct representation of adult status rather than an abundance estimate by size class alone or one lacking in information about the genetic population structure. By providing more spatial resolution on population structure, resource managers can develop and implement conservation and recovery programs informed by where they are needed most and tailor research to identify, and management actions to ameliorate, specific factors limiting an individual population.

Table 12. Redband Trout populations, as determined by genetic structure analysis and described spatially by Deschutes River reach (R) number and Tumalo Creek (TC), young-of-the-year tissue sample size (N_{YOY}) and estimates of their effective number of breeders (N_b) determined by sibship frequency analysis of genetic marker data from young-of-the-year fish captured in lateral habitats (see Bohling et al. 2017). The 95% confidence interval (CI), standard error (SE), and coefficient of variation (CV) are provided.

Population	N_{YOY}	N_b	CI:Lower	CI:Upper	SE	CV
R2.R3.R4.TC	429	1469	1283	1713	110	0.07
R5.R6.R7	441	1090	961	1256	75	0.07
R9.R10	113	309	238	405	43	0.14

Accuracy and precision of N_b estimates through sibship frequency analysis improves with increasing sample size (Wang 2009, Wang 2016). The next step in developing this study into a monitoring protocol for this study area is to explore ways to increase sample size in each local population and eventually determine the ideal sample size for each population, potentially through simulations, so that accuracy and precision of the N_b estimates are maximized while effort and cost in the field sampling are minimized.

Conclusions

Although Redband Trout in the middle and upper Deschutes River and throughout their range may not be at imminent risk of extinction, a recent status and conservation assessment acknowledged that information based on statistically rigorous spatial sampling designs about introgression, distribution, and abundance are lacking for many populations (Muhlfeld et al. 2015). This paucity of rigorous status information and the lack of a feasible and effective long-term monitoring protocol hinder resource managers from being able to assess and predict the effects of riverine management actions and anthropogenic alterations, including climate change, on Redband Trout populations (Muhlfeld et al. 2015).

The monitoring protocol in this study was designed to provide statistically rigorous spatial data on salmonid population status and it showed promise as a feasible and effective sampling method in a large watershed. High feasibility resulted from targeting YOY trout in the lateral habitat. The high detection probabilities of YOY trout and large YOY sample size obtained in this study showed that this age-class was easy to capture even in the lateral habitat of a large river. Surveying in lateral habitats, which are the most accessible part of any stream or river and require little time to survey because they tend to be shallow and narrow and have low habitat volume, resulted in a large representative sample size with minimal crew time. This monitoring protocol was effective because it provided precise, high-resolution estimates of YOY occupancy and density and yielded information about the breeding population, including unbiased and precise estimates of N_b (see Bohling et al. 2017). This study used a range of capture methods, surveys were conducted in the lateral habitats of small streams and a large river, and native and nonnative YOY salmonids were captured, which shows that this monitoring protocol could be useful in a wide range of research and monitoring contexts.

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Appendix 1. Criteria for determining young-of-the-year (YOY) trout based on age-class assignments from total length (TL) frequency histograms by sampling month and Deschutes River reach and tributary.

Deschutes Reach/Trib	Redband Trout - YOY maximum (mm TL)									Brown Trout - YOY maximum (mm TL)								
	2015						2016			2015						2016		
	7	8	9	10	11	12	1	2	3	7	8	9	10	11	12	1	2	3
1	120	120	120	120	120	120	140	140	140	130	140	160	160	170	170	170	170	170
2	120	120	120	120	120	120	120	120	120	130	140	160	160	170	170	170	170	170
3	120	120	120	120	120	120	120	120	120	130	140	160	160	170	170	170	170	170
4	100	100	110	120	120	120	120	120	120	130	140	160	160	170	170	170	170	170
Tumalo Creek	90	100	120	120	NA	NA	NA	NA	NA	85	85	110	120	NA	NA	NA	NA	NA
5	NA	NA	130	130	130	130	130	130	130	130	140	160	160	170	170	170	170	170
6	140	140	140	140	140	140	140	140	140	130	140	160	160	170	170	170	170	170
7	140	140	140	140	140	140	140	140	140	130	140	160	160	170	170	170	170	170
Spring River	NA	NA	NA	NA	NA	NA	NA	NA	NA	85	85	110	120	NA	NA	NA	NA	NA
Little Deschutes R.	120	120	120	120	NA	NA	NA	NA	NA	85	85	110	120	NA	NA	NA	NA	NA
8	140	140	140	140	140	140	140	140	140	130	140	160	160	170	170	170	170	170
Fall River	60	80	80	80	NA	NA	NA	NA	NA	85	85	110	120	NA	NA	NA	NA	NA
9	140	140	140	140	140	140	140	140	140	130	140	160	160	170	170	170	170	170
10	120	120	120	120	120	120	120	NA	NA	130	140	160	160	170	170	170	170	170

Appendix 2. Univariate logistic generalized linear modeling results for detection and occupancy probabilities of YOY trout in the Deschutes River basin study area. Covariates with P-value<0.1 were used as candidate covariates in occupancy modeling.

Redband Trout			
Detection			
Covariate	Estimate	SE	*P*
Silt/Organic (2)	-1.9	0.6	0.001
Silt/Organic	-1.7	0.6	0.002
Electrofishing sec.	0.8	0.3	0.003
Fastwater unit	1.6	0.5	0.003
Sand	3.0	1.1	0.008
Marsh	-1.4	0.5	0.010
Sand (2)	2.5	1.2	0.031
Glide	-1.0	0.4	0.032
Channel slope	0.7	0.4	0.075
Gravel (2)	3.0	1.7	0.070
Cobble (2)	2.9	1.7	0.091
Mean depth	-1.4	0.8	0.073
Clay (2)	3.6	2.7	0.190
Emergent veg.	-1.0	0.6	0.097

Redband Trout			
Occupancy			
Covariate	Estimate	SE	*P*
Outside bend	-3.7	1.3	0.004
Overhanging veg.	6.4	2.9	0.026
Fastwater unit	2.2	1.0	0.033
Bank	2.5	1.3	0.048
Emergent veg.	-2.1	1.2	0.074
Alcove/Backwater	-3.1	1.8	0.095
Glide	-1.2	0.8	0.119
Marsh	-1.6	1.0	0.120
Boulder	3.3	2.2	0.120
$7DMAM_S$	0.1	0.1	0.140
Elevation	0.0	0.0	0.157
Slope	0.9	0.7	0.194
Bedrock	5.6	4.8	0.200
Silt/Organic (2)	-1.1	0.8	0.200

Brown Trout			
Detection			
Covariate	Estimate	SE	*P*
Electrofishing sec.	0.5	0.2	0.005
Cobble (2)	3.2	1.4	0.027
Gravel	5.1	2.5	0.037
Silt/Organic (2)	-0.9	0.4	0.033
Silt/Organic	-0.8	0.4	0.039
Mean width	-0.3	0.2	0.049
Cobble (2)	1.7	1.0	0.081
Fastwater unit	0.7	0.4	0.087
March	-0.7	0.4	0.084
Mean depth	-1.2	0.7	0.090

Brown Trout			
Occupancy			
Covariate	Estimate	SE	*P*
Slope	-0.6	0.3	0.060
Bedrock (2)	-2.0	1.5	0.171
Main channel	-3.6	2.7	0.190
Pebble	-6.7	5.3	0.210
Overhanging veg.	2.2	1.8	0.227
Total habitat volume	0.0	0.0	0.228
Secondary channel	3.3	2.8	0.230
Mean habitat volume	0.0	0.0	0.231
Undercut bank	-2.2	1.9	0.233
Alcove/Backwater	-2.0	1.8	0.248
Mean width	-0.3	0.2	0.274
Elevation	0.0	0.0	0.304
Instream wood	5.3	5.6	0.343
Clay (2)	-2.0	2.1	0.353
Sand (2)	1.6	1.8	0.358
Outside bend	-1.1	1.2	0.358

Appendix 3. Detection modeling results for time component and candidate covariates with the top time model fixed for each YOY trout species. Models were evaluated by Akaike Information Criterion with a correction for small sample size (AICc); the top models were determined by the lowest AICc value and greatest Akaike weight (w_i) and then included as the baseline detection model in the occupancy modeling.

Redband Trout

p model		ψ model	Parameters	AIC_c	ΔAIC_c	w_i
~pG2	(p1=p2, p3=p4)	~1	3	321.74	0.00	0.55
~pG3	(p1, p2, p3=p4)	~1	4	322.91	1.17	0.31
~time	(p1, p2, p3, p4)	~1	5	324.88	3.14	0.11
~1	(p1=p2= p3=p4)	~1	2	327.47	5.73	0.03

p model	ψ model	Parameters	AIC_c	ΔAIC_c	w_i
~pG2 + capture method	~1	4	315.96	0.00	0.31
~pG2 + glide	~1	4	316.20	0.24	0.28
~pG2 + lateral type	~1	6	316.50	0.53	0.24
~pG2 + marsh	~1	4	318.36	2.40	0.09
~pG2 + unit type	~1	5	319.52	3.56	0.05
~pG2	~1	3	321.74	5.77	0.02

Brown Trout

p model		ψ model	Parameters	AIC_c	ΔAIC_c	w_i
~1	(p1=p2= p3=p4)	~1	2	356.71	0.00	0.65
~pG2	(p1=p2, p3=p4)	~1	3	358.82	2.11	0.23
~pG3	(p1, p2, p3=p4)	~1	4	360.61	3.90	0.09
~time	(p1, p2, p3, p4)	~1	5	362.86	6.16	0.03

p model	ψ model	Parameters	AIC_c	ΔAIC_c	w_i
~efishing seconds + mean lateral width	~1	4	345.83	0.00	0.75
~mean lateral width	~1	3	348.61	2.78	0.19
~efishing seconds	~1	3	350.78	4.95	0.06

Appendix 4. Factor levels (left) and occupancy modeling results for spatial group (sg), with baseline detection model, evaluated using Akaike Information Criterion with a correction for small sample size (AICc); the top models were determined by the lowest AICc value and greatest Akaike weight (w_i). Reaches and tributaries within a spatial grouping (A through N) that share the same number are considered a factor level for that group.

Deschutes Reach/Trib	Spatial groupings													
	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	1	1	1	1	1	1	2	2	1	2	2	2	2	1
2	2	1	2	1	2	1	2	2	2	3	3	2	2	2
3	2	1	1	1	1	1	3	3	1	2	2	1	1	1
4	3	1	1	1	1	1	3	3	1	2	2	2	1	1
Tumalo Creek	4	1	1	1	1	1	3	3	1	1	1	1	1	1
5	4	1	1	1	1	1	2	2	1	1	1	1	1	1
6	4	1	1	1	1	1	3	3	1	2	2	1	1	1
7	5	2	2	2	2	2	1	1	2	2	2	2	1	1
Spring River	5	2	2	2	2	2	1	1	2	3	3	2	2	2
8	5	2	2	2	2	2	2	2	1	3	3	2	2	2
Fall River	5	1	1	1	1	2	1	1	2	2	3	2	2	2
9	6	2	2	2	2	2	1	2	2	3	3	2	2	2
10	6	2	2	2	1	1	2	2	1	1	1	1	1	1

Redband Trout					
p model	ψ model	Para-meters	AIC_c	ΔAIC_c	w_i
~pG2 + capture method	~sgG	6	303.0	0.00	0.44
~pG2 + capture method	~sgH	6	303.3	0.28	0.38
~pG2 + capture method	~sgI	5	305.8	2.75	0.11
~pG2 + capture method	~sgE	5	307.3	4.26	0.05
~pG2 + capture method	~sgF	5	309.0	6.00	0.02

Brown Trout					
p model	ψ model	Para-meters	AIC_c	ΔAIC_c	w_i
~efishing seconds + mean lateral width	~sgJ	6	336.5	0.00	0.46
~ efishing seconds + mean lateral width	~sgK	6	337.9	1.42	0.23
~ efishing seconds + mean lateral width	~sgM	5	338.9	2.35	0.14
~ efishing seconds + mean lateral width	~sgL	5	339.8	3.32	0.09
~ efishing seconds + mean lateral width	~sgN	5	339.9	3.37	0.09

Appendix 5. Geostatistical temperature models for 7-day moving average maximum daily temperature in summer (7DMAMs) in the Deschutes River basin study area in 2015. The final model (bold) was selected by a combination of low Akaike Information Criterion (AIC) value, low root-mean-squared prediction error (RMSPE) and its standard deviation (SD), and high r^2, which was reflected in confidence interval (CI) coverage probabilities.

Fixed effect predictors	Variance components	Model type	AIC	RMSPE	SD	80% CI	90% CI	95% CI
7DMAMs ~ Elevation + Trib	LinearSill.tailup + Nugget	Spatial	124.31	1.53	1.31	0.76	0.84	0.92
7DMAMs ~ Elevation + Trib	Spherical.tailup + Nugget	Spatial	124.84	1.56	1.31	0.76	0.87	0.95
7DMAMs ~ Elevation + Trib	Exponential.tailup + Nugget	Spatial	125.87	1.55	1.30	0.74	0.87	0.95
7DMAMs ~ Elevation + Trib	**LinearSill.tailup + LinearSill.taildown + Nugget**	Spatial	**127.73**	**1.53**	**1.19**	**0.79**	**0.92**	**0.95**
7DMAMs ~ Elevation + Trib	Exponential.tailup + Exponential.taildown + Nugget	Spatial	129.76	1.54	1.29	0.74	0.87	0.95

Appendix 6A. Habitat covariates summarized by reach with Tumalo Creek, Spring River, and Fall River habitat pooled (Tribs).

Deschutes reach/tribs	Proportion																
	Site surveys	Fast-water	Glide	Pool	Off-channel	Secondary	Alcove-Backwater	Bar	Bank	Marsh	Bedrock	Boulder	Cobble	Gravel	Silt-Organic	Sand
1	0.07	0.82	0.06	0.12	0.00	0.05	0.19	0.27	0.54	0.00	0.14	0.44	0.22	0.04	0.06	0.10
2	0.10	0.59	0.25	0.16	0.03	0.10	0.15	0.10	0.52	0.23	0.08	0.25	0.23	0.07	0.20	0.16
3	0.08	0.54	0.30	0.16	0.00	0.13	0.13	0.19	0.66	0.03	0.15	0.29	0.18	0.07	0.14	0.16
4	0.09	0.58	0.33	0.09	0.00	0.08	0.20	0.23	0.54	0.02	0.10	0.34	0.16	0.06	0.16	0.19
5	0.08	0.42	0.51	0.07	0.00	0.14	0.13	0.24	0.49	0.12	0.04	0.06	0.09	0.04	0.50	0.26
6	0.08	0.06	0.94	0.00	0.00	0.00	0.07	0.08	0.51	0.33	0.04	0.00	0.00	0.03	0.88	0.06
7	0.09	0.00	0.96	0.00	0.04	0.04	0.07	0.11	0.39	0.43	0.05	0.07	0.03	0.05	0.72	0.06
8	0.08	0.00	1.00	0.00	0.00	0.14	0.01	0.12	0.32	0.54	0.00	0.02	0.01	0.02	0.84	0.11
9	0.10	0.07	0.93	0.00	0.00	0.00	0.01	0.42	0.41	0.17	0.18	0.01	0.01	0.10	0.39	0.30
10	0.08	0.05	0.95	0.00	0.00	0.05	0.11	0.18	0.31	0.39	0.26	0.00	0.04	0.07	0.40	0.23
Tribs	0.14	0.35	0.48	0.17	0.00	0.06	0.08	0.26	0.56	0.08	0.08	0.06	0.12	0.15	0.16	0.42

Appendix 6B. Habitat covariates summarized by reach (continued).

Deschutes reach/tribs	Proportion				Mean							
	Emergent veg.	Overhang veg.	Instream wood	Undercut bank	Lat. hab width (m)	Lat. hab depth (m)	Lat. hab. vol. (m^3)	Channel width (m)	E-fishing (sec/100-m)	Elevation (m)	Channel slope	Summer 7DMAM
1	0.39	0.27	0.03	0.09	1.1	0.3	33	22	666	717	0.9	21.4
2	0.41	0.30	0.05	0.09	1.5	0.4	65	17	545	800	0.4	24.9
3	0.33	0.36	0.06	0.18	1.1	0.3	39	17	425	883	0.7	23.1
4	0.31	0.28	0.09	0.12	1.4	0.3	47	18	733	991	0.7	22.0
5	0.21	0.17	0.04	0.19	1.2	0.3	38	47	844	1129	0.6	19.4
6	0.51	0.10	0.04	0.18	2.7	0.6	201	44	515	1219	0.1	18.4
7	0.51	0.08	0.06	0.17	2.1	0.5	106	46	388	1264	0.0	17.7
8	0.63	0.04	0.03	0.12	1.6	0.6	95	37	421	1268	0.0	18.0
9	0.29	0.13	0.09	0.16	1.1	0.5	51	36	382	1274	0.1	17.8
10	0.45	0.08	0.07	0.22	1.3	0.5	66	40	361	1300	0.0	17.2
Tribs	0.36	0.20	0.11	0.24	1.0	0.3	31	15	907	1235	1.1	15.0

Appendix 7. Habitat covariates summarized by lateral habitat type.

	Proportion															Mean				
Lateral habitat type	Replicate surveys	Fastwater unit	Glide	Pool	Bedrock	Boulder	Cobble	Gravel	Silt/Organic	Sand	Emergent veg.	In-stream wood	Overhanging veg.	Undercut bank	Lat. width (m)	Lat. depth (m)	Lat vol. (m^3)	Channel slope	E-fishing (sec./100-m)
Alcove-Backwater	0.07	0.41	0.42	0.17	0.11	0.24	0.14	0.03	0.28	0.18	0.37	0.05	0.18	0.19	2.5	0.40	161	0.5	588
Bar	0.20	0.50	0.45	0.05	0.12	0.12	0.15	0.09	0.20	0.29	0.25	0.08	0.22	0.11	1.4	0.29	45	0.8	645
Bank	0.53	0.33	0.57	0.10	0.12	0.17	0.10	0.08	0.31	0.21	0.36	0.07	0.23	0.21	1.2	0.42	55	0.4	590
Marsh	0.19	0.10	0.88	0.02	0.01	0.03	0.04	0.02	0.81	0.07	0.66	0.04	0.03	0.06	1.8	0.52	90	0.1	457

Appendix 8A. Selected paired photos showing an individual survey replicate during the irrigation season and during the water storage season in the middle Deschutes River.

Appendix 8B. Selected paired photos showing an individual survey replicate during the irrigation season and during the water storage season in the upper Deschutes River.


08/13/2015
03/24/2016
08/13/2015
08/13/2015


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12/16/2015


12/16/2015

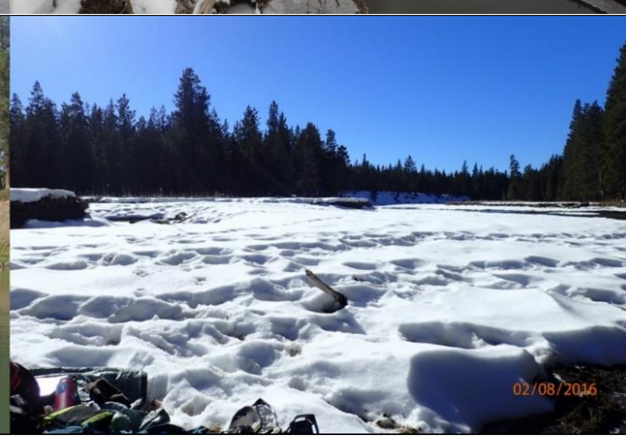

09/02/2015


02/03/2016


09/02/2015


02/03/2016


08/18/2015


02/08/2016