Upper Wenatchee Thermal Refuge Assessment

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Abstract

Several reaches in the Upper Wenatchee watershed that are major spawning habitat for endangered spring Chinook salmon (*Onchorhynchus tshawytscha*) and core rearing habitat for winter steelhead (*Onchorhynchus mykiss)* and bull trout (*Salvelinus confluentus)*, consistently exhibit high summer water temperatures that threaten species recovery. When stream reaches exceed thermal limits to salmonids, fish can persist by using cold-water refuges. The overall goal of the Upper Wenatchee Assessment was to: identify and map cold-water features, within Wenatchee Basin 303(d) impaired temperature reaches that are also spring Chinook Major Spawning Areas (MASAs), during low flow summer conditions, and identify habitat actions that will serve ESA-listed species recovery. During the summers of 2018 and 2019, Chelan County Natural Resource Department (CCNRD) staff used a quick response digital thermometer to ground truth potential cold water features, such as tributary mouths and seeps indicated in the 2001-2003 thermal infrared data. Staff collected detailed temperature and habitat data for all features with temperature differentials of at least 1.5°C. CCNRD and Cramer Fisheries Sciences staff developed protection or habitat actions aimed at increasing thermal refuge quantity and/or quality for each confirmed cold feature. CCNRD staff also collected continuous longitudinal temperature profiles during peak summer temperatures in order to characterize spatial heterogeneity within the thermal landscape that occurred during low flow and peak summer temperature conditions. In total, 40 cold water features were identified, measured, mapped, and associated habitat restoration actions were developed (Appendix C). This included 18 surface water features (tributaries or springs) and 22 ground water features (cold side channels, cold alcoves, and lateral seeps). Longitudinal temperature profiles were completed on 39.6 river miles of the 48.5 total river miles included in the study, and cross-referenced to seasonal temperature logger data that was collected by state and federal agencies. In a separate but related effort, winter drone TIR was completed on select reaches of the Entiat and Wenatchee River (Appendix A). Data suggests deep, cold pools that can serve as holding habitat for adult spring Chinook is lacking in the Upper Wenatchee, but that target restoration can potentially increase its availability. Methods were effective at locating certain types of cold water features (tributary confluences, cold water alcoves and side channels) but few mainstem upwellings and lateral seeps were located either because they were less numerous or because methodology failed to locate them. TIR coupled with LiDAR may potentially fill this gap. In addition to site specific recommendations, habitat actions are binned into several project types with detailed descriptions and pros and cons. The overall, recommended restoration strategy includes protection of areas with high functioning habitat, and implementation of low cost pilot projects with rigorous monitoring plans to determine the magnitude of thermal benefits and inform future projects.

Cold water features, longitudinal profiles, and associated attribute data and restoration recommendations are available for viewing on an interactive web portal at the following web address:

https://fishsciences.shinyapps.io/ChelanCountyNRD_ThermalRefugeMap/

Section 1: Introduction

The Upper Wenatchee River Basin supports three salmonid species listed under the Endangered Species Act: spring Chinook salmon (*Onchorhynchus tshawytscha*), winter steelhead (*Onchorhynchus mykiss)* and bull trout (*Salvelinus confluentus)*. The Upper Wenatchee River and downstream portions of most of its major tributaries (Chiwawa River, Little Wenatchee River, and Nason Creek) are included in the 2004 Washington State 303(d) list for exceeding water quality temperature standards. Documented effects of elevated temperatures on salmonids include raised metabolic rates (Berman and Qunn 1991), increased disease susceptibility (Schreck et al 2010), reduced reproductive performance (Torgersen et al 1999), decreased tolerance to environmental stressors (i.e. competition or toxic pollutants, McCullough 1999) and increased pre-spawn mortality rates (Bowerman et al 2018). In short, extreme water temperatures are physiologically stressful to salmonids and can result in direct and indirect mortality (Sauter et al., 2001) and limit recovery of listed species (NOAA, 2016).

In the Wenatchee basin, spring Chinook salmon exclusively spawn in the Upper Wenatchee basin above Tumwater Dam at river mile (RM) 31. Upper Wenatchee spring Chinook salmon are particularly vulnerable to high instream water temperatures because adults enter spawning tributaries in early summer (July – early August) and don't spawn till late summer (August – September). Therefore, spring Chinook hold in spawning tributaries during the late July – early August which corresponds to low flows and high ambient air temperatures that contribute to elevated instream water temperatures. Juvenile life stages of all three listed species (spring Chinook, winter steelhead, and bull trout) are also in the Upper Wenatchee basin in the summer and susceptible to elevated temperatures.

When stream reaches exceed thermal limits to salmonids, fish can persist by using cold-water refuges (Berman and Quinn, 1991, Li et al., 1994, McIntosh et al., 1995, Torgersen et al., 1999). For example, in the summer of 2015, the Upper Wenatchee Basin experienced a historic drought with record low flows and high water temperatures. An estimated 150 adult salmonids were observed holding in the cold plume created by the Chiwaukum creek confluence on RM 35.9 of the Upper Wenatchee River (Figure 1). This striking observation highlighted the importance of thermal refuge for ESA-listed species survival and the need to understand where these areas exist within temperature limiting reaches.

The purpose of this Thermal Refuge Assessment is to determine where thermal refuge may exist within priority reaches in the Upper Wenatchee watershed. This project is funded by the Washington Recreation Conservation Office (RCO), US Bureau of Reclamation (BOR), Washington Department of Ecology (Ecology), and was completed by conducted by the Chelan County Natural Resources Department With technical support from Cramer Fish Sciences.

Methods for this project are modelled after the Environmental Protection Agency's (EPA's) document, *Primer for Identifying Cold-Water Refuges and Restore Thermal Diversity in Riverine Landscapes* (Torgersen et al., 2012). Torgersen et al. defines thermal refuge as the following: discrete patches in the river channel in which organisms are protected from unfavorable temperature and may be either cold or warm, dependent on the season, in relation to surrounding water (Torgersen et al., 2012). For example, a thermal refuge in the winter is warmer than surrounding water (warm-water refuge), and a thermal refuge in the summer is colder than the surrounding water (i.e. cold-water refuge). The focus of this assessment is identifying the locations and habitat quality of these thermal refuges in the Upper Wenatchee Basin and then determining recommendations for restoration, and/or protection actions to improve or preserve these refuges. Because the methods of this study did not include an effort to determine fish use of these areas (and if they are actively being used as thermal refuge), we will also use the term "cold spots" or "cold water features" to denote these areas. While the primary focus of this study was to identify cold water refuges, we did include a small data collection effort to locate warm water refuges in the Entiat and Upper Wenatchee River using a Thermal Infrared (TIR) camera mounted on a drone. The results of the warm water refuge data collection effort are detailed in Appendix A and separated from the cold water refuge analysis for the purposes of clarity.

Water temperature variations along a river or stream corridor occur over multiple dimensions; variations occur over time (i.e. morning and night, winter and summer), and over space (i.e. thalweg versus bank, upstream versus downstream). Precise and consistent terminology is necessary because both spatial and temporal temperature variations have biological effects (Steel et al., 2017). This Assessment uses terminology recommended in the article "Envisioning, Quantifying, and Managing Thermal Regimes on River Networks" (Steel et al, 2017): The term *thermal regime*, "refer[s] to the time series of data that describes water temperature in one place over time". *Thermal landscape* is used when spatial variation is added, and "describe[s] water temperature patterns fluctuating over time and varying on the river network". This Assessment is focused on the following *facet* (defined as a "particular spatial or temporal element of interest") of the thermal landscape (Steel et al., 2017): *cold water features within temperature limited reaches of the Upper Wenatchee that occur during the low flow summer time period.*

The overall goal of this Assessment is to: identify and map cold-water features, within Wenatchee Basin 303(d) impaired temperature reaches that are also spring Chinook Major Spawning Areas (MASAs), during low flow summer conditions, and identify habitat actions that will serve ESA-listed species recovery. Additional project objectives include:

I. Map and characterize cold water features and longitudinal temperature patterns during the low flow summer period in the following reaches of the Wenatchee Basin:
    a. Nason Creek RM 0 – 12.5
    b. Chiwawa River RM 0 – 7
    c. Upper Wenatchee River RM 35 -54, and
    d. Little Wenatchee River RM 0 -10.
II. These data were collected using two field based methods:
    a. Cold spot checking tributary confluences and potential ground water seeps (off-channel areas, alcoves, and those indicated in 2001-2003 TIR and
    b. Ground based longitudinal temperature profiles
    c. easonal temperature loggers.
III. Collect TIR via drone during the winter of 2018 on select reaches of the Entiat River and Upper Wenatchee River. See Appendix A for details on this objective.

IV. Develop site-specific habitat actions to augment cold water features and a recommended overall restoration strategy for the study area.

Figure 1. Russ Rickets aerial photo of Chiwaukum Creek, summer 2015*

*approximately 150 adult salmonids (including all 3 ESA listed species) are pictured holding in a cold thermal refuge.

Section 2: Study Area

2A. Overview

The study reaches for this project are located within the Upper Wenatchee River watershed in Water Resource Inventory Area (WRIA) 45 (Figure 2). The Wenatchee River watershed is one of 6 sub-basins that make up the Upper Columbia Basin (the Columbia River watershed upstream of the Yakima River confluence). The Upper Columbia (UC) spring Chinook Evolutionary Significant Unit (ESU) is made up of 3 extant populations: the Wenatchee, Methow, and Entiat sub-populations and is listed as endangered (NOAA, 2015).

WRIA 45 is further divided into 12 sub-watersheds (Figure 2). This study covered portions of 4 of the 7 sub-watersheds within the Upper Wenatchee subbasin, including:

i. Nason Creek river mile (RM) 0 – 12.5
ii. Upper Wenatchee River RM 35 - 54
iii. Little Wenatchee River, RM 0 – 9.5
iv. and Chiwawa River, RM 0 – 7 (Figure 3) **.**

These reaches and sub-watersheds were selected because they meet the following criteria:

1. Exceed Washington Department of Ecology (Ecology) and the Environmental Protection Agency's (EPA) standards for stream temperature
2. Are located in spring Chinook Major Spawning Areas (MaSAs).

All aspects of the study (longitudinal temperature profiles, temperature spot checking, and habitat action development) were completed in these reaches. Winter drone-based TIR imagery collection also occurred in select reaches of the Upper Wenatchee study reach (Appendix A). The other Upper Wenatchee sub-watersheds are not included in the study either because instream water temperatures do not exceed the standards for stream temperature set by Ecology (White and Chiwaukum), or because they are not a spring Chinook MaSA (all others).

This study included a relatively small effort in the Entiat River watershed (Figure 2), which is a spring Chinook MaSA and has observations of high stream temperature (Potter et al., 2014). Winter drone-based TIR imagery collection occurred in select reaches of the Entiat River (Appendix A); however, other aspects of the project (longitudinal profiles, spot checking and habitat action development) were not conducted. The extent of the data collection effort in the Entiat was limited in scope and therefore the results are not comprehensive in identifying potential thermal refuge areas, so although this imagery is included in Appendix A of this assessment, the discussion and analysis of results inthis document does not include the limited data collection effort in the Entiat River.

2B: Physical Setting

The Upper Wenatchee watershed (the Wenatchee watershed above Tumwater dam at RM 31) encompasses the northern-most sub-watersheds of the Wenatchee watershed (Figure 2), which differ substantially in climate, land use, and climate from the southern-most watersheds. Areas in the upper Wenatchee watershed receive approximately 50 - 300 inches of precipitation a year which falls predominately as snow, compared to the lower basin receives approximately 10 - 30 inches that falls predominately as rain(Cristea and Pelletier, 2005). The lower watershed encompasses all of the major city centers and agricultural activities found within the Wenatchee watershed, with plant communities that range from continental to shrub steppe.

The Upper Wenatchee watershed is characterized by forest zones that are supported by its more maritime climate: mountain hemlock (*Tsuga mertensiana)*, silver fir (*Abies amabilis*), and douglas fir (Pseudotsuga menziesii) are dominant upland tree species (Andonaegui, 2001). The United States Forest Service owns the vast majority of land, seconded by commercial timber companies (primarily Weyerhaeuser), with some private residential ownership and neighborhoods along the rivers in the lower Nason, lower Chiwawa, and Upper Wenatchee Basins. Other development (besides residential and logging activities) include Highways 2 and 207 (Nason and Wenatchee), the Burlington Northern SantaFe (BNSF) Railroad (Nason and Wenatchee), Bonneville Power Administration (BPA) and Public Utility District (PUD) powerlines (Nason), and county and forest service roads (all).

The Wenatchee River tributaries included in this study (Chiwawa, Nason, and Little Wenatchee) account for the vast majority of the overall baseflow in the Wenatchee River (Andonaegui, 2001, Table 2). The Wenatchee watershed and its hydrograph is characterized as snowmelt-dominant, with low flows during the winter months, high flows during the snowmelt season in late spring/early summer, and a slow decline to low flow in the late summer/early fall. However, in recent years late fall/early winter rains or rain on snow events resulting in an additional peak flow event have not been uncommon, which is a pattern typical of rain/snow transient watersheds in the state (Lee and Hamlet, 2011).

Table 1. Percent contribution by watershed to annual flow of the Wenatchee River at the mouth. (copied from Andonaegui 2001).

Watershed	Percent Contribution	
	WIRPP[1]	Hindes[2]
White River	25	26
Little Wenatchee River	15	13
Chiwawa River	15	17
Nason Creek	18	12
Icicle Creek	20	19
Chumstick Creek	*3	0.2
Peshastin Creek	*n/a	4
Mission Creek	1	0.5
Other minor sources	3	**8.3

[1] Ecology, 1982. Wenatchee River Basin Instream Resources Protection Program. WIRPP Series No. 26. Water Resources Policy Development Section, Olympia, WA (pg.7) estimated % contributions to annual flow of the Wenatchee River at its mouth, based on average flows of the tributaries.

[2] Hindes, R. 1994. Wenatchee River Watershed Ranking Project, Watershed Characterization and Ranking Report. Prepared for the Chelan County Conservation District, Wenatchee, WA. (pg. 18) based % contribution to annual flows of the Wenatchee River on flow measurements made at each tributary from Oct. 1992 to Sept. 1993.

*Chumstick and Peshastin Creeks are combined

**Reflects the difference between the total acre feet of water measured at the tributaries and the total discharge on the Wenatchee River at Monitor.

Figure 2. Study sub-watersheds, and their context within the Wenatchee watershed and other adjacent Upper Columbia Basin watersheds (i.e. Lake Chelan and Entiat watersheds).

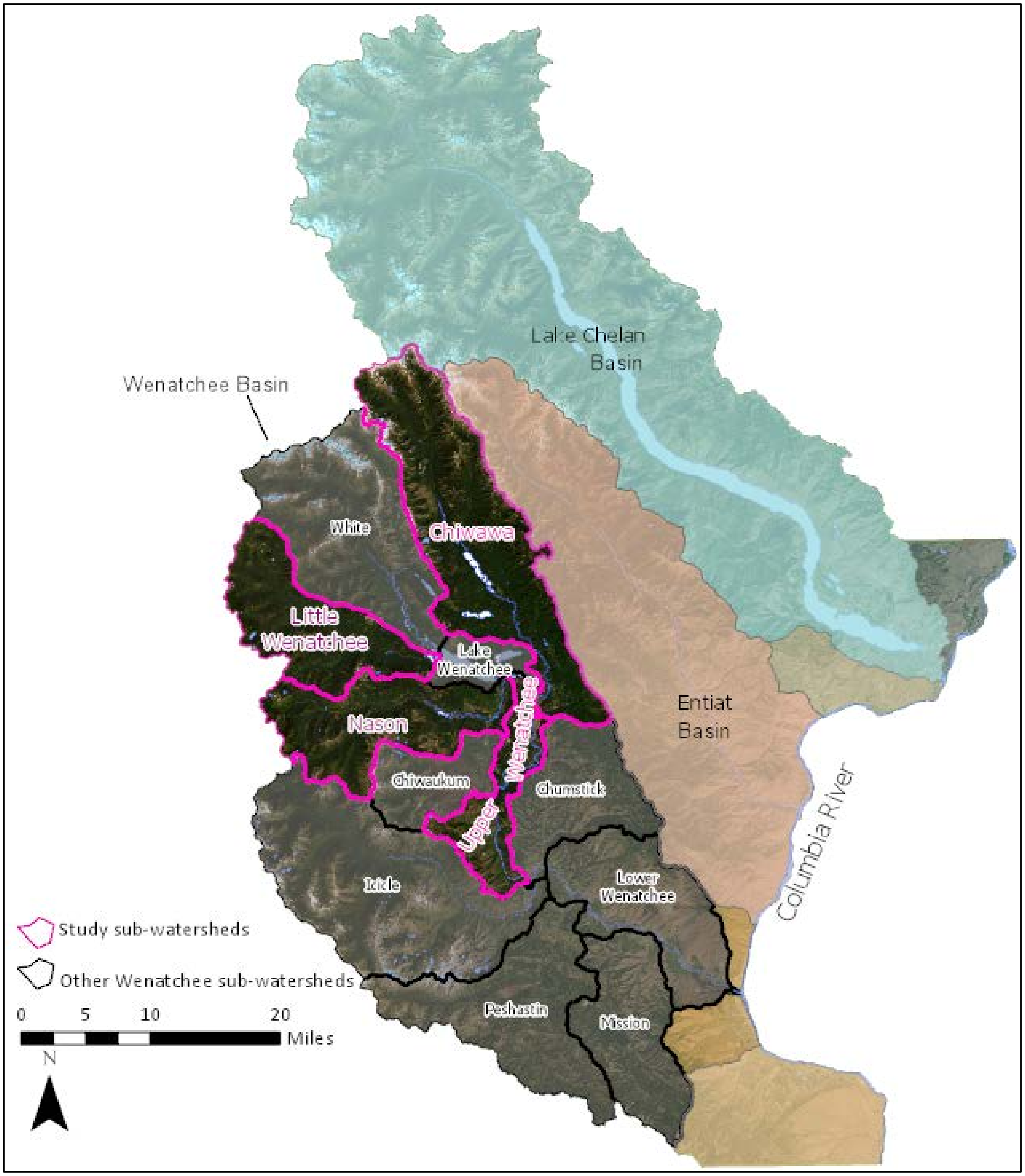


Figure 3. Study Reaches within the Upper Wenatchee Watershed.
Red crosses denote upstream reach breaks in Nason Creek, Little Wenatchee River, and Chiwawa River; downstream reach breaks in these waterbodies are at RM 0 (at Wenatchee River confluence in Chiwawa and Nason and at the Lake Wenatchee confluence in Little Wenatchee River). The red cross in the Upper Wenatchee denotes the downstream reach break; the upstream reach break is at the river's headwaters at Lake Wenatchee. All study tributaries are overlaid by 2001-2003 TIR (mosaic created by Quantum Spatial, LLC in 2018).

2C: Prior data collection efforts and Assessments

As indicated above, the focal area and attributes of this study are in response totwo separate but related mandates by the Federal Environmental Protection Agency (EPA): the listing of Upper Wenatchee spring Chinook, summer Steelhead and Bull Trout under the Endangered Species Act and the listing of Upper Wenatchee reaches included in this study as 'impaired for temperature' under the Clean Water Act. A vast amount of data collection efforts, habitat assessments, and studies have since been completed that relate to both of these important issues. The most pertinent of those efforts are summarized below. These studies and their corresponding datasets are further detailed in Table 2.

Following the Wenatchee watershed ESA listing in 1999, several watershed planning efforts and guidance documents were development to guide watershed recovery focused on restoration for ESA listed salmonids. In 2001, the guidance document titled "Salmon, Steelhead, and Bull Trout Habitat Limiting Factors for the Wenatchee Subbasin" was published that detailed habitat conditions as they affect the ability of the habitat to sustain naturally producing salmonid populations (Andonaegui, 2001). In 2006, the Wenatchee (WRIA 45) Watershed Plan was completed in response to the 1998 Watershed Management Act (RCW 90.82). This was a collaborative planning process including a wide range of stakeholders from 28 organizations including federal, state, local agencies, tribes, and non-governmental entities, agricultural and environmental representatives. Extensive public outreach occurred to gain public input as well. From the Watershed Plan the WRIA 45 Phase IV Detailed Implementation Plan (Implementation Plan) was developed over a period of several months following the development and adoption (in April 2006) of the Watershed Management Plan by Chelan County. Subsequently, the Upper Columbia Spring Chinook Salmon and Steelhead Recovery Plan was completed in 2007 and updated in 2014 in response to ESA listings. This Plan was developed by the Upper Columbia Salmon Recovery Board with close coordination with NOAA Fisheries and the US Fish and Wildlife Service and is intended as a guide to federal, state, and local entities for recovering Upper Columbia Basin spring Chinook, summer steelhead and bull trout (UCSRB, 2007). This plan was also coordinated closely with the Wenatchee Watershed Planning Process so habitat recommendations remain consistent in both plans. This document includes a Biological Strategy that details specific limiting factors to recovery, and prioritized and tiered habitat restoration types (i.e. floodplain connection, riparian, etc.) for all waterbodies in the Wenatchee sub-basin (in addition to the three other major UC sub-basins) that support ESA-listed salmonids (UCSRB, 2014). The Upper Columbia Regional Technical Team (RTT) is currently updating the Biological Strategy into one that is more reach-based and data-driven.

Fisheries data collection efforts that monitor various life stages and attributes are on-going through-out the Wenatchee and Upper Columbia watersheds. WDFW, Chelan County PUD, and Yakama Nation Fisheries monitor spring Chinook migration, spawning, and survival throughout the Upper Wenatchee Basin through a combined effort of smolt out-migration monitoring, redd and carcass surveys, and snorkel surveys. A Wenatchee spring Chinook egg to fry survival study and a life cycle model are also in progress. Based on local data collection efforts, the National Oceanic and Atmospheric Administration's (NOAA) most recent status review for the Pacific Northwest (PNW) concluded that the endangered status of UC spring Chinook is unchanged since 2010 (NOAA, 2015). The status review also states that habitat destruction and/or modification is still a risk to species' persistence, a conclusion that has not changed since the last status review despite numerous and wide-ranging habitat restoration efforts. High summer stream temperatures was listed as a main habitat concern along with habitat diversity and quantity, excessive sediment, obstructions, channel stability and low flows (NOAA, 2016).

In addition to broad guidance documents that prioritize restoration actions, several tributary and reach assessments have been conducted to date. Individual reach assessments document specific geomorphic drivers of stream habitat at the sub-watershed and reach scale, hydrology, and georeferenced habitat actions to improve conditions for ESA-listed species. Reach assessments are available for the Upper Wenatchee and Nason study reaches (Table 2). Specific habitat actions include reach-specific recommendations to increase riparian cover to reduce stream temperature; however, they do not discuss temperature heterogeneity and/or opportunities to augment or protect thermal refuge. This assessment is designed to fill that gap within study reaches.

Table 2. Prior studies addressing stream temperature, habitat condition, and ESA-listed salmonid recovery in the Upper Wenatchee subbasin.

Study	Citation/Source	General Description of Data
Nason Creek Tributary Assessment	USBOR. 2008. Nason Creek Tributary Assessment. Bureau of Reclamation Pacific Northwest Regional Office. Boise, ID	-Delineation of geomorphic reaches (3 over 10 RM) -historical and present disturbance regimes -Geomorphic reach habitat conditions and restoration opportunities
Kahler Reach Assessment - Nason Creek	USBOR. 2009. Kahler Reach Assessment, Nason Creek. Bureau of Reclamation Pacific Northwest Regional Office. Boise, ID	-Detailed floodplain delineation -Reach scale (~1 km) habitat forming process and aquatic habitat conditions and restoration strategy. --Summaries of water quality and fish distribution data
Lower White Pine Reach Assessment - Nason Creek	USBOR. 2009. Lower White Pine Reach Assessment, Nason Creek. Bureau of Reclamation Pacific Northwest Regional Office. Boise, ID	-Detailed floodplain delineation -Reach scale (~1 km) habitat forming process and aquatic habitat conditions and restoration strategy. --Summaries of water quality and fish distribution data
Upper White Pine Reach Assessment - Nason Creek	USBOR. 2009. Upper White Pine Reach Assessment, Nason Creek. Bureau of Reclamation Pacific Northwest Regional Office. Boise, ID	-Detailed floodplain delineation -Reach scale (~1 km) habitat forming process and aquatic habitat conditions and restoration strategy. --Summaries of water quality and fish distribution data
Upper Wenatchee Reach Assessment	Inter-fluve, Inc and Yakama Nation Fisheries. 2012. Upper Wenatchee River Stream Corridor Assessment and Habitat Restoration Strategy	-Geology and historical/present landuse -Hydrology, including 2 - 100 yr. flows -Reach scale (~1 km) habitat forming process and aquatic habitat conditions and restoration strategy. -Summaries of water quality and fish distribution data
Wenatchee River Temperature Total Daily Maximum Load Study	Cristea N. and Pelletier G. 2005. Wenatchee River Watershed Temperature Total Maximum Daily Load Study. Washington Department of Ecology, Olympia, WA. Publication No. 05-03-011.	-Temperature data and listings in the Wenatchee Basin -Discussion of results of Thermal Infrared Radiation (TIR) surveys -Shade data and targets
TIR data and report	Watershed Sciences, LLC 2003. Aerial Surveys in the Wenatchee River Sub-Basin, WA Thermal Infrared and Color Videography.	-Results of 2001-2003 TIR flights, including graphical longitudinal temperature profiles and notable thermal anomalies. Shapefiles and images available upon request.
Wenatchee River Temperature Total Daily Maximum Load Report	Schneider D and Anderson R. 2007. Wenatchee River Watershed Temperature Total Maximum Daily Load: Water Quality Improvement Report. Washington Department of Ecology, Olympia, WA. Publication No. 07-10-045.	-Analysis of temperature loading affecting listed tributaries, targets and recommendations to reduce loading.

Table 2 Cont.

Study	**Citation/Source**	**General Description of Data**
The Upper Columbia Salmon Recovery Plan	UCSRB, 2007. Upper Columbia spring Chinook salmon, steelhead, and bull trout recovery plan: UCSRB Wenatchee, WA.	-Information on threats to ESA-listed species and an all H (Hatcheries, Harvest, Hydropower and Habitat) plan to de-list
Upper Columbia Biological Strategy	RTT, 2017. A Biological Strategy to Protect and Restore Salmonid Habitat in the Upper Columbia Region. A Draft Report to the Upper Columbia Salmon Recovery Board from the Upper Columbia Regional Technical Team.	-Guidance to habitat restoration practitioners with specific and tiered habitat limiting factors and prioritized habitat actions for each HUC-8 level watershed
Salmon, Steelhead, and Bull Trout Habitat Limiting Factors for the Wenatchee Subbasin	Andonagui C. 2001. Salmon, Steelhead, and Bull Trout Habitat Limiting Factors. WA State Conservation Commission	Historical and present habitat conditions that effect ESA listed species.
NorWeST stream temperature model	Isaak, D.J.; Wenger, S.J.; Peterson, E.E.; Ver Hoef, J.M.; Hostetler, S.W.; Luce, C.H.; Dunham, J.B.; Kershner, J.L.; Roper, B.B.; Nagel, D.E.; Chandler, G.L.; Wollrab, S.P.; Parkes, S.L.; Horan, D.L. 2016. NorWeST modeled summer stream temperature scenarios for the western U.S. Fort Collins, CO: Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2016-0033	Modeled shapefiles of spatially continuous present and future stream temperature at 1 km scale. Based on air and water temperature data and available across the Northwest
MODIS stream temperature model	McNyset, K.M, Volk, C.J, Jordan, C.E. 2015. Developing an Effective Model for Predicting Spatially and Temporally Continuous Stream Temperatures from Remotely Sensed Land Surface Temperatures. Water. 7(12).	Spatially (1 km) and temporally (8 days) continuous stream temperature model across Wenatchee and Entiat. Based on land surface temperature data
SSNM	Aimee Fullerton, NOAA Biologist personal communication	Model is in progress to generate spatially continuous stream temperature estimates that are based on close networks of logger data. Finer spatial resolution than previous models.
ESA-listed species abundance, survival, and movement	WDFW, Chelan County PUD, and Yakama Nation Fisheries; data available upon request. Redd and juvenile abundance data available at https://www.ucsrb.org/map-portal/	Redd surveys, smolt traps, snorkel surveys and survival studies are conducted. Generated metrics include SAR estimates, life stage specific survival, and abundance estimates.
Stream temperature loggers	WDFW and NOAA/USFS partnership, among other agencies.	Seasonal temperature data for all
WA Ecology stream gages	https://fortress.wa.gov/ecy/eap/flows/station.asp?sta=45J070	Flow and temperature data for Wenatchee tributaries
USGS stream gages	https://waterdata.usgs.gov/wa/nwis/current/?type=flow	Flow and limited temperature data for Wenatchee mainstem

The Wenatchee River and several of its tributaries are on the Washington State's 303-d list of water quality impaired waters because of high temperatures (Cristea and Pelletier, 2005). A temperature Total Maximum Daily Load (TMDL) was completed for the Wenatchee Basin in 2005 (Cristea and Pelletier, 2005) and includes detailed temperature data from 2002-2003, and calculations of effective shade (based on vegetation and topography). The TMDL study was followed by a TMDL Report which includes a Detailed Implementation Plain to address temperature exceedances (Schneider and Anderson, 2007).

All study streams are listed as impaired on the State of Washington's 303 (d) list due to exceedances and each have numerous listings (Table 3). Washington Administration Code (WAC) 173-201A designates all reaches included in this study as Core Summer and Salmonid Habitat (Table 4) with a highest 7-DAM temperature criteria of 16°C.

Table 3. Temperature listings within study reaches addressed in the Wenatchee River TMDL

WATERBODY_NAME	LISTING ID	CATEGORY 2014	PARAMETER NAME	MEDIUM NAME
WENATCHEE RIVER	3730, 41145, 42865, 42866, 42977, 73038, 73040	4A	Temperature	Water
NASON CREEK	8425, 39377, 42918, 42921, 42922, 42923, 73052, 74086	4A	Temperature	Water
LITTLE WENATCHEE RIVER	39364, 39365, 39366, 39367, 39368, 39370, 40764	4A	Temperature	Water
CHIWAWA RIVER	39356, 39359, 73037, 73048	4A	Temperature	Water

Table 4. Aquatic Life Temperature Criteria in Fresh Water, from Washington Administration Code (WAC) 173-201A-200)

Category	**Highest 7-DAM**
Char Spawning and Rearing	12°C (53.6°F)
Core Summer and Salmonid Habitat*	16°C (60.8°F)*
Salmonid Spawning, Rearing, and Migration	17.5°C (63.5°F)
Salmonid Rearing and Migration Only	17.5°C (63.5°F)
Non-anadromous Interior Redband Trout	18°C (64.4°F)
Indigenous Warm Water Species	20°C (68°F)

*all study reaches fall under this category

Thermal infrared (TIR) surveys were completed in 2001 – 2003 as part of the Wenatchee Basin TMDL study (Watershed Sciences LLC, 2003). The entire Wenatchee River and all temperature listed tributaries were included in the survey, which was conducted from an aircraft during the hottest days of summer (July and August). This type of imagery can be used, and was in this Assessment, to identify features associated with cold-water refuges at multiple scales (Torgersen et al., 2012). See data review section of the Methods for more details on this dataset.

Other Wenatchee Basin temperature data collection and modeling efforts are also available that describe current and future stream temperature conditions. These include, but are not limited to:

- *Stream temperature logger data* –Stream temperature loggers were deployed and data is available through the Columbia Habitat Monitoring Program (CHaMP) that ran from 2011 - 2017. Staff from the NOAA Fisheries and the US Forest Service (USFS) took on management of Wenatchee Basin CHaMP loggers, and added additional loggers in 2018. The Washington Department of Fish and Wildlife (WDFW) also manages seasonal temperature data in the Wenatchee Basin. Temperature data is available through Ecology and USGS stream gauges.
- *NorWeST model* – Available data includes spatially continuous (1 km) shapefiles of the 10 year average (1993-2011) of August daily mean stream temperature, and future August temperature means under the A1B climate warming trajectory. Model uses air and stream temperature data (Isaak et al., 2016).*
- *MODIS model* – South Fork Research (SFR) center developed water temperature models for every 8 days from 2001 -2015. The model is based on Land Surface Temperature data collected by the MODIS satellite. Currently available datasets include daily mean water temperature that is both spatially (1 km scale) and temporally (every 8 days) continuous across the Wenatchee and Entiat basin (McNyset et al., 2015)
- *Wenatchee Spatial Stream Network Model (SSNM)* – This effort is currently in development but was conducted in nearby Snoqualmie River, WA and met with high success (Marsh et al., 2017). NOAA will use data collected from the stream temperature loggers co-managed with USFS (mentioned above) to complete this model. The Wenatchee Basin SSNM will predict continuous spatial patterns in water temperature, rely on a closer network of temperature loggers, and will likely result in a finer resolution than previous modeling efforts (Aimee Fullerton NOAA, personal communication).
- *Washington State Climate Change Model* - A Pacific Northwest based dominant river-tracing-based streamflow and temperature (DRTT) model was completed and includes predicted climate change impacts on stream flow and temperature in Washington State (Wu et al., 2012, Elsner et al., 2009). Modeled streamflow in snowmelt dominant streams like those in the Wenatchee basin showed a general increase in winter, decrease in summer, and a 1-2 month shift toward an earlier streamflow peak (i.e., from late May/early June to mid-April). Stream temperatures in snow dominant basins (like the Wenatchee) showed the largest projected mean summer temperature increase compared to the other basin types in the study (rain-snow transition and rain dominant) with modeled 1.23 °C, 1.82°C, and 2.74°C increases by the 2020s, 2040s, and 2080s, respectively (Wu et al., 2012).

Section 3: Methods

The assessment approach was to 1) compile temperature logger data from local partners (WDFW, NOAA, and USFS) to characterize the 2018 and 2019 summer thermal regime, 2) review relevant datasets (2001 – 2003Thermal Infrared aerial surveys, stream network shapefiles, aerial imagery) to identify "potential" cold spots, 3) ground truth all potential cold spots and collect habitat data on any that are found, 4) conduct ground-based longitudinal temperature profiles on select reaches to characterize the thermal landscape of study reaches during low flow maximum water temperature conditions, and 5) collect winter season TIR imagery with a FLIR camera mounted on a drone in select reaches of the Upper Wenatchee and Entiat Rivers to experiment with the utility of this method (see Appendix A for methods, results, and discussion of this effort).

3A: Compiled 2018 and 2019 temperature logger data

Temperature loggers have been installed and temperature data downloaded and managed throughout the Wenatchee basin by WDFW and a collaborative effort between the NOAA Fisheries and the USFS. WDFW manages 27 Wenatchee Basin sites, and NOAA and USFS manage 33 Wenatchee Basin sites. Of the total 60 sites, 10 are in study reaches - 2 in both the Little Wenatchee and Chiwawa reaches and 3 in both Nason Creek and the Upper Wenatchee reach. Rather than install more temperature loggers, CCNRD staff partnered with Heather Johnson (WDFW), Aimee Fullerton (NOAA) and Shannon Claeson (USFS) to obtain temperature data for 2018 and 2019. CCNRD used this temperature logger data to characterize summer temperature regimes between and within the four study reaches.

Seven day average maximums (7-DAM) were calculated from raw logger data by averaging the maximum daily stream temperature for the hottest seven consecutive days from each year. Washington State's 303(d) list under the Clean Water Act uses 7-DAMs (sometimes abbreviated "7-DADMax") as the temperature criteria metric. Thus, CCNRD used daily maximum temperature and 7-DAMs to provide context in this study.

3B: Data review and georeferenced list of potential cold spots

The goal of data review was to use available datasets and visual layers to locate potential cold water features to guide cold water spot checking. These "potential cold spots" included tributary confluences and areas under hypothesized cold hyporheic and/or ground water influence, i.e. adjacent to major wetlands or beaver complexes, side-channels and alcoves. These areas in addition to those that historical TIR imagery showed as "cold" constituted the complete list of potential cold spots that were field verified in this study.

CCNRD staff compiled and reviewed several data layers to come up with a georeferenced list of potential cold water spots of the type listed above. Datasets include the 2001 – 2003 TIR imagery, the Chelan County stream layer, the Washington Department of Natural Resources stream layer (DNR stream layer), and aerial imagery (Table 5). Details of each layer and the review process are below.

Table 5. Data sets included in data review and potential cold spot identification.

Data set	Review targets	Potential cold spots type
2001 - 2003 TIR	1. Images interpreted as cold water and included in results section of the original TIR reports 2. Images not included called out in report but that indicate potential temperature variability.	Tributary mouths, cold seeps, springs
Chelan County stream layer	Tributary confluences in target reaches	Major tributary mouths
DNR stream layer	Tributary confluences in Chiwawa only	Minor tributary mouths
Aerial Imagery (Google Earth and Chelan County 2006 - 2017 imagery rasters)	Side channels, alcoves, mainstem areas adjacent to beaver complexes and wetlands and off channel habitats.	Ground water seeps and upwelling

The TIR imagery included in this study's review was collected by Quantum Spatial, LLC (formerly Watershed Sciences, LLC) in the summers of 2001, 2002 and 2003. Quantum Spatial was under contract with Ecology, and conducted airborne thermal infrared (TIR) remote sensing surveys on selected streams in the Wenatchee River Subbasin (including all this assessment's study reaches) to inform the Wenatchee Basin Temperature Total Maximum Daily Load study (TMDL).

The 2001-2003 TIR imagery dataset included: a database of TIR images and associated aerial images, an ArcMap dataset with thermal profiles at a 0.1 km scale, excel files that include image number and temperature with specific call outs for apparent cold and warm features, and 2 summary reports. CCNRD reviewed the reports and excel files and included areas that the original analysis called out as potential cold areas on the list of potential cold spots. CCNRD also hired Quantum Spatial in 2017 to create an ArcGIS compatible continuous mosaic of the TIR imagery (Figure 3). CCNRD reviewed the GIS mosaic to identify areas that appeared to indicate cold features but were not specifically called out in the original reports. These areas were also added to the list of potential cold spots.

Chelan County stream layer includes both named and unnamed tributaries in all of the four study reaches. Every tributary confluence that was on this layer and fell within the study reaches was added to the list of potential cold spots.

The DNR stream layer has additional small streams, some that are not included in the Chelan County stream layer. CCNRD staff also reviewed this dataset. Many streams that are included on this dataset, but are not on the Chelan County stream layer, are known to be ephemeral and dry at low flow. Therefore, in order to utilize field staff effort and time efficiently, most of these streams were not included in the list of potential cold spots. However, they were added to the list of the potential cold spots for the Chiwawa River because there were otherwise very few tributary confluences in the Chiwawa River data set.

CCNRD also reviewed aerial imagery for all study reaches to locate potential cold spots. Aerial imagery data sets included Google Earth satellite imagery and Chelan County's Arc GIS aerial imagery mosaics from 2006 through 2017. Areas of interest included side channels, alcoves, and main channel areas that may include cold ground water flow because they are adjacent to off-channel wetland or beaver ponds. These areas of interest were added to the potential cold spots list.

CCNRD staff compiled potential cold spots from all reviewed data layers into 4 excel spreadsheets (one per reach). Each potential cold spot was listed with UCSRB RM, latitude/longitude, a description of the spot including data source, and 4 blank columns corresponding to field notes, checked, found, date and method. The four blank columns were designed to be filled out after field staff navigated to the site, with checked and found designed as yes/no columns and method defined as the method field staff used to ground truth the potential cold spot (either float or spot check, see those methods below). A 'yes' in the checked and found column indicated the cold spot was "checked" (the location was ground truthed) and "found" (a differential of at least 1°C was discovered at that location).The excel spreadsheets were converted to shapefiles and loaded into the MapPlus survey program on a CCNRD staff field iPad. This program allows the user to navigate to the georeferenced potential cold spot and fill out the blank columns in the field.

3C: Cold spot microhabitat sampling

The goal of cold spot checking was to use a fast response thermocouple with a digital readout to ground truth potential cold spots and collect habitat and temperature data if a cold spot was confirmed. Staff also encountered several tributaries, springs, alcoves and side-channels, that were not identified through the data review process, and checked and collected data on these as they were encountered while walking or floating the river.

Cold water features can be located using a hand held digital thermometer (Cooper-Atkins Corp., model 35200-K, Ebersole 2003). CCNRD used the model K thermometer mounted on a 6 foot wooden dowel ("thermometer probe") to locate cold water features. To ground truth potential cold spots, CCNRD staff 1) navigated via GPS coordinates to the potential cold spot, 2) used the thermometer probe to record a background or ambient temperature (river water temperature near and just upstream of the target location), 3) swept the thermometer probe in and near the target location and measured the minimum temperature found. If the minimum temperature was at least 1°C colder than the ambient temperature, the potential cold spot was marked found and additional measurements, habitat data and description information was collected. Additional data included dominant substrate, depth, channel unit type (i.e. pool, glide), plume extent in two dimensions, fish cover, and GPS location. Steps 2 and 3 of this process were also conducted when staff encountered an area of interest (i.e. a tributary not on a stream layer) that was not on the potential cold spots list.

For a full list of data collected with descriptions, please see Table 6. Collected data varied slightly based on whether the spot was a surface water input (i.e. tributary or spring) versus a ground water input (i.e. cold seep or upwelling). CCNRD staff chose to bin cold spots into "surface water" and "ground water" features for ease of habitat data collecting and to guide restoration action development. **Surface water**

features include *tributary mouths* (i.e. plume from a small stream confluence) and *springs* (i.e. emergent surface water located near the stream bank that flows into and creates a cold plume in the mainstem water body). **Ground water features** were not associated with surface water flow and instead emerged within the water column. For this study's purpose, *cold seeps* are features with emergent cold ground and/or hyporheic water (primarily ground water). Features in this category are diverse, and can include lateral seeps, cold side-channels or cold alcoves (Dugdale 2013) and were often associated with an adjacent wetland, beaver pond complex, or off-channel area. An *upwelling* is ground and/or hyporheic flow (primarily hyporheic) that emerges out of the river substrate in the main channel, such as at a riffle crest or at the end of a gravel bar (Dugdale, 2013). Cold spot naming conventions are as follows (waterbody abbreviations are listed in Table 6 and are N, UW, LW, and C):

Surface water (i.e. tributary or spring) features:

Waterbody abbreviation_T_rivermile.

Ground water (i.e. seeps or upwelling) features:

Waterbody abbreviation_seep_rivermile. For example, a tributary confluence on Nason Creek at rivermile 4.5 would be: N_T_4.5. A seep at the same location would be N_seep_4.5.

Table 6. Description of all data collected on found cold spots

Column name:	Choices if applicable	Choices defined	Column description
Waterbody	N	Nason Creek	River where the cold spot was found
	UW	Upper Wenatchee	
	LW	Little Wenatchee	
	C	Chiwawa	
Rivermile			UCSRB rivermile at the cold spot
Site Name			first letter of river_T for tributary or spring or CS for cold seeps_ rivermile (i.e. N_T_11.7)
Date and Time			when habitat data was collected
Tributary name*			the tributary creating cold plume (i.e. Kahler Creek, or unnamed)
Source**			ambient of background temperature upstream and out of the influence of the cold spot
Location			Latitude/longitude
Upstream temp			ambient or background temperature, upstream and out of the influence of the cold spot
Temp of Tributary*			temperature of tributary that creates cold plume, just upstream of confluence
Max temp plume			warmest temperature recorded in plume, with a differential of at least 1°C
Min temp plume			coldest temperature recorded in plume, with a differential of a least 1°C
Differential range			value range: max differential to min differential (upstream temp minus max temp plume)
max differential			upstream temp minus min temp plume
Cover type	boulder	boulder	Fish cover present at the cold spot site. If just a small area is covered, column may say for example "Wood and none"
	Depth	depth	
	Veg	vegetation	
	Wood	Wood	
	none	none	
	other	other	
Habitat Unit type	Pool	Pool	Habitat channel unit at the cold spot site
	Eddie	Eddie	
	Riffle	Riffle	
	Shallow_Edge	Shallow Edge	
	Glide	Glide	
	Side_C	Side Channel	
	Alcove	Alcove	

*data collected for tributary and spring inputs only

**data collected for ground water/hyporheic inputs only

Table 6 cont..

Column name:	Choices if applicable	Choices defined	Column description
Dominant substrate	B	boulder	dominant benthic substrate at the cold spot site
	C	cobble	
	CG	course gravel	
	G	gravel	
	S	sand	
	BR	bedrock	
Wetted width trib (m)*			wetted width of tributary or spring at the mouth
Min depth cold water (m)			minimum depth found in measured plume
Max depth cold water (m)			maximum depth found in measured plume
Average depth cold water (m)			the overall dominant depth found at the cold spot
Bank	LB	Left Bank	Location of the cold spot in relation to the river channel
	RB	Right Bank	
	Thalweg	Thalweg	
Y distance 2°C differential (m)			distance at least a 2°C differential persisted perpendicular to channel
X distance 2°C differential (m)			distance at least a 2°C differential persisted parallel to channel
Y distance 1°C differential (m)			distance at least a 1°C differential persisted perpendicular to channel
X distance 1°C differential (m)			distance at least a 1°C differential persisted parallel to channel
2°C differential plume size			2°C Y distance multiplied by 2°C X distance
1°C differential plume size			1°C Y distance multiplied by 1°C X distance
Describe Plume			General observations on how the dynamics and characteristics of the cold water plume
Other Habitat Notes*			General observations about habitat quality of the cold plume
Describe Source and Habitat**			General observations about habitat quality and hypothesized source of the cold plume
Restoration notes?			Recommended and/or potential restoration action
Number salmonids			number salmonids observed in the cold plume
Species salmonids			species of the salmonids observed in the plume
photo			photo of the cold plume

*data collected for tributary and spring inputs only

**data collected for ground water/hyporheic inputs only

3D: Longitudinal Profiling

Continuous stream temperature profiles were acquired for a total of 40 RMs (7 RMs in Chiwawa, 9 RM in Little Wenatchee, 6.5 RM in Nason Creek and 17.5 RM in Upper Wenatchee). This included 9 longitudinal temperature profile events (“profiles”) conducted on 9 different days (2 profiles each for the Chiwawa, Little Wenatchee and Upper Wenatchee and 3 profiles for Nason Creek). A fourth Nason Creek profile was conducted from RM 0.5 – 2.5, but the data was lost due to a malfunction in the Solinst Levellogger. Nason Creek profiles were conducted via a combination of walking and floating in a tube; all other profiles were conducted in an inflatable kayak (IK). CCNRD steered the water craft to stream margins when there was an area of interest (i.e. an alcove or tributary confluence) but in general profiles represent thalweg temperatures. Thus, longitudinal profiles are a good complement to cold microhabitat sampling which generally focus on inputs from stream margins. Staff towed the profile temperature logger at or near the stream bottom to pick up any upwelling areas, and stopped for at least a minute to drop the logger down at each large pool that could serve as adult spring Chinook holding habitat.

The longitudinal RM length of each profile represented the river/creek stretch that could feasibly be floated during the period of the day maximum stream temperatures are encountered, between approximately 14:00 and 20:00, and primarily depended on water velocity. CCNRD watched weather forecasts and temperature gauge data closely so that all profiles were done on clear, sunny days, and near or at the peak of summer stream temperatures (late July – early August). In order to acquire longitudinal profile data, CCNRD staff towed a Solinst Levellogger that logged near continuous temperature readings (1 value every second) behind the water craft (IK or float tube). The Solinst Levellogger is appropriate for fine scale temperature profiles because it records 1-second interval changes in temperature (Vaccaro and Maloy, 2006). In order to protect the Solinst from damage caused by the stream bed and to provide a shield to insolation, CCNRD staff built a vented case of PVC pipe with bolts to hold the Solinst in place similar to the one described by Vaccaro and Maloy (2006).

In order to georeferenced Solinst temperature readings; a GPS Garmin simultaneously acquired a continuous track by recording position every three seconds. The GPS clock was synchronized with the Solinst clock, so that the two time series (temperature and location) could be matched in excel following data download. Thus, the final profile included both temperature readings and corresponding GPS points at three second intervals.

In addition to temperature profile data collected with the Solinst (or “moving” temperature) and GPS location, a third set of time series data that we refer to as “fixed” temperatures was also collected during time of the profile. Prior to starting on a profile float, CCNRD staff installed a Hobo Tidbit temperature data logger (UTBI-001 Tidbit v2; Onset Computer Corporation) at or near the upstream end of the profile. Fixed loggers measured diurnal (in contrast to spatial) changes in stream temperature and provided a means to estimate temporal variability of surrounding ambient temperature at the upstream location. Like the Solinst, Tidbits were set to record temperature every second. Tidbit clocks were synchronized with the GPS and Solinst and the three time series matched following data download.

Profile data was collected in order to explore spatial temperature variability of the floated reach during low flow, peak temperature conditions (i.e. a “facet” of the thermal landscape). Raw moving temperature data represents a combination of spatial and diurnal (one aspect of temporal) temperature variability. In order to best represent our facet of interest, we processed profile temperature data in two ways: 1) raw moving temperatures were graphed with fixed temperatures with time and RM on the x-axis, and 2) “standardized” temperatures were calculated by subtracting the estimates of temporal variability captured by fixed loggers from moving temperatures. These standardized temperatures therefore represent an estimated snapshot of the longitudinal temperature profile of one floated reach at one point in time. Standardized or adjusted temperature values were calculated by adding temperature differentials to the fixed temperature recorded when the profile was at its midway point (i.e., if the profile was recorded from 13:00 to 17:00, the temperature at the fixed site at 15:00):

Temperature differentials=
moving temperature at X hour:minute:second – fixed temperature at X hour: minute: second

Standardized temperatures =
Fixed temperature midway in float time + temperature differentials

Because fixed loggers were placed at the upstream end of each reach, positive differentials represented a downstream warming trend while negative differentials represented deviation from that trend and can indicate relatively cold features. Both standardized and raw profile data are reported on as graphs (raw) and maps (standardized).

Section 4: Results and Discussion

4A: Compiled 2018 and 2019 Temperature Logger Data

**see Appendix B (AppB) for additional Figures*

The 2018 and 2019 seasonal temperature logger data (courtesy of WDFW, NOAA and USFS) in Nason Creek, Upper Wenatchee River, Little Wenatchee River, and Chiwawa revealed all 7-DAMs were above the Washington State Criteria of 16°C for Core Summer Salmonid Habitat (Table 7 . Upper Wenatchee and Nason Creek were the warmest sub-watersheds evaluated in both 2018 and 2019, followed by the Chiwawa River and Little Wenatchee (Figures 4 and 5). The 7-DAMs consistently occurred between the 2nd and 12th of August in both 2018 and 2019, except at the Nason_Upper site in 2018 where the 7-DAM occurred in late July (Table 7). In all sub-watersheds, 2018 7-DAMs were cooler than in 2019. In the Chiwawa watershed, 2019 7-DAMS were 1 – 1.5°C warmer than in 2018. In all other sub-watersheds, 2019 7-DAMs were warmer than 2018 by just a few tenths of a degree (Table 7).

Table 7. Summary of compiled temperature data

Code	Site Name	Years	RM	7-DAM, °C	7-DAM, dates	CO*
NAL	Nason_Mouth	2018, 2019	0.5	21.7	8/4/19 - 8/10/19	WDFW
				21.1	8/5/18 - 8/11/18	
NA2	Nason_Lower	2018, 2019	7.4	18.2	8/3/19 - 8/9/19	NOAA/USFS
				19.5	8/5/18 - 8/11/18	
NAU	Nason_Upper	2018, 2019	12	17.9	8/2/19 - 8/8/19	WDFW
				18	7/26/18 - 8/1/18	
MS4	Wenatchee_Swiftwater	2019	33.7	19.7	8/4/19 - 8/10/19	NOAA/USFS
MS5	Wenatchee_Plain	2019	44.5	22.9	8/2/19 - 8/8/19	NOAA/USFS
UWE	Wenatchee_LakeWenatchee	2018, 2019	50.7	22.6	8/4/19 - 8/10/19	WDFW
				22.3	8/5/18 - 8/11/18	
LWN	LittleWenatchee_Lower		2.7	18.6	8/5/19 - 8/11/19	WDFW
				18.3	8/6/18 - 8/12/18	
LW2	LittleWenatchee_Upper		9.75	18.1	8/3/19 - 8/9/19	NOAA/USFS
CHL	Chiwawa_Mouth	2018, 2019	0.5	20	8/2/19 - 8/8/19	WDFW
				18.5	8/5/18 - 8/11/18	
CHU	Chiwawa_Lower	2018, 2019	6.8	17.5	8/2/19 - 8/8/19	WDFW
				16.5	8/5/18 - 8/11/18	

**raw data courtesy of Heather Johnson, WDFW, Aimee Fullerton, NOAA and Shannon Claeson, USFS*

Figure 4. Daily Maximum Temperatures in Summer 2018 at all Study Reaches.

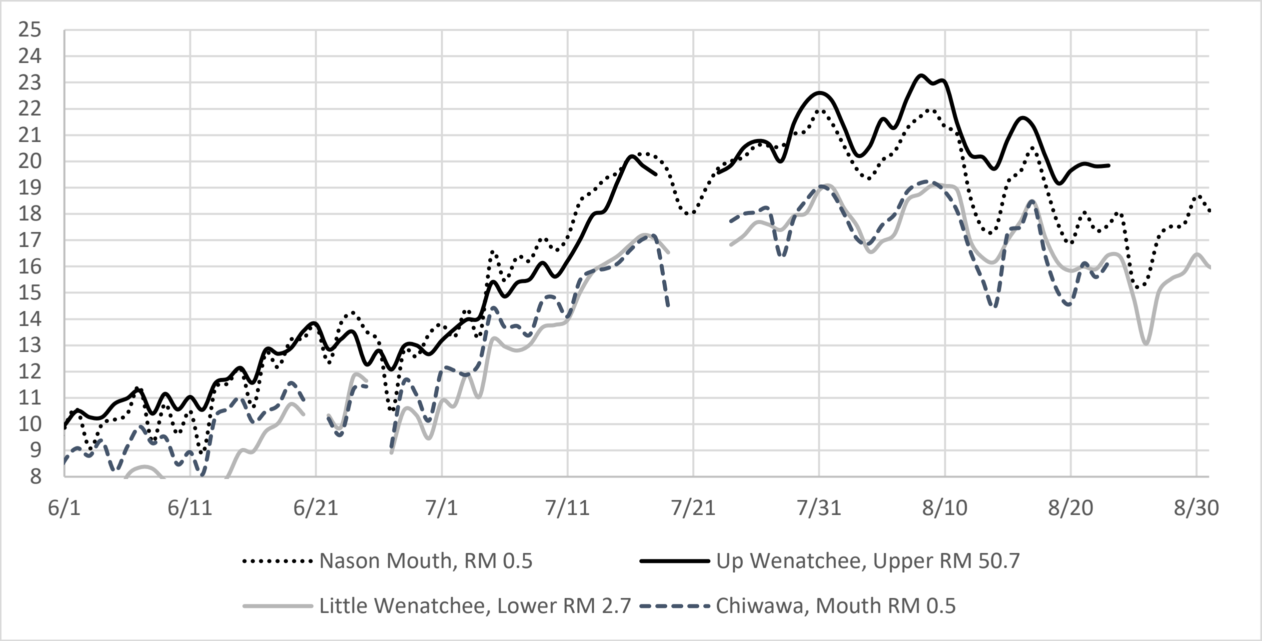
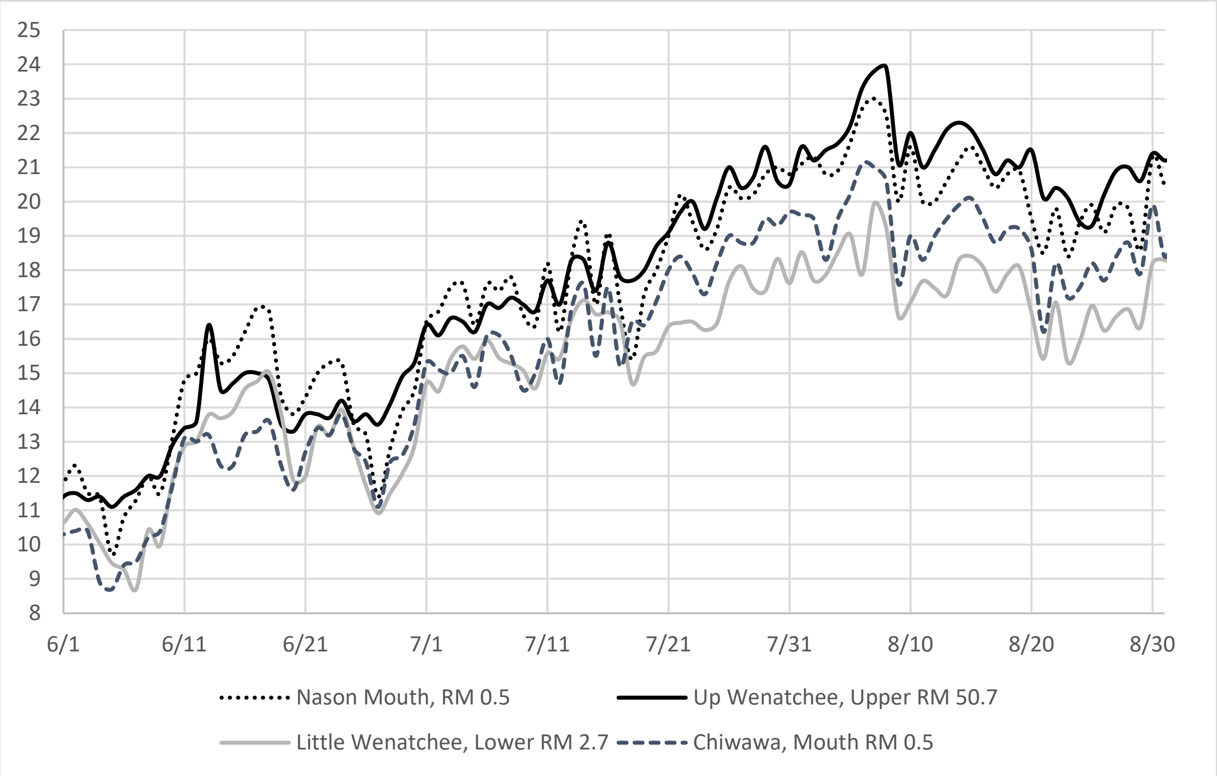


Figure 5. Daily Maximum Temperatures in Summer 2019 at all Study Reaches.



Based on logger data, all four study reaches have some degree of downstream warming (Appendix B. Figures 1, 2, 4, 6, 7 and 8 and Table 7). This is the case between the two upper sites in the Upper Wenatchee River. However, the third and lowermost Wenatchee_Swiftwater site was significantly cooler in the summer months and warmer in the winter months (Appendix B Figure 4), and its 7-DAM, was 3°C cooler than the upper sites (Table 7). This logger is located within the Tumwater Canyon, an eight mile river stretch naturally confined by canyon walls and Highway 2, where local Biologists and residents often observe large schools of spring Chinook salmon holding in the late summer and early fall. ther than the Wenatchee_Swiftwater site, the Little Wenatchee River had the least amount of downstream warming (Appendix B Figure 6). The Little Wenatchee is also the only reach that does not flow through any residential areas and has the virtually pristine riparian corridor, the only development being isolated sections with the forest service road and the rock mining pit at RM 2.5.

These broad scale patterns corroborate with longitudinal profiles, which are discussed in detail below.

4B: Data review and georeferenced list of Potential cold spots

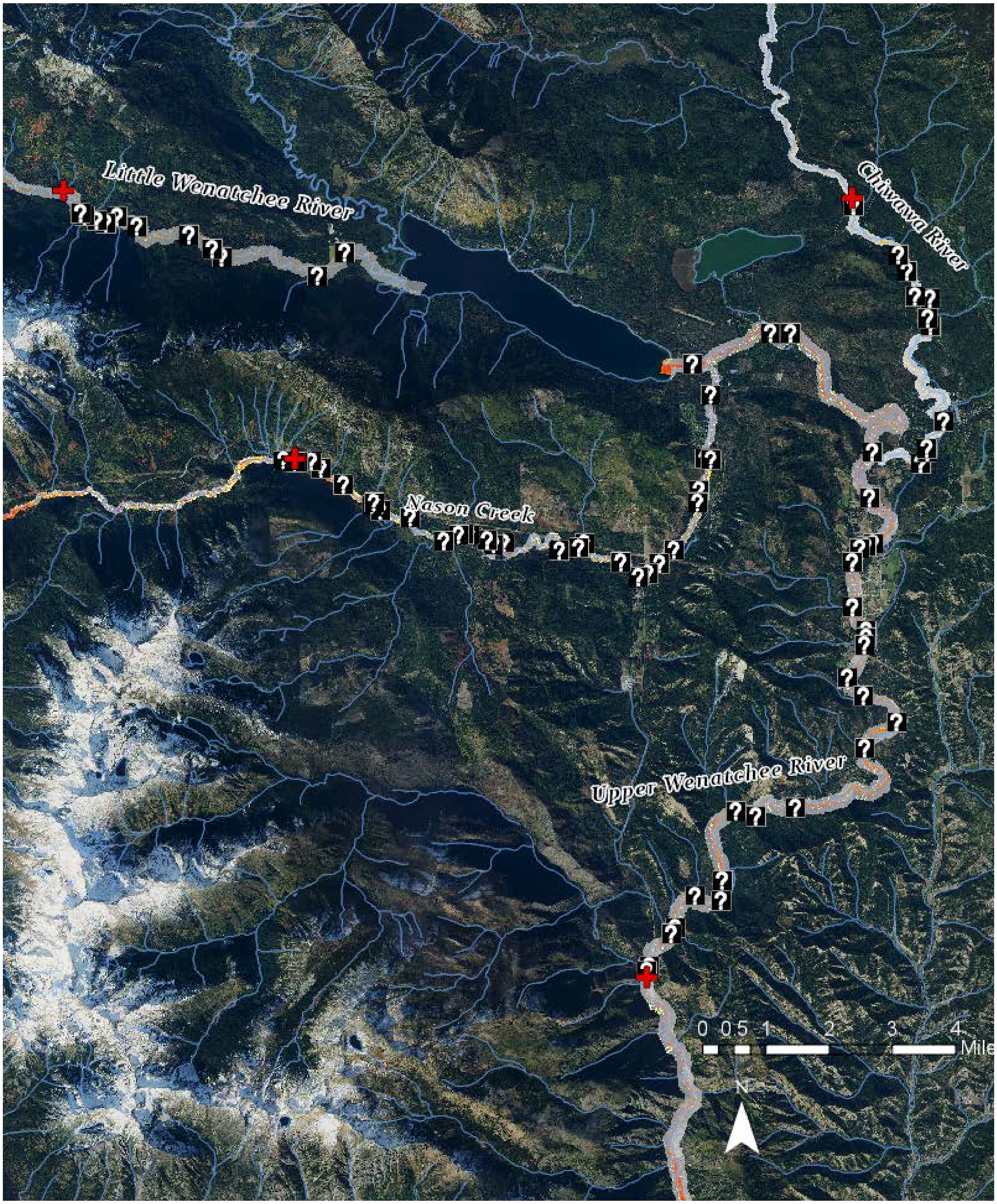
Data review resulted in a list of 90 potential cold spots (Table 8). The cold spots and associated attributes (source data layer, latitude, longitude, and yes/no columns indicating whether the spot was checked and found) was stored and georeferenced in the iPad mapping app (Map Plus). Potential cold spots totaled 38 in Nason Creek, 28 in Upper Wenatchee, 12 in little Wenatchee and 12 in the Chiwawa

River (Table 8, Figure 6). Although the vast majority of potential cold spots were checked, a total of 6 were not, due mostly to one or a combination of the following factors: unsafe or difficult access (most common), running out of time (Deadhorse creek on Upper Wenatchee). Shapefiles of potential cold spots with all attributes are available online on the UCSRB data portal.

Table 8. Summary of Potential Cold Spots included in complete georeferenced list.

Reach	Stream layer	Cold seeps on FLIR imagery	Aerial imagery (i.e. alcoves)	Checked	Notes
Nason Creek RM 0 -14	2	16	12	28 (2 unchecked)	Could not access lower FLIR potentials at RM 2.5 and 2.7, most likely wet mud. Most of FLIR potentials were not located.
Upper Wenatchee RM 54 - 35	19	8	1	26 (2 unchecked)	FLIR potential at RM 35.1 unsafe to access, several tribs dry.
Little Wenatchee RM 0 – 10	5	5	1	12	FLIR more reliable than stream layer for cold areas, only one stream potential was found.
Chiwawa RM 0 – 7	10	1	1	10 (2 unchecked)	FLIR potential at RM 1.1 was unsafe to access, could not find mouth of Deep Creek. All DNR tribs were dry
TOTAL	37	46	7	84 (6 unchecked)	Details in Appendix X

Figure 6. Potential cold spots (question marks) with reach breaks (red crosses) and 2001-2003 TIR layer.



4C: Cold spot microhabitat sampling

Cold spot microhabitat sampling located a total of 40 cold water features in the study area, which includes 18 surface water features, and 22 ground water features (Table 9, Figure 7). Of these features, 26 were on the potential cold spots list. The other 14 were encountered during a longitudinal temperature float or while spot checking a potential cold spot in close proximity.

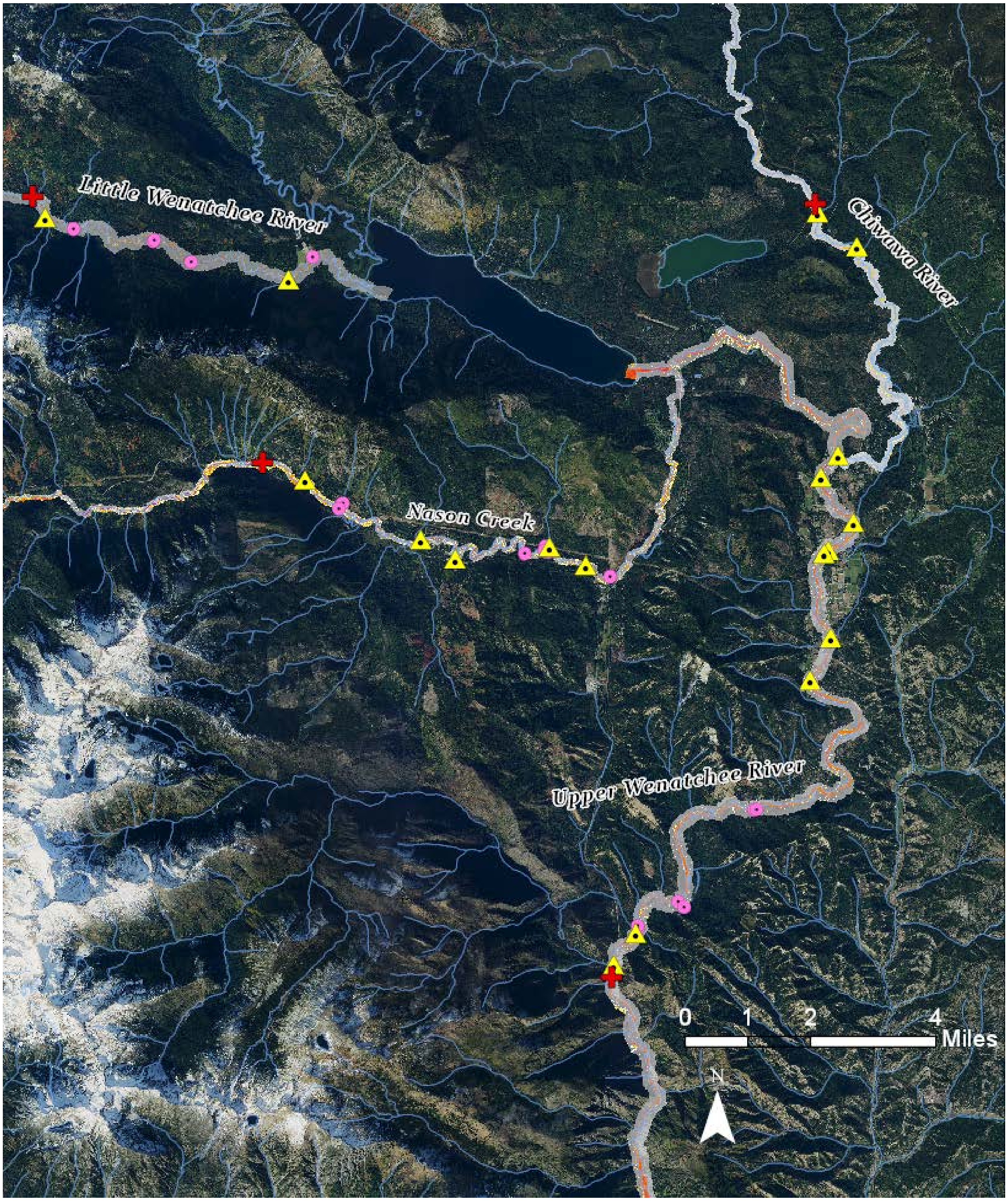
CCNRD staff collected habitat data and used the digital thermometer to measure plume size at all but three sites. Detailed habitat data is not available for UW_T_46.9, LW_T_3.3 and LW_seep_5.7 because they were encountered during floats and equipment was either not present (UW_T_46.9) or malfunctioning (LW_T_3.3). Additionally, LW_seep_5.7 was identified not at the time it was encountered but after reviewing longitudinal profile data.

Table 9. Summary of cold water features found

	Nason	Upper Wenatchee	Little Wenatchee	Chiwawa
Total cold water features	**14**	**16**	**8**	**2**
Total found surface water features	5	9	2	2
Total found ground water features	9	7	6	0
Reach length in RM	14	19	10	7
Cold spots per RM*	1	0.8	0.8	0.3

Appendix C includes photos, names, habitat data, detailed notes, close up maps showing setting and source of ground water features, and waterbody maps showing location of surface water features. Each cold spot includes a recommended habitat action, preservation, or no action, which is discussed further in the Restoration Recommendation section of this Assessment.

Figure 7. Found Cold Features. Includes surface water features (yellow triangles), ground water features (pink circles), reach breaks (red crosses) and 2001-2003 TIR layer



4D: Longitudinal Temperature Profiles

Table 10. Details of the nine longitudinal temperature floats conducted in the four study reaches

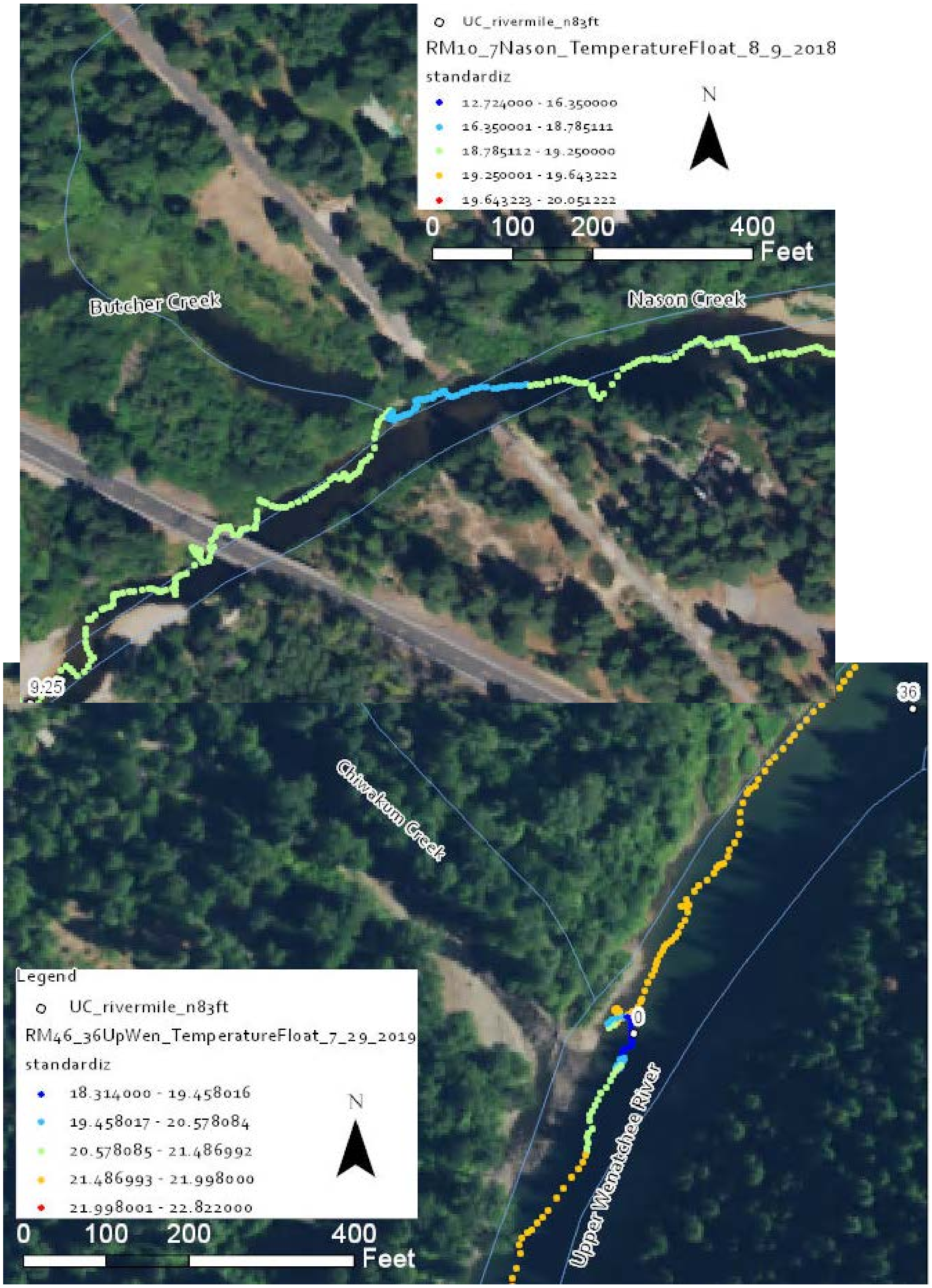
Study Reach	**Float Reach**	**Float Date**	**Float Time (all PM, PST)**	**Fixed temperature logger location**	**Spatial temperature range (°C)**	**Fixed temperature range (°C)**
Nason, RM 0 -14	7.0 - 5.5	8/12/2015	2:27 - 4:32	RM 7	17.2 - 24.2	20.3 - 20.8
	10 - 7	8/9/2018	1:42 - 4:30	RM 10	12.9 - 20.3	18.4 - 19.3
	12 - 10	8/6/2018	3:27 - 4:58	RM 12	15.1 - 17.7	16.3 - 17.0
Upper Wenatchee, RM 54 - 35	46.5 - 36. 5	7/29/2019	3:24 - 8:00	RM 46.5	17.9 - 23.0	21.1 - 21.7
	54 - 46.5	7/22/2019	4:20 - 7:25	RM 53.5	18.0 - 19.9	19.4 - 19.7
Little Wenatchee, RM 0 - 10	6.2 - 0	8/6/2019	1:49 - 7:06	RM 6	17.2 - 20.3	18.9 - 21.2
	8.7 - 6.2	8/7/2019	1:40 - 4:17	RM 8.7	13.2 - 20.7	17.9 - 19.4
Chiwawa, RM 0 - 7	3 - 0	8/7/2018	3:50 - 4:45	RM 3.3	17.5 - 19.0	17.4 - 17.7
	6.9 - 3.3	8/8/2018	2:20 - 3:50	RM 6.9	15.7 - 17.8	16.5 - 17.2

Longitudinal profiles were all conducted during low flow conditions when temperatures were at or near their yearly maximum (Appendix D Figures 1, 8, 13 and 18), and provide a snapshot of continuous temperature pattern under these seasonal conditions. These also represent the conditions that ESA salmonids are most likely to seek out and/or use cold thermal refuge areas (Torgersen et al., 2012). The Levellogger, which recorded profile temperatures, was towed through the thalweg of the river, as close to the bottom of the water column as possible. However, staff would often go to the margin of the river if a tributary or other feature was sited. Only cold signatures of the two large, major tributaries (Chiwawa and Chiwaukum), registered past the river margin (plumes of both these rivers occupied approximately one third of the channel width).

Some temperature profiles such as both of the Wenatchee profiles and the lower Chiwawa profile show warmer temperatures at the beginning of the profile. Before starting a float, CCNRD staff took a few stationary minutes when the Levellogger was first submerged to allow the logger to calibrate to water temperatures and away from hot summer air temperatures. However in the above noted cases this calibration time was likely not sufficient and resulted in warmer temps at profile onset (Appendix C: Figures 10, 12 and 20).

In all profiles, after initial Levellogger calibration from air to water temperature, data suggests the instrument (towed through the water column) was able to pick up near instantaneous changes in temperature (documented in Vaccaro and Maloy, 2006, wherein the probe captured temperature change over 1-second intervals). For example, once temperature and GPS data was combined (using time as the match column) cold water plumes at tributary mouths registered as expected within a margin of error likely attributable to the GPS unit (i.e. roughly < 50 feet, Figure 8) that still allows for meaningful interpretation regarding the sources of heterogeneity observed in the profile (discussed in more detail below). However, fine scale changes (10 – 100 m) such as riffle crest hyporheic upwelling may have been undetected. On the other hand, data suggests reach scale changes (0.1 – 1 km) such as riparian cover or hyporheic upwelling as a result of increased sinuosity (0.1 – 1 km) were detected (i.e. Upper Wenatchee and Little Wenatchee profiles, see below). Although staff stopped at all large pools to allow the logger to drop and assure logger calibration, none of these areas registered as significantly colder than ambient water temperatures.

Figure 8. Thermal profiles near Butcher Creek and Chiwaukum Creek show good location accuracy of cold inputs.



Longitudinal profiles are discussed in detail in the following paragraphs. All interpretations are based on data. Interpreted sources of "cold dips" (sharp decreases in temperature visible in graphs) have high confidence, because they are associated with known tributaries or other features, and/or were identified in cold spot checking as cold areas. Cold dips are listed for each reach and are associated with the river margin unless noted with an asterisk. Other trends discussed below, such as downstream warming due to increased sinuosity or changes in riparian cover, are hypotheses that require further study to verify. Interpretations refer to figures in Appendix D.

Nason profiles

Three Nason longitudinal temperature profiles were conducted, all in early-mid August. The 2018 profiles were conducted during daily maximums between 20 and 22°C, and during the 7-DAM (AppD Figure 1). The lower profile (RM 7 -5.5) was completed in 2015 during a pilot study and when the daily maximum temperature reached 21°C. However, 2015 was a record drought year when the 7-DAM occurred in late June/early July, which is uncharacteristically early (AppC Figure 1).

In general, all three Nason Creek floats show little temperature heterogeneity, save from some cold dips due to isolated inputs of cold water (Appendix D Figures 2-7), and warm and cold areas associated with isolated water pockets in the fragmented and disconnected side channel at RM 5.8 (Appendix D Figure 2 and Black line in Appendix D Figure 3). Data suggests some downstream warming in the lowermost Nason profile between RM 6.5 to 5.7 (Appendix D Figures 2 and 3) and in the upper Nason profile between RM 10.5 to 10 (Appendix D Figure 6 and 7). Both of these areas of warming are associated with changes in riparian cover and were detected at the downstream end of openings in the riparian corridor (residential area in the upper profile, BPA powerline corridor in the lower). Changes in water temperature have been found to occur at the downstream end of changes in shade (Johnson, 2004)

Starting from downstream and moving upstream, cold dips are associated with the following features:

- Kahler Creek (N_T_5.8) > 4°C temperature differential at RM 5.8 (Appendix D Figure 2 and 3)
- Side channel at RM 5.8 – 5.9 : N_seep_5.9 and N_seep_5.8 (Appendix D Figure 2 and 3)
- Unnamed Spring/Trib (N_seep_8.3), > 6°C temperature differential at RM 8.3 (Appendix D Figure 4 and 5)
- Butcher Creek (N_T_9.1) > 1°C temperature differential at RM 9.1 (Appendix D Figure 4 and 5)
- Lower White Pine oxbow connection (BNSF railroad bridge), > 0.5 differential at RM 9.4 (Appendix D Figure 4 and 5)
- Unnamed Trib (N_T_11.7) > 2.5°C temperature differential (Appendix D Figure 6 and 7)

Upper Wenatchee profiles

Two Upper Wenatchee longitudinal temperature profiles were conducted in late July 2019, before temperatures peaked in early August. Daily maximum was 19.7 °C during the upper float (RM 54-46.5, Lake Wenatchee to Plain Bridge) and 21.7°C during the lower float (RM 46.5 -6.5, Plain Bridge to Tumwater; Appendix D Figure 8).

Profile data suggests that downstream warming occurs through residential areas of both profiles. In the lower profile, this warming ceases downstream of the USFS property boundary and subsequently increase in shade (similar to Johnson et al., 2004, Figure 8 below). Like the lower profile, downstream warming is apparent through the residential area of the upper profile (Appendix D Figure 11 and 12). The Chiwawa river, which accounts for 15 -17 % of Wenatchee River discharge (Table 1), causes a sharp decrease in temperature that retains almost a 0.5°C difference from upstream till the end to the profile.

The probe also picked up cooler water just below the headwaters at Lake Wenatchee (Appendix D Figure 11 and 12). This stretch of water is quite deep and slow moving and could potentially retain some temperature stratification (similar to the lake just above) with cooler temperatures at depth where the probe was recording temperatures (the initial warm temps are likely due to logger calibration).

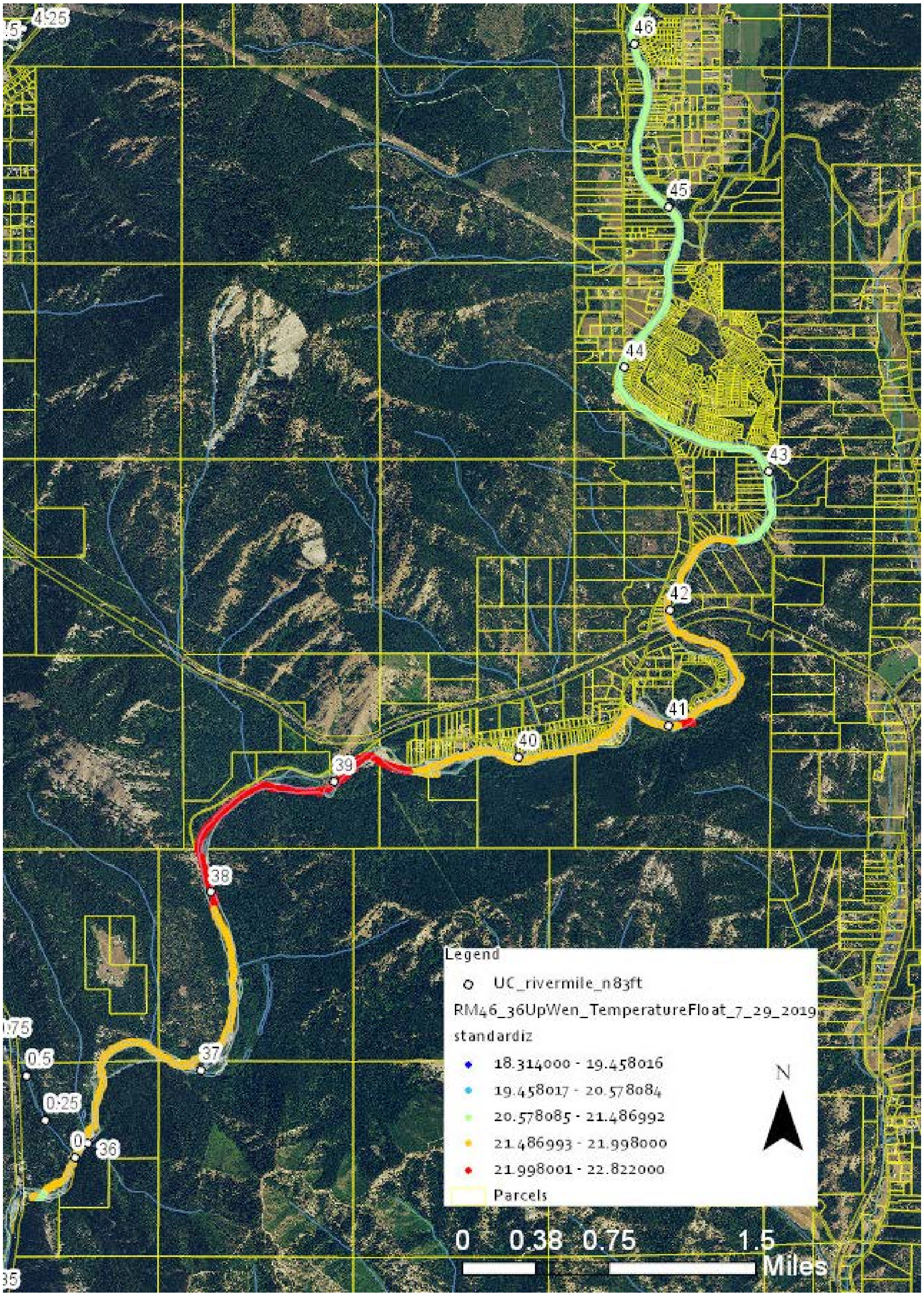
Starting from downstream and going upstream, cold dips are associated with the following features. (*in river thalweg. All other cold dips refer to the river margin):

- Chiwakum Creek (UW_T_35.8) - 3.5°C differential at RM 35.8 (Appendix D Figures 9 and 10)
- Chiwawa irrigation return (UW_T_46.9) - 3°C differential at RM 46.9 (Appendix D Figures 11 and 10)
- Unnamed tributary (UW_T_48) - < 0.5 °C differential at RM 48.0 (Appendix D Figures 11 and 10)
- Chiwawa River (UW_T_48.5) - 3°C differential at RM 48.5 (Appendix D Figures 11 and 10)
- Lake Wenatchee <0.7 °C differential between RM 54 and 53 (Appendix D Figures 11 and 10)*

There is no hypothesis regarding the source of the dips at RM 48.3 and RM 47. 6 (Appendix D Figure 12).

Figure 9. Lower profile of Upper Wenatchee Reach with parcel layer.

Downstream warming continued through residential area, until it steadied and cooled just past USFS boundary and intact riparian area.



Little Wenatchee profiles

Two Little Wenatchee longitudinal temperature profiles were conducted on August 6th and 7th 2019, just before the daily maximum water temperature peaked on August 10th at 20°C (Appendix D Figure 13). The daily maximum was 18.5°C during the lower profile (RM6 - 0) and 19.1 °C during the upper profile (RM 9 - 6).

The Little Wenatchee River flows into Lake Wenatchee, and UCSRB rivermiles (based on the National Hydrography Dataset stream lines) name the actual mouth of the Little Wenatchee as RM 1, with RM 0 out in the lake. Therefore, RM 1 to 0 of the profile represent Lake temperatures, ending at the boat ramp at Glacier View campground near the head of Lake Wenatchee. No significant change in temperature was recorded from the mouth of Little Wenatchee River out into the deeper waters of the Lake during the lower profile survey on August 6th (Appendix D Figure 14 and 15, RM 1 – 0.5). However, temperatures did warm 1°C at the end of the profile when the logger was recording in shallower waters near the lake shore (Appendix D Figures 14 and 15 RM 0.5 – 0).

The lower temperature profile of Little Wenatchee River shows the most heterogeneity of any of the profiles in this study, and resembles a “complex” profile classification (Fullerton et al., 2015). Colder sections of this profile (i.e. RM 4.5 to 2.5) could be related to increased hyporheic exchange common in highly sinuous channels with riffle-pool morphologies and large wood (Boano et al., 2006; Wondzell and Goodself, *in review*). The fixed logger associated with the profile was, like all other profiles, installed at the top of the reach. However, this proved to be the warmest location of the profile (Appendix D Figure 15), potentially because it was closest to the road, was on a straight stretch and in a location with split flow. This location (RM 6), also recorded the warmest temperatures of the upper temperature profile. This profile (RM 9 – 6) is less sinuous then the lower river, shows less heterogeneity and suggests downstream warming (Appendix D Figures 16 and 17).

Starting from downstream and going upstream, major cold dips are associated with the following features. (*in river thalweg. All other cold dips refer to the river margin)

- Unnamed tributary (LW_T_3.3) - 1.6°C differential at RM 3.3 (Appendix D Figures 14 and 15)
- Area below channel spanning log jam (LW_seep_5.7) – 1.3°C differential at RM 5.7 (Appendix C Figures 14 and 15)*
- Outlet of off-channel wetland habitat (LW_seep_6.5 and LW_seep_6.5_2 are both within the off channel area). -0.9°C differential at RM 6.5 (Appendix D Figures 15 and 17)
- Cold margin habitat (LW_seep_8.1 and LW_seep_8.1_2) –0.7°C differential at RM 8.1 (Appendix D Figures 15 and 17).

-Unnamed spring (LW_T_8.6) – 4.5°C differential at RM 8.6 (Appendix D Figures 15 and 17).*

Chiwawa profiles

Two Chiwawa longitudinal temperature profiles were conducted on August 7th and 8th 2018, during peak maximum daily water temperatures (Appendix D Figure 18). Daily maximum was 18.1°C during the lower profile (RM 3 - 0) and 19.0 °C °C during the upper profile (RM 7 - 3). Both profiles show fairly consistent downstream warming with very little heterogeneity. This reach of Chiwawa (RM 0-7) is characterized by a plane-bed morphology with markedly less complexity than upstream. Hyporheic flow has been associated with pool-riffle morphologies, but little hyporheic influence is expected in plane-bed channels due to low spatial heterogeneity in surface texture (Buffington and Montgomery, 1999; Wondzell and Goodself, *in review*).

The relatively warm temperatures recorded in the beginning of the lower Chiwawa profile (at RM 3, Appendix D: Figures 19 and 20) are likely due to logger calibration, as discussed previously. The top of the upper profile (RM 6.9, Appendix D Figures 17 and 18) is located at Alder Creek, which is the likely source of the only cold dip observed in the profile (C_T_6.9). The upper profile also includes the site of the Wenatchee Chiwawa Irrigation District's diversion – however no discernable change in Chiwawa river temperature was recorded downstream of this site (Appendix D Figure 22).

Section 5: Restoration Actions

CCNRD teamed with Cramer Fish Sciences (CFS) to develop a strategy and framework for implementing projects aimed at protecting or augmenting cold water features in the Upper Wenatchee Watershed. Implementation of restoration projects that aim to increase the fish capacity and/or habitat quality of cold water features are not widespread, therefore research informing these types of projects is limited. We propose implementing a pilot project or series of pilot projects to guide further actions. Below is a proposed strategy for overall project implementation and protection in the Upper Wenatchee Watershed. Significant progress has been made through this Thermal Refuge Assessment to accomplish Steps 1 and 2, though further refinement to verify hypotheses identified in this assessment are encouraged. Steps 4 – 6 represent restoration actions that could occur simultaneously or in a varying order):

1) Develop support to adopt a watershed perspective to identify opportunities where important thermal anomalies occur
2) Identify and document areas where the thermal anomalies occur
3) Implement actions (i.e. land purchases, signage, outreach etc.) to protect cold features with pristine, high functioning habitat.
4) Implement a small number of low-cost pilot projects to determine magnitude of thermal benefits
    a. Measure the extent to which the thermal anomaly occurs during the low flow period where thermal (heat) flux is greatest
    b. Design intensive pre and post monitoring into the project scope to be able to capture the effectiveness of the project prescription

   c. Develop a prescription to enhance existing thermal features (e.g., deflector structure to increase plume size)
   d. If opportunities and funding allows, develop a reach based pilot project to test how well habitat enhancement techniques (e.g., placement of large wood to create pool habitat and sort sediment) can improve hyporheic connectivity
5) Reconnect disconnected features
   - Reconnect cool water habitats where feasible to active channels to enhance the benefits of the feature for fish
6) Enhance/restore habitat around thermal features
7) Develop a set of reach-scale targets based on findings from these pilot projects (i.e. thermal refuge density)

The developed framework includes descriptions of different project types that research suggests may result in accomplishing protection or habitat enhancement goals for each of the cold water feature types (Trib Confluence, Upwelling, Spring, Seep). This "matrix" was applied to the cold water features identified in this Assessment to come up with the actions listed in Appendix C.

Table 11. Matrix linking action recommendations with project-specific goals.

P/E = Protect or enhance. L = Likely to meet goal. P = Possible to meet goal. N = Not likely to meet goal.

Goal	***Riparian Enhancement***	***Deflector Structure***	***Channel-Spanning Wood***	***Reconnected Floodplain***	***LWS to encourage Pool Formation***	***LWS to increase fish cover***
Create New Features	N	P	L	L	L	L
P/E Seep	L	L	P	P	N	L
P/E Spring	L	L	P	P	P	L
P/E Upwelling	L	L	P	L	L	L
P/E Trib Confluence	L	L	P	L	L	L

This framework provided should be a "living matrix" in which edits and new project types are added as results of pilot projects and input from the Upper Columbia salmon recovery community are integrated. Some examples and associated details of project types, including those in the matrix, are listed below and may be helpful in selecting prescriptions to test in the pilot project.

- Riparian Enhancement: Native plant installation adjacent to cold water feature or in a degraded riparian area to increase shade on the waterbody, and provide a source for allochthonous inputs of organic matter over time

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- Pros

        - Buffers against thermal gain from solar radiation (shade), provides important organic matter to streams, relatively simple and low-cost for implementation, high certainty in the outcome.
    - Cons
        - Cannot lower stream temps, just reduce the rate of warming. May not see an effect for 10 years. Effectiveness is proportional to the amount of the channel that is shaded; relatively ineffective in wide channels.
    - Applications
        - Protecting a seep, spring, tributary influx, or coolwater upwelling in reaches with degraded riparian zone
    - References
        - (Ebersole et al., 2003; Forney et al., 2013)

- Deflector structures: An engineered log structure(s) designed to slow water velocity, reduce thermal mixing of cold water with warmer water, and thus enlarge an existing cold plume.
    - Pros
        - Increase fish capacity of cold thermal feature. Protect important thermal refuge, enhance quality of thermal habitats by providing predator and water velocity refuge
    - Cons
        - Scenarios should be modeled to ensure best design choice, complicated hydraulic interactions at multiple flow stages
    - Applications
        - On a cold feature with water velocity - spring, tributary influx, or coolwater upwelling
    - References
        - (Marcoe et al., 2018)

- Placing channel-spanning large wood: Wood placed across the river channel from bank to bank.
    - Pros
        - May provide local temperature buffering, increase hyporheic exchange locally, promote overbank flows and thereby increase exfiltration to buffer water temps, create deep pools for thermal refuge
    - Cons
        - Equivocal results on temperature impacts from previous studies in which large wood was placed for reasons other than temperature, requires wood structures with high hydraulic purchase, downstream propagated effects are limited
    - Applications
        - Creating new thermal features (coolwater upwellings)
        - Not optimal for protecting or enhancing an existing thermal feature, unless part of a hydraulic shield
    - References
        - (Hester and Gooseff, 2010; Sawyer et al., 2012)

- <u>Reconnecting floodplains:</u> Removing obstructions and/or enhancing connection between the river channel and it's floodplain

    - Pros
        - Expand thermal refuge opportunities, potentially increase number of or longevity of thermal anomalies, provides additional benefits for salmonids at sensitive life stages
    - Cons
        - Requires more room for river channel to adjust, requires floodplain availability and regular access for max benefit (inundation at 1-2-year recurrence interval)
    - Applications
        - May create new thermal features (e.g., seeps, upwellings, via groundwater recharge and hyporheic exchange) within relatively low-gradient tributary and mainstem reaches flowing through undeveloped floodplains
        - Not optimal for protecting or enhancing an existing thermal feature
    - References
        - (Roni et al., 2019)

- <u>Addition of Large Wood Structures (LWS) in the channel:</u> LWS designed to encourage pool formation and/or provide fish cover.

    - Pros
        - Increase habitat quality of existing cold feature or increase habitat diversity of a homogeneous reach. Can promote upwelling and increase hyporheic connectivity. LWS can be designed to create scour pools that redistribute sediment resulting in cold water upwelling or connectivity.
    - Cons
        - Can be expensive.

- <u>Inducing thermal anomalies via groundwater pumping:</u> Using a high capacity pump charged by a solar panel to pump groundwater from upslope locations to a discharge point. Pumping triggered by signal from water temperature sensor programmed to ESA-species temperature threshold
    - Pros
        - Transforms diffuse input of groundwater discharge to a focused input that creates cold-water refuge
        - Pump/temperature sensor automation assures refuge is only created when most urgently needed
        - Can be coupled with other methods (i.e., defector structure)
    - Cons
        - Requires infrastructure and maintenance
        - Cost benefit analysis unknown
        - Does not use or mimic natural methods
    - References
        - (Kurylyk et al., 2014)

Section 6: Conclusion

The Upper Wenatchee Thermal Refuge Assessment completed in 2018 and 2019 completed the objectives set for the study. In total, 40 cold water features were identified, measured, mapped, and associated habitat restoration actions were developed (Appendix C). Longitudinal temperature profiles were completed on 39.6 river miles of the 48.5 total river miles included in the study, and cross-referenced to seasonal temperature logger data that was collected by state and federal agencies. Winter drone TIR was completed on select reaches of the Entiat and Wenatchee River (Appendix A).

The identified cold water features are aspects of the thermal landscape that were present during peak temperature summer conditions and during low flow in the summers of 2018 or 2019. The persistence of these features across years, and the specific discharge and temperature range that these features occur, is unknown and should be investigated prior to implementing restoration actions. Thermal anomalies and thermal profiles have been shown to vary significantly with mean annual discharge, likely due to temporal variability in groundwater levels (Dugdale et al., 2013). However, research has shown tributary confluence cold feature types are relatively consistent, so these areas may require less pre-design monitoring than ground water features. Lateral seeps, not associated with cold side-channels or cold alcoves, are the most variable of any refuge type (Dugdale et al., 2013). This Assessment found primarily tributary confluences and ground water seeps in cold side-channels and cold alcoves. A total of three lateral seeps were identified: N_seep_6.3, LW_seep_8.1 and LW_seep_8.1_2. These features are likely less persistent than other areas.

This study checked 96 % of all potential cold water areas that were identified during the data review process. However, it is inevitable that some cold features remain unidentified especially given the variability discussed above. In particular, main channel cold water upwellings (i.e., due to a substrate change) were not identified during this assessment. This is likely not because they are not present, but because the methods used in this study were not appropriate for identifying this feature type. Winter drone flights (as discussed in Appendix A) may provide an opportunity to identify cold water upwellings in future assessments. However, this technology would lend itself better in areas other than the Upper Wenatchee where deep snow and ice made finding a suitable condition window very difficult. There were also only three lateral seeps identified, a cold feature type that is likely in more abundance, especially when annual mean discharge is high (Dugdale et al. 2013). The majority of the cold water features that were identified in this study were perennial tributary confluences, cold side-channels, and cold alcoves. All but one (Clear Creek on Chiwawa River, which came in slightly warm) of the perennial tributaries that were spot checked were cold inputs.

A significant finding of this study is the lack of adult spring Chinook holding habitat, in the form of large and cold holding pools, in all study reaches. Although there are a number of large pools, particularly in the Upper Wenatchee, none of the pools registered as significantly colder than ambient water temperatures during longitudinal profiles. Staff dropped the moving logger to depth in each large pool encountered, and the profile method was able to register other cold areas (i.e. tributary confluences), so although possible method error seems unlikely. However, local observations have confirmed large schools of adult spring Chinook holding in several of the large pools that are located downstream of the study area in the Tumwater Canyon reach of the Wenatchee River. Logger data indicates stream temperatures in this downstream location were up to 3°C cooler than upstream, indicating it as important cold water refuge. Moreover, warmer winter temperatures in Tumwater suggest likely ground water influence. However, these pools are some distance from spawning grounds upstream highlighting the need for more intact holding habitat, especially for Nason Creek, the Upper Wenatchee and lower Chiwawa.

Unfortunately, the vast majority of cold water features identified in this study did not extend into pool habitat. Even the largest cold features (Chiwakum and Chiwawa river confluences) were characterized by relatively shallow margin habitat. During microhabtat sampling, CCNRD staff recorded warm ambient water temperatures in the large pool feature directly adjacent to the Chiwakum confluence. Using a deflector structure to encourage cold water into this existing pool feature could increase salmonid fish capacity. Deflector structures on other cold surface water features identified in this study, designed to reduce thermal mixing and encourage pool formation, could also improve adult holding habitat in the Upper Wenatchee.

Another cold water habitat feature that could serve as adult spring Chinook holding habitat and may have been missed by this study is lateral seeps into deep margin habitat. These areas often occur adjacent to mature riparian areas (Wawrzyniak et al 2017) and may include an undercut bank. As discussed above, research suggests lateral seeps are not consistent year to year (Dugdale et al 2013), however they could serve as opportunistic holding habitat for a small number of adult spring Chinook when they do occur. Using a combination of LIDAR and TIR data (similar to Wawrzyniak et al 2017) to model the effects of groundwater inputs in reaches with mature riparian could complement results of this assessment. CCNRD staff observed these types of areas (deep water margin habitat with mature riparian) particularly in the Little Wenatchee where roots of large old growth cedar trees are a common feature of river banks. Little Wenatchee longitudinal profiles exhibit a higher degree of heterogeneity than other study reaches. Using a combination of LIDAR and TIR data (similar to Wawrzyniak et al 2017) to model the effects of groundwater inputs in reaches with mature riparian could complement results of this assessment.

In general, implementing recommended habitat actions on the groundwater features identified in this study would likely only improve habitat quality, quantity, and accessibility for juvenile salmonids. However, groundwater pumping has the potential to create adult spring Chinook holding habitat. While this method is tentatively recommended on a handful of cold groundwater features (Appendix C), these recommendations come with several caveats concerning feasibility (including maintenance requirements), cost benefit, and infrastructure footprint.

In summary, broad scale management recommendations regarding thermal refuge in the Upper Wenatchee are as follows (please see Section 5 and Appendix C for more detail):

- Preserve spring Chinook adult holding habitat in Tumwater canyon

- Add deflector structures to cold surface water features with significant flow to reduce thermal mixing, encourage pool formation and improve habitat quality for adult holding and juvenile rearing.
- Use LiDAR and TIR methodology to model deep cold margin habitat in the Little Wenatchee and other areas with mature riparian, and explore its habitat suitability as adult spring Chinook holding habitat.
- Implement recommended habitat action on ground water features to target juvenile rearing.
- Proceed with caution on groundwater pumping projects.
- Experiment further with winter TIR drone technology for locating upwelling areas.
- Include detailed monitoring and data-based design in any Thermal Refuge project.

In conclusion, the data provided in this assessment should provide a good baseline for restoration actions to protect and augment thermal refuge areas that can increase the survival of ESA-listed species during temperature limiting conditions. Data can also inform sponsors of any habitat restoration project and ensure that their project does not inadvertently compromise an existing cold water feature. A pilot project with a rigorous monitoring plan to both inform the impending and future designs is a crucial element of any actions targeting improved thermal refuge moving forward.

Cold water features, longitudinal profiles, and associated attribute data and restoration recommendations are available for viewing on an interactive web portal at the following web address:

https://fishsciences.shinyapps.io/ChelanCountyNRD_ThermalRefugeMap/

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