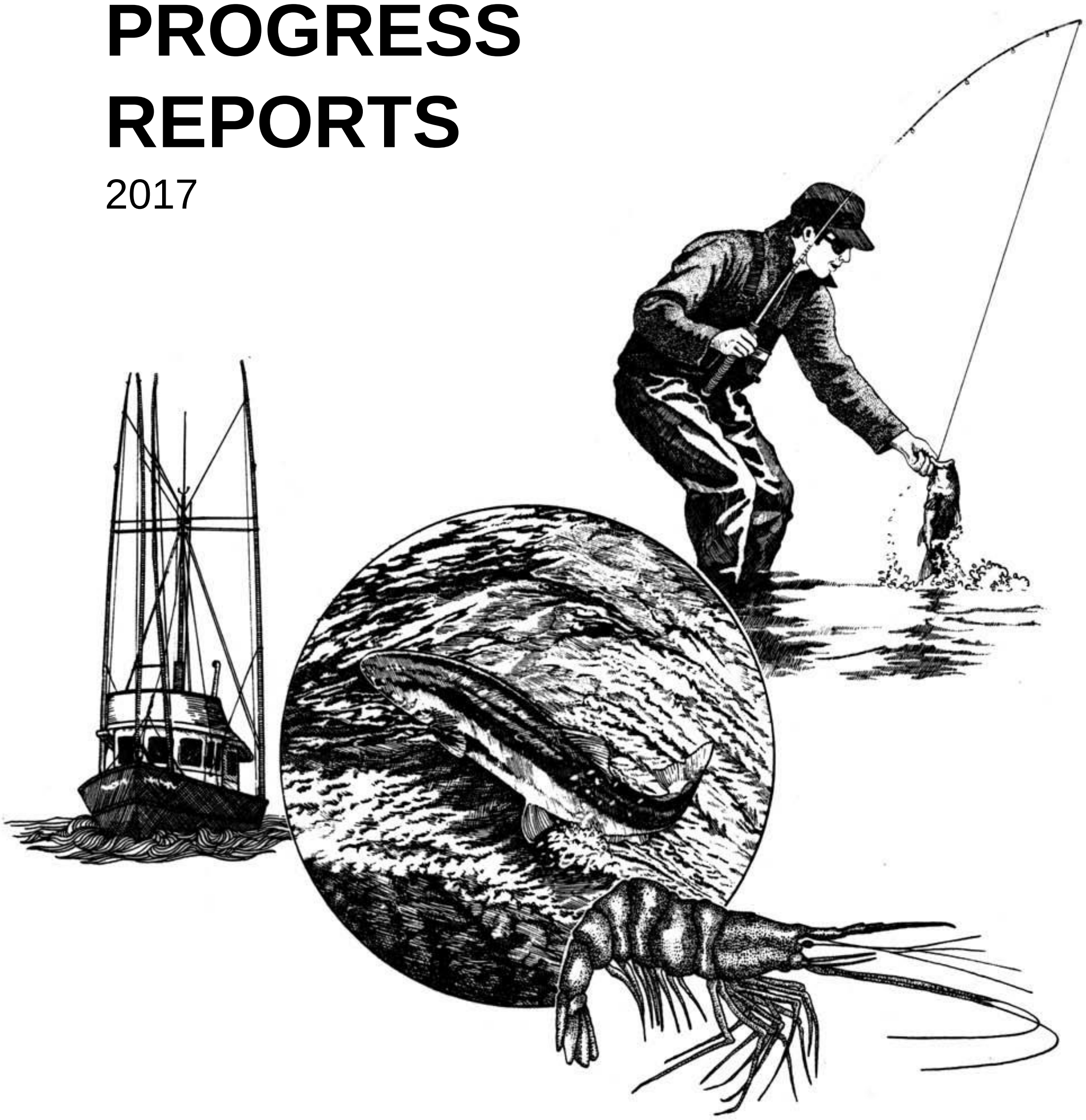
PROGRESS REPORTS

2017



FISH DIVISION
Oregon Department of Fish and Wildlife

Bull Trout Conservation and Recovery in the Odell Lake Core Area:
Adult Status in Trapper Creek and Thermal and Physical Habitat Suitability in 2016

Bull Trout Conservation and Recovery in the Odell Lake Core Area: Adult Status in Trapper Creek and Thermal and Physical Habitat Suitability in 2016

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Executive Summary

Bull Trout, within their historical range in the upper Deschutes River basin, are extant only in the Odell Lake basin, comprising Odell Lake, Odell Creek, Davis Lake, and their tributaries. The "Recovery Plan for the Coterminous United States Population of Bull Trout (*Salvelinus confluentus*)" refers to this basin as the Odell Lake Core Area (OLCA) and describes this population as isolated, one of the smallest in the Coastal Recovery Unit, and imperiled by several threats. These threats include negative interactions with introduced Lake Trout, potential spawning and rearing habitat limitations, incidental angler pressure, hybridization with Brook Trout, and the many risks associated with small population size. Recent status assessments of this core area in 2012-2014 found critically low adult abundance in Trapper Creek (43-50 adults), which is the main spawning area in the OLCA, and low relative juvenile abundance in Crystal Creek, the coldest segment of Odell Creek, and Charhaven Creek. In 2015, the annual census redd count in Trapper Creek suggested this small spawning population may have experienced a steep decline. In 2016, as a result of this apparent decline in Trapper Creek redd numbers and the need for a better understanding of the thermal and physical habitat factors potentially limiting Bull Trout in this core area, we assessed the adult populations in Trapper Creek and Crystal Creek using video monitoring stations (Chapter 1, this report) and evaluated thermal and physical habitat throughout the potential OLCA distribution using an array of temperature data loggers and synoptic habitat surveys (Chapter 2).

We operated video stations July through mid-October, 2016, in Trapper and Crystal creeks and conducted a census count of adfluvial adult Bull Trout, individually-identified from videos records, as fish moved between the lake and creek. We counted 22-23 individual adult Bull Trout (9 males, 13-14 females) and 2 adult Bull Trout x Brook Trout hybrids (1 male, 1 female) using Trapper Creek during the spawning period. This count represented a 43-53% decline in adult abundance since 2012. This decline was also reflected in relative juvenile abundance estimated in 2017 during the annual census night-snorkeling surveys and annual census redd counts in 2016 and 2017 in Trapper Creek. One reason for this decline was an apparent lack of recruitment into the spawning age classes from 2012 to 2016. Excluding hybrids, mean total length of adult Bull Trout using Trapper Creek during the spawning period shifted from 65 cm in 2012 to 85 cm in 2016. The cause of this decline in recruitment to adulthood is unknown. The video station in Crystal Creek recorded a single juvenile Bull Trout, but no adults were observed in this stream. Ongoing rearing in Crystal Creek suggests there is suitable habitat for Bull Trout in Crystal Creek, but it is still not clear why there is little to no spawning occurring in this stream. Brook Trout are common in upper Trapper Creek and are occasionally observed in the lower Bull Trout zone. Juvenile hybrids have been observed occasionally during annual snorkel surveys and an adult hybrid was captured during the spawning period in 2005. The two hybrid adults observed in this study show that hybridization and the presence of Brook Trout in Trapper Creek is an ongoing threat in this core area. Low adult abundance and additional evidence of hybridization in Trapper Creek and a lack of spawning in Crystal Creek in 2016 suggests that development and implementation of a formal strategy to manage and conserve Bull Trout in this core area is warranted.

We constructed thermal maps and summarized selected habitat characteristics for this study area and used a combination of thermal and physical habitat suitability criteria to identify factors influencing Bull Trout distribution and abundance and areas of opportunity for management actions designed to increase the availability of suitable habitat and improve Bull Trout status in the OLCA. In the first phase, we evaluated water temperature because Bull Trout distribution is largely delineated by cold water. We used September mean daily water temperature at 53 temperature logger observation sites of <9°C, 9-12°C, and >12°C to respectively classify the thermal suitability of spawning habitat as high, medium, and low. A geostatistical model was fit to 2016 data from observation sites and used to predict summer temperature metrics at 50-m intervals throughout the study area. Summer thermal habitat for juvenile

rearing was evaluated using empirically-based temperature thresholds that influence occurrence throughout the species range. Trapper and Crystal creeks, tributaries of Odell Lake, and Charhaven and Maklaks creeks, which flow into Odell Creek, had high thermal suitability for spawning and juvenile rearing. Odell Creek had more temperature variability because it was composed of three major segments: a lake segment (rkm 8-12.8) influenced by Odell Lake surface temperature, a cold segment (rkm 3.4-8) influenced by three cold tributaries, and a burn segment (rkm 0-3.4) still in an early stage of recovery after a stand-replacing forest fire in 2003. For spawning, the lake segment had low thermal suitability; the cold segment had 3.8 km of high and 1.0 km of medium suitability; and the burn segment had 1.2 km of high and 3.1 km of medium suitability. For juvenile rearing in Odell Creek, there was no highly suitable thermal habitat, the lake segment had low thermal suitability, the cold segment had medium suitability, and the burn segment had reaches of medium and low suitability.

Within thermally suitable habitat, other important factors influence the occurrence and density of Bull Trout rearing and spawning, including wetted width, channel slope, presence of deep scour pools, and pool tailouts with spawning gravel and minimal fine sediment. Trapper Creek had suitable size and slope and many deep scour pools. In pool tailouts, substrate was highly suitable for spawning; but there was a relatively high percentage of surface fines, which may be limiting spawning by embedding gravel. Lower Crystal Creek contained high suitability rearing habitat with many deep scour pools and instream wood, but it did not contain suitable spawning gravel. Upper Crystal Creek substrate was highly suitable for spawning habitat but still contained relatively high surface fines, which may be limiting spawning. Charhaven Creek is the coldest and second largest tributary in the OLCA and has highly suitable channel slope. This stream supports low-density rearing and occasional spawning in this stream or nearby in Odell Creek; however, it is completely lacking in scour pools, tailout habitat, and spawning gravel, which may be limiting rearing and spawning. The Odell Creek cold segment contains highly suitable channel width and slope, many deep scour pools, and suitable spawning gravel in the pool tailouts; however, thermal habitat was generally of medium suitability and may seasonally curtail bull trout distribution and limit abundance. Improving summer stream temperatures in the cold segment through management actions would be difficult, especially considering the projected impact of global climate warming on rivers and lake. The Odell Creek burn segment, with the highest scour pool frequency, deepest pools, lowest surface fines in scour pool tailouts, and highly suitable spawning substrate in tailouts, had the best physical habitat in the core area. Surveys in the burn segment prior to the 2003 forest fire usually detected rearing Bull Trout, but recent post-fire surveys and video station monitoring of this segment did not detect this species. Low thermal suitability for juvenile rearing, rather than physical habitat factors, is likely limiting Bull Trout in this segment. Influencing summer water temperatures in the burn segment would be difficult in the next 20-50 years. Over the long-term, however, this segment could experience substantial cooling from restoration of a mature riparian canopy.

Bull Trout are highly imperiled in the OLCA and in need of management actions that reduce the risk of this species disappearing from this core area. This study provides managers with information needed to identify reach-level patches of thermally suitable habitat and the habitat attributes within these patches that may be limiting Bull Trout status. This habitat information can be useful in the development and implementation of a formal strategy to manage and conserve Bull Trout in this core area. Future research should focus on continuing to improve our understanding of thermal habitat in the OLCA, especially in Odell Creek, by refining the thermograph array for long-term monitoring and improved resolution near the Odell Creek tributaries; constructing the geostatistical temperature model that incorporates annual air temperature and discharge, canopy cover, and pre- and post-fire temperature data, and downscaling projections of climate predictors into the model.

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Chapter 1: Video station count of individual adult Bull Trout using Trapper Creek during the spawning period in 2016

Introduction

Bull Trout (*Salvelinus confluentus*) were once found throughout the upper Deschutes River watershed. They have been extirpated from the majority of this historical range and now only occur in the Odell Lake Core Area (OLCA), which includes Odell Lake, Odell Creek, Davis Lake and their tributaries. The OLCA Bull Trout population was isolated from the Deschutes River by a lava flow about 5500 years ago that created a natural dam on the northeast side of Davis Lake, which blocked fish passage into the Deschutes River. The OLCA harbors the only Bull Trout population in Oregon that expresses a naturally-occurring adfluvial life history, with fish using both Odell Lake and tributary streams for different parts of their life cycle. Status assessments suggest that this unique population is also highly at risk of extinction from several threats (USFWS 2015). These threats include negative interactions with introduced Lake Trout (*S. namaycush*), spawning and rearing habitat limitations, high incidental angler pressure, the presence of sympatric Brook Trout (*S. fontinalis*), and the risks associated with small population size (USFWS 2015).

Trapper Creek is considered the primary, and likely the only consistently used, spawning area in the OLCA (Meeuwig et al. 2015). Census redd surveys of this stream have been conducted almost annually since 1996 and redd counts are relatively low; rarely exceeding an annual count of 15 observed redds (Figure 1.1). Resource managers concerned about this population are uncertain of how this redd count correlates with adult abundance. Previous attempts at calibrating the redd count to adult abundance relied on installation and maintenance of a weir and trap; however, this effort was discontinued when otters discovered the trap and preyed upon captured adult Bull Trout (Oregon Department of Fish and Wildlife [ODFW], unpublished data). In 2012, another calibration attempt was conducted using a video monitoring station that allowed fish to pass back and forth through a slot in a weir that was monitored by an underwater digital video camera. The camera was connected to a motion-sensitive digital video recorder that recorded short videos of adult Bull Trout swimming freely from the lake to the stream and back again with no trapping or handling necessary. Using this system, the adult population entering Trapper Creek during the spawning period in 2012 was estimated as 43-51 individually-recognized Bull

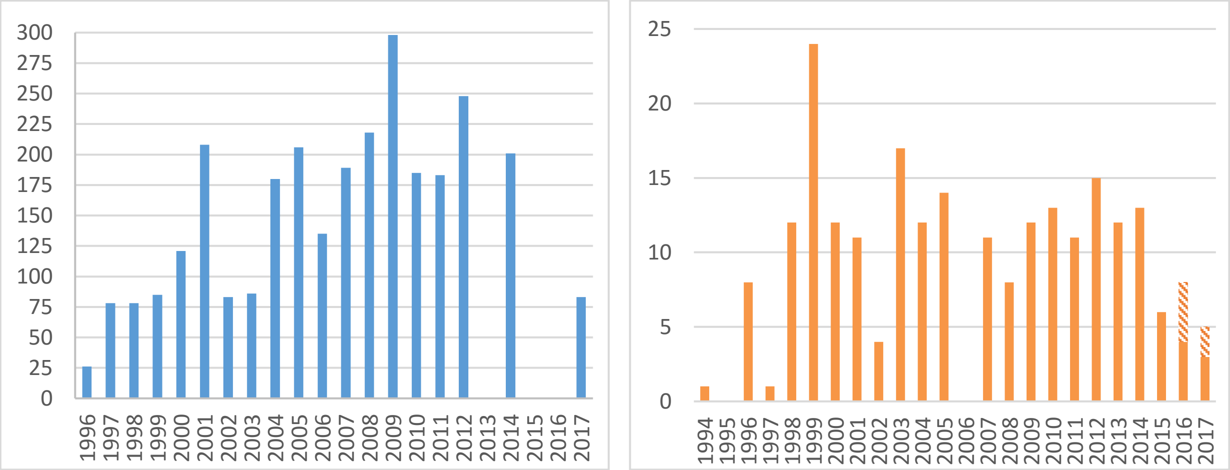

Figure 1.1. Juvenile counts during snorkel surveys (left panel) and redd counts (right) for Trapper Creek. No juvenile surveys were done in 2013, 2014 and 2015 and no redd surveys were done in 1995 and 2006. In 2016 and 2017, low (striped bar) and high (solid bar) confidence of identifying each redd was recorded by the surveyor.

Trout. In 2015, the census redd count in Trapper Creek decreased to 6 redds, which was more than a 50% decline relative to redd counts over the previous 15 years (Figure 1.1). Additionally, extensive electrofishing surveys in 2013-2014 in the OLCA captured 5 juvenile bull trout from multiple age-classes rearing in Crystal Creek, which led to speculation about Bull Trout potentially spawning in this stream. Based on the continued and elevated concern for the Trapper Creek population and the discovery of rearing Bull Trout in Crystal Creek, resource managers wanted more direct information about adult abundance in these two streams. Therefore, the objectives of this study were to use video stations to monitor adult Bull Trout use of these two streams and conduct a census count of unique adults passing through the stations during the spawning period.

Study Area

Trapper Creek and Crystal Creek are cold (mean summer temperature, <5°C) spring-fed tributaries that flow into the west side of Odell Lake. Trapper Creek is currently the primary Bull Trout spawning area in the OLCA. A popular campground is located along the lower 0.4 km of the creek, while the upper portion is surrounded by wilderness area. Most, if not all, Bull Trout spawning in Trapper Creek occurs within 1 km of Odell Lake. A 3-m waterfall preceded by a substantial debris jam with a step height over 2 m, about 1.5 km upstream from Odell Lake, is thought to be a barrier to upstream fish passage. Although Crystal Creek is smaller than Trapper Creek, historical records indicate it was once an important Bull Trout spawning tributary (OSGC 1947). Crystal Creek flows into Pebble Bay, which is located on the southwest side of Odell Lake. A railroad, constructed in 1920, passes along the southern shore of Odell Lake, crossing Crystal Creek about 1 km upstream from Odell Lake. The culvert under the railroad tracks is thought to mark the upstream end of the Bull Trout distribution based on electrofishing and environmental DNA surveys (Meeuwig et al. 2015).

Methods

In summer and fall of 2016, video stations were installed and operated on Crystal Creek, 250 m upstream of Odell Lake and Trapper Creek, 15 m from the lake. Each station consisted of a weir with a fish passage chute and a solar-powered, underwater digital video and lighting system. The weir was constructed of weir panels of various sizes (0.4-1.2 m tall and 3 m long). Each panel consisted of a frame made with aluminum chain-link fence rails and gate elbows (3.5 cm diameter, 17 ga), with welded wire fencing (2.5 x 5.0 cm mesh) affixed to the panel frame using hose clamps. These panels were placed end to end from each corner of the fish chute to the stream bank. They were held upright by fence posts that were pounded into the stream bed. Sandbags filled with local stream sediment were used to line the base of the weir panels to protect the weir from scour and prevent fish from swimming through gaps under the panels. To allow for volitional fish passage and recording of passage events, each weir was fitted with a custom-built aluminum sheet-metal (16 ga, 1.6 mm) fish passage chute (Figure 1.2). The chute was divided into two areas separated by a Plexiglas window. One side of the passage chute consisted of a fish passage slot through which fish could swim freely; the other side excluded fish and housed a submersible digital camera (Sony Super HAD Color CCD, 400 TVL, 3.6 mm board lens; Jet Security USA, Inc.) and LED lights. The camera was placed in a PVC housing that was attached to the outside wall of the chute, with the camera extending into the chute and pointed through the Plexiglas window toward the fish passage slot. Measuring boards (5-cm graduations) were bolted to the floor and background wall of the passage slot so fish length could be estimated by the video analyst. The video feed was split and monitored by two motion-activated digital video recorders (DVRs) (mDVR-14, Supercircuits, Inc.). The DVRs were programmed to begin recording when 8% of the pixels in the video image were in flux and end recording 5 seconds after motion ended. The second DVR, with the same settings, was used as a backup and could be downloaded if the primary DVR malfunctioned. The DVRs

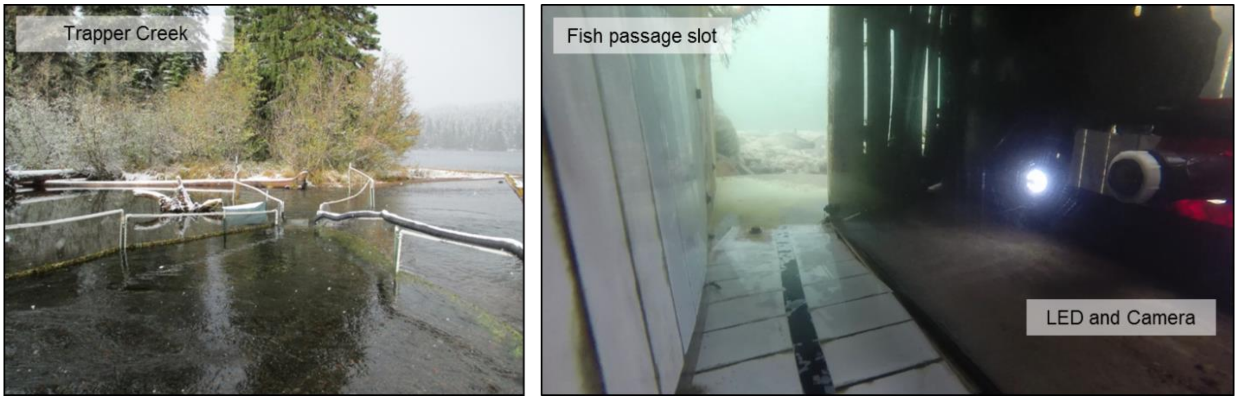

Figure 1.2. Trapper Creek video station and underwater view of fish passage chute.

saved video records on removable memory cards. Tarps were suspended above the ends of the passage chute to reduce light noise and glare on videos. To record fish passage events at night, underwater lights were affixed inside the camera side of the chute and pointed through the Plexiglas window to illuminate the passage slot. Each site was powered by three 12 Volt deep-cycle batteries that were charged by an 80 Watt solar panel (Kyocera) and solar controller (Sunsaver 20). In-line 12 V - 12 V DC power converters (Wall Industries, Inc.) were used to stabilize current to the cameras and lights and 12 V - 5 V converters were used to power the DVRs. All batteries and DVRs were housed in a steel lockbox.

The video stations were checked 1-2 times per week. During this check, weir panels were cleaned of all debris and the weir was examined for any gaps that could allow fish to pass without using the fish chute. If gaps were found they were plugged with sandbags and stream sediment. Camera angle and sun shades were adjusted as needed and battery voltage was checked to ensure continued operation. Memory cards from the primary DVR were removed and replaced with an empty card once per week. Memory cards were taken back to the office, downloaded to a computer, and then data were backed up in two locations. All video records were reviewed by a video analyst and sorted by species. For all adult Bull Trout videos, we recorded date, time, passage direction (upstream or downstream), sex, and total length. Adult Bull Trout were individually identified by unique physical characteristics. Scars, injuries, maxillary shape, fin condition, color, size, and body condition were useful for identifying individual fish. Females often lacked many of these characteristics making them more difficult to individually identify.

Results

The Trapper Creek video station was operated from July 12 to October 17, 2016. A high flow event peaked on October 13-14 and damaged the weir, possibly allowing fish to pass the weir undetected during this period; we repaired the weir on October 14. Continued heavy rain and weir damage led to the removal of the video station on October 17. The Trapper Creek video station recorded 20,875 videos, of which 732 contained Bull Trout. Of those with Bull Trout, 92% were of adults (199 female and 474 male videos) and 8% were of juveniles (Bull Trout < 250 mm). Juveniles from age-0 to age-3 were observed but not quantified. We identified 22-23 individual adult Bull Trout, composed of 9 males and 13-14 females (Figures 1.3 and 1.4). Additionally, we identified 2 adults as likely Bull Trout x Brook Trout hybrids (1 male and 1 female), based on the coloration pattern of their dorsal fin and caudal fin shape (Figure 1.5). Bull Trout in Trapper Creek were active during all hours of the day (Figure 1.6). Male fish made an average of 7 trips (range, 1-8) in and out of Trapper Creek, while females ranged from 1-4 trips. Individual males had an average detection duration (i.e., time between first and last video observation) of 17 d, while females averaged just 7 d (Figure 1.7). Most fish made multiple short trips back and forth through the video weir (e.g., sometimes only spending a few seconds in Trapper Creek) before spending

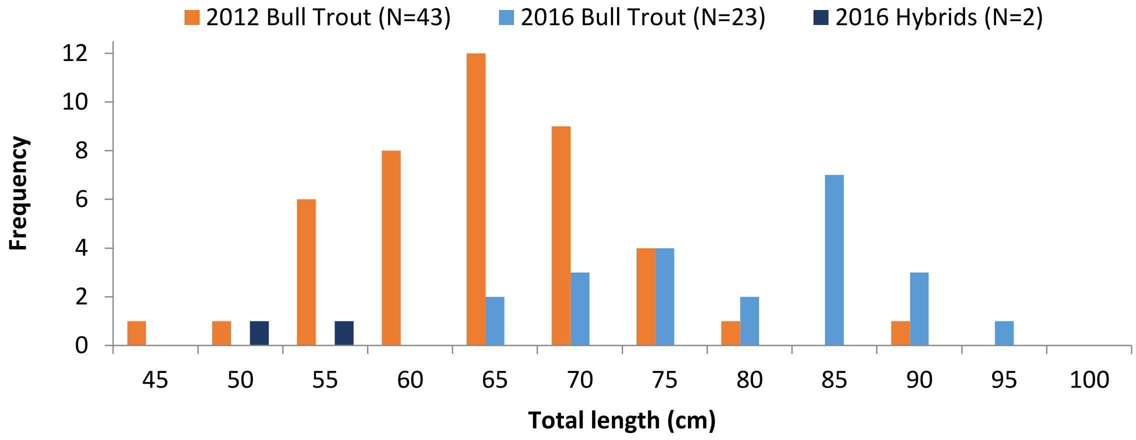

Figure 1.3. Length-frequency histogram of adult Bull Trout entering Trapper Creek as monitored by video stations in 2012 and 2016. The dark blue bars represent the two suspected Bull Trout x Brook Trout hybrids observed in 2016.

Figure 1.4. Still photos from video records of Bull Trout passing through the Trapper Creek video station. Top left: male Bull Trout with abdominal injury, and potential blindness in left eye. Top right: male with ragged edge on opercle and broken fin ray on dorsal. Bottom left: gravid female Bull Trout with scratch on side. Bottom right: relatively indistinct female.

Figure 1.5. Photo of suspected female Bull Trout x Brook Trout hybrid. Coloration and spotting can be seen on dorsal fin, which is a characteristic often observed in hybrids.

a more prolonged period upstream of the weir in Trapper Creek (e.g., 1-15 days). Females no longer appeared gravid during their final observation, indicating that spawning had occurred.

Bull Trout males were observed in Trapper Creek upon installation of the video station and were upstream prior to July 12. One of these fish had a large abdominal wound and may have been blind in one eye, making it easy to identify on the video (Figure 1.4). The first female did not arrive at the video station until August 16. Of the nine males that were identified, four left the Trapper Creek area before any females had been observed and were not seen at the video station again. Three other males moved upstream from August 16 through August 25, but were not observed moving downstream. At least three females were also seen passing upstream with no return downstream through the fish chute. Although it is possible they stayed upstream until the video station was damaged or after it was removed in mid-October, it is also possible they did not survive the spawning season based on the behavior and duration of time other fish stayed upstream. One adult Bull Trout was confirmed dead (E. Moberly, ODFW, personal communication), appearing to be the result of an otter kill.

The two Bull Trout x Brook Trout hybrids were observed at the video station in mid-October, almost two weeks later than the last observation of an adult Bull Trout. A family of nine otters was seen throughout the study period and almost daily during late August and September. Fishing is prohibited in Trapper Creek, but while conducting surveys we observed two large flatfish lures with dual treble hooks and two fishing hooks snagged on instream wood within the first 50 meters of Trapper Creek. We also regularly observed anglers in boats fishing on Odell Lake in the prohibited zone near the mouth of Trapper Creek. Four individual Bull Trout (2 females and 2 males) were clearly recognizable from previous sampling when a video station was run in the same location on Trapper Creek in 2012 (Meeuwig et al. 2015). Estimated growth from 2012 to 2016 for these individuals was 20 cm and 30 cm for the females and 15 cm and 35 cm for the males. It is likely that other individuals were present in samples from 2012 and 2016, but identification was difficult when fish did not have obvious scarring, injuries, or deformities to aid in identification.

The video station in Crystal Creek was operated from July 13 to October 24, 2016. This station recorded 12,639 videos; one juvenile Bull Trout (estimated length 40-80 mm) was observed on September 3 and 4 when the juvenile temporarily entered the camera area of the fish chute. Its close proximity to the camera made it difficult to precisely estimate its length. No adult Bull Trout was observed. Kokanee (*Oncorhynchus nerka*) were first recorded in Crystal Creek on September 26 and comprised about half of all the videos recorded at this station. We did not quantify the number of Kokanee passing upstream since individuals could pass back and forth multiple times and were difficult to individually identify. A small number of Redband Trout (*O. mykiss*) and several river otters were also observed throughout the study period.

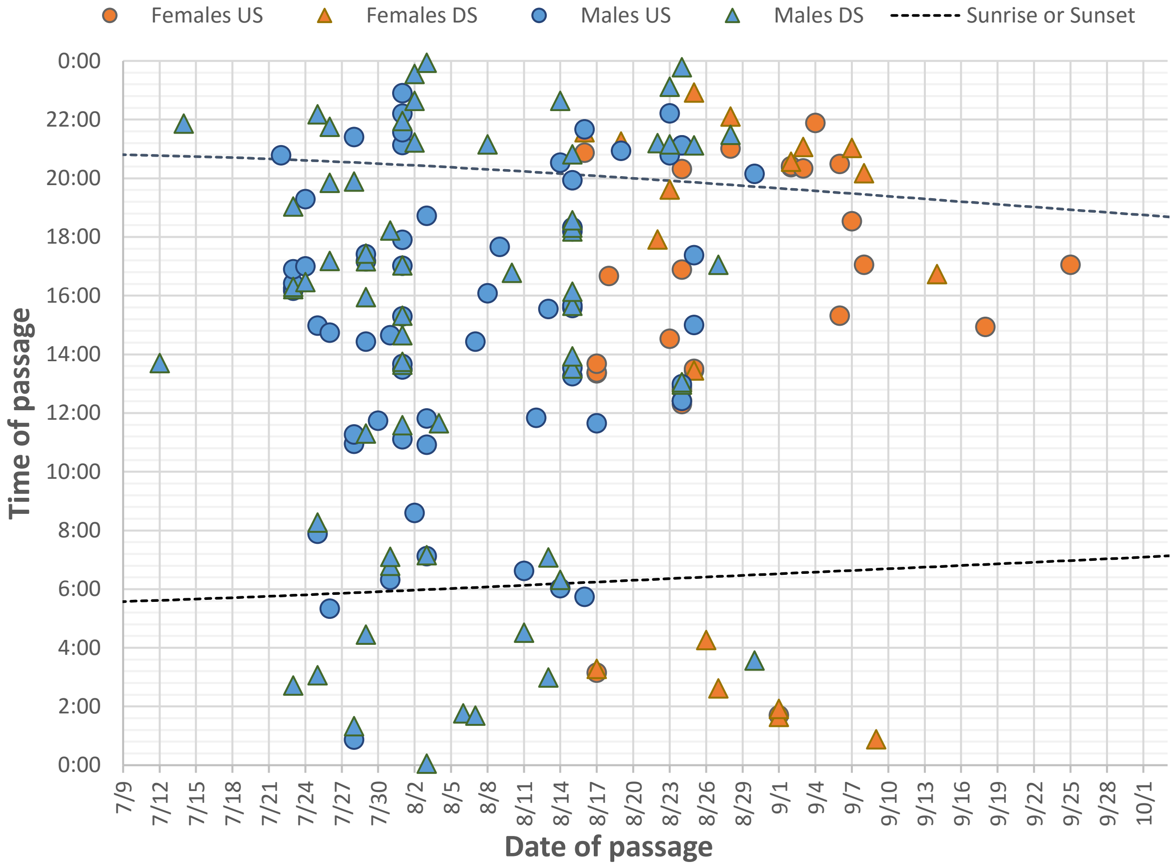

Figure 1.6. Bull Trout passage timing and direction during the monitoring period of July 12 to October 17, 2016.

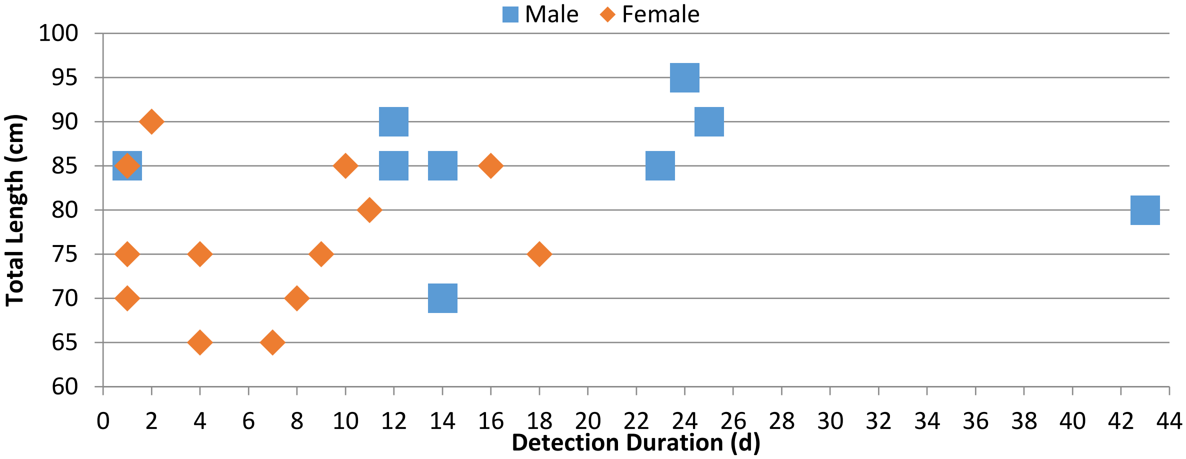

Figure 1.7. Detection duration (i.e., the number of days from first to last observation) of individual adult Bull Trout at the Trapper Creek video station. Hybrids are excluded.

Discussion

The video count of adult Bull Trout at the Trapper Creek video station showed a 43-53% decline in the number of adults attempting to spawn in 2016 compared to 2012. A similar decline was also observed in Trapper Creek from 2012 to 2016 in the juvenile Bull Trout counts during night snorkeling and the census redd counts (Figure 1.1). A decline of this magnitude in a population previously determined to be relatively small is of critical conservation concern, especially given that it is the only known consistent spawning population in this core area.

Coincident with this decline is an apparent lack of recruitment of individuals into the adult population from 2012 through 2016 (Figure 1.3). Excluding hybrids, mean total length of adult Bull Trout using Trapper Creek during the spawning period shifted from 65 cm in 2012 to 85 cm in 2016. We do not know what is causing this apparent reduction in recruitment into the adult population. It may be one or a combination of the many threats to Bull Trout in the OLCA: negative interactions with nonnative Lake Trout, spawning and rearing habitat limitations, high incidental angler pressure in the lake and illegal angling in Trapper Creek, negative interactions with nonnative Brook Trout; or environmental, demographic, or genetic stochasticity associated with the small population size.

Previous status assessments and surveys noted the presence of nonnative, sympatric Brook Trout as a potential threat to Bull Trout. In Trapper Creek, juvenile Bull Trout x Brook Trout hybrids were captured during 2000-2001 snorkel surveys and photographed (N. Dachtler, U.S. Forest Service, personal communication) and an adult hybrid was captured during the spawning period and photographed in 2005 (Ted Wise, ODFW, personal communication). This study provides more recent evidence of hybrids surviving to adulthood to either spawn or forage in Trapper Creek. The video station in 2016 recorded two potential hybrids entering Trapper Creek. The video record of one suspected hybrid had substantially higher resolution and image clarity than the video record of the other suspected hybrid, which moved quickly through passage slot during its recording. The higher-resolution video record was sent to several regional *Salvelinus* sp. experts, who were asked to watch the video and identify the species of char. There was high confidence and near consensus among these experts that it was a Bull Trout x Brook Trout hybrid. There is a known population of Brook Trout in upper Trapper Creek, which is thought to be the source for the Brook Trout occasionally seen in the Bull Trout spawning and rearing zone in lower Trapper Creek. It is not clear where the hybridization is taking place. Bull Trout may be spawning farther upstream in the system than currently thought, where Brook Trout are more abundant; or Brook Trout may be spawning in the Bull Trout zone, which is the more likely scenario. Currently, there is no evidence of Brook Trout coming into Trapper Creek from the lake. Unfortunately, the video station was damaged by high flows and removed shortly after the hybrids were observed, so we are lacking details about their behavior and it is unknown if additional hybrids entered Trapper Creek after the video station was removed. This evidence of hybridization strongly suggests that the presence of Brook Trout in Trapper Creek is an ongoing threat to Bull Trout in the OLCA, especially considering the size of the adult population. Continued monitoring of adult Bull Trout in Trapper Creek would provide information on trend in abundance, hybridization, and hybrid behavior, which may further illuminate the threat level and suggest potential conservation actions regarding adult hybrids. Continued adult monitoring would also be useful for detecting the response to management actions undertaken to conserve this population.

During this study, we found evidence of two other potential threats to the critically small spawning population in Trapper Creek. First, video data showed that a large family of otters regularly used Trapper Creek and also potentially pose a predatory threat to the adult Bull Trout population. It is unlikely that otter predation is contributing to the lack of recruitment of Bull Trout to adulthood, but they may be reducing adult abundance or spawning success in Trapper Creek. Alternatively, otter occupancy in Trapper Creek may coincide more with Kokanee spawning activity. Second, fishing lures found snagged to instream wood in lower Trapper Creek and boats on the lake observed fishing inside the prohibited zone near the Trapper Creek mouth suggest that illegal angling may be a threat to spawning Bull Trout despite regulations and signage prohibiting angling in this stream and floats delineating the no-fishing zone on the lake. Neither of these potential threats have been quantified. We suggest an otter-specific evaluation of video station data from 2012 (Meeuwig et al. 2015) and 2016 (this study) may help inform spatial and temporal overlap among otter, adult Bull Trout, and Kokanee occupancy in Trapper Creek. This analysis may help elucidate the potential for predatory effects on the small population of adult Bull Trout that use Trapper Creek for spawning. We also suggest managers consider quantifying the threat of illegal angling in Trapper Creek during the period of use of spawning Bull Trout.

In 2014, electrofishing surveys in Crystal Creek detected five Bull Trout composed of two or three age-classes (11-22 cm FL), which suggested either multiple independent discoveries by exploring juveniles or spawning by adults (Meeuwig et al. 2015). In 2016, the video station in Crystal Creek recorded a single juvenile Bull Trout, but did not record any use of this stream by adults. It is unlikely adult Bull Trout spawned in the 250 m downstream of the video station given that the stream bottom of this section is composed mostly of fine sediment. Ongoing rearing in Crystal Creek suggests there is suitable habitat for Bull Trout in Crystal Creek, but it is still not clear why there is little to no spawning occurring in this stream. Kokanee likely spawn annually in Crystal Creek, but if Bull Trout spawning occurs intermittently (i.e., not every year) it could be easily missed. More information is needed about the suitability of Bull Trout rearing and spawning habitat in this stream.

In conclusion, we observed a decline in the number of adult Bull Trout entering Trapper Creek during the spawning season between 2012 and 2016. We observed a shift in the size structure of spawning Bull Trout towards larger individuals suggesting a lack of recruitment into the adult population. Additionally, we provide additional evidence of Bull Trout x Brook Trout hybrids exhibiting spawning behavior in Trapper Creek. In Crystal Creek, we observed one juvenile Bull Trout, suggesting that this habitat meets at least minimum criteria for Bull Trout spawning, or rearing, or both. Finally, given the apparent small population size of Bull Trout in the OLCA, development and implementation of a formal strategy to manage and conserve Bull Trout in this core area is warranted.

Chapter 2: An evaluation of the suitability of thermal and physical habitat for Bull Trout in the Odell Lake Core Area

Introduction

Bull Trout were listed in 1998 as a threatened species under the US Endangered Species Act because of a decline in distribution and abundance across their range and continued exposure to substantial threats likely to further reduce their status (USFWS 1998). This range-wide characterization of species status also applies to Bull Trout in the upper Deschutes River watershed. Bull Trout have been extirpated from Crescent Lake and the upper Deschutes River and its tributaries, and now are only extant in the Odell Lake basin. This basin includes Odell Lake, Odell Creek, Davis Lake and their tributaries; hereafter referred to as the Odell Lake Core Area (OLCA). Recent status assessments of OLCA Bull Trout suggest that this species is at critically low adult abundance in Trapper Creek (Meeuwig et al. 2015, Chapter 1 in this report), which is an Odell Lake tributary and the main spawning area in the OLCA. An assessment also confirmed the presence of juvenile Bull Trout in very low relative abundance in the Odell Lake tributary Crystal Creek, and Odell Creek and its largest tributary (Meeuwig et al. 2015). However, it is not clear why the OLCA population displays this pattern of distribution and abundance, especially in the area disjunct from Odell Lake.

One of the putative factors that may be limiting distribution and abundance of Bull Trout in the OLCA is low availability of suitable spawning and rearing habitat (USFWS 2015). Bull trout are the most cold-water adapted salmonid in this region (Selong et al. 2001); therefore, suitable habitat for Bull Trout is largely delineated by cold water. For example, Bull Trout spawn in stream temperatures generally below 9-10°C (Fraley and Shepard 1989; Pratt 1992; Rieman and McIntyre 1993), ideal temperature for egg and embryo survival is below 4°C (McPhail and Murray 1979), and juvenile Bull Trout in stream reaches with maximum daily temperatures above the 14-16°C range have a <0.5 probability of occurrence (Dunham et al. 2003). Within thermally suitable patches, habitat characteristics such as steep channel slope and small stream size (see Isaak et al 2009) have been shown to curtail Bull Trout distribution and abundance. There is less agreement on other habitat factors that influence Bull Trout distribution and abundance and Dunham et al. (2003) outline many possible explanations for this result; however, Bull Trout have been associated with other habitat characteristics and a lack of habitat complexity may reduce distribution and abundance (Al-Chokhachy et al. 2010).

Table 2.1. Stream discharge measured during baseflow conditions, measurement date, and site dimensions. Discharge at Odell 1 was estimated at the by Oregon Water Resources Department.

			Depth (m)		Discharge	
Stream	Date	Wetted width (m)	Mean	Max	m^3s^{-1}	ft^3s^{-1}
Odell 1	8/31/2016	NA	NA	NA	1.84	65
McCord	10/19/2016	3.7	0.09	0.21	0.15	5
Maklaks	9/26/2016	6.0	0.16	0.26	0.25	9
Charhaven	8/31/2016	11.2	0.30	0.38	0.46	16
Odell 2	8/31/2016	7.8	0.40	0.73	0.89	31
Crystal	8/31/2016	4.5	0.15	0.24	0.08	3
Trapper	8/31/2016	6.7	0.30	0.56	0.70	25

The "Recovery Plan for the Coterminous United States Population of Bull Trout (*Salvelinus confluentus*)" states that the current lack of an understanding of the thermal and physical habitat template in the OLCA hinders informed decision-making about how and where to take actions that are most likely to improve Bull Trout status (USFWS 2015). A better understanding of the spatial extent and distribution of suitable habitat will help identify factors influencing Bull Trout distribution and abundance and areas of opportunity for management actions that could increase the availability of suitable habitat. In this study, we addressed this lack of habitat information by using an array of temperature data loggers to produce a thermal map and by conducting a synoptic habitat inventory of potential spawning and rearing habitat. Our specific objectives were to 1) estimate the extent of potential bull trout spawning and rearing habitat in the OLCA and 2) identify potential areas of opportunity and their habitat limitations.

Study Area

The OLCA is situated in the central Cascades of Oregon (Figure 2.1). A lava flow about 5,500 years ago created Davis Lake and blocked Odell Creek from its direct route to the Deschutes River. Water still flows to the river through fissures in the basalt, but it is a complete barrier to fish movement and native populations of Bull Trout, Redband Trout (*Oncorhynchus mykiss gairdneri*), and Mountain Whitefish (*Prosopium williamsoni*) have been isolated in the OLCA for millennia. We monitored water temperature and conducted habitat surveys in the cold spring-fed McCord Cabin Springs, Maklaks Creek, Charhaven Creek, Crystal Creek, and Trapper Creek, and the warmer Odell Creek (Figure 2.2). These study streams varied in discharge from 0.08 and 1.84 m^3s^{-1} (Table 2.1). Odell Creek was divided into three segments based on their distinct thermal conditions for the purposes of temperature modeling (Figure 2.1). The upper segment (4.8 km long), named the "lake segment", began at the outlet to Odell Lake and was largely composed of warm surface water from the lake. The middle segment (4.6 km) started at the confluence of Charhaven Creek and was dubbed the "cold segment" because of the influence of these cold tributaries. The lower segment (3.4 km), which was called the "burn segment", experienced a stand-replacing wildfire across the entire floodplain in 2003 and still contains very little riparian vegetation and canopy cover.

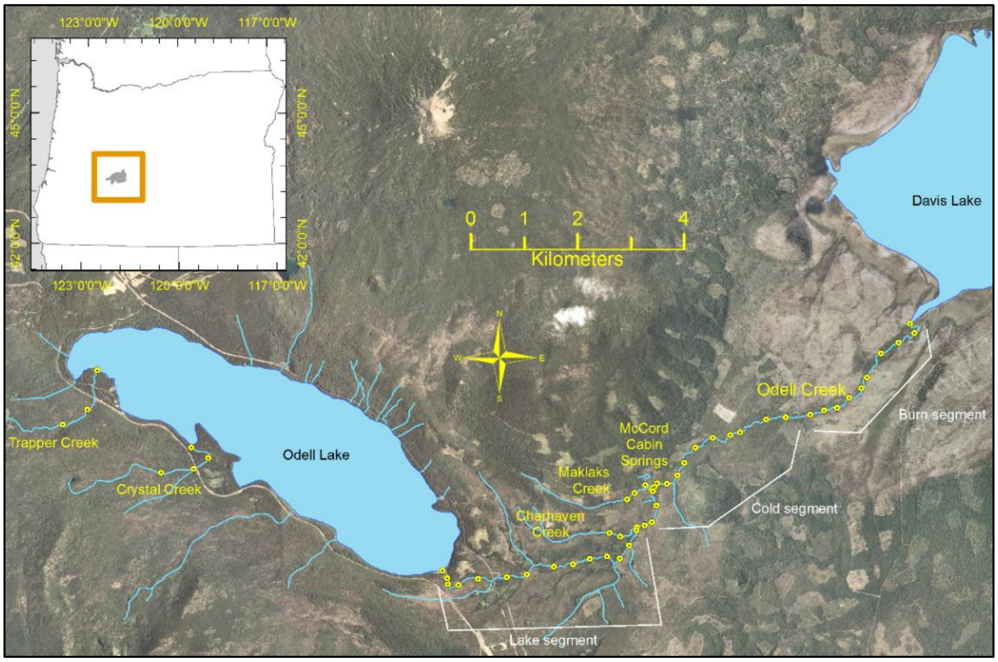

Figure 2.1. Map of the Odell Lake Core Area and thermograph locations (yellow circles).

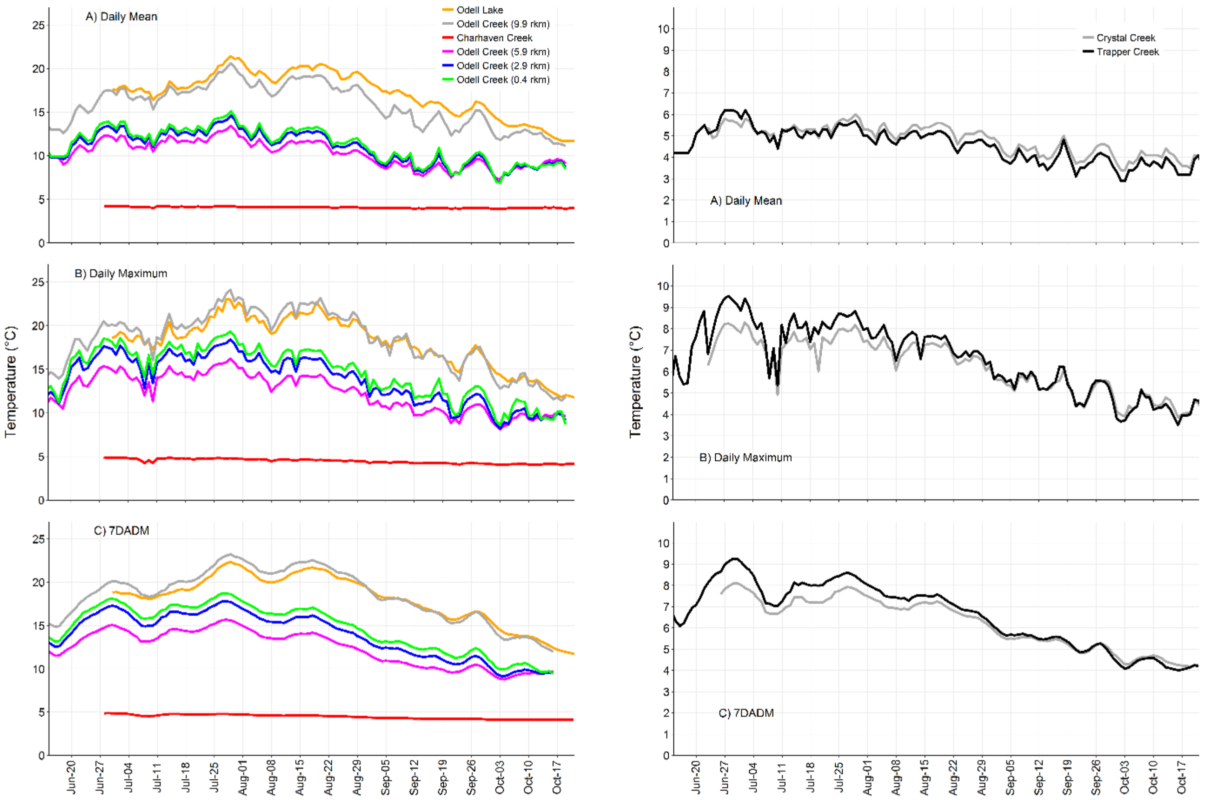

Figure 2.2. Stream temperature summary profiles characterizing thermal habitat at selected data logger locations in the Odell Lake Core Area. 7DADM stands for maximum 7-day moving average daily maximum (7DADM).

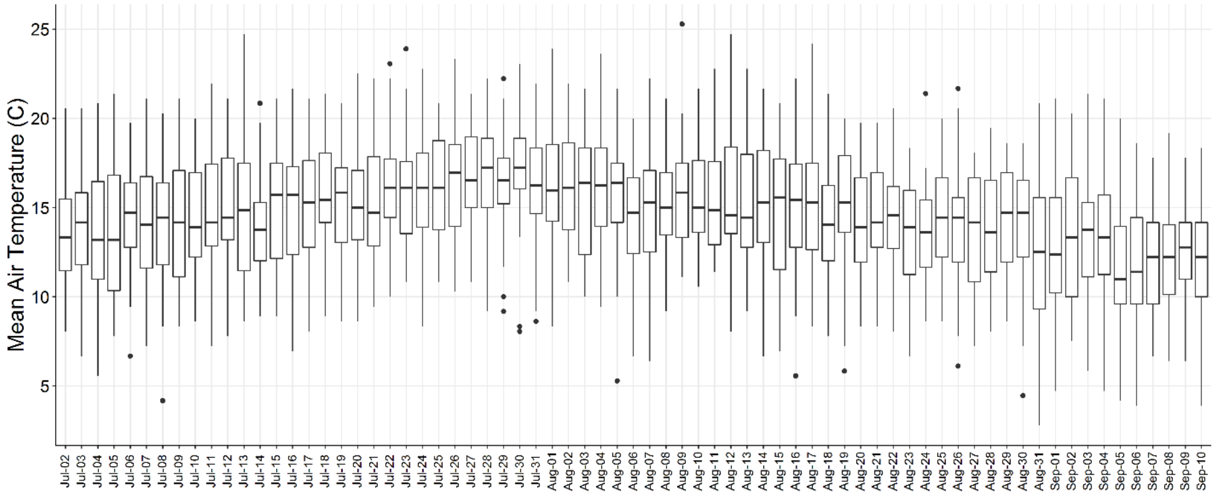

Figure 2.3. Boxplots of mean daily summer air temperature from 1974-2016 at the Odell Lake East NOAA weather station. Data were downloaded from the National Center for Environmental Information website (https://www.ncdc.noaa.gov/cdo-web/datasets/GHCND/stations/GHCND:USC00356252/detail). Boxplots describe median (center line), inner quartiles (boxes), 1.5*Interquartile range (whiskers), and outliers (points).

Table 2.2. Stream temperature metrics used to delineate Bull Trout habitat patches (from Isaak et al. 2009), including the maximum 7-day moving average daily maximum (7DADM). Italicized temperatures are delineations for Bull Trout patches with sympatric Redband Trout reported in Haas (2001). Summer was defined as July 1 through August 31.

Thermal suitability	Summer mean (°C)	Summer maximum (°C)		7DADM (°C)
High	≤10	≤16	*≤12*	≤15
Medium	>10 to ≤12	>16 to ≤19	*>12 to ≤16*	>15 to ≤17.5
Low	>12	>19	*>16*	>17.5

Methods

Thermal habitat

Water temperature was recorded every 30 minutes during the summer study period at 53 observation sites by digital temperature loggers (Hobo Water Temp Pro v2, Onset, MA, U.S.A, ±0.5 °C) placed in locations spread throughout the study area (Figure 2.1). Data loggers 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 the observed temperature data and site-specific covariates, was used to estimate summer mean, maximum, and maximum seven-day moving average of the daily maximum temperature (7DADM) for a set of prediction sites spaced at 50-m intervals throughout the study area. Mean air temperatures generally peak in late July (Figure 2.3) and for our analysis summer was defined as the period from July 1 through August 31, 2016. Maximum 7DADM was calculated at the observation sites by the following equation:

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

where T is the maximum temperature at day t during the summer period s. These stream temperature descriptors have been used to delineate thermally suitable Bull Trout habitat patches in various studies (e.g., Gamett 2002, Dunham et al. 2003, Isaak et al. 2010, Jones et al. 2014). We used the metrics summarized by Isaak et al. (2009) to evaluate thermal suitability of juvenile rearing habitat in this study area (Table 2.2). Several studies suggest Bull Trout initiate spawning when stream temperature declines below 9°C (McPhail and Murray 1979; Weaver and White 1985; Fraley and Shepard 1989; Kitano 1994), although these studies rarely specify the exact temperature metric being used. Bull Trout reportedly initiated spawning at mean daily stream temperatures between 9.3 and 11.5°C in Pine Creek, Oregon (Chandler et al. 2001) and 9.4 and 11.7°C in the Lostine River, Oregon (Howell et al. 2010). As peak Bull Trout spawning in Trapper Creek (Meeuwig et al. 2015) and elsewhere in northeast Oregon (Starcevich et al. 2012) generally occurs in September, we used mean daily temperatures of <9°C, 9-12°C, >12°C in September to respectively classify spawning habitat as high, medium, and low thermal suitability. We also summarized canopy cover estimates by reach because of its strong influence on stream temperature (Jones et al. 2014, Isaak et al. 2010).

Physical habitat

Habitat surveys were conducted using a combination of continuous surveys developed by the Oregon Department of Fish and Wildlife (Moore et al. 2010) and methodology developed to evaluate pool tailout substrate (AREMP 2013). Continuous surveys started at the mouth of each creek in the study area and worked upstream. Data were collected on electronic tablets using ArcCollector (ESRI ArcGIS, Redlands, CA). During the continuous surveys, the stream was divided into channel unit types based upon their natural geomorphology and using the definitions in Moore et al. (2010). Within each channel unit, we recorded unit type, channel type (i.e., main, primary, and secondary channels) and a visual estimate of the percent flow in each channel, unit length, mean unit width (measured at three locations and averaged), slope, channel shade, average depth for faster water units and maximum depth for pools, maximum pool tailout depth, visual estimates of substrate classes, number of protruding boulders, undercut bank, and the length and diameter of each piece of instream large wood. We used a laser rangefinder to measure the length and three widths of the unit and to verify length for long pieces of wood. Channel shade was measured with a clinometer on both the right and left banks from the center of the channel and at the start of the channel unit looking upstream (Moore et al. 2010). Slope was also measured for each unit using the clinometer. Undercut banks were recorded as being present in a unit if any undercut was at least 1 m in length and 0.15 m wide. Substrate was classified into six categories: silt and fine organic matter, sand (<3 mm diameter), gravel (3-64 mm), cobble (65-120 mm), boulders (>120 mm), and bedrock. The percentage of the wetted area for each substrate category was visually estimated to the nearest 5%. Boulders greater than 0.5 m diameter with any exposed portion were counted as protruding boulders and not included in the substrate estimates. Instream large wood was defined as a piece of dead wood with a minimum diameter of 0.15 m and minimum length of 3 m. A piece of instream large wood within, partially within, or suspended <1 m above the wetted channel was individually recorded. A key piece of instream wood was defined as >0.6 m diameter and at least 10 m in length.

The criterion for recording and characterizing a pool channel unit was all pools that were at least 50% of the wetted width of the stream. The criteria for recording and characterizing a pool subunit was the presence of spawning gravel (8-64 mm) and a width of 25% of the wetted stream width. In pool tailouts, percent surface fines were measured using the AREMP (2013) field protocol and individual pieces of substrate were measured. This surface fines protocol entailed the use of a 36 x 36 cm steel frame with 50 evenly distributed intersections to assess the number of fine particles along the pool tail crest. At each intersection the substrate was classified to be ≤2 mm (i.e., fine sediment), >2 mm, or unmeasured. Unmeasured intersections included large boulders greater than 512 mm, wood or organic matter, and dense vegetation mats. From these data, percent fines in the pool tailout was calculated. At each of the four metal corners of the grid, an individual piece of substrate was measured. A piece of substrate was selected by reaching down at each corner of the grid without looking and picking up the first substrate piece touched. Using a ruler, the intermediate axis (i.e., not the largest or smallest axes) of the substrate was measured and recorded to the nearest mm. Silt and sand were recorded as 1-mm substrate. A grid was placed in the tailout 1 m upstream from, and perpendicular to, the contour line of the pool tail crest. If the width of the pool was less than 5 m, 3 grids were evenly spaced along the contour of the tailout; pools 5-10 m wide, 5 grids were completed; in pools greater than 10 m wide, 7 grids were completed. Dam pools generally do not have typical tailouts composed of spawning substrate and were not evaluated.

We evaluated habitat suitability in three phases. First, along with stream temperature, we used channel width and slope as criteria for predicting relative occurrence probability and reach abundance and for guiding the identification of areas of opportunity for enhancement (Table 2.3). Bull trout are unlikely to occur where stream width > 2 m (Rieman and McIntyre 1995, Dunham and Rieman 1999) and, within thermally suitable stream reaches, juvenile rearing occurrence and densities are likely to increase with stream width (Lanka et al. 1987, Rieman and McIntyre 1995, Dunham and Rieman 1999). Although Bull Trout have been detected in stream channels with 15% slope (Dunham and Rieman 1999), there is evidence that reach slope and bull trout occurrence are inversely related (Ripley et al. 2005, Wenger et al. 2011). Reported mean reach slope of occupied reaches ranged from 1.1% in several basins in

Washington (range, 0.0-6.8%; Dunham et al. 2003) to 3.0% in the Kakwa River Basin in Alberta, Canada (range, 0.0-7.0%; Ripley et al. 2005).

In the second phase of evaluation, we focused on the reach-scale characteristics for which there is empirical evidence for numerical thresholds that influence rearing and spawning occurrence and abundance and which also are amenable to enhancement. These characteristics are residual pool depth and scour pool frequency, scour pool tailout surface fines and substrate size, and gravel substrate percentages in scour pools (Table 2.3). In an occupancy analysis of stream reaches in the interior Columbia River basin, Al-Chokhachy et al. (2010) found Bull Trout were generally not detected in reaches where reach-level estimates of residual pool depth were <0.30 m. Redd location has been associated with transitional bedforms like pool tailouts (Baxter and Hauer 2000, Bowerman et al. 2014). In many substrate analyses of Bull Trout redds, gravel (2-65 mm diameter) is the most common substrate size, and median substrate size (i.e., D50) ranges from 3-58 mm (Baxter and McPhail 1996, Guzevich and Thurow 2017). Bowerman et al. (2014) found that the percent of fines in natural and artificial redds in the Metolius River basin was inversely related to embryo survival and emergence.

In the third phase, we summarized several habitat complexity attributes that have been associated with Bull Trout occurrence and distribution and for which numerical thresholds representing levels of habitat suitability are more difficult to define. These include pool frequency, instream large wood volume and number of key pieces, coarser substrate categories (i.e., cobble, boulder) and number of emergent boulders, and secondary channel area (Table 2.3). For example, Bull Trout densities have been positively correlated to pool frequency (Saffell and Scarnecchia 1995) and to instream wood in several basins across several states (Fraley and Shepard 1989, Dambacher and Jones 1997, Jakober et al. 1998, Rich et al. 2003, Citation). Coarser substrates have been identified as important cover to small Bull Trout (Al-Chokhachy et al. 2010).

Table 2.3. Criteria used to evaluate areas of opportunity for enhancement and habitat suitability for Bull Trout.

Reach-level habitat characteristics	Habitat suitability		
	High	Medium	Low
Mean wetted width (m)	>5	2-5	<2
Slope (%)	0-3	>3-7	>7
Residual scour pool depth (m)	>0.3	0.25-0.3	<0.25
Surface fines in tailouts (%)	0-10	>10-15	>15
D50 in tailouts (mm)	5-40	>40-65	>65
Gravel in scour pools (%)	>50	25-50	<25
Pool frequency (100 m^{-1})	Many	Some	Few-None
Large wood volume (100 m^{-1})	High	Medium	Low
Key large wood pieces (100 m^{-1})	Many	Some	Few-None
Coarser substrate (%)	High	Medium	Low
Emergent boulders (N)	Many	Some	Few-None
Secondary channel area (%)	High	Medium	Low

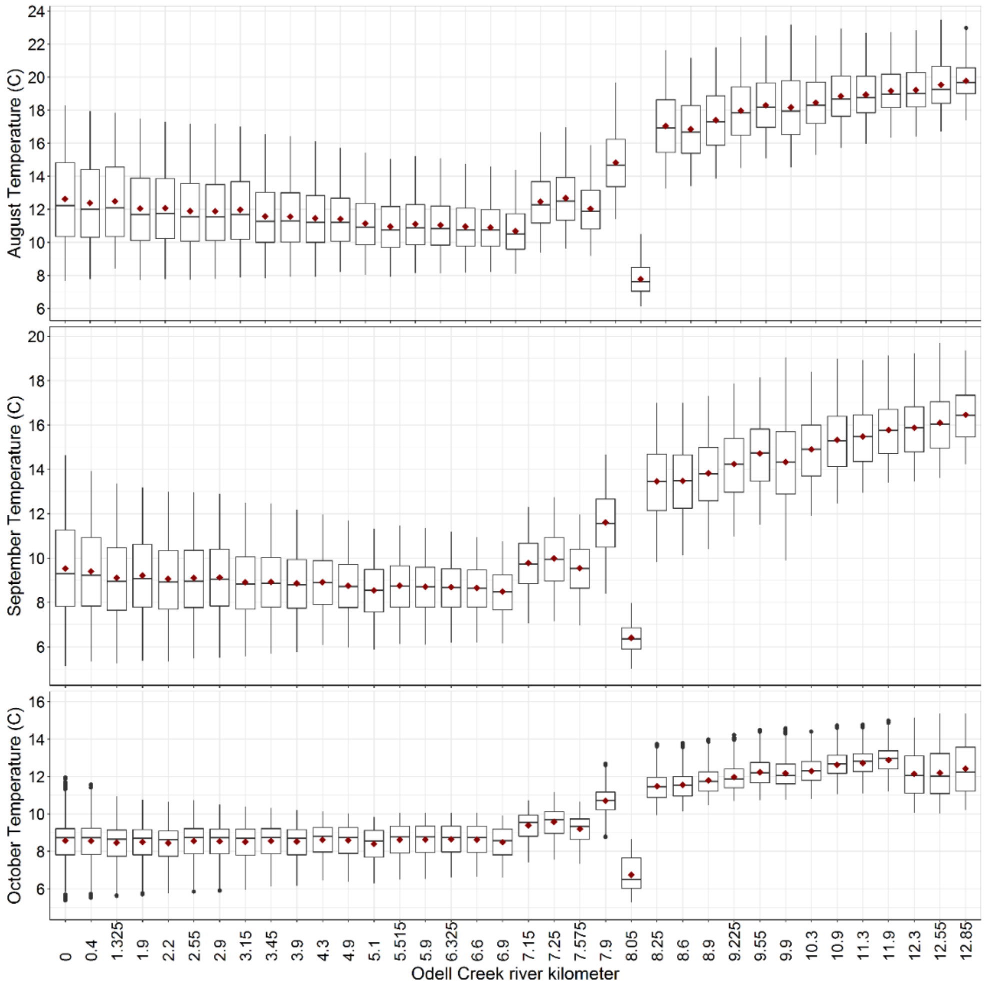

Figure 2.4. Stream temperature at each temperature observation site in Odell Creek during the putative Bull Trout spawning period in the OLCA. Boxplots describe median (center line), mean (diamond), inner quartiles (boxes), 1.5*interquartile range (whiskers), and outliers (points).

Data Analysis

Stream temperature model

A stream-temperature model was built using a geostatistical method designed to incorporate the spatial autocorrelation inherent in stream networks (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 the stream temperature metrics (i.e., summer mean, maximum, and maximum 7DADM) at prediction sites spaced at 50-m intervals throughout the study area. The predictor variables evaluated for significance ($\alpha = 0.05$) were elevation, slope, and separate indicator variables for cold tributary (i.e., McCord Cabin Springs, Maklaks Creek, Charhaven Creek, Crystal Creek, and Trapper Creek) and the following three sections of Odell Creek: burn segment, cold segment, and lake segment. Elevation and slope were 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. The spatial models that were fit included flow-routed distance measures designed for stream networks (i.e., tail-up and tail-down hydrologic distances) as well as Euclidean distance to describe spatial autocorrelation in the model predictions (see Appendix I). Also using the SSN package, universal kriging (Le and Zidek 2006) was used to predict the temperature metrics 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 for this study area was selected using the lowest AIC value (see Appendix I for model comparison). Model fit of the data was described by the coefficient of multiple determination (r^2), which represents the percentage of variation accounted for by the model, and the predictive ability of the model was described by the root-mean-squared prediction error (RMSPE) from the LOOCV. RMSPE is the standard deviation of the residuals (i.e., differences) between the predictions and actual observations.

Physical habitat

Habitat characteristics were summarized by approximated 500-m reaches within each stream and in Odell Creek within the three major segments (i.e., burn, cold, and lake segments). The reaches were delineated using GIS and varied in length (mean, 482 m; range, 160-667 m) for two reasons. First, some reaches were longer than 500 m because habitat units were included in a reach if their start point fell within the 500-m reach. The endpoint of the last unit in the reach often extended past the 500 m delineation and this length was added to the total length. Second, short reaches were created by habitat units remaining at the end of tributary streams and Odell Creek segments. Pool and pool tailout characteristics were displayed using boxplots. Residual pool depth was calculated as the difference between maximum pool depth and maximum pool tailout depth.

Table 2.4. Parameter estimates and summary statistics for the final temperature model used to predict the summer mean, maximum, and maximum 7-day moving average maximum daily stream temperature (7DADM) at 50-m intervals throughout the study area. Root mean square prediction error (RMSPE) of the leave-one-out cross validation analysis is presented. The factor “Lake segment“ consisted of the upper segment of Odell Creek and “Cold trib” consisted of Trapper, Crystal, Charhaven, Maklaks, and McCord Cabin Springs creeks.

Model fixed effects	β	SE	*t*	*P*-value	RMSPE	r^2
Summer mean					0.90	0.96
Intercept	12.241	0.281	43.600	<0.001		
Lake segment	5.928	0.402	14.800	<0.001		
Cold trib	-7.622	0.341	-22.400	<0.001		
Summer maximum					1.36	0.95
Intercept	18.3980	0.933	19.72	<0.001		
Lake segment	6.633	0.800	8.290	<0.001		
Cold trib	-11.538	0.601	-19.190	<0.001		
Maximum 7DADM					1.30	0.94
Intercept	17.814	0.909	19.597	<0.001		
Lake segment	6.271	0.774	8.107	<0.001		
Cold trib	-11.036	0.577	-19.111	<0.001		

Results

Thermal habitat for spawning

The cold tributaries had high thermal suitability for spawning (Figure 2.2). The Odell Creek lake segment (rkm 8.25-12.85) did not provide suitable thermal spawning habitat as mean temperatures did not fall below 12°C in September (Figure 2.4). The cold segment of Odell Creek had high quality thermal spawning habitat at rkm 8.05 (September mean, 6.4°C); this observation site was 150 m downstream from Charhaven Creek and was likely in the temperature plume of this cold tributary. Between rkm 8.05 and 7.9, a large secondary channel from the lake segment reentered the primary channel raising September mean temperatures to medium suitability (9.5-11.6°C). At the observation sites from rkm 6.9 to 3.15, influenced by the other cold tributaries, September means (8.5-8.8°C) are in the high suitability range. In the burn segment, high thermal suitability of September mean temperatures (8.9°C) are present at observation sites from rkm 4.3 to 3.15. For the remainder of the burn segment, September mean temperatures are at medium suitability (9.1-9.5°C).

Summer temperature modeling

The models for each temperature metric that were most strongly supported by the data were composed of indicator variables for the lake segment and cold tributaries; the linear models were as follows:

$$\begin{aligned} Mean &= 12.24 + 5.93(Lake\ segment) - \ 7.62(Cold\ trib) + z + \varepsilon, \\ Maximum &= 18.40 + 6.63(Lake\ segment) - 11.54(Cold\ trib) + z + \varepsilon, \\ 7DADM &= 17.81 + 6.27(Lake\ segment) - 11.04(Cold\ trib) + z + \varepsilon, \end{aligned}$$

where z contains the spatially autocorrelated variance components and ε contains random error. All explanatory variables were statistically significant. The linear models explained 94-96% of the variation in the data and had a RMSPE of 0.90, 1.36, and 1.30, respectively (Table 2.4). RMSPE is the standard deviation of differences between predictions and actual observations in the LOOCV. These models were used to produce thermal maps for each temperature metric.

Thermal habitat for juvenile rearing

The cold tributaries were rated high for thermal suitability for all three temperature metrics (Figure 2.5). The lake segment of Odell Creek showed low suitability as mean and maximum summer stream temperature exceeded 17.6°C and 23.4°C, respectively. Based on the summer mean criterion, there was no high suitability thermal habitat in Odell Creek; there was 4.2 km of Odell Creek habitat of medium thermal suitability (11.8-12.0°C) spanning the cold segment and a portion of the burn segment; the lower 3.9 km of Odell Creek was unlikely to support rearing juvenile Bull Trout (Figure 2.5). Considering the maximum temperature criterion, there was no high suitability thermal habitat in Odell Creek; there was 6.95 km of medium suitability thermal habitat, spanning the cold segment and most of the burn segment; and the lower 1.15 km of Odell Creek was unlikely to support rearing juveniles (Figure 2.5). For the maximum 7DADM criterion, there was no highly suitable thermal habitat in Odell Creek; there was 5.25 km of medium suitability thermal habitat; and the lower 2.8 km of the burn segment was unlikely to support rearing Bull Trout (Figure 2.5).

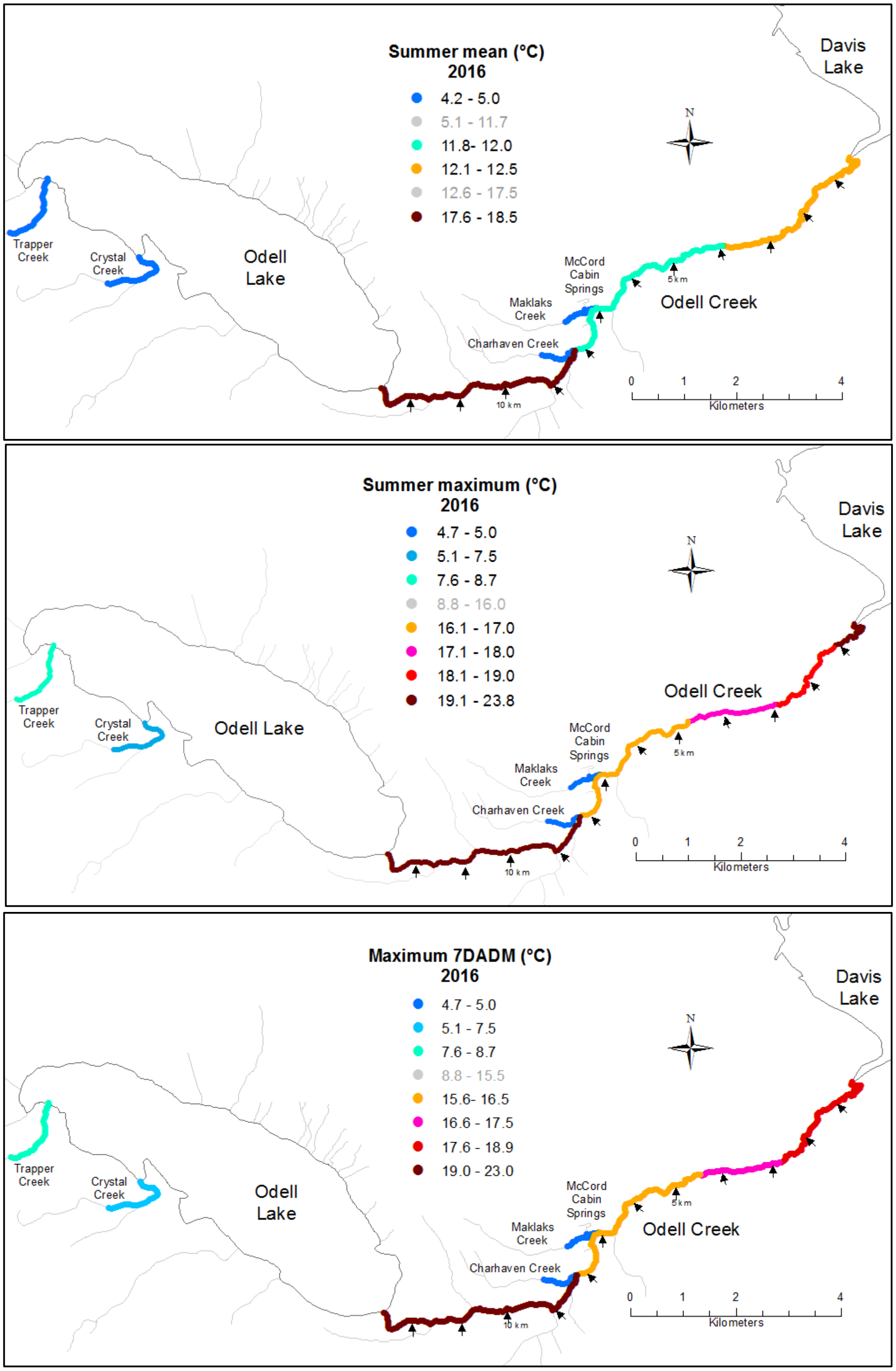

Figure 2.5. Thermal maps of stream temperature predictions in 2016, at 50-m intervals, from geostatistical models built from continuous water temperature records at 53 thermograph locations. Summer was defined as July and August and 7DADM stands for the maximum 7-day moving average maximum daily temperature. Gray temperature ranges were not present in the study area. Arrows indicate stream kilometers from Davis Lake.

Table 2.5. Suitability ratings for habitat factors useful in evaluating and prioritizing areas of opportunity for restoration and enhancement actions for Bull Trout.

Reach-level habitat characteristics	Odell Lake Segment	Odell Cold Segment	Odell Burn Segment	Maklaks	Charhaven 1	Charhaven 2	Crystal 1	Crystal 2	Trapper 1	Trapper 2	Trapper 3
Temperature metrics	Low	Med	Low-Med	High	High	High	High	High	High	High	High
Mean wetted width	High	High	High	Med	High	High	Med	Med	High	High	High
Slope	High	High	High	Med	High	High	High	High	High	Med	Med

Physical habitat

Habitat surveys were conducted on all of Odell Creek, the first 1.5 km of Trapper Creek, 1.5 km of Crystal Creek, 0.95 km of Charhaven Creek, and 0.4 km of Maklaks Creek. In the first phase of the habitat suitability evaluation, we compare mean summer temperature, mean wetted width, and slope among the tributary reaches and Odell Creek segments to identify areas of opportunity for enhancement (Table 2.5). For each 500-m reach in Odell Creek, mean wetted channel width was >5 m and channel slope was <3% (Figure 8). Among the cold tributaries, the Crystal Creek reaches were <5 m mean wetted width; all other reaches were >5 m wide. Maklaks Creek and the second and third reaches of Trapper Creek had channel slopes >3%; all other reaches were under 3% channel slope (Figure 2.6).

In the second evaluation phase, we summarized several attributes of scour pools for each study reach in Odell Creek (Figure 2.7) and the cold tributaries (Figure 2.8). In Odell Creek reaches, mean residual depths of scour pools were highly suitable for juvenile rearing in the burn segment (range in means, 0.51-0.77 m) and most reaches of the cold segment (0.35-0.90 m). In the lake segment, residual pool depths were mostly low suitability, including no scour pools in five reaches (0.20-0.60 m). Surface fines and median substrate size (i.e., D50) in the tailouts and overall gravel percentage in scour pools were highly suitable for spawning habitat in the burn segment (Figure 2.7). These substrate attributes were highly suitable in the first half of the cold segment and declined to medium suitability in upstream reaches in the cold segment. There were no scour pools in Maklaks or Charhaven creeks, so residual depth and tailout substrate attributes could not be measured in these tributaries. Mean residual pool depths were highly suitable for juvenile rearing in Crystal and Trapper creeks (Figure 2.8). Surface fines and D50 in pool tailouts were not suitable for spawning in the first reach of Crystal Creek; in the second reach, suitability improved to medium for surface fines and high for D50. Gravel made up only about 30% of scour pool area in Crystal and Trapper creeks.

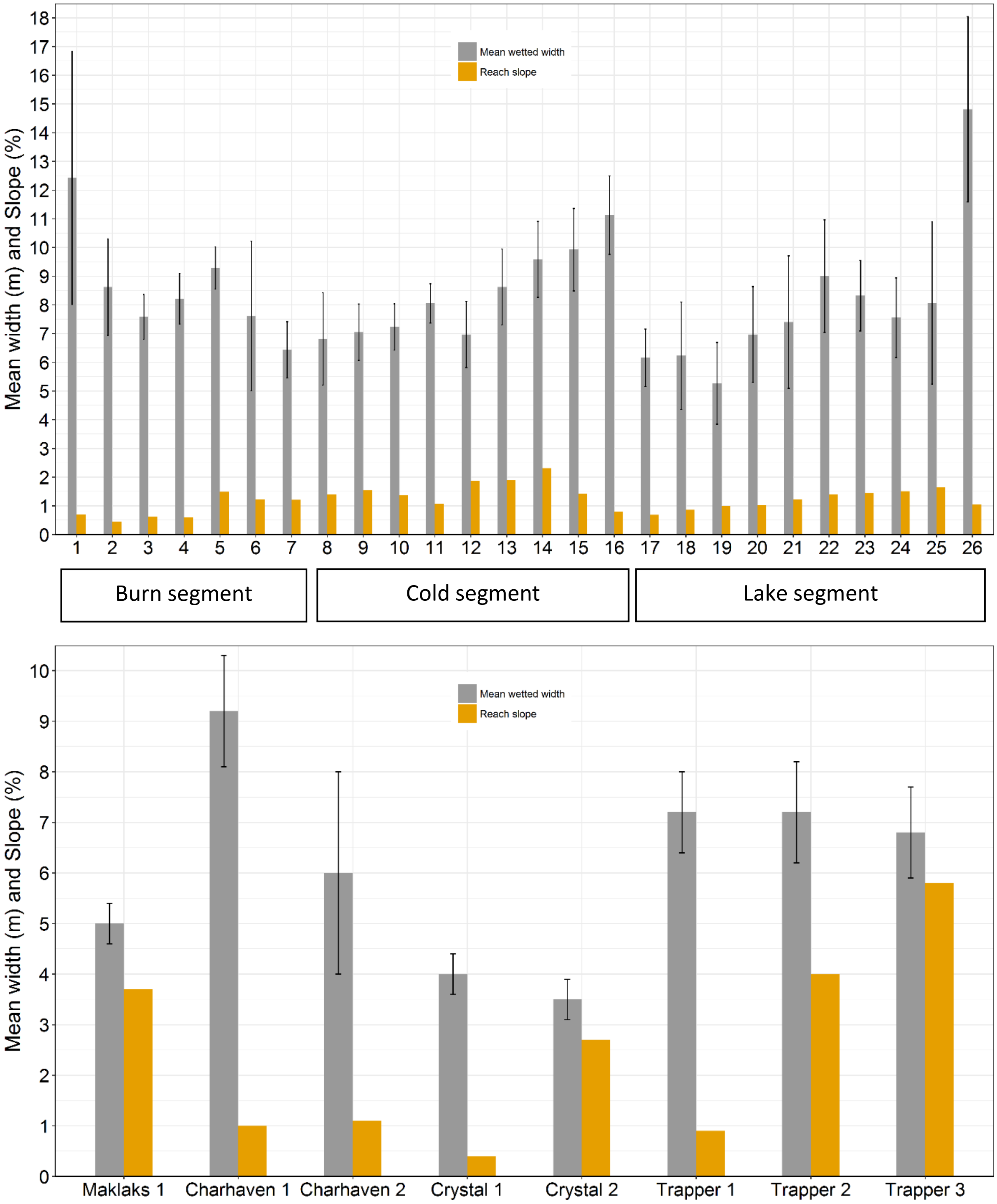

Figure 2.6. Wetted channel width (mean and 95% confidence interval) and channel slope for 500-m reaches within Odell Creek segments (upper) and the cold tributaries (lower).

In the final evaluation phase, we summarized several additional habitat complexity characteristics (Table 2.6). In Odell Creek, the reach-level frequency of deep pools (i.e., >0.3 m residual depth) was relatively high in the burn segment (0.7-2.9 pools·100 m^{-1}), relatively moderate in the cold segment (0.1-0.8 pools·100 m^{-1}), and relatively low in the lake segment (0.0-2.9 pools·100 m^{-1}). The number of key pieces of instream wood was relatively low throughout the OLCA (0.0-1.2 key pieces·100 m^{-1}).

Discussion

We constructed a map of stream temperatures and summarized selected habitat characteristics in the Odell Lake Core Area (OLCA) in 2016 to provide greater context for Bull Trout distribution, abundance, and movement patterns presented in a recent status assessment (Meeuwig et al. 2015) and to evaluate and identify areas of opportunity for improving Bull Trout status in the OLCA through management actions. In the first phase of evaluating OLCA habitat, we identified habitat reaches that were thermally suitable and unlikely to be limited by channel size or slope for spawning and rearing and then rated these reaches by suitability criteria. All of the tributaries in this study, which are fed mostly by cold springs throughout the summer and fall, showed high thermal suitability for spawning. These tributaries ranged between 4-5°C mean summer temperature, which is below reported spawning temperature thresholds in August and September in other basins (McPhail and Murray 1979; Weaver and White 1985; Fraley and Shepard 1989; Kitano 1994, Chandler et al. 2001, Howell et al. 2010). The suitability of Odell Creek for Bull Trout spawning is more difficult to evaluate because the reported maximum spawning temperature threshold has not been well defined in previous studies. Many of the studies that report a spawning temperature threshold do not identify the specific temperature metric (e.g., McPhail and Murray 1979; Weaver and White 1985; Fraley and Shepard 1989; Kitano 1994), and the temperature threshold may differ among populations (e.g., Chandler et al. 2001 versus Howell et al. 2010) or interannually (Howell et al. 2010). Furthermore, many streams that do not support Bull Trout spawning eventually reach temperatures suitable for Bull Trout spawning at some point in the fall, but it is not clear by what time period temperatures must become suitable in order for spawning to occur in a stream. Based on these studies and assuming September stream temperature is a good proxy or synthetic variable for evaluating spawning habitat potential, we devised September spawning temperature criteria. Applying these criteria to Odell Creek, the cold and burn segments provided some potential spawning habitat in September, ranging from high to medium thermal suitability (September reach means, 6.4°C and 8.5-11.6°C). All of the tributaries showed high thermal suitability for juvenile rearing. In Odell Creek, there was no highly suitable thermal habitat for juvenile rearing, the lake segment was not thermally suitable for summer rearing, the cold segment was rated medium suitability across the temperature metrics, and the burn segment was composed of reaches of medium and low suitability.

Using the first phase criteria, Trapper Creek, Crystal Creek, Charhaven Creek, Maklaks Creek, and the cold and burn segments of Odell Creek were composed of medium or high suitability in summer temperatures, stream size, and slope and identified as potential areas of opportunity for enhancing Bull Trout status in the OLCA. Reaches rated medium suitability may be more likely to constrain the relative effectiveness of well-designed enhancement actions. For example, the cold and burn segments of Odell Creek may be constrained by summer rearing temperatures of medium suitability, Crystal Creek was relatively small, the second and third reaches of Trapper Creek were relatively steep, and Maklaks Creek was relatively small and steep. However, individual reaches do not exist in isolation and Bull Trout likely require multiple reaches to provide suitable habitat at different life stages; therefore, there are spatial, temporal, and interspecific factors to consider when deciding where to direct management actions for species recovery.

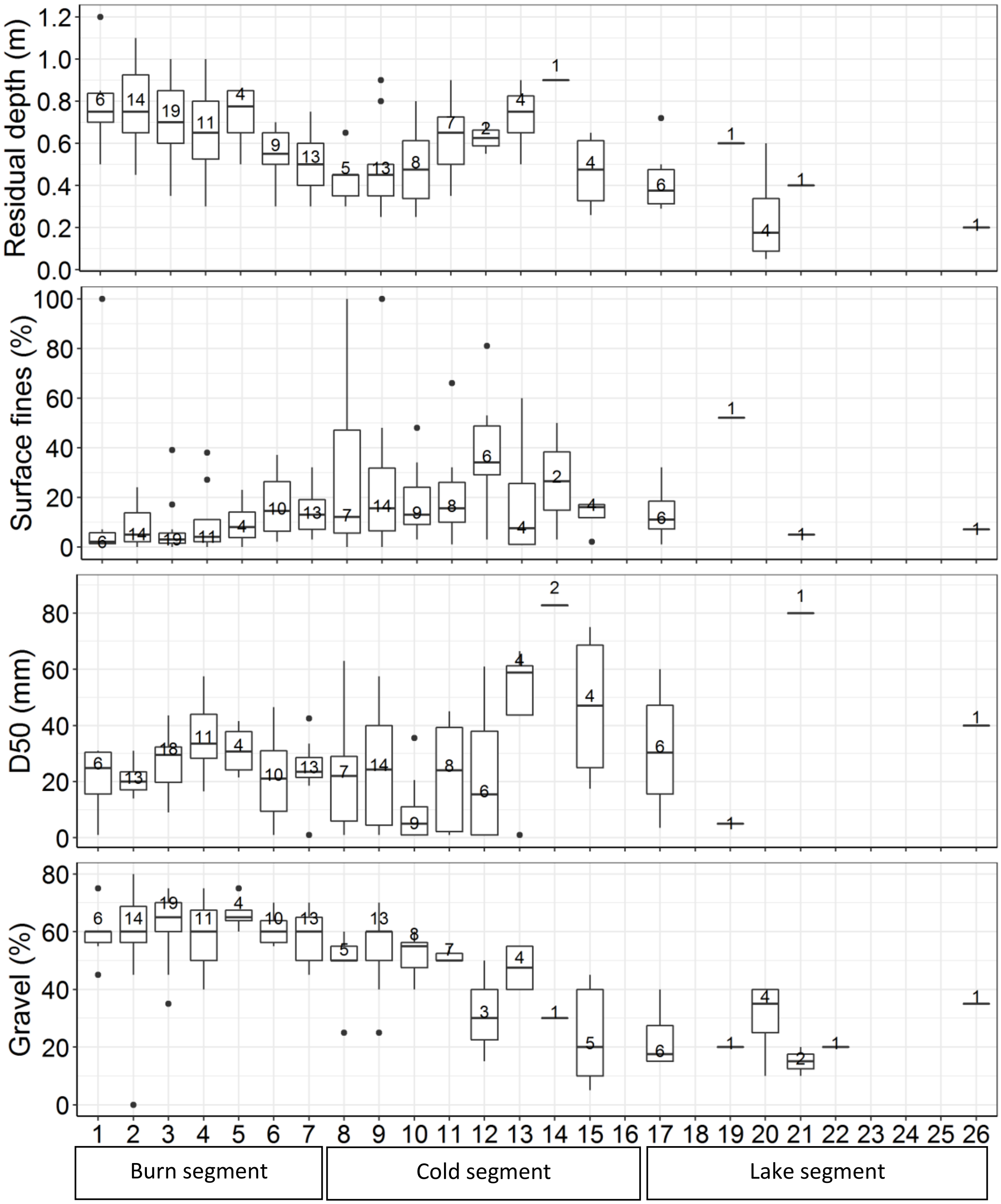

Figure 2.7. Scour pool characteristics for 500-m reaches within Odell Creek segments. D50 represents the median diameter of substrate in scour pool tailouts. Boxplots describe median (center line), inner quartiles (boxes), 1.5*interquartile range (whiskers), and outliers (points). The number of scour pools or tailouts summarized in each boxplot is shown.

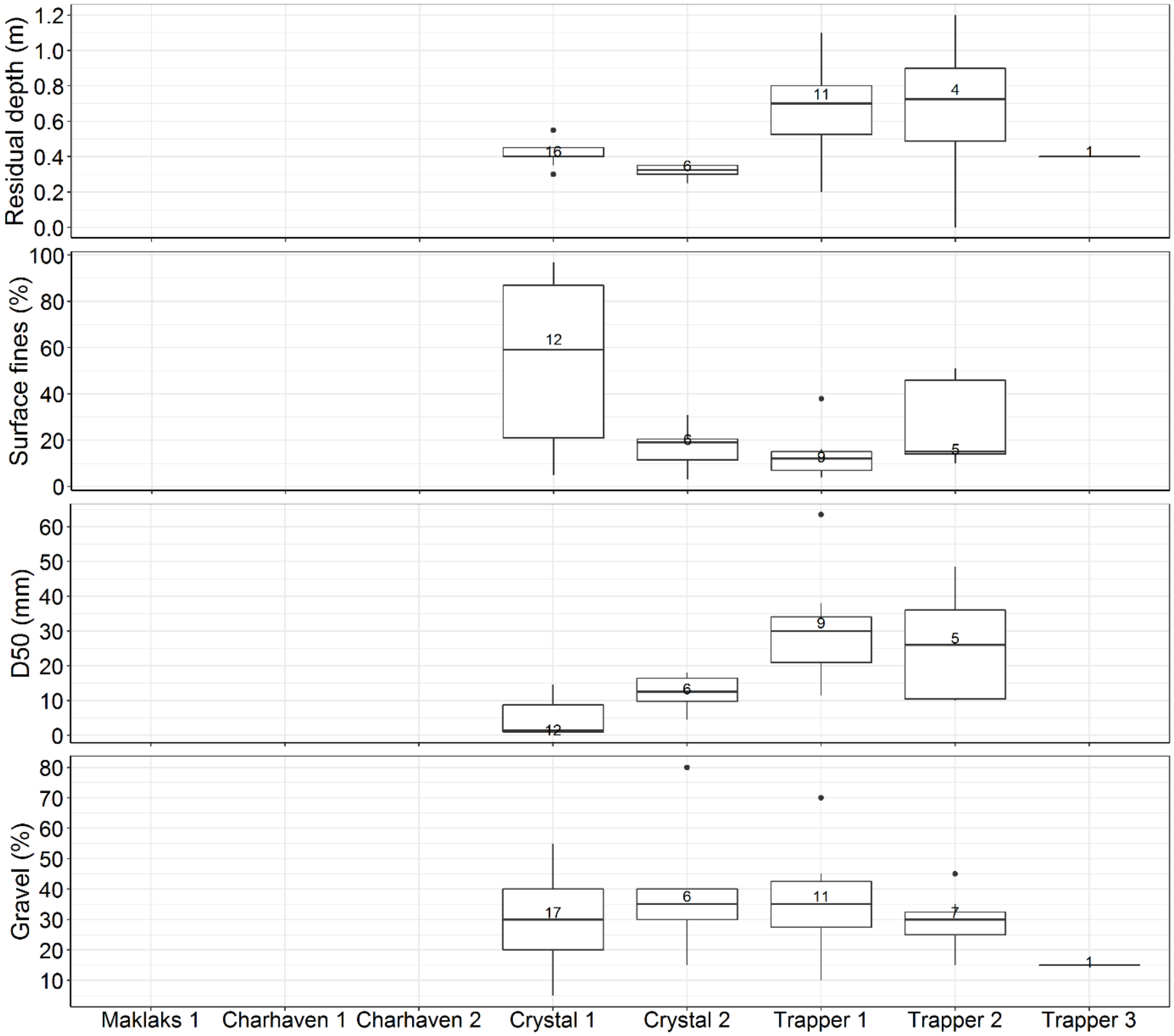

Figure 2.8. Scour pool characteristics for the reaches of the cold tributaries. D50 represents the median diameter of substrate in scour pool tailouts. Boxplots describe median (center line), inner quartiles (boxes), 1.5*interquartile range (whiskers), and outliers (points). The number of scour pools or tailouts summarized in each boxplot is shown.

The spatial arrangement and temporal variability in reach-specific habitat characteristics could influence the spatio-temporal distribution of Bull Trout. For example, Crystal Creek is small relative to Charhaven Creek, but Crystal Creek still may have greater potential to improve Bull Trout status in this core area. Crystal Creek historically was considered the primary producer of Bull Trout in the OLCA (OGSC 1946); multiple juvenile age classes of Bull Trout were recently detected in Crystal Creek rearing in very low relative abundance (Meeuwig et al. 2015), which shows rearing is possible and suggests spawning may still occur in this stream; and Odell Lake is adjacent and can provide thermally suitable summer rearing habitat for larger juveniles and adults. Charhaven Creek, in contrast, joins Odell Creek at the break point of the lake segment, which has low thermal suitability during summer, and the cold segment, which is only of medium thermal suitability in summer. In other words, upstream and downstream of Charhaven Creek there was no summer rearing habitat of high thermal suitability in 2016. In 2013 and 2014, at least 5 Bull Trout (14-16 cm total length) were detected moving downstream through a video station from Charhaven Creek to Odell Creek and at least 10 Bull Trout (range, 12-25 cm total length) moved downstream through a video station in the cold segment. Most of this downstream movement occurred in mid-August of both years, which was 2-3 weeks after peak stream temperatures in the cold segment (Meeuwig et al. 2015). These data show that Bull Trout were finding suitable habitat in Charhaven Creek and the Odell Creek cold segment and may be extending their distribution as thermal suitability improved later in the season. More information is needed about how Bull Trout find and use thermally suitable habitat in the cold and burn segments of Odell Creek and its cold tributaries in order to fully evaluate thermal habitat potential in this section of the OLCA.

Climate warming is a long-term temporal factor that is likely to have an especially adverse effect on thermal suitability in Odell Creek. The mean annual air temperature of the planet has already increased 0.94°C from the 20th century average because of greenhouse gases produced from human activities accumulating in the atmosphere (NOAA 2016). The production of greenhouses gasses has not abated and recent climate scenarios predict mean global air temperature to increase by 1.2-3.6°C by 2059 (Jones et al. 2014). Air temperature is an important factor influencing stream temperature (Isaak et al. 2010, Mayer 2012, Luce et al. 2014) and there is some evidence that mean summer air temperature has increased since 1974 at Odell Lake (Figure 2.9). Furthermore, lakes absorb solar radiation, which dramatically increases surface outflow water temperatures (Hieber 2002), and lake surface temperatures across the globe are warming more rapidly than air temperatures (O'Reilly et al. 2015). This suggests that the spatial and temporal extent of suitable thermal habitat in Odell Creek, given the influence of Odell Lake, may shrink due to the effects of climate warming. Since this could affect the likelihood of success of management actions to enhance Bull Trout status, and possibly threaten the long-term persistence of Bull Trout in this section of the OLCA, we need a better understanding of how the Odell Creek stream temperature regime will respond to projected climate warming.

Another potential constraining factor is the temperature mediated interaction with other species. There is evidence that even slight differences in stream temperature can shift dominance in a stream reach from one fish species to another (DeStaso and Rahel 1994, Saffel and Scarnecchia 1995; Takami et al. 1997, Haas 2001), which may be of consequence to Bull Trout in Odell Creek. Haas (2001) conducted extensive fish surveys in the Kootenay region, British Columbia, and reported that Redband Trout appeared to exclude Bull Trout from stream reaches with maximum temperature >16°C, Redband Trout were dominant in reaches with maximum temperature between 12-16°C, and Bull Trout were not the dominant species until maximum reach temperature was under 12°C. Hass (2001) concluded that the presence of Redband Trout shifted the thermal suitability of stream habitat to substantially lower temperature (Table 2.2). In Odell Creek, Redband Trout is the dominant species, including in the cold segment (Meeuwig et al. 2015). It is possible that the medium thermal suitability in summer in the cold segment may be closer to maximum-growth temperatures of *O. mykiss* (13.1-17.2°C; Bear et al. 2007 and Hokanson et al. 1977, respectively) than it is to those of Bull Trout (13.2°C, Selong et al. 2001); as a result, it may be conferring a competitive advantage to this species over Bull Trout. Furthermore, climate warming may increase the competitive advantage of Redband Trout in Odell Creek. This type of interspecific, mediating factor driven by stream temperature deserves more research in regard to Bull Trout and may need to be considered when planning enhancement actions in the OLCA.

In the physical habitat evaluation of the OLCA, we focused on summarizing variables that influence the occurrence and density of Bull Trout within suitable thermal habitat in order to highlight habitat variables that may be limiting or could be improved by management actions. Trapper Creek may be the highest priority for maximizing restoration and enhancement potential because it is the primary and maybe the only consistent spawning area of Bull Trout in the OLCA, and recent evidence suggests that this small adult population (43-51 adults in 2012, Meeuwig et al. 2015) has declined dramatically over the last five years (22-23 adults in 2016, Chapter 1 in this report). Therefore, identifying and ameliorating potential limiting habitat factors as soon as possible is critical in Trapper Creek. Even though median substrate size in scour pool tailouts was highly suitable for spawning in Trapper Creek, the relatively high percentage of surface fines also in these tailouts may indicate that these spawning gravels are embedded (McHugh and Budy 2005) and unavailable for spawning. Another factor that may be limiting spawning in Trapper Creek is the relatively low availability of spawning gravel in scour pools. The percent surface area of gravel substrate in scour pools was two or three times greater in the burn and cold segments of Odell Creek compared to Trapper Creek. Given the decline of the spawning population to critically low numbers and low relative abundance in recent years of rearing juveniles in Trapper Creek, further investigation of these potentially limiting factors is warranted and improving spawning suitability in Trapper Creek may be needed to ameliorate this potential threat.

Crystal Creek is another area of opportunity within the OLCA for improving Bull Trout status. As discussed above, this stream was once considered a primary spawning stream and still supports low-density juvenile rearing and possibly spawning (Meeuwig et al. 2015). The first reach can be characterized as high suitability rearing habitat because of relatively high residual scour pool depth, pool frequency, and instream large wood characteristics. However, it does not contain suitable spawning habitat because of a high percentage of surface fines and fine substrate in the tailouts and relatively low levels of gravel substrate in the scour pools. The low channel slope of this reach is a contributing factor in the high accumulation of fine substrate and may prevent improvement of the reach as spawning habitat. The spawning habitat in the second reach improves relative to the first reach, but the second reach still contains relatively high surface fines and fine gravel in the pool tailouts and a generally low availability of gravel substrate in scour pools. It is not clear if the culvert under the railroad tracks has reduced the recruitment of gravel into this second reach, but adding gravel downstream of the culvert may ameliorate this potentially limiting factor and improve its spawning habitat potential in the second reach of Crystal Creek.

Charhaven Creek is the coldest and second largest spring-fed tributary in the OLCA, with about 65% of the baseflow discharge of Trapper Creek, and it has relatively low slope, which makes it a potentially important area of opportunity for improving both rearing and spawning habitat for Bull Trout. Previous fish surveys suggests that Charhaven Creek supports low-density Bull Trout rearing and occasional spawning in this stream or nearby in Odell Creek (Meeuwig et al. 2015). However, this stream is completely lacking in scour pools, pool tailout habitat and associated spawning gravels, and is composed of mainly fine substrate and cobble. It is not clear why a stream of this size and slope lacks gravel or the scouring force to create pools. This national forest has a long history of logging, which likely included removing large wood from streams. Throughout the OLCA key pieces of instream wood are rare, on average about one piece for every 200 m of stream length. Large wood pieces have been associated with scour pool formation (Hauer et al. 1999) and sediment storage (Wohl and Scott 2016). Whatever the case, spawning and rearing in Charhaven Creek may be limited by the lack of scour pools and spawning gravel and should be investigated for potential management actions that might enhance Bull Trout status in this section of the OLCA. Any management action may be complicated by the fact there is no road crossing this stream, which makes this area the most difficult to access within the OLCA, and brook trout are present in the upper 200 m of Charhaven Creek.

Table 2.6. Summary of habitat complexity variables in the Odell Lake Core Area.

Stream/segment	Reach	Reach Length	Pools (100 m-1)		Large Wood (100m-1)		Boulders (100m-1)	Substrate (%)			Canopy Closure (%)	Channel area (%)	
		Total (m)	All	Deep	Volume (m3)	Key Piece (no.)		Fines	Gravel	Cobble		Primary	Secondary
Odell Creek/Burn	1	483	0.9	0.9	4.3	0.0	2.1	42	54	3	10	88	12
Odell Creek/Burn	2	538	2.1	2.1	4.5	0.0	1.3	33	66	1	7	88	12
Odell Creek/Burn	3	542	2.9	2.9	12.2	0.2	0.2	32	68	0	4	88	12
Odell Creek/Burn	4	464	2.0	2.0	14.9	0.0	0.0	41	55	0	2	92	8
Odell Creek/Burn	5	508	0.8	0.8	8.4	0.0	0.0	26	70	0	0	98	2
Odell Creek/Burn	6	486	0.8	0.7	8.7	0.0	0.0	37	60	3	0	38	62
Odell Creek/Burn	7	424	1.1	1.1	10.5	0.1	0.0	29	61	9	11	48	52
Odell Creek/Cold	8	435	0.6	0.6	4.1	0.1	0.6	39	50	11	43	52	48
Odell Creek/Cold	9	582	0.9	0.9	6.1	0.2	0.0	34	55	11	42	49	51
Odell Creek/Cold	10	489	0.8	0.7	5.6	0.1	0.0	24	48	18	44	48	52
Odell Creek/Cold	11	531	1.3	1.3	17.2	0.7	0.2	26	53	20	56	95	5
Odell Creek/Cold	12	501	0.6	0.4	26.3	0.9	0.0	30	53	17	53	64	36
Odell Creek/Cold	13	549	0.6	0.6	14.2	0.7	0.4	23	50	27	59	89	11
Odell Creek/Cold	14	441	0.2	0.2	6.2	0.0	0.9	20	48	31	58	100	0
Odell Creek/Cold	15	439	1.0	0.6	37.7	0.8	3.7	15	33	44	63	96	4
Odell Creek/Cold	16	667	0.1	0.1	57.4	1.2	27.7	15	10	55	64	100	0
Maklaks Creek	1	426	0.5	0.0	28.2	0.2	14.3	47	28	18	66	100	0
Charhaven Creek	1	472	0.2	0.0	32.3	0.6	0.6	54	18	27	62	99	1
Charhaven Creek	2	296	0.8	0.0	24.0	0.3	0.3	46	7	46	64	94	6
Odell Creek/Lake	17	370	1.1	0.8	39.7	1.1	5.6	15	34	43	59	59	41
Odell Creek/Lake	18	429	0.3	0.2	26.9	0.5	4.4	16	23	48	52	93	7
Odell Creek/Lake	19	512	0.4	0.2	21.4	0.2	2.6	18	31	49	58	77	23
Odell Creek/Lake	20	596	1.1	0.7	25.1	0.5	2.0	11	17	71	63	88	12
Odell Creek/Lake	21	507	0.7	0.5	13.4	0.3	5.7	11	26	59	47	85	15
Odell Creek/Lake	22	555	0.2	0.0	13.3	0.3	6.5	1	18	77	60	95	5
Odell Creek/Lake	23	485	0.4	0.4	21.4	0.4	7.3	9	22	61	57	88	12
Odell Creek/Lake	24	497	0.0	0.0	27.2	0.3	36.9	11	29	43	58	87	13
Odell Creek/Lake	25	465	0.0	0.0	26.7	0.4	27.3	8	32	38	65	97	3
Odell Creek/Lake	26	351	0.3	0.0	30.1	0.9	31.0	6	36	47	58	100	0
Crystal Creek	1	538	2.5	2.4	42.7	1.1	0.5	77	22	1	54	85	15
Crystal Creek	2	583	1.5	0.8	25.3	0.4	3.0	56	42	2	59	81	19
Trapper Creek	1	528	2.0	1.7	42.8	0.8	25.0	25	31	31	53	86	14
Trapper Creek	2	541	1.3	0.7	19.1	0.7	187.5	9	17	41	60	96	4

Figure 2.9. Mean summer air temperature (i.e., July 1 to August 31) at the Odell Lake East NOAA weather station from 1974 through 2017. Some years are missing summer data. Data were downloaded from the National Center for Environmental Information website (https://www.ncdc.noaa.gov/cdo-web/datasets/GHCND/stations/GHCND:USC00356252/detail).

Maklaks Creek and McCord Cabin Springs are cold spring-fed streams that are smaller and steeper than Charhaven Creek. Bull Trout have occurred in channels with similar characteristics in other basins (Dunham et al. 2003), so they are included here as potential areas of opportunity for improving Bull Trout status. Maklaks Creek also has a paucity of scour pools and gravel. The habitat of McCord Cabin Springs was not surveyed because of time constraints, but it likely has characteristics similar to Maklaks Creek since they are less than 100 m apart and run down the same hillslope. Maklaks Creek can be easily accessed via a road crossing and would likely be improved as potential suitable habitat for Bull Trout by management actions that increase pool frequency and spawning gravel availability.

The Odell Creek cold segment is an area of opportunity because it contains highly suitable slope and width, a relatively high frequency of deep pools, reaches with high and medium levels of gravel in scour pools, and suitable spawning gravel in the pool tailouts. Tailouts in the cold segment have a high percentage of surface fines compared to the burn segment, which may suggest embeddedness that makes some of these tailouts unavailable for spawning. Spawning temperatures in September and summer rearing temperature are generally of medium suitability; which, for reasons discussed above, may seasonally curtail bull trout distribution and limit abundance in these reaches.

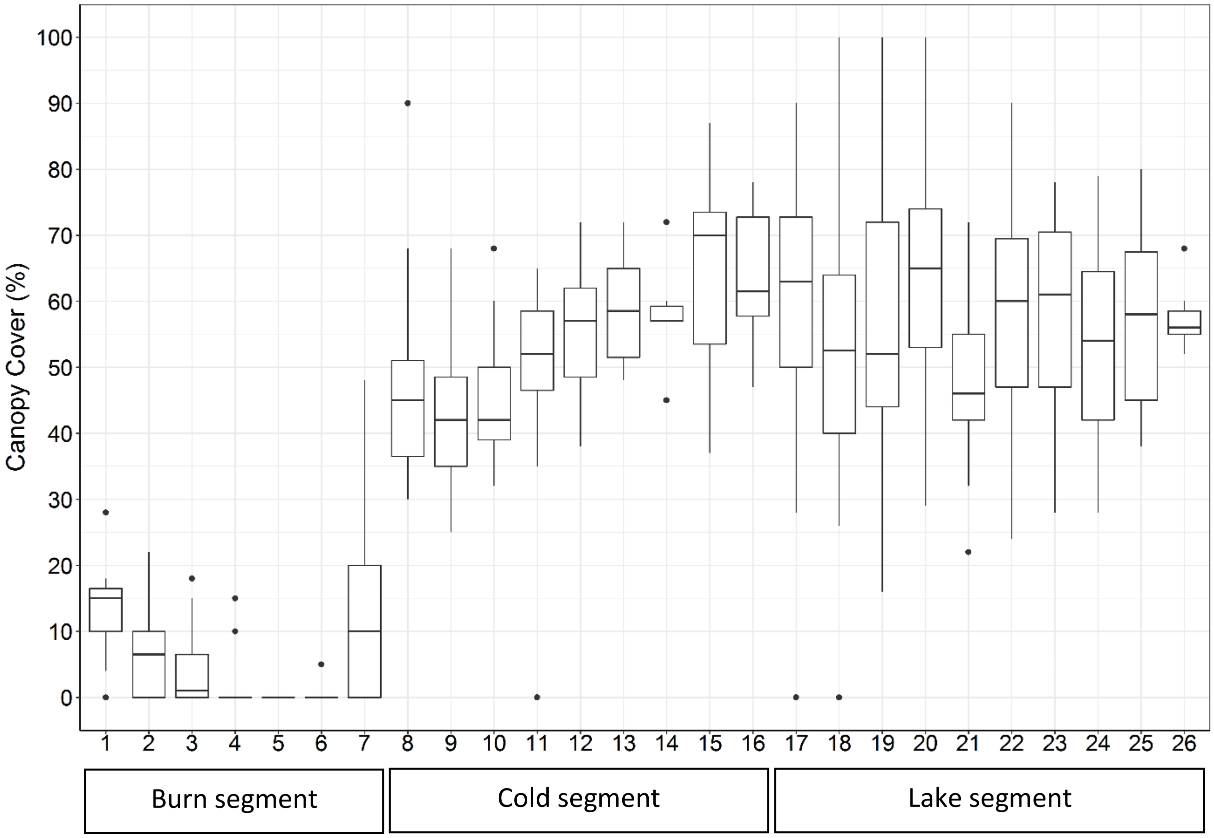

Figure 2.10. Canopy cover summary for channel units in 500-m reaches within Odell Creek segments. Boxplots describe median (center line), inner quartiles (boxes), 1.5*interquartile range (whiskers), and outliers (points).

Improving summer stream temperatures in the cold segment through management actions would be difficult. Upstream of the cold segment, the lake segment of Odell Creek is lacking in pool habitat, which may reduce the amount of groundwater flow through stream sediment and its associated cooling effect (Allan 1995). The lake segment cooled slightly in the summer of 2016 from the outflow of Odell Lake (summer mean, 22.9°C; summer maximum, 23.7°C) downstream to the reach upstream of the Charhaven Creek confluence (22.5°C; 23.4°C). There are a number of small cold spring seeps entering the lake segment that likely contribute to the downstream cooling effect. It is unknown if these cold seeps are the sole cause of the downstream cooling effect or if groundwater discharge in the stream itself is a contributing factor. Theoretically, increasing pool frequency through pool construction or large wood additions could push more warm streamwater underground, but it is not clear if this would significantly increase cool groundwater discharge into the stream and the cooling capacity of the lake segment. Given that summer water temperatures at the Odell Lake outflow are likely to rise due to the effects of climate warming, determining the effect of habitat restoration actions in the lake segment may be necessary in order to explore ways to preserve or enhance thermal habitat downstream in the cold segment. There is additional importance to enhancing the Bull Trout population in the cold segment and its cold tributaries because it is disjunct from Odell Lake and juvenile Bull Trout rearing in Charhaven Creek or suitable reaches in Odell Creek would not have to contend with the nonnative piscivore Lake Trout (*S. namaycush*).

The Odell Creek burn segment has the best physical habitat for spawning and rearing in the entire OLCA. This segment has the highest pool frequency, deepest pools, lowest surface fines in scour pool tailouts, highly suitable gravel size for spawning in tailouts, and highest percentages of gravel in scour pools in general. Mean stream temperatures around 9°C in September suggest that this segment may provide thermal habitat for spawning, but the temperature metrics suggest that this segment was unsuitable in the summer of 2016 for rearing juvenile Bull Trout. As with the cold segment, influencing summer water temperatures in the burn segment would be very difficult in the next 20-50 years. Over the long-term, however, this segment could experience significant cooling from restoration of a mature forest canopy in the riparian zones. In 2003, this segment experienced a stand-replacing wildfire and as of 2016 was still lacking riparian canopy cover (Figure 2.10). Loss of riparian canopy dramatically increases the input of direct solar radiation into a stream, which is the most important factor in stream heating (Johnson and Jones 2000). For example, after a severe fire on a stream in the Boise River basin, Idaho, the mean stream temperature increased 2.6°C and the maximum increased 3.5°C relative to a nearby reference stream (Dunham et al. 2007). In an example from a stream in the Cascade Mountain range in Oregon, a riparian clear-cutting treatment resembling a severe fire increased maximum stream temperature 7°C (Johnson and Jones 2000). Surveys in the burn segment prior to the 2003 fire usually detected rearing Bull Trout, but recent post-fire surveys and video station monitoring of this segment did not detect this species (Meeuwig et al. 2015). These examples and others (e.g., Isaak et al. 2010) suggest that restoring riparian forest along the burn segment could be an effective temperature-reducing measure for the burn segment. Parameterizing a geostatistical temperature model for Odell Creek that incorporates additional variables, such as annual air temperature and discharge, canopy cover, and pre- and post-fire temperature data, will be helpful for determining the effect of the fire on the burn segment thermal regime and whether restoring the riparian canopy will be effective at providing Bull Trout with suitable thermal habitat.

Bull Trout are highly imperiled in the OLCA (Meeuwig et al. 2015, Chapter 1 in this report) and in need of management actions that ameliorate threats and reduce the risk of this species disappearing from this core area. This study provides managers with a thermal map that can be used to identify patches of thermally suitable habitat for rearing and spawning and make informed decisions about where to focus management actions. It also provides managers with spatially-referenced habitat attributes that can be used to identify where attributes critical for rearing and spawning may be limiting Bull Trout occurrence and density. This information can provide guidance for specific management actions in thermally suitable areas of opportunity. Future research should focus on continuing to improve our understanding of thermal habitat in the OLCA, especially in Odell Creek, by refining the thermograph array for long-term monitoring and improved resolution near the Odell Creek tributaries, constructing the geostatistical temperature model described above, and downscaling climate projections for air temperature and discharge into the model. These steps will improve our understanding of current and future thermal habitat suitability for Bull Trout and increase the effectiveness of future management actions to enhance the status of this species throughout this core area.

References

Al-Chokhachy, R., B. B. Roper, T. Bowerman, and P. Budy. 2010. A review of Bull Trout habitat associations and exploratory analyses of patterns across the interior Columbia River Basin. North American Journal of Fisheries Management 30(2):464–480.

Allan, J.D. 1995. Stream Ecology: Structure and function of running waters. Chapman and Hall. 379 pp.

(AREMP) Aquatic and Riparian Effectiveness Monitoring Program. 2013. Field protocol manual.

Angelo, V. S. D., and C. Muhlfeld. 2013. Factors influencing the distribution of native Bull Trout and Westslope Cutthroat Trout in streams of western Glacier National Park. Northwest Science 87(1):1–11.

Baxter, C. V, and F. R. Hauer. 2000. Geomorphology, hyporheic exchange, and selection of spawning habitat by Bull Trout (*Salvelinus confluentus*). Canadian Journal of Fisheries and Aquatic Sciences 57:1470–1481.

Bear, E.A., T.E. McMahon, and A.V. Zale. 2007. Comparative thermal requirements of Westslope Cutthroat Trout and Rainbow Trout: implications for species interactions and development of thermal protection standards. Transactions of the American Fisheries Society 136: 1113-1121, DOI: 10.1577/T06-072.1.

Bowerman, T., B. T. Neilson, and P. Budy. 2014. Effects of fine sediment, hyporheic flow, and spawning site characteristics on survival and development of Bull Trout embryos. Canadian Journal of Fisheries and Aquatic Sciences 71:1059–1071.

Chandler, J.A., M.A. Fedora, and T.R. Walters. 2001. Pre- and post-spawn movements and spawning observations of resident Bull Trout in the Pine Creek watershed, eastern Oregon. In M.K. Brewin, A.J. Paul, and M. Monita, editors. Bull trout II conference proceedings. Trout Unlimited Canada, Calgary, Alberta. Pages 167-172.

Cristea, N. C., and S. J. Burges. 2010. An assessment of the current and future thermal regimes of three streams located in the Wenatchee River basin, Washington State: some implications for regional river basin systems. Climatic Change 102:493–520.

Dambacher, J. M., and K. K. Jones. 1997. Stream habitat of juvenile Bull Trout populations in Oregon and benchmarks and habitat quality. 353–360 *in* Friends of the Bull Trout Conference Proceedings, pages 353–360. Editors, Brewin, M.K., A.J. Paul, and M. Monita.

DeStaso, J., III, and F. J. Rahel. 1994. Influence of water temperature on interactions between juvenile Colorado River cutthroat trout and brook trout in a laboratory stream. Transactions of the American Fisheries Society 123:289–297.

DeVries, P. 2007. A comparison of visual and measurement-based techniques for quantifying cobble embeddedness and fine-sediment levels in salmonid-bearing streams. North American Journal of Fisheries Management 27:1025–1026.

Dunham, J. B., and B. E. Rieman. 1999. Metapopulation structure of Bull Trout: Influences of physical, biotic, and geometrical landscape characteristics. Ecological Applications 9(2):642–655.

Dunham, J. B., A. E. Rosenberger, C. H. Luce, and B. E. Rieman. 2007. Influences of wildfire and channel reorganization on spatial and temporal variation in stream temperature and the distribution of fish and amphibians. Ecosystems 10:335–346.

Dunham, J., B. Rieman, and G. Chandler. 2003. Influences of temperature and environmental variables on the distribution of Bull Trout within streams at the southern margin of its range Margin. North American Journal of Fisheries Management 23:894–904.

Fraley, J. J., and B. B. Shepard. 1989. Life history, ecology and population status of migratory Bull Trout (*Salvelinus confluentus*) in the Flathead Lake and River System, Montana. Northwest Science 63:133–143.

Gamett, B. L. 2002. The relationship between water temperature and Bull Trout distribution and abundance. PhD thesis. Utah State University.

Guzevich, J. W., and R. F. Thurow. 2007. Fine-scale characteristics of fluvial Bull Trout redds and adjacent sites in Rapid River, Idaho, 1993 – 2007. Northwest Science: 91:198–213.

Haas, G. R. 2001. The mediated associations and preferences of native Bull Trout and Rainbow Trout with respect to maximum water temperature, its measurement standards, and habitat *in* Bull Trout II Conference Proceedings, pages 53–55. Editors, Brewin, M.K., A.J. Paul, and M. Monita.

Hauer, R.F., G.C. Poole, J.T. Gangemi, and C.V. Baxter. 1999. Large woody debris in Bull Trout (*Salvelinus confluentus*) spawning streams of logged and wilderness watersheds in northwest Montana. Canadian Journal of Fisheries and Aquatic Sciences 56: 915–924.

Hieber, M., C. T. Robinson, U. Uehlinger, and J. V. Ward. 2002. Are alpine lake outlets less harsh than other alpine streams? Archiv fur Hydrobiologie 154:199–223.

Hokanson, K. E. F., C. F. Kleiner, andT. W. Thorslund. 1977. Effects of constant temperatures and diel temperature fluctuations on specific growth and mortality rates and yield of juvenile Rainbow Rrout, *Salmo gairdneri*. Journal of Fisheries Research Board of Canada 34: 639-648.

Howell, P. J., J. B. Dunham, and P. M. Sankovich. 2010. Relationships between water temperatures and upstream migration, cold water refuge use, and spawning of adult Bull Trout from the Lostine River, Oregon, USA. Ecology of Freshwater Fish 19:96–106.

Isaak, D., B. Rieman, and D. Horan. 2009. A watershed-scale monitoring protocol for Bull Trout. General Technical Report RMRS-GTR-224. Fort Collins, CO.

Isaak, D. J., C. H. Luce, B. E. Rieman, D. E. Nagel, E. E. Peterson, D. L. Horan, S. Parkes, and G. L. Chandler. 2010. Effects of climate change and wildfire on stream temperatures and salmonid thermal habitat in a mountain river network. Ecological Applications 20:1350–1371.

Jakober, M.J., T.E. McMahon , R.F. Thurow, and C.G. Clancy. 1998. Role of stream ice on fall and winter movements and habitat use by Bull Trout and Cutthroat Trout in Montana Headwater Streams. Transactions of the American Fisheries Society 127:223-235. DOI: 10.1577/1548-8659(1998)127<0223:ROSIOF>2.0.CO;2.

Jeffrey, L., K. Eric, R. Ervin, C. Richard, M. Charles, L. David, C. Linda, and M. R. Guide. 2004. Guide to effective monitoring of aquatic and riparian resources. General Technical Report RMRS-GTR-121. Fort Collins, CO.

Johnson, S. L., and J. A. Jones. 2000. Stream temperature responses to forest harvest and debris flows in western Cascades, Oregon. Canadian Journal of Fisheries and Aquatic Sciences 57(S2):30–39.

Jones, L. A., C. C. Muhlfeld, L. A. Marshall, B. L. McGlynn, and J. L. Kershner. 2014. Estimating thermal regimes of Bull Trout and assessing the potential effects of climate warming on critical habitats. River Research and Applications 30:204–216.

Kitano, S., K. Maekawa, S. Nakano, and K. D. Fausch. 2017. Spawning behavior of Bull Trout in the Upper Flathead Drainage, Montana, with special reference to hybridization with Brook Trout. Transactions of the American Fisheries Society 123:988-992.

Robert P. Lanka R.P., W.A. Hubert, and T.A. Wesche. 1987. Relations of geomorphology to stream habitat and trout standing stock in small Rocky Mountain streams. Transactions of the American Fisheries Society 116: 21-28. DOI:10.1577/1548-8659(1987)116<21:ROGTSH>2.0.CO;2.

Le, N. D., and J. V. Zidek. 2006. Statistical analysis of environmental space-time processes. Spring Science and Business Media, Inc., New York, NY.

Luce, C., B. Staab, M. Kramer, S. Wenger, D. Isaak, and C. McConnell. 2014. Sensitivity of summer stream temperatures to climate variability in the Pacific Northwest. Water Resources Research 50:3428–3443.

Mayer, T. D. 2012. Controls of summer stream temperature in the Pacific Northwest. Journal of Hydrology 475:323–335.

McPhail, J. D., and C. B. Murray. 1979. The early life-history and ecology of Dolly Varden (*Salvelinus malma*) in the Upper Arrow Lakes.

Meeuwig, M. H., S. J. Starcevich, E. J. Bailey, S. P. Clements, and J. L. McCormick. 2015. Bull trout conservation and recovery in the Odell Lake Core Area: Distribution, behavior, ecology, and fisheries evaluations (2013-2014). ODFW Information Report. Corvallis, Oregon.

Mesa, M. G., L. K. Weiland, H. E. Christiansen, S. T. Sauter, and D. A. Beauchamp,. 2017. Development and evaluation of a bioenergetics model for Bull Trout. Transactions of the American Fisheries Society 142(1):41–49.

Moore, K. M. S., K. K. Jones, J. M. Dambacher, and C. Stein. 2006. Methods for stream habitat surveys: Aquatic Inventories Project, Version 20. Oregon Department of Fish and Wildlife, Aquatic Inventories Project, Conservation and Recovery Program, Corvallis OR.

(NOAA) National Oceanic and Atmospheric Administration. National Centers for Environmental Information, State of the Climate: Global Analysis for Annual 2016, published online January 2017, retrieved on September 11, 2017 from https://www.ncdc.noaa.gov/sotc/global/201613.

O’Reilly, C. M., and 64 authors. 2015. Rapid and highly variable warming of lake surface waters around the globe, Geophysical Research Letters 42: 10773–10781. doi:10.1002/2015GL066235.

(OSGC) Oregon State Game Commission. 1946. Cascades lakes survey report. Oregon State Game Commission.

Peterson, E. E., and J. M. Ver Hoef. 2014. Stars: An ArcGIS toolset used to calculate the spatial information needed to fit spatial statistical models to stream network data - University of Washington. Journal of Statistical Software 56:1–17.

Pratt, K. L. 1992. A review of Bull Trout life history. Pages 5–9 in P. J. Howell and D. V. Buchanan, editors. Proceedings of the Gearhart Mountain Bull Trout workshop. American Fisheries Society, Oregon Chapter, Corvallis.

Rich, C.F., T. E. McMahon, B. E. Rieman, and L. William. 2003. Local-habitat, watershed, and biotic features associated with Bull Trout occurrence in Montana streams. Transactions of the American Fisheries Society 132:1053–1064.

Rieman, B. E., and J. D. Mclntyre. 1993. Demographic and habitat requirements for conservation of bull trout. Page General Technical Report INT-302. Ogden, UT.

Rieman, B. E., and G. L. Chandler. 1999. Empirical evaluation of temperature effects on bull trout distribution in the Northwest. Page US. EPA Report. Boise, Idaho.

Ripley, T., G. Scrimgeour, and M. S. Boyce. 2005. Bull trout (*Salvelinus confluentus*) occurrence and abundance influenced by cumulative industrial developments in a Canadian boreal forest watershed. Canadian Journal of Fisheries and Aquatic Sciences 62:2431–2442.

Saffel, P. D., and D. L. Scarnecchia. 1995. Habitat use by juvenile Bull Trout in belt-series geology watersheds of northern Idaho. Northwest Science 69:304–316.

Schultz, L. D., M. P. Heck, D. Hockman-wert, T. Allai, S. Wenger, N. A. Cook, and J. B. Dunham. 2017. Spatial and temporal variability in the effects of wild fire and drought on thermal habitat for a desert trout. Journal of Arid Environments 145:60–68. Elsevier Ltd.

Selong, J. H., T. E. McMahon, A. V. Zale, and F. T. Barrows. 2001. Effect of temperature on growth and survival of Bull Trout, with application of an improved method for determining thermal tolerance in fishes. Transactions of the American Fisheries Society 130:1026–1037.

Sinokrot, B. A., and H. G. Stefan. 1993. Stream temperature dynamics: Measurement and modeling. Water Resources Research 29:2299–2312.

Starcevich S.J., P.J. Howell, and S.E. Jacobs. 2012. Seasonal movement and distribution of fluvial adult Bull Trout in selected watersheds in the Mid-Columbia River and Snake River basins. PLoS ONE 7(5): e37257. doi:10.1371/journal.pone.0037257.

Takami, T., F. Kitano, and S. Nakano. 1997. High water temperature influences on foraging responses and thermal deaths of Dolly Varden *Salvelinus malma* and White-Spotted Charr *S. leucomaenis* in a laboratory. Fisheries Science 63:6–8.

Tennant, L. B., R. E. Gresswell, C. S. Guy, and M. H. Meeuwig. 2016. Spawning and rearing behavior of bull trout in a headwater lake ecosystem. Environmental Biology of Fishes 99:117–131.

(USFWS) U.S. Fish and Wildlife Service. 1998. Determination of threatened status for the Klamath River and Columbia River distinct population segments of Bull Trout. Federal Register 63:31647-31674.

Ver Hoef, J. M., and E. E. Peterson. 2010. A moving average approach for spatial statistical models of stream networks. Journal of the American Statistical Association 105:6–18.

Ver Hoef, J. M., E. E. Peterson, D. Clifford, and R. Shah. 2014. SSN: An R Package for Spatial Statistical Modeling on Stream Networks. Journal of Statistical Software 56:1–45.

Weaver, T. M., and R. G. White. 1985. Coal Creek fisheries monitoring study, No. III. Final Report. Montana Cooperative Fisheries Research Unit, Bozeman, Montana.

Wenger, S. J., D. J. Isaak, J. B. Dunham, K. D. Fausch, C. H. Luce, H. M. Neville, B. E. Rieman, M. K. Young, D. E. Nagel, D. L. Horan, and G. L. Chandler. 2011. Role of climate and invasive species in structuring trout distributions in the interior Columbia River. Canadian Journal of Fisheries and Aquatic Sciences 68:988–1008.

Wohl, E., and D. N. Scott. 2017. Wood and sediment storage and dynamics in river corridors. Earth Surface processes and Landforms.

Appendix I. Top 10 geostatistical temperature models for summer mean and maximum and maximum 7-day moving average maximum daily temperature (7DMAM) in the Odell Lake basin study area in 2016. The final models (bold) were selected by the lowest Akaike Information Criterion (AIC) value. Other model attributes presented are root-mean-squared prediction error (RMSPE) and its standard deviation (SD), and confidence interval (CI) coverage probabilities.

Fixed effect predictors	Variance components	AIC	RMSPE	SD	80% CI	90% CI	95% CI
Summer mean ~ Lake segment + Cold trib	**Gaussian.Euclid + Nugget**	**144.44**	**0.90**	**1.03**	**0.92**	**0.96**	**0.96**
Summer mean ~ Lake segment + Cold trib	Spherical.Euclid + Nugget	144.52	0.90	1.03	0.92	0.96	0.96
Summer mean ~ Lake segment + Cold trib	Spherical.taildown + Nugget	144.70	0.91	1.03	0.92	0.96	0.96
Summer mean ~ Lake segment + Cold trib	Cauchy.Euclid + Nugget	144.84	0.91	1.03	0.92	0.96	0.96
Summer mean ~ Lake segment + Cold trib	Exponential.taildown + Nugget	145.13	0.91	1.03	0.94	0.96	0.96
Summer mean ~ Lake segment + Cold trib	LinearSill.tailup + Nugget	145.33	0.91	1.03	0.92	0.96	0.96
Summer mean ~ Lake segment + Cold trib	Spherical.tailup + Nugget	145.47	0.92	1.03	0.94	0.96	0.96
Summer mean ~ Lake segment + Cold trib	Exponential.tailup + Nugget	145.47	0.94	1.04	0.92	0.96	0.96
Summer mean ~ Lake segment + Cold trib	Exponential.Euclid + Nugget	145.52	0.94	1.05	0.92	0.96	0.96
Summer mean ~ Lake segment + Cold trib	Mariah.taildown + Nugget	146.05	0.92	1.03	0.94	0.96	0.96
Maximum ~ Lake segment + Cold trib	**Gaussian.Euclid + Nugget**	**188.79**	**1.36**	**1.06**	**0.92**	**0.94**	**0.94**
Maximum ~ Elevation + Lake segment + Cold trib	Gaussian.Euclid + Nugget	189.39	1.36	1.08	0.92	0.94	0.96
Maximum ~ Lake segment + Cold trib	Cauchy.Euclid + Nugget	189.63	1.36	1.05	0.92	0.94	0.94
Maximum ~ Lake segment + Cold trib	Spherical.taildown + Nugget	189.66	1.36	1.04	0.92	0.96	0.96
Maximum ~ Elevation + Lake segment + Cold trib	Cauchy.Euclid + Nugget	189.99	1.35	1.08	0.92	0.96	0.96
Maximum ~ Lake segment + Cold trib	LinearSill.taildown + Nugget	190.04	1.37	1.04	0.92	0.96	0.96
Maximum ~ Lake segment + Cold trib	Spherical.Euclid + Nugget	190.55	1.38	1.04	0.92	0.94	0.96
Maximum ~ Elevation + Lake segment + Cold trib	Spherical.taildown + Nugget	190.63	1.35	1.05	0.94	0.96	0.96
Maximum ~ Lake segment + Cold trib	Exponential.taildown + Nugget	190.80	1.36	1.03	0.94	0.96	0.96
Maximum ~ Elevation + Lake segment + Cold trib	LinearSill.taildown + Nugget	191.00	1.37	1.06	0.92	0.96	0.96
Maximum 7DADM ~ Lake segment + Cold trib	**Gaussian.Euclid + Nugget**	**184.51**	**1.30**	**1.06**	**0.92**	**0.94**	**0.94**
Maximum 7DADM ~ Elevation + Lake segment + Cold trib	Gaussian.Euclid + Nugget	185.09	1.30	1.08	0.92	0.96	0.96
Maximum 7DADM ~ Lake segment + Cold trib	Cauchy.Euclid + Nugget	185.37	1.30	1.05	0.92	0.94	0.94
Maximum 7DADM ~ Lake segment + Cold trib	Spherical.taildown + Nugget	185.41	1.30	1.04	0.92	0.96	0.96
Maximum 7DADM ~ Lake segment + Cold trib	LinearSill.taildown + Nugget	185.68	1.31	1.04	0.92	0.96	0.96
Maximum 7DADM ~ Elevation + Lake segment + Cold trib	Cauchy.Euclid + Nugget	185.71	1.29	1.08	0.92	0.96	0.96
Maximum 7DADM ~ Lake segment + Cold trib	Spherical.Euclid + Nugget	186.25	1.32	1.04	0.92	0.94	0.96
Maximum 7DADM ~ Elevation + Lake segment + Cold trib	Spherical.taildown + Nugget	186.34	1.29	1.05	0.94	0.96	0.96
Maximum 7DADM ~ Lake segment + Cold trib	Exponential.taildown + Nugget	186.51	1.30	1.03	0.94	0.96	0.96
Maximum 7DADM ~ Elevation + Lake segment + Cold trib	LinearSill.taildown + Nugget	186.74	1.31	1.06	0.92	0.96	0.96