Lower Columbia River Thermal Refuge Study, 2015–2018

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EXECUTIVE SUMMARY

The lower Columbia River serves as rearing habitat and a migration corridor for multiple endangered and threatened salmonid species. There is growing concern that summertime Columbia River water temperatures, which have been increasing for several decades, are inducing thermal stress on populations of these fish that utilize the river during this period. In response to this concern the Lower Columbia Estuary Partnership, with funding from EPA, completed a multi-year, three phase study to document the extent and quality of cold-water inputs to the lower Columbia River which are, or potentially could be, utilized by summer migrating salmonid species for thermal respite from warm Columbia River mainstem water.

Tributaries entering the lower Columbia are often cooler during the summer relative to the Columbia mainstem itself, and thus can provide thermal respite for migrating salmonids. In Phase 1 of this study we monitored summertime thermal and discharge characteristics of the 15 primary tributary complexes that enter the Columbia River in the lower Columbia River Gorge (below Bonneville Dam) during 2015 (including some limited data collection in 2014). We compared these results to preliminary criteria we have outlined for defining what set of conditions constitutes suitable refuge for adult and juvenile salmonids, to assess each stream's current capacity for providing thermal refuge. In making this assessment, we considered three different stream 'zones': the confluence; upstream reaches with no floodplain component; and upstream reaches with a floodplain component. We observed small cold-water plume formation at 5 of the 15 tributary complex confluence zones. Of these five, we believe only Eagle Creek is currently providing suitable refuge for adult salmonids, based on a comparison of observed site characteristics (water temperature, plume size (area), and water depth) with our preliminary criteria. We observed large numbers of adult fish at the Tanner Creek confluence, however this may be due to the hatchery presence just upstream from the confluence. Whether or not this confluence is utilized by non-returning adults was difficult to assess. Because it does not meet our minimum depth criteria for adult salmonids of 2 meters, we consider it unsuitable for adult migrants. All five of these confluences are considered suitable as refuge for juvenile salmonids, although none were observed during one sampling (snorkeling) event. In addition to providing thermal refuge, the cold water at these confluences may also provide thermal cues for fish to seek cooler water upstream. Even for streams where we did not observe plumes, we noted evidence of suitable refuge areas in higher reaches. Based on our criteria, 12 of these tributaries had suitable flow and temperature conditions to offer thermal respite within floodplain or higher gradient reaches. The four smallest streams lost surface flow at locations near their respective confluence zones for some duration of time during the summer. At a number of these sites, however, juvenile fish use continued throughout the summer, upstream of where surface flow subsided. Due to time/staff limitations and equipment loss, we were unable to fully survey four of the streams.

Phase 2 of the study, in 2016, focused on three objectives: filling data gaps from the Phase 1 monitoring of lower Columbia Gorge tributaries; characterizing the temperature profile of the Columbia River mainstem; and documenting the extent and quality of cold-water inputs throughout the reach extending from Longview, at River mile 67, to Bonneville Dam at River mile 140, including the confluence zones of major tributaries within this reach. Repeated monitoring of lower Gorge tributaries during Phase 2 again resulted in some equipment loss and malfunction, leaving gaps remaining at some tributaries; however, successful data collection at five of the tributaries helped confirm, or revealed additional, findings from Phase 1 monitoring. Because similar climate anomalies (warmer and dryer than average) appeared in both 2015 and 2016, temperature and discharge results did not differ significantly between Phase 1 and Phase 2, for tributaries that were monitored in both years. The additional Phase 2 monitoring confirmed significant diurnal variation in stream temperatures that is strongly coupled to air temperature. This diurnal variation is stronger in lower flow streams relative to higher ones, and shallower streams relative to deeper ones. Data also showed that, for streams with an alluvial fan near their confluence, hyporheic flow may be a significant component of flow during low-flow periods, with water entering and exiting the ground at various locations. Again, this was more noticeable for lower flow

streams relative to higher flow streams. Temperature monitoring of the mainstem Columbia River confirmed known patterns: mainstem waters are well mixed throughout the water column, and uniform over long reaches. We observed minimal variation (<0.1°C) in water temperature between the surface and maximum depth, and between Bonneville Dam (River Mile 147) and Longview, WA (River Mile 67). Other than major tributaries, we noted almost no additional cold-water inputs to the Columbia River between Longview and Bonneville Dam. One exception was a small outlet from the Columbia Springs hatchery near Camas, Washington, just upstream of the I-205 bridge overpass, where adult salmonids (possibly returning hatchery individuals) were observed. We only noted suitable cold-water refuge temperatures at three of the major tributary confluences: the Cowlitz (14.9 °C minimum), Kalama (15.5 °C minimum), and Lewis (16.0 °C minimum) rivers. At these locations, we did not observe significant plumes of cold water extending into the mainstem. As with the smaller tributaries of the Gorge, cold water at these confluences was rapidly diluted upon entering the mainstem, even at depth. With so few significant cold-water inputs to the lower Columbia, a gap of nearly 60 miles exists between suitable thermal refuge zones for adult salmon, extending from the Lewis River confluence at River Mile 87 to the Eagle Creek confluence at River Mile 147. Based on this finding, we added a third phase of this study, to investigate techniques of enhancing cold-water plume formation at selected lower Gorge tributaries which could potentially provide additional thermal refuge zones and effectively reduce this gap.

In Phase 3 of this study, completed in 2018, we used 3-dimensional hydrodynamic and water temperature modeling to investigate the feasibility of increasing cold-water plume size at three selected lower Columbia Gorge tributary confluences: Bridal Veil Creek, Horsetail/Oneonta Creek, and Multnomah/Wahkeena Creek. Of the 15 Gorge tributary complexes we studied in Phases One and Two, these confluence zones showed the highest potential for enhancement based on factors including stream flow and temperature, depth, and proximity to the migratory path of salmonids. Results indicate that, despite low tributary flows, each of these confluences has the potential to maintain significantly larger plumes (up to 10x current extents), through the placement of flow diversion structures and manipulation of existing landforms. We found potential plume sizes to be on the order of those seen at small thermal refuge zones in the mid-Columbia (Eagle Creek), with cumulative sizes for all three tributaries approaching that of Herman Creek in the mid-Columbia, where heavy use by summer migrating salmonids has been observed. While the potential for plume enhancement based on physical factors has been confirmed, this phase of the study provided a limited assessment of several practical considerations of implementing this technique, including social, cost, constructability, and geomorphic aspects, all of which will need to be addressed in future phases of development.

As Columbia River summertime temperatures continue to increase, the importance of cold-water habitat that can be utilized by migrating salmonids, i.e. thermal refuges, will likely increase as well. This study provides a better understanding of the present extent, quality, and use of thermal refuges in the lower Columbia River, and investigates management actions that can be taken to increase available cold-water habitat as its importance to the survival of these endangered stocks increases due to the expected impacts of a changing climate.

ACKNOWLEDGMENT

The Lower Columbia Estuary Partnership (LCEP) would like to thank the United States Environmental Protection Agency for providing the funding this project.

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INTRODUCTION

Columbia River summertime water temperatures have steadily increased over the last several decades (Figure 1) and are expected to increase further based on predictions from numerous climate models. Peak temperatures during this period typically range from 21-24 °C and are expected to increase by as much as 1.7 °C by 2040 and 3.0 °C by 2080 (Figure 2). Furthermore, the duration of time that water temperatures meet or exceed these values is expected to increase as well. Similar increases in temperature and duration can be expected for many Columbia River tributaries, many of which also are expected to experience decreased summer discharge in the coming decades.

During summer months, the mainstem Columbia River serves as rearing habitat as well as a migration corridor for adult and juvenile populations of several endangered and threatened salmonid species, including fall Chinook salmon (*O. tshawytscha*) and summer steelhead (*O. mykiss*), along with other native species of concern such as Pacific lamprey (*Lampetra tridentata*). The negative effects that water temperatures seen in the Columbia River during the summer can have on salmonids are well documented (Haskell et al. 2002; Lee et al. 2003; Richter et al. 2005; Goniea et al. 2006; Crossin et al. 2008; Keefer et al. 2008; Eliason et al. 2011). Keefer et al. (2011) suggest that temperatures above ~19 °C induce stress in adult migrants, and that higher temperatures are associated with stronger negative costs. Beechie et al. (2012) summarizes established temperature thresholds and recommended temperature criteria for a variety of Pacific salmon and steelhead at various life cycle stages. A summary of published criteria and threshold temperatures that are relevant to this study are presented in Table 1. In general, these studies indicate that adult fish become stressed at temperatures above 18–20 °C, and juveniles begin to feel stress at temperatures above 15–16 °C.

Based on the studies noted above and others, and the concurrent timing of summer fish runs with warm river temperatures (Figure 3), we presume that adult and juvenile salmonids migrating through the lower Columbia River during these months currently experience stressful environmental conditions. Based on climate change predictions, this level of stress is likely to increase in coming decades, as a result not only of increasing water temperatures, but an increase in the duration of time that water remains above critical threshold temperatures as well. Furthermore, as the duration of the warm water window increases, stocks that currently migrate during periods outside of critical temperature ranges and may be less adapted physiologically to warm temperatures than summer and early fall migrants (e.g. sockeye salmon (*Oncorhynchus nerka)*) may see increased exposure to adverse water temperatures as well.

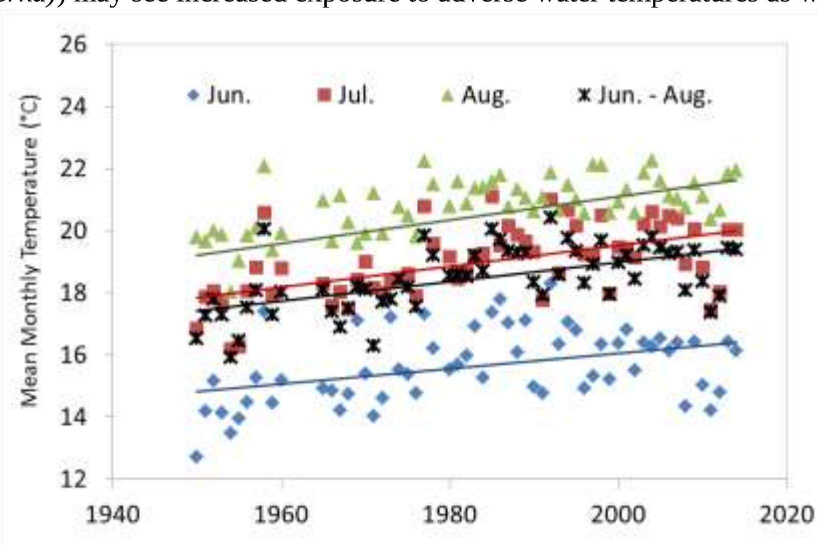
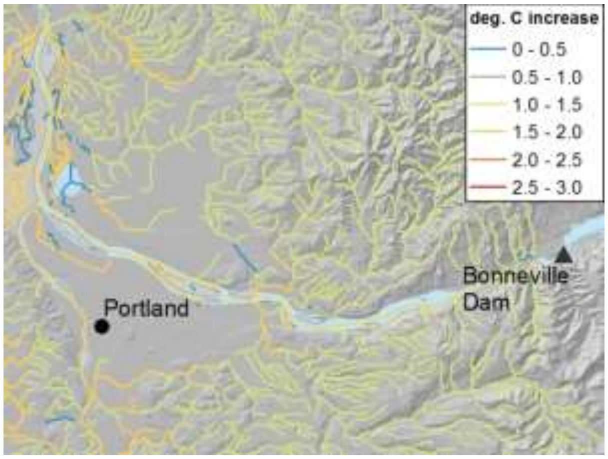
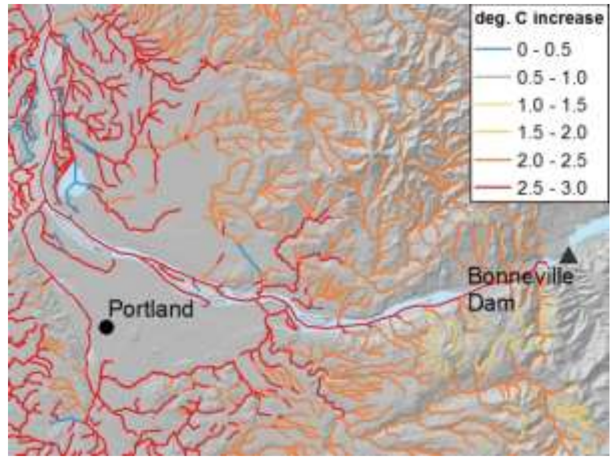


Figure 1. Mean summertime water temperature at Bonneville Dam, 1950–2014. Source: Columbia River DART.





a) predicted increase by 2040

a) predicted increase by 2080

Figure 2. Expected increases in river and stream temperatures for the lower Columbia region based on climate change predictions. a) current–2040; b) current–2080. Source: USFS Rocky Mountain Research Station NorWeST Stream Temperature Model.

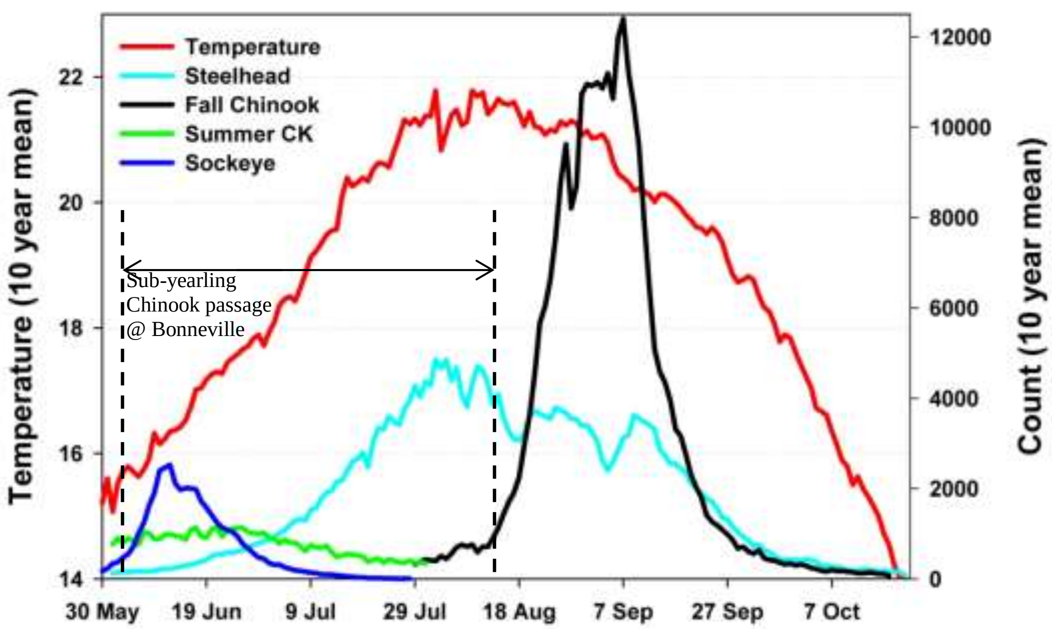


Figure 3: Ten-year (1996–2005) mean lower Columbia River water temperature (°C) and timing and mean run size of adult salmonid species at Bonneville Dam. The image is from Keefer et al. (2010), modified to include the typical window of downstream migration through Bonneville Dam for sub-yearling Chinook salmon based on Fish Passage Center data for Bonneville Dam.

Table 1. Published temperature thresholds and recommended temperature criteria for salmonids.

Life stage	Temperature threshold or criterion (°C)	Source
Adult migration, all species: optimal threshold	18–19	Keefer et al. 2010
Adult Chinook migration: lethal threshold	22	Beechie et al. 2012
Adult steelhead migration: thermal blockage	22	Beechie et al. 2012
Adult migration, all species: recommended criterion	18	Beechie et al. 2012
Juvenile Chinook rearing: optimal threshold	14.8	Beechie et al. 2012
Juvenile rearing, all species: recommended criterion	16	Beechie et al. 2012

The states of Oregon and Washington, with guidance from EPA, the Clean Water Act, and the Endangered Species Act, have set biologically based numeric criteria for maximum allowable temperatures of waterways used by salmonids, and in 2015 NOAA Fisheries, EPA, and Oregon DEQ began a federal court mandated three-year plan to map, protect, and restore zones of cold-water habitat for salmonids in the Columbia and lower Willamette Rivers. Keefer et al. (2010) documented the use of cold-water 'thermal refuge' zones by migrating adult salmon and steelhead when summertime water temperatures reach or exceed a species-specific threshold temperature, ranging from approximately 19–21°C. This, and related studies, focused on major tributary confluences in the mid-Columbia portion of the migration corridor, between Bonneville and John Day dams. Cold-water inputs from these tributaries (Deschutes River, White Salmon River, Herman Creek, and others) were found to be 2–7ºC cooler than the mainstem Columbia River, at the times they were sampled.

Presumably, such cold-water refuge zones are similarly important for juvenile salmonids migrating downstream during the summer months, which experience the same mainstem thermal conditions, yet, as noted in Table 1, may have lower tolerances for warm temperatures. Between Bonneville Dam and Portland, in the lower Columbia River Gorge, several small tributaries enter the mainstem Columbia. While flows are considerably smaller relative to the larger upstream tributaries, these streams typically remain quite cold throughout the summer. Fish monitoring by LCEP (Hanson et. al 2016) and other studies (Roegner et. Al 2012; Teel et. al 2014; Sather et. al 2016) has documented use of this reach of the lower Columbia River by endangered or threatened upriver juveniles during outmigration, even during summer months. Juvenile Chinook salmon have been detected during beach seine sampling in the months of June and July, for various years (Sather et. al 2016). At the Horsetail/Oneonta Creek confluence, a PIT tag array was installed in 2014 to monitor use of this stream by migrating upriver stocks. From June–August of 2015 we detected juveniles of various species including summer steelhead, sockeye, spring Chinook, and fall Chinook passing into and out of the site (LCEP unpublished, 2015, 2017). These observations provide evidence that endangered stocks are utilizing these tributaries during summer months, perhaps as relief from warmer mainstem conditions.

In 2015, LCEP, with funding from EPA, initiated this three-phase, complementary study to the NOAA Fisheries/EPA/OR DEQ plan, focusing on a portion of the lower Columbia River that extends from approximately the city of Longview, WA (river mile 67) to the Bonneville Dam (river mile 146), the upstream extent of tidal influence in the river. The objective of the study is to document cold-water inputs to this reach of the lower Columbia River, and where possible, investigate strategies for restoring or enhancing cold-water refuge zones for adult and juvenile salmonids. Through monitoring of water temperature, discharge, and physical parameters of identified inputs, we assess how each may be providing thermal refuge for salmonids using the lower river during the summer months, under current climatic conditions. A significant uncertainty we hope to address is the question of what conditions constitute a suitable thermal refuge for salmonids of varying age and species. For example, while thermal thresholds and recommended thermal criteria have been estimated for various life stages of salmonid species, other factors that may influence use of cold-water sources, such as spatial extent (area), water depth, velocity, etc., are less well defined. Additionally, tolerances for physical habitat conditions may change as temperatures approach critical thresholds; ideally, established criteria would account for this. Through a combination of monitoring and fish observation, we hope to better predict what combinations of these factors provide suitable refuges for migrating fish.

The three phases of the LCEP study are as follows:

Phase 1: Lower Columbia Gorge Tributary Monitoring (summer 2015, with some additional summer 2014 data)

Phase 2: Lower Columbia River Mainstem and Large Tributary Confluence Monitoring (summer 2016)

Phase 3: Enhancement of Cold-Water Refuge Zones at Lower Columbia Gorge Tributary Confluences (2017–2018)

Because specific goals and objectives of any given phase were influenced by results of prior phases, methods and results for each phase are presented as standalone sections in this document. By characterizing the extent and nature of cold-water inputs to the selected reach of the lower Columbia River, and considering strategies for enhancement and protection of cold-water 'zones', we hope to gain a better understanding of how salmonids are using the lower Columbia River during summer months, how this use may be impacted by a changing climate, and how resiliency to rising water temperatures in the future may be improved at the population scale.

PHASE 1 OF 3: LOWER COLUMBIA GORGE TRIBUTARY MONITORING

Background, Phase 1

Between river mile (RM) 126 (near Corbett, OR) and RM 146 (at Bonneville Dam), 17 small tributaries enter the lower Columbia River, at 14 confluences. This area is part of the lower Columbia Gorge. Despite being fed by sources other than snowmelt, these streams remain relatively cold year-round. Stream discharges are characterized by larger flows, with intermittent heavy storm event pulses, during the late fall through early spring wet season, and smaller, but relatively steady flows from the late spring through early fall dry season. A number of these tributaries support small populations of native and hatchery produced salmonids, and they are also utilized to some extent by migrating populations of upper Columbia salmon stocks at various times of the year (Hanson et. al 2016; LCEP unpublished 2015, 2017). LCEP and other organizations have implemented several floodplain and in-stream enhancement projects in these tributaries over the past two decades. These projects included fish passage enhancements (culvert removal or modification), large wood placement, riparian planting, channel realignment, and flow enhancement (through decreased diversion of stream flow for alternate uses).

Because these tributaries constitute some of the only cold-water inputs to the lower Columbia River upstream of Portland, OR, and due to their importance for supporting endangered salmonids and other wildlife species, LCEP focused on characterization of flow and water quality of these streams in the initial phase of this project. These tributaries can provide thermal refuge for summer migrating salmonids in multiple ways, depending on their respective properties. During these months, juvenile fish could potentially seek shelter within three general stream zones: in higher gradient, faster moving reaches above the confluence and floodplain; in the slower moving floodplain reaches; and at the confluences with the Columbia where, given adequate stream flow and favorable topographical conditions, a cold-water plume may form. Furthermore, even at confluence zones where absolute water temperatures are higher than those thought to provide suitable thermal refuge, temperatures relative to the mainstem Columbia may still be sufficiently low enough to cue fish to enter the stream and find colder water upstream. These cues may be temporal in nature, varying with atmospheric and/or hydrologic conditions.

This initial phase of the LCEP Thermal Refuge Study documented summer time stream temperatures and discharge for the 17 lower Columbia Gorge tributaries (and 14 confluence zones). Confluence, floodplain, and high gradient zones of each were evaluated for their respective potential to provide thermal refuge. We also included Eagle Creek, for a total of 18 tributaries and 15 tributary confluences (Figure 4). Eagle Creek is located immediately upstream of the Bonneville Dam. Because it is similar in size and nature to the lower Columbia River Gorge tributaries, and due to its location immediately above Bonneville Dam where returning adult salmonids experience multiple stressors, we included it in the study. For the purposes of this report, we consider each tributary confluence as a unit of measure. For example, Horsetail Creek and Oneonta Creek were manipulated during construction of Interstate 84 to enter the Columbia at a common confluence zone, and so we refer to this single study unit as the ‘Horsetail/Oneonta Creek’ unit. The same is true for Multnomah/Wahkeena. Based on this organization, the 15 individual confluences comprise the study sites.

Figure 4. The 15 Columbia River Gorge stream confluences and associated streams included in Phase 1 of the Thermal Refuge study.

Methods, Phase 1

To guide our monitoring plan we evaluated each tributary with respect to the potential thermal refuge zones (see Background for zone descriptions) we expected to be present. We based this evaluation on existing topographical data (LiDAR elevations, as well as Level 5 geomorphic catena of the Columbia River Estuary Ecosystem Classification. See Figure 5), and results from a hydrodynamic/water quality model that we developed to simulate plume formation at the mouth of each tributary (Figure 6). Table 2 lists the stream characteristics identified in the evaluation, and the resulting monitoring plan for each stream. We monitored the following data parameters for each tributary, where appropriate:

1. Stream temperature. We placed HOBO temperature loggers (manufactured by ONSET) at selected sites within each tributary, to record water temperatures at 30-minute intervals for the duration of the summer (2015). Logger locations were chosen based on our preliminary stream classification. For tributaries with significant lengths of floodplain (greater than approximately 1,000’), we monitored temperatures above, below, and in the floodplain, to evaluate effects on water temperature of these slower flowing, and often exposed, reaches. More typical of the Columbia River Gorge, with its steep, confined topography, are tributaries that do not have a significant floodplain component, but instead flow at a relatively high gradient directly to the river, often through an alluvial fan feature. Because we did not expect significant warming to occur along these tributaries, we typically placed a single logger close to their respective confluences with the Columbia River. In some of these cases, where upstream

access required little effort, or where additional features were present which could potentially impact stream temperatures, we placed additional loggers at these locations. For example, both Tanner and Eagle Creeks have state operated fish hatcheries located along their lower reaches. We monitored temperatures above and below hatchery intake and outfall locations for both tributaries, to document any hatchery-related influences on stream temperatures.

All deployed loggers were placed as deep as possible in the water column, to minimize effects of solar radiation and to keep loggers submerged as long as possible as stream flows decreased throughout the summer.

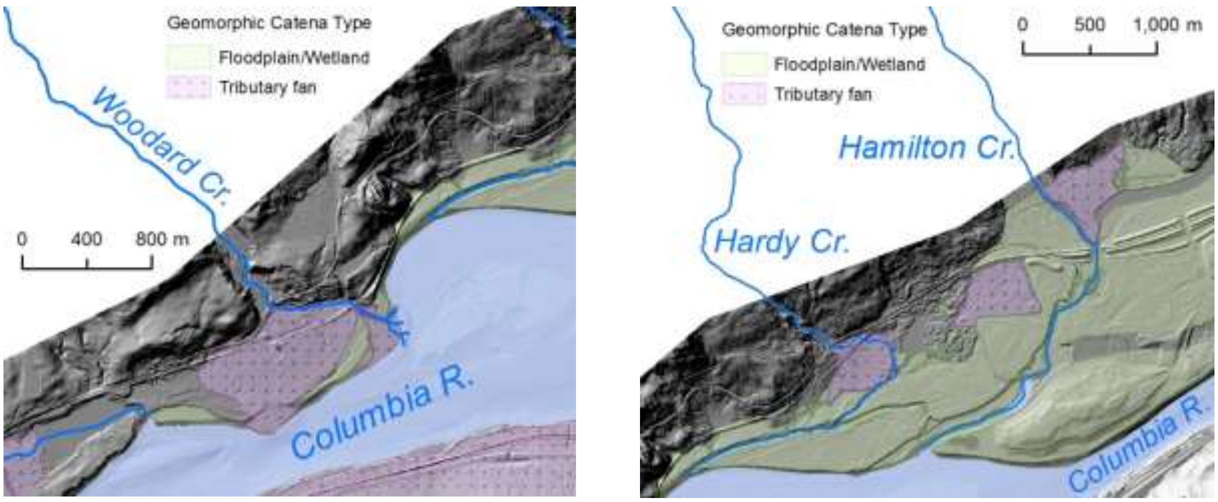


Figure 5. Typical stream topographies for Columbia Gorge Tributaries. Left: Woodard Creek, characteristic of higher gradient streams that enter the river confluence directly through an alluvial fan system, with limited or no floodplain zone. Right: Hamilton and Hardy creeks, characteristic of streams that enter a longer floodplain zone above the confluence, often through an alluvial fan as well. LiDAR topography illustrates the relative slopes of these features.

2. Cold-water plume assessment. To assess the nature of cold-water 'plumes' that were detected at any stream confluences, we monitored water temperature using the following two methods:

- Towed temperature sensors: To capture the horizontal and vertical distribution of cold water discharged from these streams into the Columbia River, we towed temperature sensors through the water at the confluences of selected streams, at the surface (0–1 ft.), at mid depth (2–3 ft.), and at depth (3 ft.–bottom depth). For most sites we manually recorded temperatures using a handheld YSI instrument, at recorded GPS locations. For other sites we used a series of ONSET temperature loggers mounted on an adjustable pole at fixed depths and synched with a GPS to log temperature/location information. Due to the slow response time of these loggers, this method produced mixed results (see Results section).

- Temperature logger array: Based on preliminary hydrodynamic model results we expected plume formation to be dynamic due to varying discharge (from the Columbia River and the tributaries, Fig. 6), wind patterns, and solar radiation. At stream confluences where a definitive 'plume' was observed, we planned to deploy 3D arrays of temperature loggers for an extended period to capture these temporal patterns.

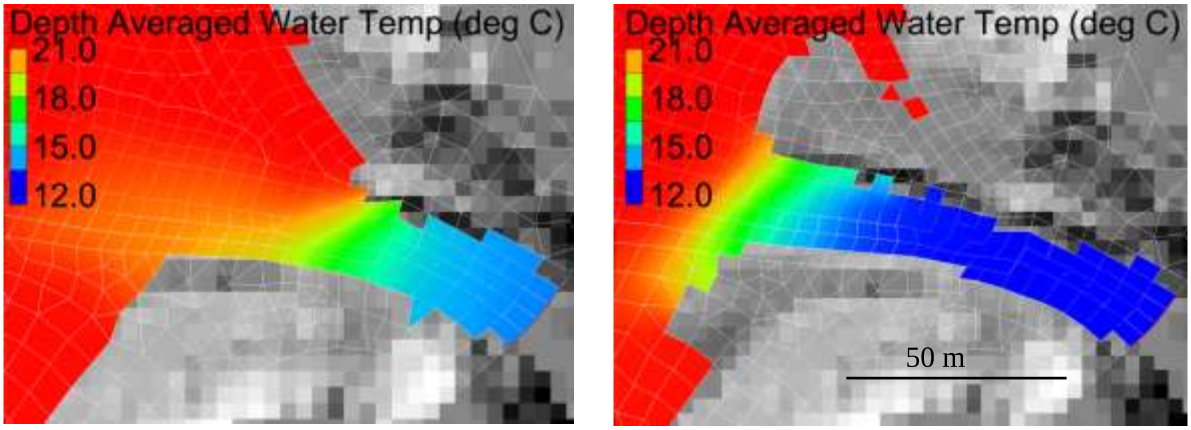


Figure 6. Simulated depth-averaged water temperatures at Tanner Creek confluence from hydrodynamic and water quality modeling. Left: Resulting water temperatures with a simulated Columbia River discharge of 120,000 cubic feet per second (cfs). Right: Resulting water temperatures with a simulated Columbia River discharge of 180,000 cfs. For both simulations, Tanner Creek discharge was held constant. While model results were not validated, results illustrate the potential influence of Columbia River discharge on the extent of the cold-water plume at the tributary confluence.

3. Stream discharge. Multiple physical factors influence whether a plume of cold water will form at the confluence of any given tributary, and the size and nature of that plume. In our preliminary hydrodynamic modeling prior to the study we observed that stream discharge was a significant factor in plume formation. Thus, we planned to collect these data in addition to water temperature. We calculated stream discharges from current velocities measured at known stream cross sectional intervals. We measured current velocities using a standard current velocity meter.

4. Bathymetry. Preliminary model simulations indicated that topographic/bathymetric features at confluence zones are also an important factor in plume formation at confluence zones. Tributaries that discharge into sheltered embayments away from stronger Columbia River currents were more likely to form plumes compared to streams that discharge directly into the higher velocity main channel. This is consistent with observations by M. Keefer, which show that thermal refuge areas in the mid-Columbia study are typically seen to form downstream of some type of flow deflection structure which creates sheltered, lower velocity environments capable of retaining the colder tributary waters for longer periods of time (M. Keefer, personal communication). Many of the tributary confluence zones investigated in this study are alluvial fans with braided channel networks that may shift alignment from year to year, changing the location of water entering the Columbia and potentially altering cold-water plume formation. To better understand finer scale, dynamic aspects of plume formation at these tributary complexes, adequate resolution elevation data is required. Unfortunately, for most of these locations the bathymetric data included in the lower Columbia River Digital Terrain Model (currently the highest quality and most readily available elevation data for the region), consists of river cross section data at 150-meter spacing, which is coarse relative to the size of features that we expected to see (tens of meters) based on our modeling. To better assess the nature of plumes that we observed, we planned to collect higher resolution bathymetric data using an RTK GPS unit.

Table 2 shows the Phase 1 monitoring plan, based on our stream evaluation. Monitoring took place in summer 2015, with some additional data already collected in 2014 (see Table 3 results).

Table 2. Research plan for Phase 1 (summer 2015) of the lower Columbia River Thermal Refuge Study.

Site	Stream temperature monitoring locations	Plume Mapping	Dis-charge	Bathy-metry	Data plan based on preliminary stream evaluation and hydrodynamic model simulation
Bridal Veil Cr.	Col. R. confluence	X	X	X	Alluvial fan system, no floodplain zone. Potential for plume formation. Evaluate plume and stream conditions.
Duncan Cr.	Col. R. confluence	X			Alluvial fan system, constrained by a dam/lake at Columbia R. confluence. Plume formation unknown. Evaluate stream temperature and plume conditions.
Eagle Cr.	Col. R. confluence; upstream of hatchery intake	X	X		Limited floodplain zone. Potential for plume formation. A state operated fish hatchery that partially dewaters the creek during summer months is located 0.5 mi. upstream of Col. R. confluence. Evaluate plume and stream conditions.
Gibbons Cr.	Col. R. confluence; upstream of floodplain				Alluvial fan system above a long floodplain zone where stream flows through an artificial channel. Constrained by a fish ladder at Col. R. confluence. Evaluate stream temperature.
Goodbear/ Archer Cr.	Col. R. confluence		X		Alluvial fan system, no floodplain zone. Evaluate stream conditions.
Hamilton Cr.	Col. R. confluence		X		Alluvial fan system above a long floodplain/slough zone. Constrained by development further upstream. Evaluate stream and slough conditions.
Hardy Cr.	Col. R. confluence		X		Alluvial fan system above a long floodplain/slough zone. Evaluate stream and slough conditions.
Horsetail/ Oneonta Cr.	Col. R. confluence	X	X		Alluvial fan system above a floodplain zone where recent restoration and temperature monitoring have occurred. Potential for plume formation. Evaluate plume and stream conditions.
Latourell Cr.	Col. R. confluence; upstream of floodplain				Alluvial fan system above a long floodplain reach that is constrained by a culvert and lake above confluence. Recent restoration work and monitoring have occurred in the floodplain zone. Evaluate stream temperature.
Lawton Cr.	Col. R. confluence; upstream of floodplain	X	X		Alluvial fan system, no floodplain zone. Unknown plume potential. Evaluate plume and stream conditions.
McCord Cr.	Col. R. confluence		X		Alluvial fan system, no floodplain zone. Evaluate stream conditions.
Moffet Cr.	Col R. confluence		X		Alluvial fan system, no floodplain zone. Evaluate stream conditions at confluence.
Multnomah/ Wahkeena Cr.	Col. R. confluence	X	X	X	Alluvial fan system with a short, modified floodplain zone. Potential for plume formation. Recent restoration and monitoring have occurred in floodplain zone. Evaluate plume and stream conditions.
Tanner Cr.	Col. R. confluence; upstream of hatchery intake	X	X		Limited floodplain zone. Potential for plume formation. A state operated fish hatchery is located 0.5 mi. upstream of Col. R. confluence. Evaluate plume and stream conditions.
Woodard Cr.	Col. R. confluence		X		Alluvial fan system, no floodplain zone. Evaluate stream conditions.

Results, Phase 1

Available time and resources did not allow for collection of all data at all sites as planned. We subsequently addressed some of the data gaps during Phase 2 of the study in 2016, however because this was not the focus of that phase, additional collection was limited. Table 3 summarizes the data that was collected in the summer of 2015 (with some additional data having been collected in summer of 2014), based on the initial monitoring plan (Table 2). Monitoring locations are illustrated in Figure 7. Presentation of results follows.

Table 3: Data collected for Phase 1 (summer 2015) of the lower Columbia River Thermal Refuge Study.

		Plume Mapping				
Site	**Stream temperature monitoring interval**	**Towed sensors**	**Sensor array**	**Discharge**	**Bathymetry**	**Data Collection Notes**
Bridal Veil Cr.	6/26/15–10/05/15	8/05/15 12:30 pm		8/5/15 10:30 am	8/5/15	[1]Time/staff limitations prevented deployment of logger array.
Duncan Cr.	data logger lost					Temperature logger deployed at Col. R. confluence was subsequently buried by several feet of fill prior to data collection (retrieval attempted on 10/06/15).
Eagle Cr.	Above hatchery intake: 6/26/15–10/7/15. Col. R. confluence: 6/26/15–8/10/15.	8/29/14 11:00 am		Above hatchery intake: 8/11/15 10:00 am		
Gibbons Cr.	6/10/15–11/3/15 downstream logger lost	N/A	N/A	N/A	N/A	Downstream temperature logger at Col. R. confluence lost prior to data collection.
Goodbear/ Archer Cr.	6/26/15–8/5/15	N/A	N/A		N/A	Surface flow ceased in early August, before discharge data could be collected.
Hamilton Cr.	6/26/15–10/7/15		N/A		N/A	[1]Time/staff limitations prevented stream discharge and slough temperature monitoring in 2015.
Hardy Cr.	6/26/15–9/16/16		N/A		N/A	Time/staff limitations prevented stream discharge and slough temperature monitoring in 2015. [1]Stream temperature data was not retrieved until 2016.
Horsetail/ Oneonta Cr.	6/26/15–10/5/15	8/11/15 1:30 pm	N/A	8/11/15 2:00 pm	N/A	See Note 1.
Latourell Cr.	Above floodplain reach: data logger lost. Columbia R. confluence: data not collected in 2015	N/A	N/A	N/A	N/A	Upstream temperature logger lost prior to data collection. Downstream logger data was not retrieved
Lawton Cr.	8/6/15–10/7/15		N/A	upstream: 8/6/15, 9/4/15 Col. R confluence: 9/4/15 1:00 pm	N/A	Initial temperature logger was lost prior to data collection. Deployed new logger on 8/6/15.
McCord Cr.	8/26/15–10/6/15	N/A	N/A	8/10/15 9:30 am	N/A	Surface flow ceased in late June, before discharge data could be collected.
Moffet Cr.	8/26/15–10/6/15	N/A	N/A	8/11/15 11:00 am	N/A	
Multnomah/ Wahkeena Cr.	6/10/15–10/28/15	[2]7/29/14 10:30 am		[2]7/29/14 10:00 am		Time/staff limitations prevented deployment of logger array. Bathymetric survey occurred in 2016 (Phase 2).
Tanner Cr.	Above hatchery intake: 6/26/15–10/7/15. Columbia R. confluence: data logger lost	8/29/14 9:00 am 8/05/15 1:00 pm	N/A	8/05/15 12:30 pm		[1]Downstream temperature logger lost prior to data collection.
Woodard Cr.	6/26/15–10/6/15	N/A	N/A		N/A	Flow was too low at time of discharge data collection. Estimated discharge at < $1m^3$/sec on 8/06/15. See Note 1.

Note 1: Additional data collected in 2016, see Phase 2 report section for results. Note 2: Data was collected in summer 2014.

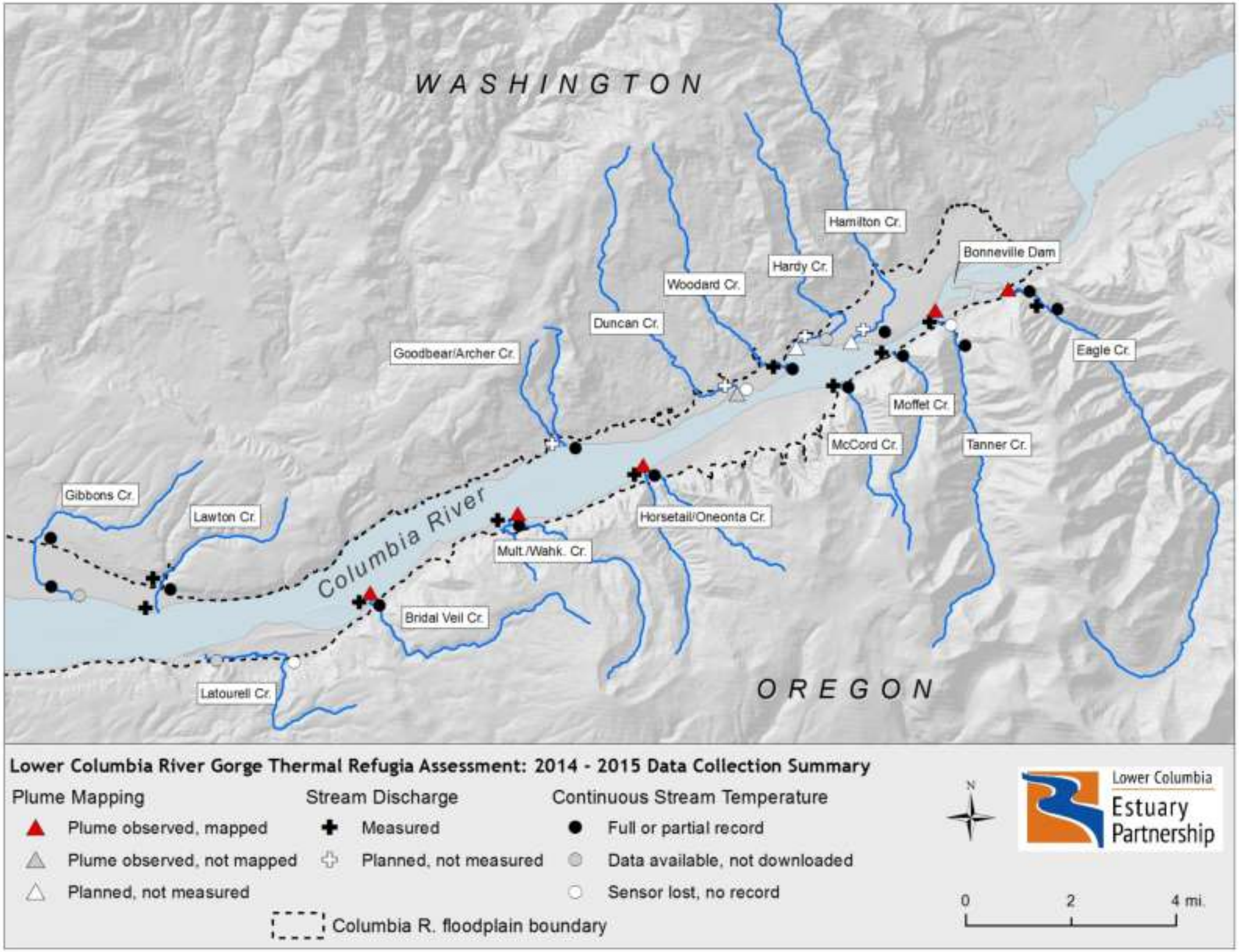


Figure 7. Data collection locations for the Columbia River Gorge Thermal Refuge Study.

Stream temperature monitoring results

Temperature data collection was straightforward, however some confounding factors limited success. Many of the studied stream reaches are heavily used by the public, and despite best efforts to keep temperature loggers hidden from sight, three (Tanner Creek downstream, Latourell Creek upstream, Lawton Creek) were lost and presumed stolen prior to data downloads. The logger placed at the Duncan Creek confluence was subsequently buried under several feet of fill and could not be recovered. Logger data at Gibbons Creek (floodplain), Latourell Creek (floodplain), and Hardy Creek (floodplain) was not recovered in 2015 due to time limitations and rising water levels in the late fall (Hardy Creek data was subsequently retrieved in 2016, however). Overall, temperature records were obtained for 15 of the 20 locations monitored. Most loggers were deployed from June 26–October 5 of 2015 and provided continuous coverage during that period, at 30-minute intervals. Table 4 summarizes the temperature results for the monitored streams. Water temperature plots are shown in Figure 9.

Observed stream temperatures ranged from 2–10 °C cooler than mainstem Columbia River temperatures. Stream depths ranged from approximately 0.5–3 feet deep, and throughout this range diurnal temperature variations due to influence of air temperature were observed. In addition to water depth, the magnitude of diurnal variation may have been influenced by the level of exposure to direct sunlight. For example, a variation of 6°C was typical for Woodard Creek (Figure 9m), compared to 2°C variation at Moffet Creek (Figure 9j). These two streams are roughly the same depth and of comparable discharge. However, Moffet Creek remains well shaded upstream of our logger location, while Woodard Creek flows through approximately 0.1 miles of exposed floodplain directly upstream of its respective logger, allowing for increased exposure to solar radiation and a likely increase in daytime heating.

Larger diurnal variations apparent in the temperature records are indicative of periods where stream flow ceased and the sensor has become exposed to atmospheric temperatures. While most streams in the study retained flow continuously throughout the summer of 2015 at their respective logger locations, the four noted below became dry for periods of days to months. The Hamilton Creek temperature record (Figure 9e) showed several short duration peaks (24–25 °C) throughout July and August. These are a result of warmer Columbia R. water backwatering the site at the logger location. These higher water events are evident in flow and stage records for the Columbia R. below Bonneville Dam (USGS, Columbia R. DART).

- McCord Creek: Lost flow July 1 and remained dry for the duration of summer.
- Goodbear/Archer Creek: Lost flow July 29 and remained dry for the duration of summer.
- Hamilton Creek: Lost flow in early September and remained dry for the duration of summer.
- Woodard Creek: Lost flow for a few days in late August, and again in late September.

Loss of surface flow during the summer months is a common occurrence for these tributaries, whose confluence zones typically consist of lower gradient, alluvial fan systems with braided channels composed of accumulations of coarse substrate. When flow from higher gradient, upstream reaches enters an alluvial fan it is distributed into multiple lower flow channels. As flows then decrease throughout the dry Pacific Northwest summers, not enough water is available to maintain flow in these channels. Without adequate energy to maintain surface flow, the water that remains typically sinks below the surface, either reappearing as surface water further downstream, or entering the Columbia River as groundwater. This subsurface flow may also provide some additional cooling effect on the water, as we have observed in other studies (Lower Columbia Estuary Partnership Greenleaf Creek Alternatives Analysis, 2014). Given the extreme climatic conditions in the Pacific Northwest during summer 2015 (see Discussion), it is likely that surface flow at these tributary confluences may have ceased earlier in the summer, and remained dry for longer periods, than what normally would be observed. We do not have historical discharge records to confirm this, however.

It should be emphasized that the temperature plots only reflect conditions at the data logger locations. At McCord Creek and Woodard Creeks, we observed streamflow upstream of the loggers during periods when the loggers were dry (Figure 8). This, again, is typical of these alluvial fan systems. At McCord Creek, we observed juvenile salmonids using the wetted portions of the stream during these periods.

The seasonal temperature trend for most tributaries closely mirrored water temperatures in the mainstem Columbia River (included for reference in all Figure 9 plots). For most streams, the highest temperatures occurred in early–mid July, with slight cooling through the end of July, and steadier cooling seen from mid-August onward.

Figure 8. Flow at McCord Creek, 8/10/15. Left: dried out stream bed at data logger location just above Columbia River confluence. Right: Stream flow (measured at approximately 1 cfs) upstream of logger location, under railroad culvert. Juvenile salmonids were observed using the pool below the culvert.

Table 4: Stream characteristics derived from hourly stream temperature records, 6/26–10/5 2015.

Site	***Flow Characteristics for Period of Record (6/26–10/5 2015)**	**Temp. range for continuous flow periods from 6/ 26–9/14 2015 (Min. / Max. / Avg.)**
Bridal Veil Cr.	Continuous	9.8 / 17.7 / 13.8
Duncan Cr.	Data logger lost	
Eagle Cr. above hatchery Eagle Cr. above confluence	Continuous	12.3 / 22.3 / 16.7 16.2 / 24.0 / 21.1
Gibbons Cr. above floodplain Gibbons Cr. floodplain	Continuous Awaiting data	11.5 / 22.3 / 16.9
Goodbear/Archer Cr.	No flow 7/29–10/5	13.1 / 20.2 / 16.0
Hamilton Cr.	Unknown before 9/6 No flow 9/6–10/5	7.9 / 25.1 / 11.2
Hardy Cr.	Continuous	13.3 / 18.4 / 25.3
Horsetail/ Oneonta Cr. @ confluence	Continuous	12.3 / 21.1 / 17.0
Latourell Cr. above floodplain Latourell Cr. above confluence	Data logger lost Awaiting data	
Lawton Cr.	Continuous	12.4 / 20.6 / 16.2 (8/6–9/14 only)
McCord Cr.	No flow 7/1–10/5	Dry for majority of summer
Moffet Cr.	Continuous	13.0 / 19.8 / 16.6
Multnomah/ Wahkeena Cr.	Continuous	10.1 / 21.2 / 14.4
Tanner Cr. above hatchery Tanner Cr. above confluence	Continuous Data logger lost	9.3 / 14.5 / 11.9
Woodard Cr.	Intermittent	11.9 / 20.7 / 15.4
Columbia R. mainstem (reference)		**19.2 / 24.0 / 21.9**

*Periods of zero stream flow observed in temperature records reflect hydrologic conditions at the logger locations only. For some streams, flow was observed upstream of data logger locations during periods when the loggers were dry.

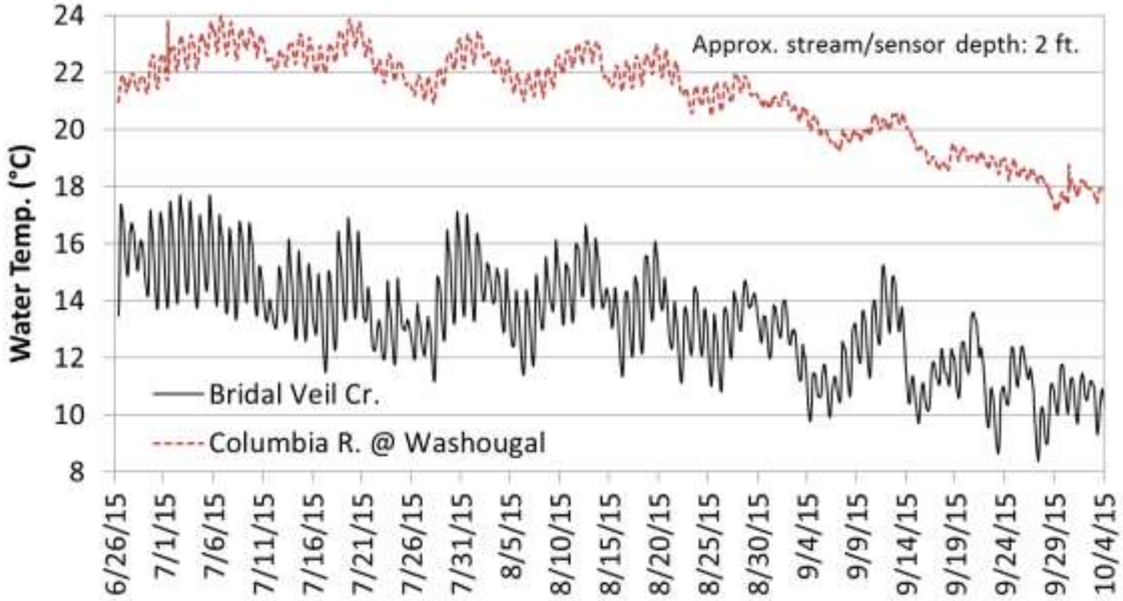


Fig. 9a. Bridal Veil Creek

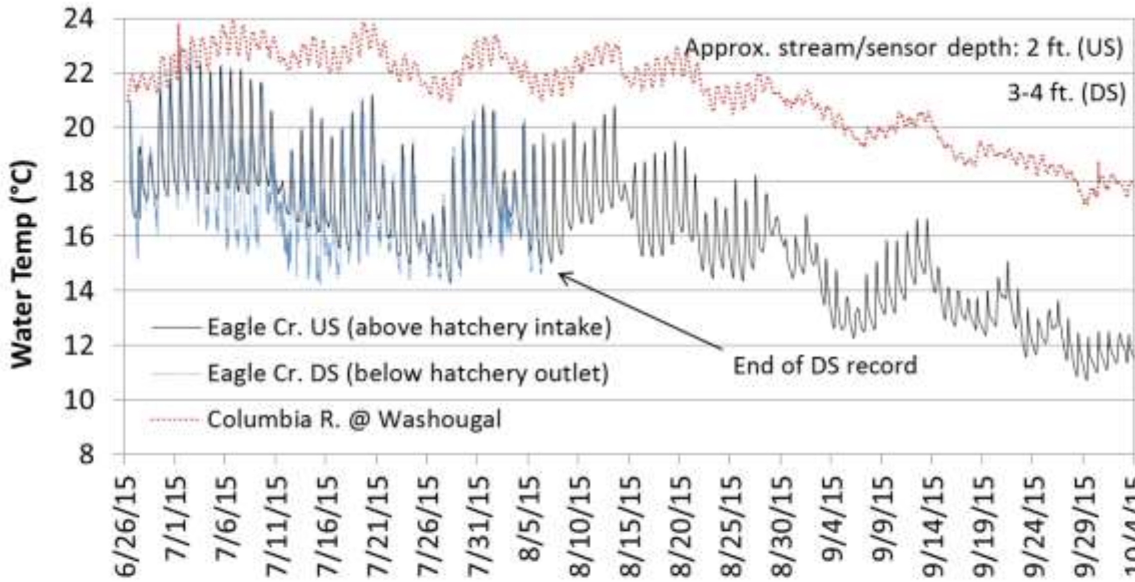


Fig. 9b. Eagle Creek

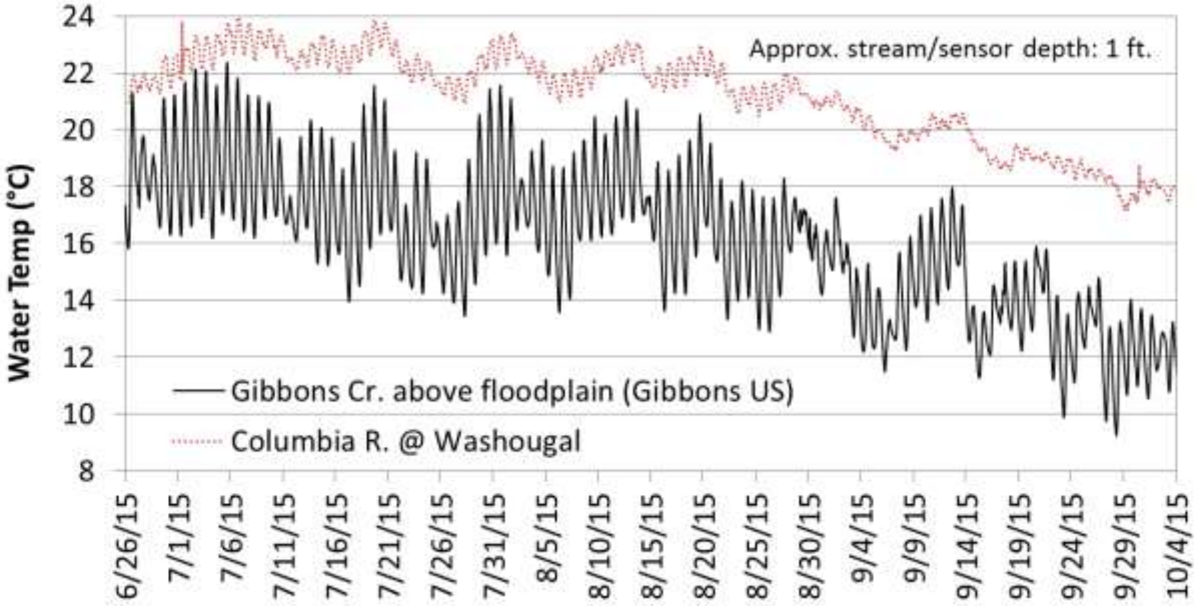


Fig. 9c. Gibbons Creek

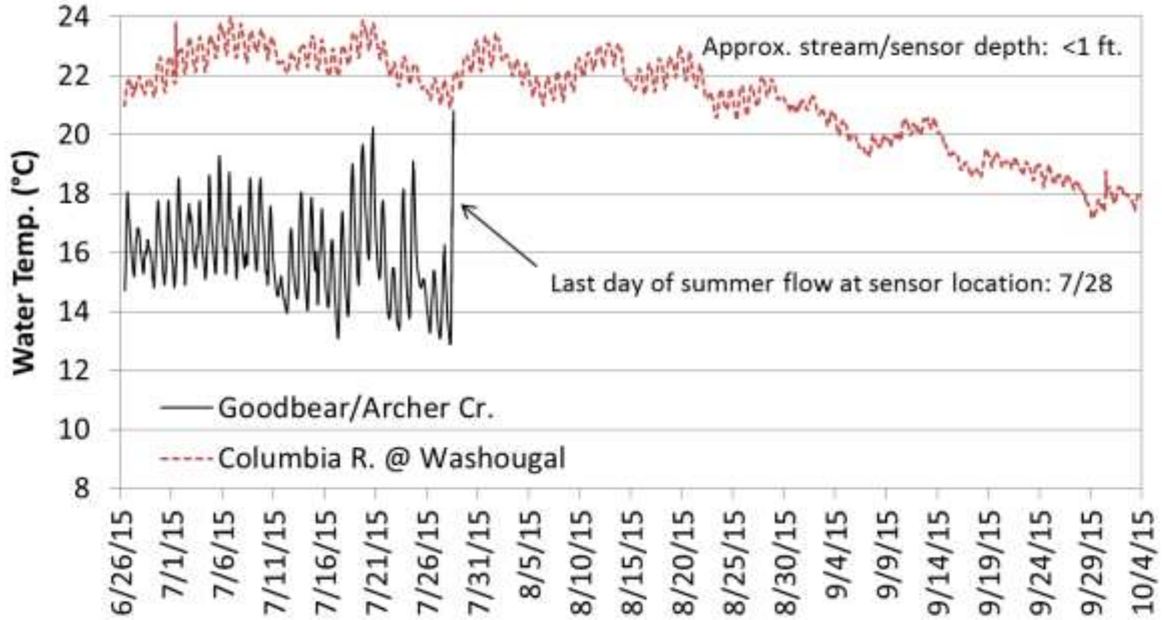


Fig. 9d. Goodbear/Archer Creeks

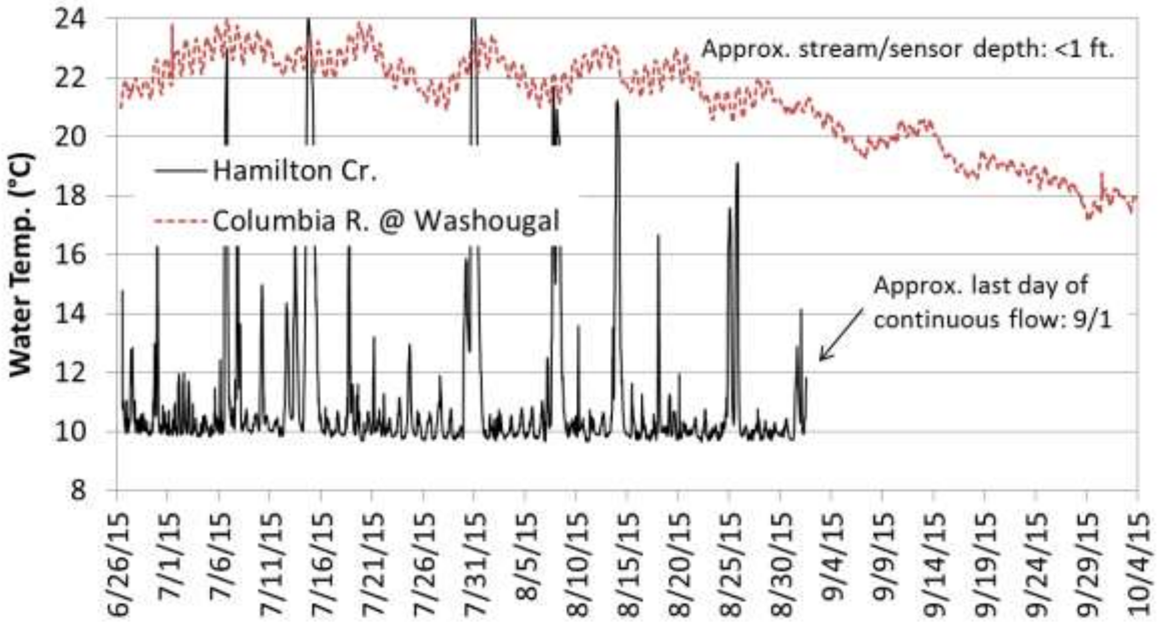


Fig.9e: Hamilton Creek

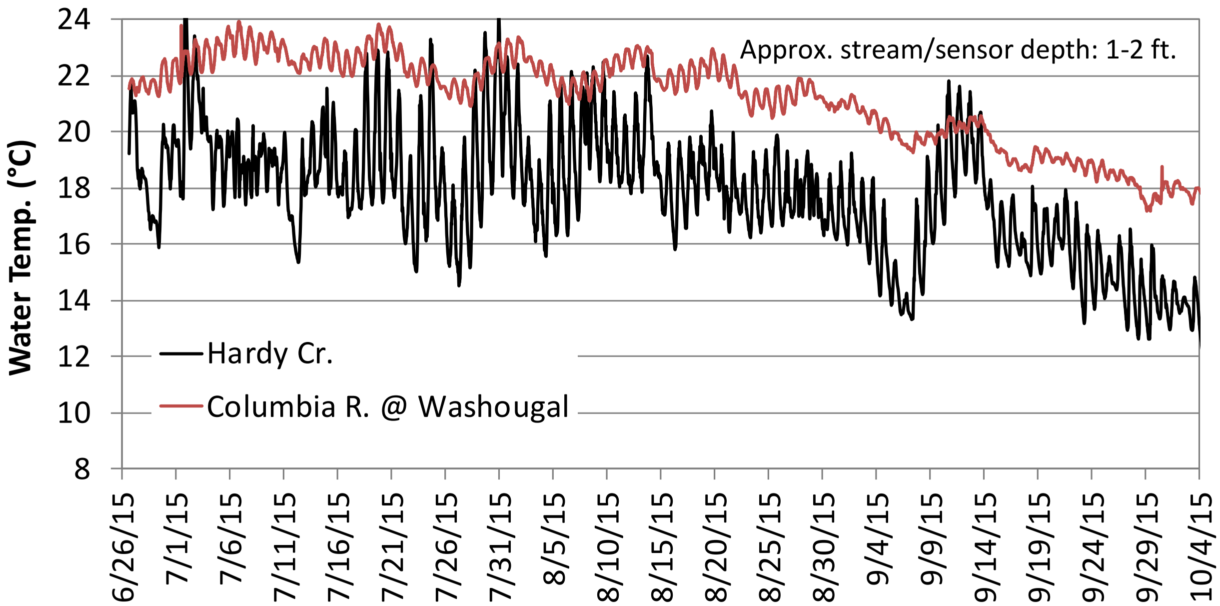


Fig. 9f. Hardy Creek

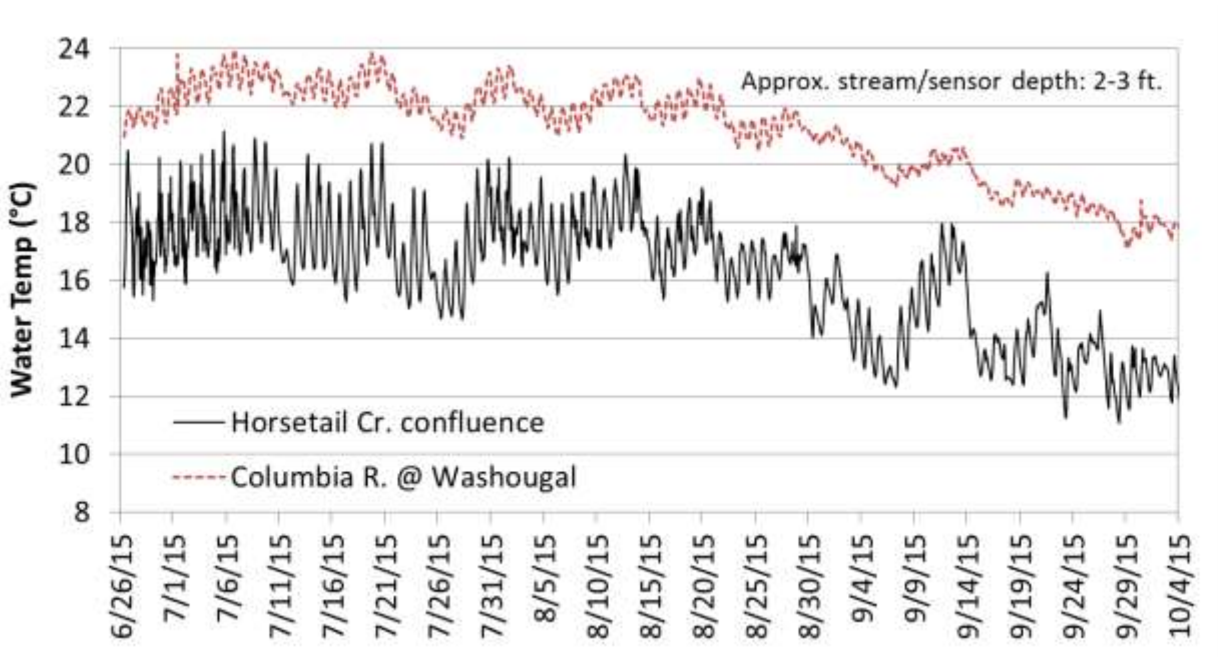


Fig. 9g. Horsetail/Oneonta Creek

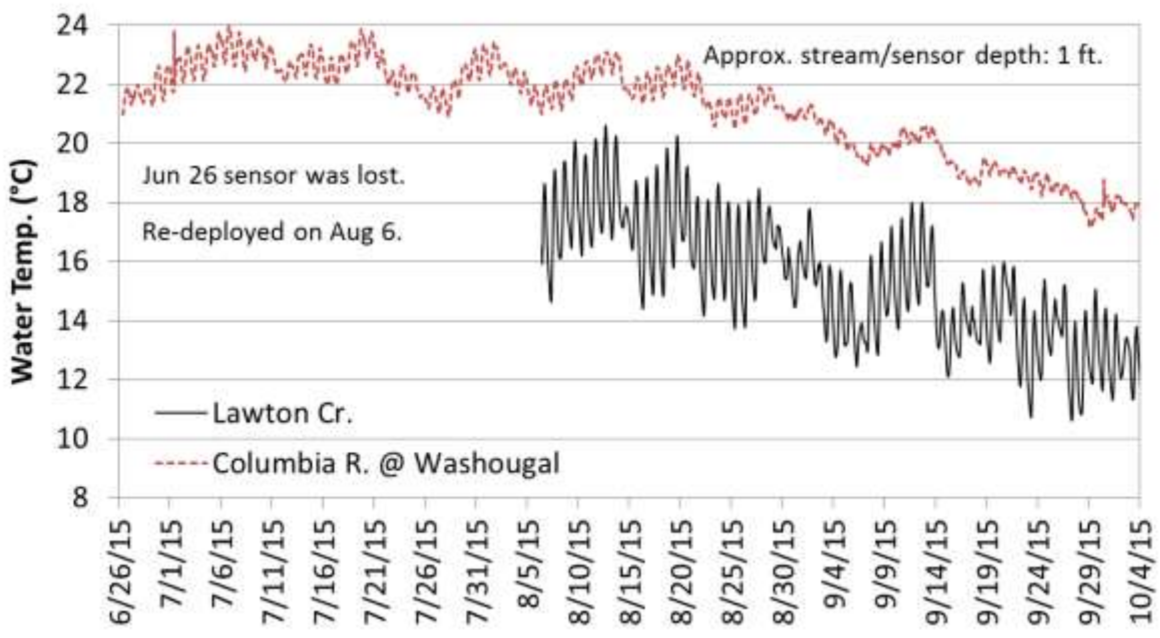


Fig. 9h. Lawton Creek

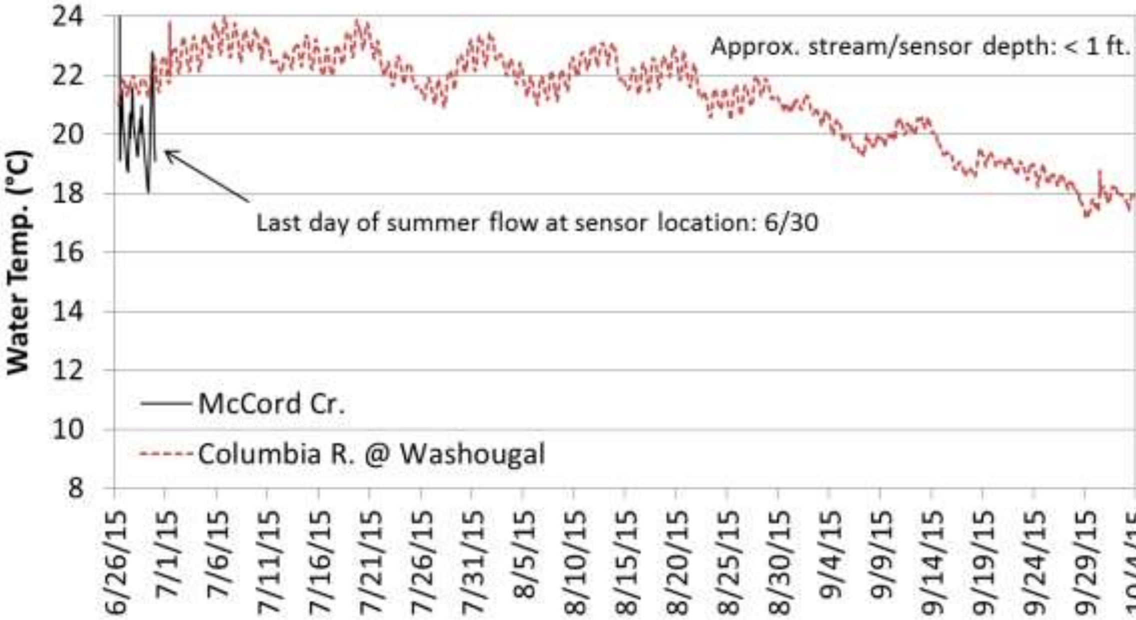


Fig. 9i. McCord Creek

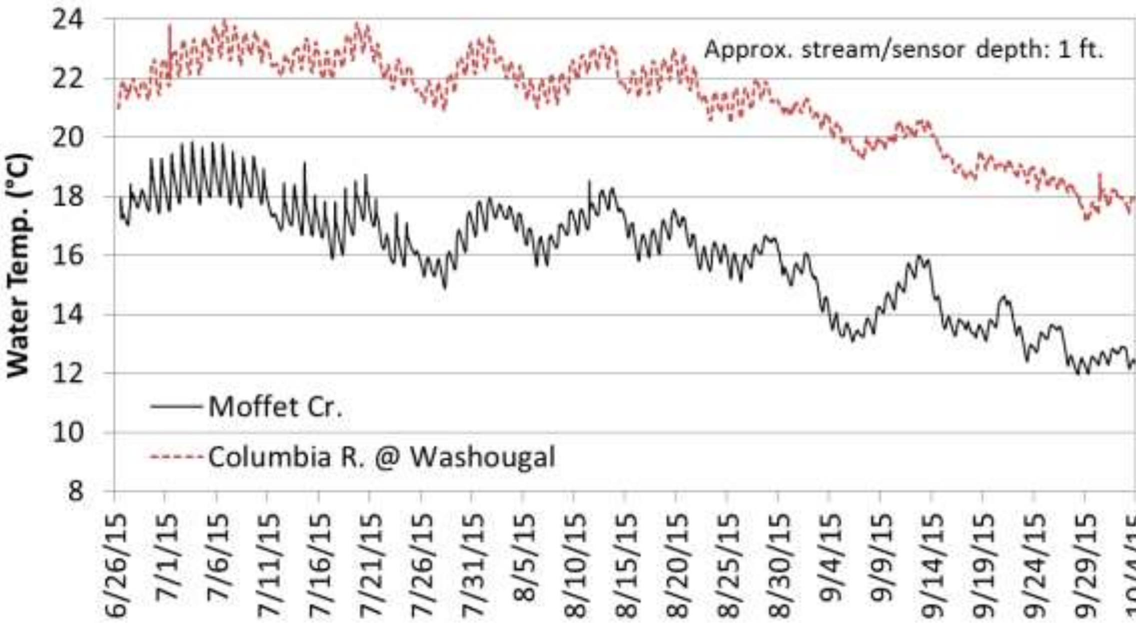


Fig 9j. Moffet Cr.

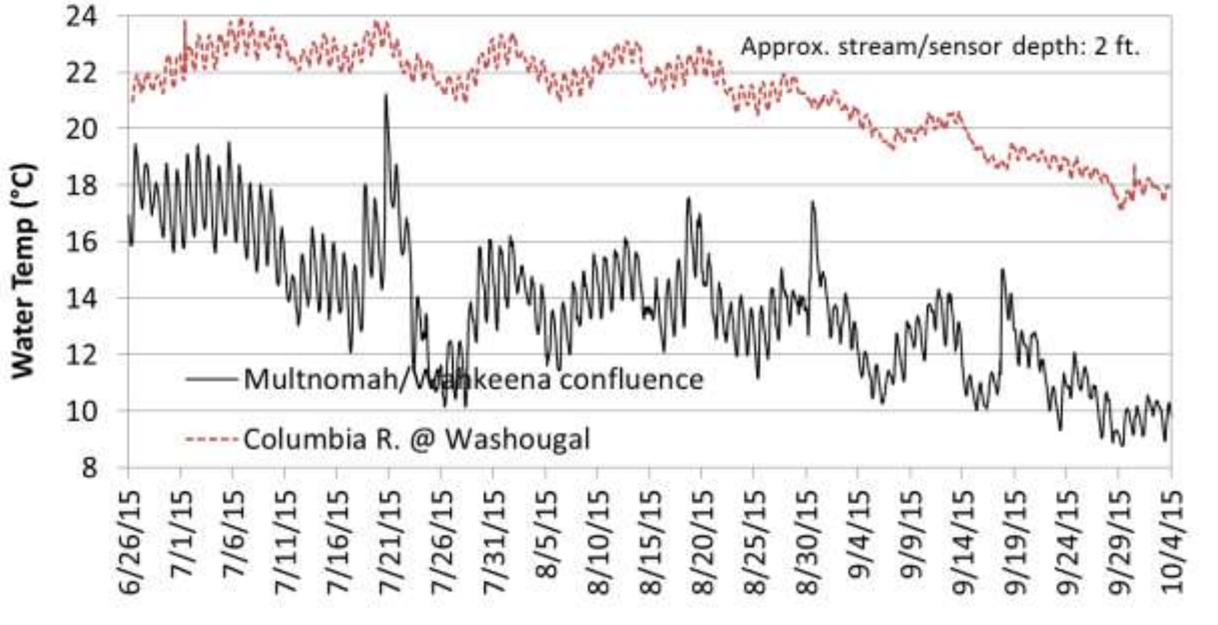


Fig. 9k. Multnomah/Wahkeena Creek

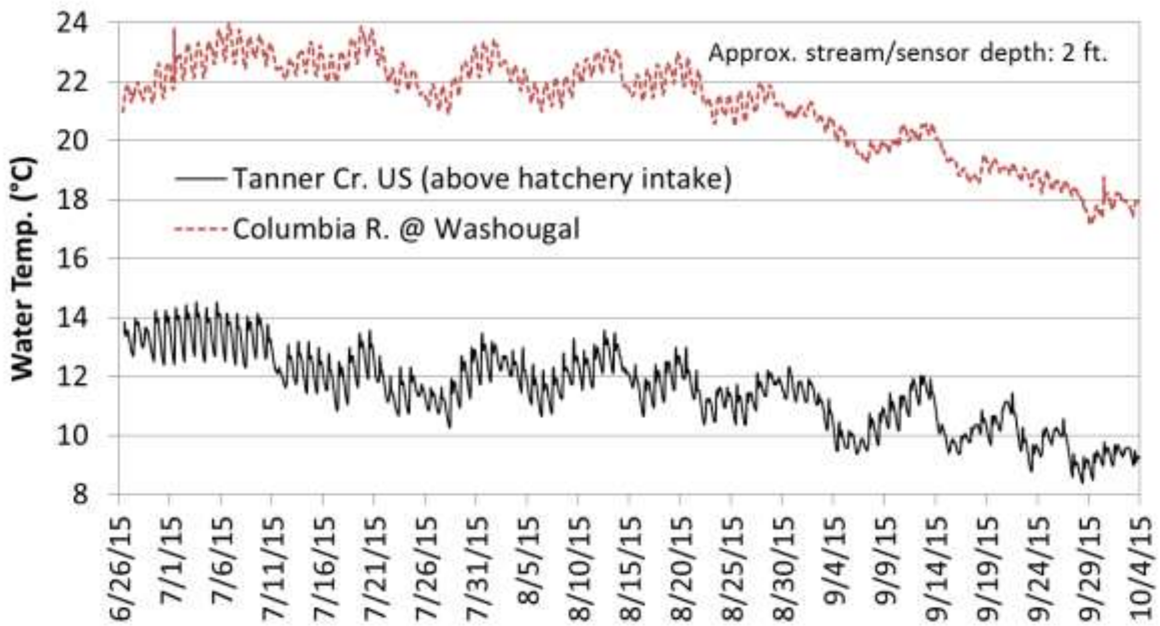


Fig. 9l. Tanner Creek

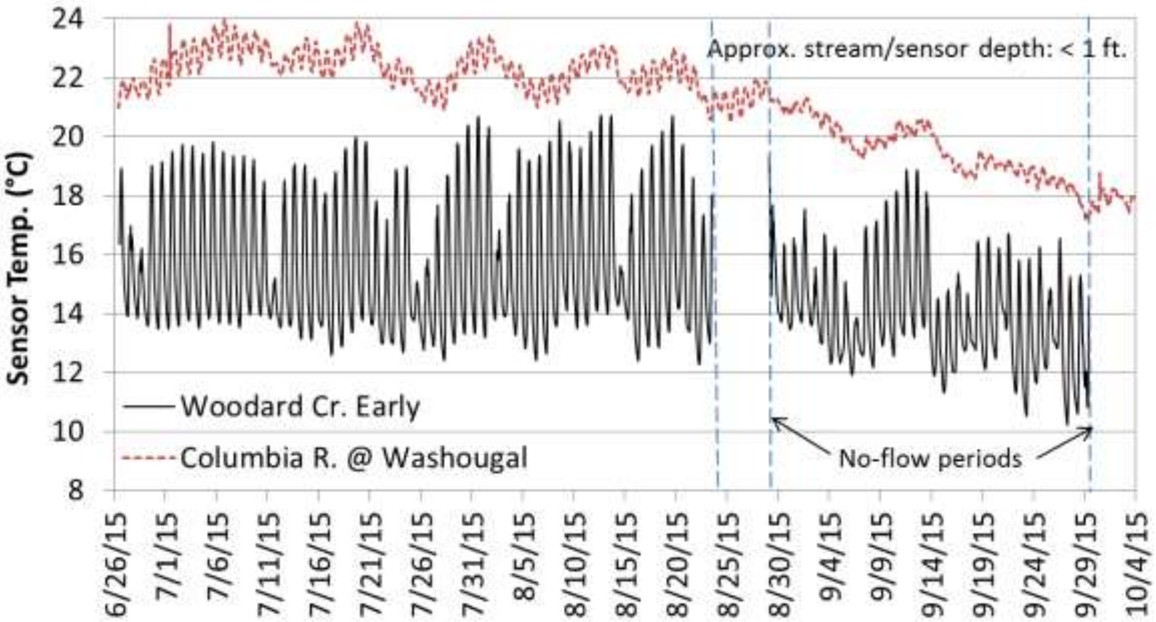


Fig. 9m. Woodard Creek

Figure 9. Hourly temperature logger records at monitored locations.

Cold-water plume mapping

For the 15 tributary confluences in the study, we recorded temperatures with a YSI multi-parameter instrument to confirm presence/absence of any significant plume of cold water resulting from stream discharge into the Columbia River. For observed plumes we recorded additional temperature readings to map the distribution of cold water. We detected and mapped plumes at 5 of the 15 stream confluences surveyed. Table 5 lists general characteristics of the observed plumes. Additional detail can be found in the site maps in the Appendix.

Table 5. Temperature characteristics for observed cold-water plumes.

Stream confluence (with Columbia R.)	Measurement date/time	[1]Temperature: Approx. Acres	Notes
Bridal Veil Cr.	8/5/15 11:30 PDT	<20 °C: 0.6 ac. <18 °C: 0.3 ac. <16 °C: 0.1 ac.	
[2]Duncan Cr.	10/6/15 11:00 PDT		Cold water observed but not mapped
Eagle Cr.	8/29/14 10:30 PDT	<20 °C: 1.5 ac.	
Horsetail/Oneonta Cr.	8/11/15 13:30 PDT	18.5 °C: 0.2 ac.	Uniform temp. profile with depth
Multnomah/ Wahkeena Cr.	7/29/14 10:00 PDT	<20 °C: 0.25 ac. <19 °C: 0.1 ac.	
Tanner Cr.	8/10/15 13:00 PDT	<14.4 °C: 0.5 ac.	Uniform temp. profile with depth

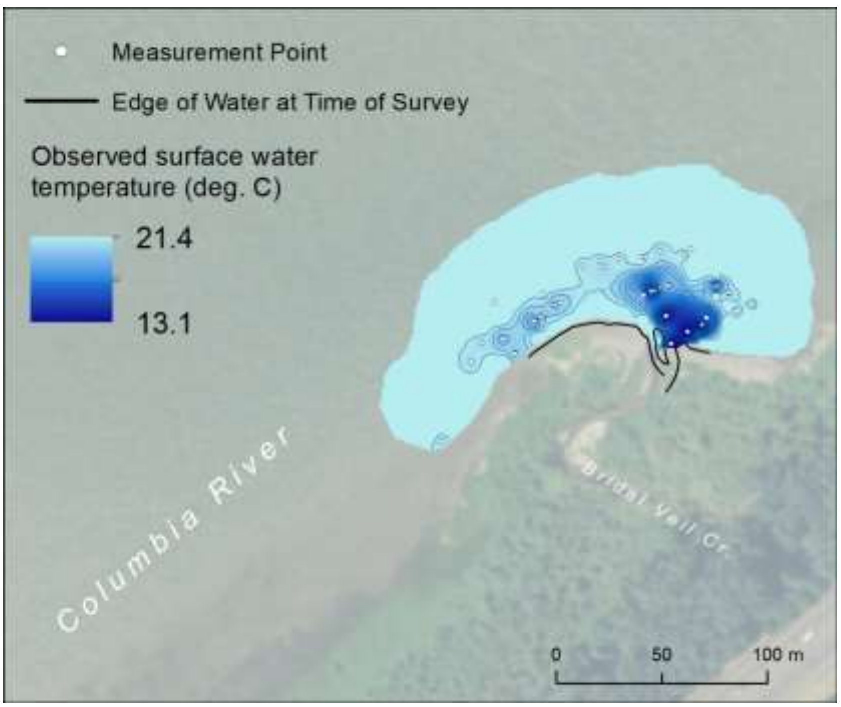
Notes:

1) Approximate extent of water at the specified temperature, measured at 3 ft. depth (or max. depth if < 3 feet).

2) Duncan Creek was not monitored in summer; however, we detected a 3 deg. C difference between confluence and mainstem temperatures when visiting the site in October. This indicated potential presence of a summer time plume, and further study to confirm this is planned for 2016.

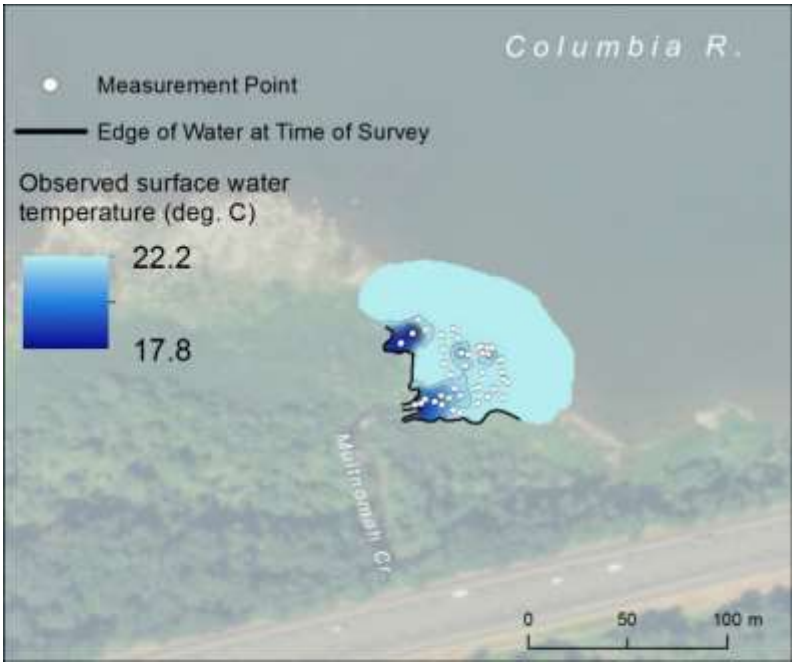
At the Bridal Veil, Multnomah/Wahkeena, Horsetail/Oneonta, and Tanner Creek confluences, we mapped plume temperatures manually using a YSI instrument in combination with a handheld GPS to record spatial location. We recorded temperatures at 0–1ft. below the water surface, 2–3 ft. below the water surface, and 3–4 ft. below the water surface (where water was deep enough). Raster grids and contour lines of water temperature were generated from recorded point data, for each of the monitored depth levels. Figure 10 shows results for surface water (0–1 ft. depth) temperature distribution obtained from measurements at the Bridal Veil Creek confluence.

At most confluences where a plume was detected, we observed a larger extent of cold water at depth compared to surface waters. The degree of stratification was observed to increase with the level of solar heating of surface waters, with plumes mapped later in the day showing a greater level of stratification of water temperature, compared to morning observations. Figure 11 illustrates this difference in temperature between surface water and water at depth, for measurements taken at the Multnomah/Wahkeena confluence zone. Other confluences showed little to no temperature stratification, even when mapped later in the day. Because our measurements were limited to only one or two points in time, we do not attempt to attribute this to any decisive factor. However, in addition to solar heating, likely effects on stratification include Columbia River topography and current velocities at the confluence locations, as well as level of discharge (stream, and Columbia River). As an additional component of mapping cold-water plumes, we planned to install arrays of temperature loggers at plume locations to better understand the temporal and spatial temperature variations. However, due to limitations in time and staff availability this measurement was not completed in this phase of the study.



Surface Water Temperature	Acres
< 20 °C	0.6
< 18 °C	0.3
< 16 °C	0.1

Figure 10. Mapped cold-water surface plume at Bridal Veil Creek confluence. Measurements were taken on 8/5/2015 at 11:30 am. Columbia River temperature at time of measurement: 21.4 ° C.



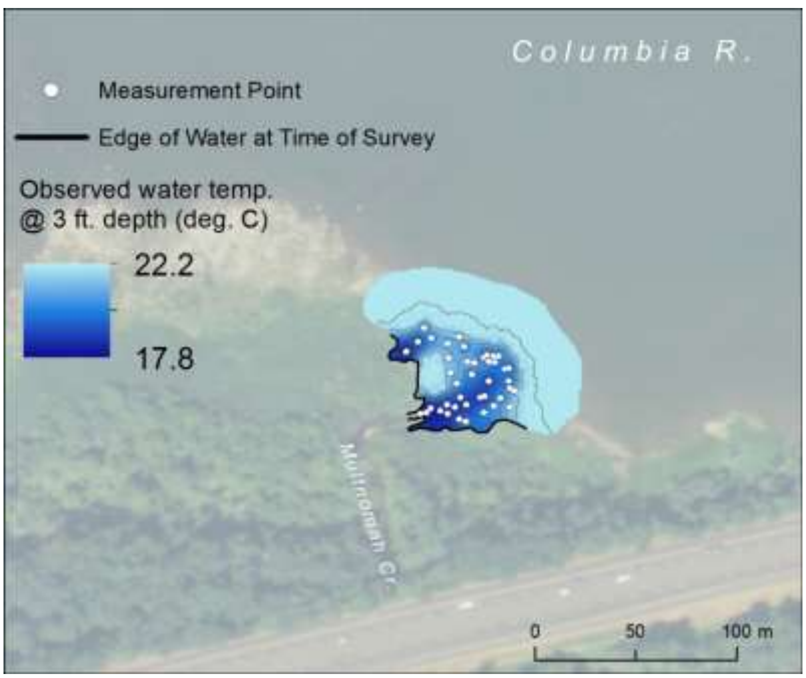


Figure 11. Cold water distribution at the confluence of Multnomah/Wahkeena Creeks with the Columbia River. Top: observed temperatures at 0–1 ft. depth. Bottom: observed temperatures at 3 ft. depth. Measurement Date: 7/29/14 at 10:00 am. Columbia River temperature at time of measurement: 22.2 °C.

A second mapping method, using ONSET data loggers towed through the water at fixed depths and synched to a time-stamped recorded GPS track, produced mixed results. The method was primarily limited by the slow temperature response time (approximately 10 minutes) of the loggers that were used. We attempted to map plumes at the Tanner Creek and Eagle Creek confluences using this method in 2014, however results are not presented here.

Stream discharge

Stream discharge measurements were straightforward but limited due to time and staff limitations. Many streams were not surveyed. For those that were, we generally recorded only one or two measurements. Stream discharge results are presented in Table 6, in descending order.

Table 6. Observed stream discharges.

Site	Measurement date/time	Calculated discharge (cubic feet per second)
Tanner Cr. below hatchery	8/10/15 13:00 PDT	53
Eagle Cr. above hatchery	8/11/15 10:30 PDT	13.9
Bridal Veil Cr.	8/5/15 10:30 PDT	7.1
Multnomah/ Wahkeena Cr.	7/29/14 10:00 PDT	6.5
Horsetail/ Oneonta Cr. @ confluence	8/11/15 14:30 PDT 8/05/16 13:00 PDT	3.0 3.9
Lawton Cr.	8/6/15 10:00 PDT	1.5
McCord Cr.	8/10/15 11:30 PDT	[1]1.1
Moffet Cr.	8/11/15 11:00 PDT	0.4
Woodard Cr.	8/6/15 11:00 PDT	[2]Estimated < 0.5

Notes:
1. Measurement taken upstream of where surface flow ended.
2. Measurement not taken due to low flow/irregular topography. Displayed value is an estimate.
3. Measurements were not taken for Duncan, Goodbear/Archer, Hamilton, Hardy, or Latourell Creeks.

Bathymetric data collection

To update our hydrodynamic and water quality model, which can be used to better understand effects of topography on cold-water plume formation at stream confluences, we intended to collect bathymetric data at confluences where plumes were observed. This was only accomplished at the Bridal Veil Creek confluence during Phase 1, due to time and staff limitations. This data will be incorporated into our model for future analysis. Data collection for other stream confluences is planned for future phases of this study.

Results summary

Figure 12 summarizes results of Phase 1 monitoring of stream temperature, discharge, and cold-water plume observation for the 15 lower Gorge tributary complexes that were monitored.

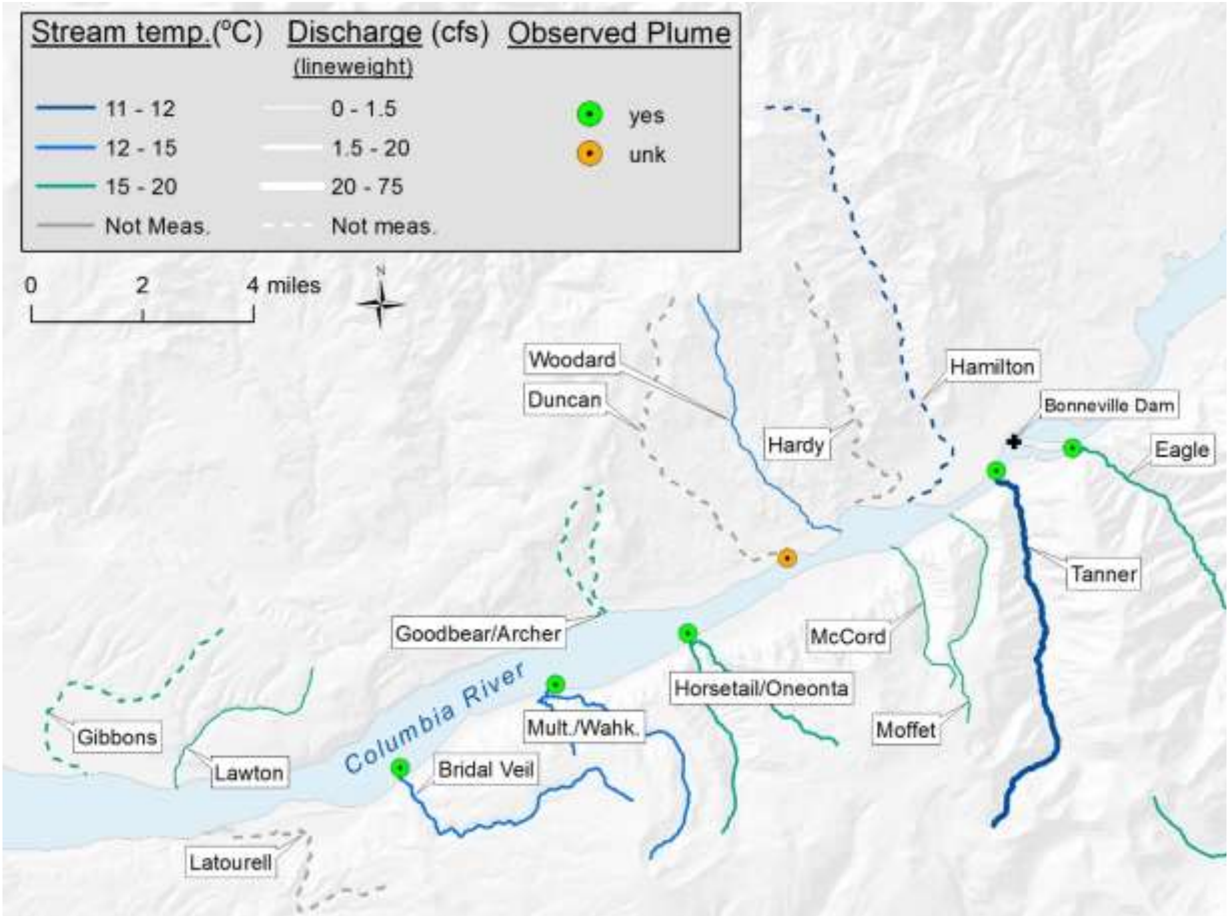


Figure 12. Summary of data results for stream temperature, discharge, and cold-water plume mapping for the 15 lower Columbia Gorge tributary complexes. Average stream temperature is indicated by color. Relative magnitude of discharge is indicated by line-weight.

Discussion, Phase 1

As summertime water temperatures in the lower Columbia River continue to increase and exert increasing thermal stress on species like salmon and steelhead, cold-water inputs may serve as critical zones of thermal refuge for these fish, where they can seek relief from warmer mainstem temperatures. The purpose of this study phase was to document locations of cold-water sources to the Columbia River along the lower Columbia Gorge, and to assess their potential for providing thermal refuge to both adult and juvenile salmonids. The study focused on the 15 lower Gorge tributaries that enter the lower Columbia River between approximately the Sandy River confluence (Columbia River mile 123) and the Bonneville Dam (Columbia River mile 146). Due to shortages of staff time for conducting measurements, we were unable to collect all data and assess each stream as intensively as planned. In addition, lost or stolen temperature loggers resulted in incomplete data collection at four of the streams. However, in combination with previously existing data for some streams, the data collected during this study phase offers a reasonably comprehensive assessment of summertime temperature and discharge characteristics for these tributaries.

Of the 15 tributary confluences studied, one was monitored during summer 2014 (Multnomah/Wahkeena Cr.) while the remaining were monitored during summer 2015. Climatic conditions in the Pacific Northwest deviated significantly from average up to and during the 2015 monitoring period. Precipitation levels were below normal for much of the region from winter through early summer of 2015 (Figure 13). Combined with higher than average temperatures during this same period (Figure 14), resulting mountain snow packs throughout Oregon, Washington and Idaho, and for the Cascades in particular, were significantly reduced compared to normal (Figure 15). The overall effect of these climatic conditions on Columbia River hydrology during this period was significant. With reduced snowpack, the typical spring/early summer freshet was reduced as well (Figure 16). Higher than average early summer temperatures also likely resulted in mainstem water temperatures that were higher, and increased quicker, than average (Figure 17). For the cold-water streams comprising this study, we presume that these same effects (in particular: lower than average rainfall and higher than average air temperatures from late May through early July) likely contributed to lower than normal stream flows and higher water temperatures in 2015, compared to average. Supporting data from other Estuary Partnership monitoring of these streams supports this hypothesis (Schwartz, 2015). With reduced flows, streams that may typically dry out later in the year may have done so earlier in 2015 (McCord, Goodbear/Archer Creeks). Other streams that were observed to dry out later in the summer, either intermittently or for an extended duration (Woodard, Hamilton) may normally do so for shorter periods. Reduced flows may have also resulted in smaller plume areas than what typically may form at stream confluences. Despite being a departure from today's normal, these climate conditions and the resulting impacts on stream/river flows and temperatures are generally consistent with climate model predictions for future decades. While perhaps anomalous for the current period, the observations that we documented during summer 2015 may likely be indicative of the thermal regime that aquatic species will experience in coming decades, and the extent of thermal refuges that will be available to them in the lower Columbia River.

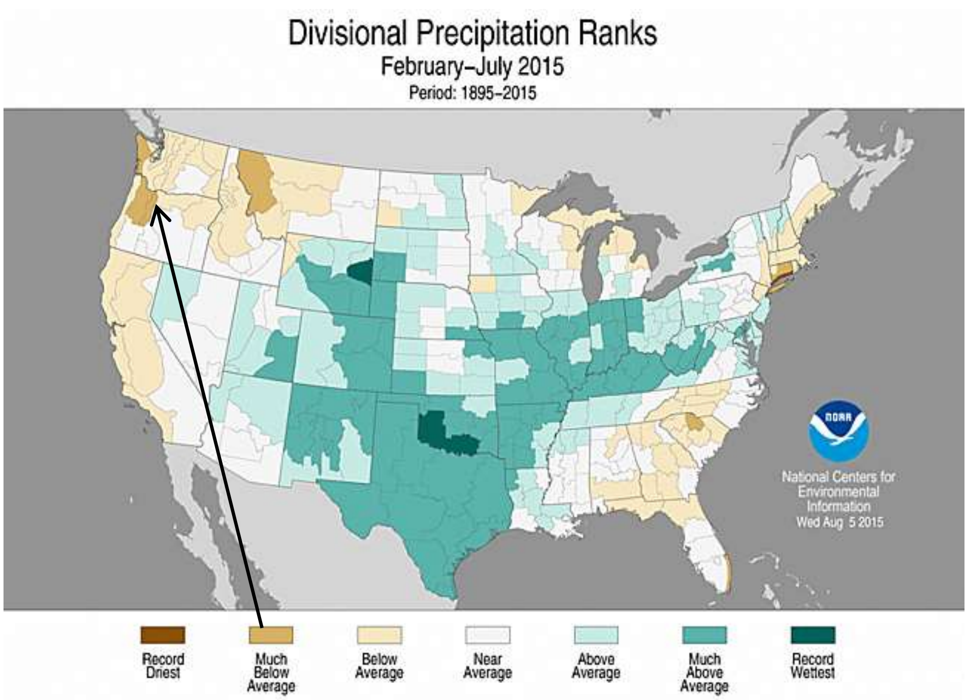


Figure 13. National Precipitation Rank map, February–July 2015. Source: NOAA National Centers For Environmental Information online (www.ncdc.nooa.gov)

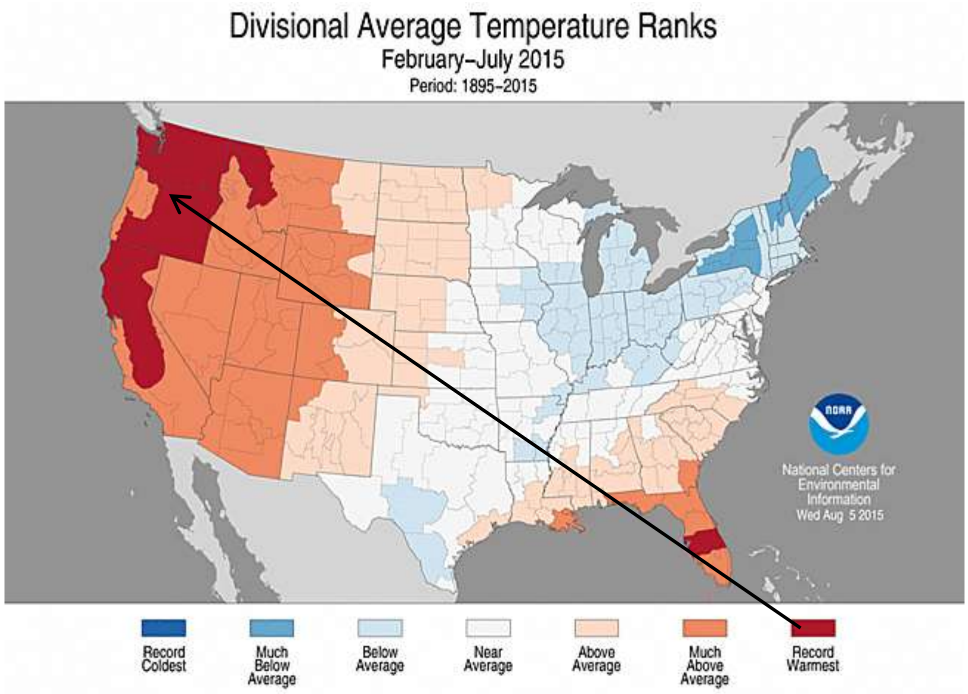


Figure 14. National Average Temperature Rank map, February–July 2015. Source: NOAA National Centers For Environmental Information online (www.ncdc.noaa.gov)

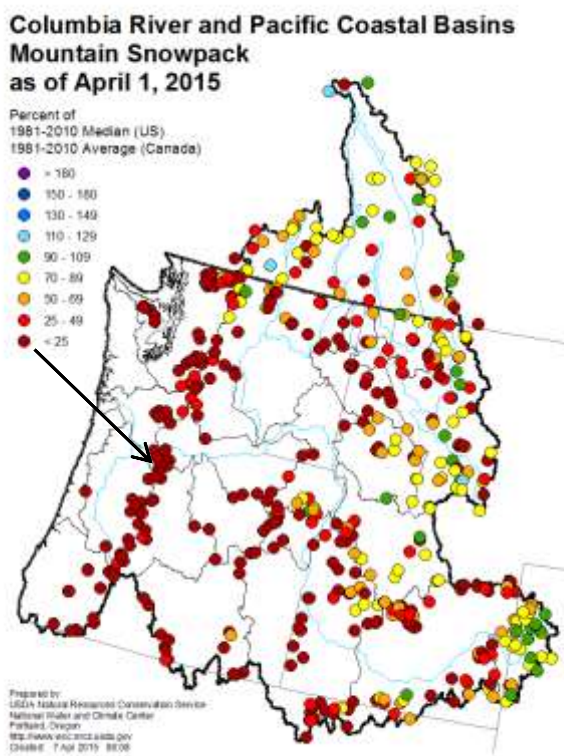


Figure 15. Columbia River Basin Mountain Snowpack, April 1, 2015. Source: USDA Natural Resources Conservation Service National Water and Climate Center (www.wcc.nrcs.usda.gov)

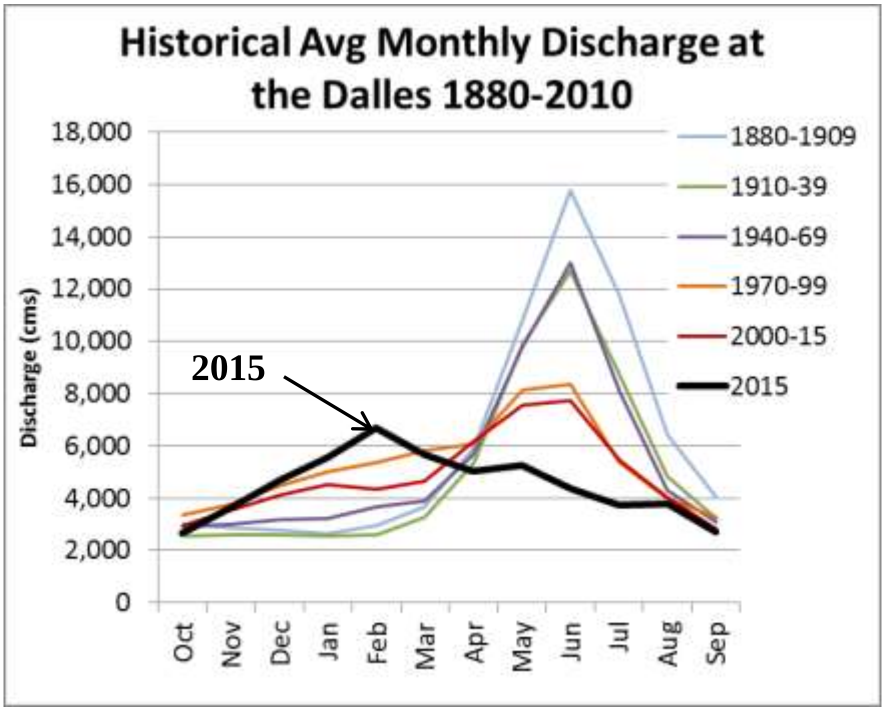


Figure 16. Average Columbia River monthly discharge at the Dalles Dam for selected periods of record. Data Source: Columbia River DART. Image courtesy of Amy Borde, Pacific Northwest National Laboratory.

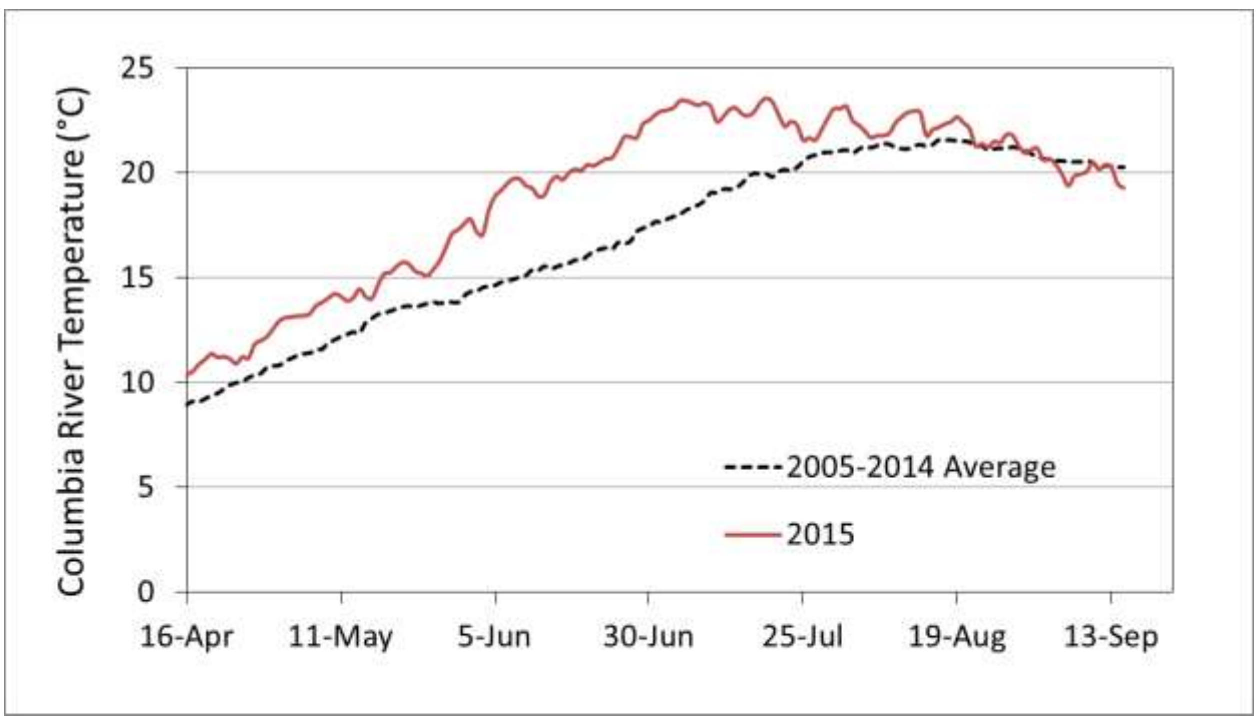


Figure 17. Columbia River daily average water temperature: 2015 spring/summer vs. 10-year (2005–2014) average. Source: Columbia River DART.

As part of our assessment of the Columbia River Gorge tributaries, we documented thermal conditions within two general zones that may offer thermal refuge to fish: a) tributary confluences with the Columbia River; and

b) stream reaches upstream of the confluence. For upstream reaches, we further categorized the streams based on three general hydrological and geomorphological features characteristic of Gorge tributaries:

- Higher flow alluvial fan systems with no floodplain component (3 of 15 tributaries)
- Lower flow alluvial fan systems with no floodplain component (6 of 15 tributaries)
- Alluvial fan systems with a significant floodplain component (6 of 15 tributaries)

As mentioned above, this initial study phase focused on water temperature. At this point we have limited knowledge about what range of temperatures and other physical characteristics of these stream and confluence zones provide suitable salmonid refuge, particularly regarding juveniles. While we did qualitatively note any fish presence we observed, because we were not specifically focused on fish use in this study we are limited to making general predictions about how these observations may relate to water temperatures and other parameters that we measured, and the potential for these streams to provide thermal refuge. In future phases we hope to intensively monitor fish use of these streams and couple these observations to stream data from this phase to better define our criteria for what constitutes suitable thermal refuge for salmonids. It should also be noted that because we were not focused on observing fish, and because visibility (water clarity) was often poor and our monitoring was limited temporally, we cannot rule out their presence in areas where we did not observe them. The following paragraphs summarize our findings for the confluence and stream zones monitored in this study, with regard given to potential for providing thermal refuge for salmonids.

Tributary confluences

Cold-water plumes were observed at 5 of the 15 tributary confluences studied: Bridal Veil, Eagle, Horsetail/Oneonta, Multnomah/Wahkeena, and Tanner creeks. To be considered a cold-water plume for the purposes of this study, we used a criterion of at least 2 °C less than the mainstem temperature at the time. This is generally consistent with values from other studies (Beechie et al. 2012, Keefer et al. 2010) for adult salmon and steelhead, however this criterion has not been established for juvenile salmonids.

Well-defined plumes were observed at confluences of tributaries with relatively high discharges (roughly 3 cfs or higher). This was consistent with results from our preliminary water quality modeling. Modeling also suggests that plumes are likely to form only at confluences that are sheltered, or otherwise distanced from, mainstem currents. This physical characteristic, confirmed in our field observations, presents potential implications for restoration which will be examined in later phases of this study. By re-routing tributaries, or otherwise modifying surrounding topography near their confluence zones to divert mainstem flow around them, cold-water plumes can potentially be created where they did not previously exist (at confluences with lower stream discharges, for example), or made larger for an existing stream discharge. With rising Columbia River temperatures expected due to climate change, this technique could potentially increase available cold-water habitat.

We noted adult fish presence at two of the tributary confluences where plumes were detected: Tanner and Eagle Creeks. However, these streams are heavily utilized by returning hatchery fish, and so we do not draw any conclusions about use by stocks migrating further upstream. We did not observe juvenile fish at any of these confluences. In general, because we were not looking for fish, and because we visited sites so infrequently, we cannot confirm consistent use of any of these locations by salmonids. This is particularly true for juveniles, which may require specialized observation techniques. It is interesting to note that for some confluences where we did not detect significant plumes, we did observe adult salmonids (Lawton Creek confluence, for example). At others, we noted heavy use by fishermen, either directly at or near the respective confluence (McCord Creek, Moffet Creek). These observations indicate that even confluences without a concentrated plume of cold water may still benefit salmonids in some way or, at a minimum, be attractive to them. Small pockets of cold water directly at confluence zones may provide thermal cues for fish to seek colder water upstream. Isolated pockets of cold water may also exist away from the immediate confluence, and thus may not have been detected in our monitoring. This would be consistent with the nature of flow through these alluvial fan systems, where water entering the confluence zone from a single upstream channel branches into multiple channels, which are often below the ground surface. This subsurface flow can provide additional cooling of the stream water before it enters the Columbia at locations which are then difficult to identify. Future monitoring of the mainstem, outside of the immediate confluence zone, may be planned to investigate this potential source of cold water.

Other than water temperature, additional characteristics which were not closely studied may affect fish use of plumes at the confluence. These may include water depth, proximity to human presence and presence of predators, all of which may influence juvenile and adult salmonid use differently. Moreover, observations and model results indicate that these plumes are highly temporal in nature. Plume size and temperature were found to vary with exposure to solar radiation, wind speed, and both river and stream discharge. All of these may influence the amount of time that these cold-water habitats are available to both adult and juvenile fish. Through more intensive monitoring of fish use we hope to better define the extent to which fish may be utilizing these confluence habitats, now that we have identified and characterized them.

While establishing a temperature criterion for defining suitable cold-water refuge for salmonids is relatively straightforward, our studies suggest that defining size criteria (i.e. area and depth) are not. Since we noted adult fish even at confluences where well-defined plumes did not exist, such sources could, at least to some extent, be considered sources of refuge. To provide benefits to large numbers of fish, however, it is reasonable to assume that larger plume sizes are necessary. To set size criteria it is useful to consider the range of plume sizes observed in this study relative to the small plume sizes upstream of Bonneville Dam where this and other studies (Keefer 2011) have documented significant use by adult migrating salmonids. Of those where regular fish use has been documented Eagle Creek has the smallest plume (measured at approximately 1.5 acres, Table 5). While we did not measure the size of Herman Creek, the next largest plume, from image analysis and other information (Dominguez, 2010) we estimate it to be approximately 20 acres. By comparison, all other observed plumes that we measured were considerably smaller, ranging from 0.2 to 0.6 acres. In addition to area, water depth must also be considered when establishing criteria for suitable refuge. Based on other information (Bottom et al. 2005, Keefer et al. 2006) migrating adult salmon are typically found in water deeper than approximately 2 meters, while juveniles tend to prefer water depths greater than 0.5 meter. In our studies, confluence zones where plumes were observed ranged in depth from roughly 1–2 meters, with additional fluctuation of roughly 1 meter due to due to variation in Columbia R. stage. Of these, only Eagle Creek had sizeable areas where water depth exceeded 2 meters. Furthermore, in some areas (Tanner Creek, as well as Lawton Creek where minimal plume formation was noted) adult salmonids were observed in water that was 1–2 meters in depth. Based on these observations and previous research, we have outlined a set of preliminary criteria which define suitable cold-water refuge zones for summer migrating Columbia R. salmonids (Table 7).

Table 7. Preliminary criteria defining suitable thermal refuge at tributary confluences for summer migrating Columbia R. salmonids.

Criterion	Value	Notes
Temperature	< Columbia R. mainstem temp. – 2°C	
Area	1 acre minimum	
Depth	1–2 meters minimum	2 meters is optimal, 1 meter may be adequate. Needs further study

If we apply the temperature, size, and depth criteria outlined above to observations of plume characteristics at the lower Gorge tributaries, the following general observations can be made:

- The Eagle Creek confluence is currently the only confluence meeting all criteria for adult salmon use.
- Tanner Creek, Bridal Veil Creek, Multnomah/Wahkeena, and Horsetail/Oneonta Creek confluences are generally too small or too shallow to support adult salmon. Restoration and/or enhancement techniques

potentially could increase the suitability for each of these to provide refuge. This is addressed in Phase 3 of this study.

- All 5 confluences are currently capable of providing thermal refuge to juvenile salmonids.

Upstream reaches with floodplain component

Six of the fifteen tributaries surveyed in this study have floodplain zones greater than approximately 1000' in length above their respective confluences with the Columbia River. Flow in these reaches is typically low velocity due to low elevation gradients. Exposure to solar radiation can be high due to historical clearing of forest for human use, and in some cases, broad, shallow channels and expansive emergent wetland zones flanking the streams. These factors can lead to significant heating of stream water in these zones during summertime daylight hours. Moreover, for three of these six streams flow in the floodplain is directed through manmade lakes (Horsetail/Oneonta, Latourell, Multnomah/Wahkeena creeks), further exacerbating heating. This effect is well documented in other Estuary Partnership habitat and restoration monitoring efforts, where temperature increases exceeding 5 deg. C were observed through man-made, floodplain lakes along Oneonta and Multnomah Creeks. It should be noted that despite periods of elevated temperatures, these stream reaches may still be considered suitable refuge if their respective temperatures are cold enough during other times. At the same time, designation of a stream as suitable refuge does not imply that it is consistently cold throughout the summer. Rather, the implication is that it can provide refuge for fish at some point during the critical period when the Columbia R. mainstem temperatures are of concern.

Both Hamilton and Hardy creeks discharge into long (0.5–1.0 mile) sloughs that are backwatered by the Columbia River. This backwatering effect, when combined with relatively low discharges from these streams, acts to inhibit any plume formation at these confluence zones. Along Hardy Creek Slough, however, we did observe a significant number of juvenile salmonids utilizing the slough, typically at locations where cold water was entering (from both Hardy Creek and other undocumented sources).

Two of the floodplain reaches monitored in this study (Horsetail/Oneonta and Multnomah/Wahkeena creek complexes) have seen significant restoration work in recent years, specifically aimed at improving thermal conditions during summer months. Actions have included improved management of stream flows (retrofitting the Wahkeena Cr. diversion structure to increase instream flows), reconfiguring stream channels (eliminating a diversion of Oneonta Cr. through a gravel pond), and riparian planting. Analysis of the effectiveness of this work is currently underway. While some of these floodplain reaches are utilized by adult salmon later in the year for access to spawning habitats, in the summer months they are likely utilized primarily by juveniles, due to their relatively low flows.

Overall, of the six streams with floodplain reaches surveyed, we identified three that are potentially providing suitable thermal refuge for salmonids (most likely juveniles) during the summer: Hardy Cr.; Horsetail/Oneonta Cr.; and Multnomah/Wahkeena Cr. This conclusion is based on both data gathered here and previously existing data collected through restoration monitoring. Other streams could likely benefit from similar restoration practices.

Upstream reaches with no floodplain component (high and low flow alluvial fan systems)

In general, the nine higher gradient tributaries without a significant floodplain component remained cold throughout the summer, however discharges were highly variable between streams. Average temperatures for all streams were below 18 °C (averaged over the period of record, 6/26–10/4 2015), although some showed daytime peak temperatures in the 20–22°C range. It is unclear if some of this variation was attributable to direct heating of loggers by solar radiation, versus actual heating of the water column. While most loggers were placed as deep as possible, some streams were less than 2 feet deep, and minimal effort was made to shield loggers from sunlight. Because of these large diurnal temperature variations observed in some of the streams (particularly lower flow streams), the amount of time that they may be suitable as thermal refuge for salmonids may vary. Further study of these areas is planned.

Measured flows in these nine streams ranged considerably, from approximately 0.5–50 cfs. Many of the lower flow streams lost surface flow near their confluence zones. Woodard and Hamilton Creeks appeared to lose surface flow only for intermittent periods in late summer, while surface flow in McCord and Goodbear/Archer Creeks ended in July and remained that way for the duration of the summer. For some of these streams (McCord Cr., Woodard Cr.) flow was still observed in higher reaches during these periods, indicating that these areas are still capable of providing thermal refuge to juvenile fish throughout the summer. This is supported by the observation of juvenile fish in higher reaches of McCord Creek during periods when the confluence zone was dry. In addition, surface water that is no longer flowing may be entering the Columbia R. as groundwater through these alluvial fan systems, and providing cold-water refuge at nearby, unknown locations. Further study of these areas is planned.

Based on these observations, all nine of these higher gradient streams appear to be providing some level of thermal refuge to juvenile salmonids. For adults, this opportunity is likely dependent on the magnitude of stream flow, as well as the capability of maintaining consistent surface water flow to the Columbia River. Adult fish were seen using lower Bridal Veil Creek, which had a measured flow of 6.3 cfs. We did not observe adults in any streams with flows lower than that value at the times when we were there, but again, our qualitative observations cannot confirm or deny fish presence.

Table 8 summarizes what we noted as potential thermal refuge zones for lower Columbia Gorge tributaries, based on our 2014–2015 temperature study and supported by previously existing data. Documented fish observations from this study are noted where they occurred. In general, 14 of the 15 tributaries surveyed showed some potential for providing thermal refuge to salmonids. Observed plume formation was limited to five confluence zones, while upstream reaches of 12 of the streams may be suitable for use.

While most of the streams in this study were observed to be providing potential thermal refuge for salmonids even under the relatively extreme climate conditions experienced in 2015, the fate of these streams based on climate change predications is more uncertain. As the Columbia River continues to warm, their relative importance will increase, however little is currently known about how they will respond. Finally, the beginning phase of this study was limited to the streams of the lower Columbia Gorge. To better understand how fish may be utilizing cold water along the entire lower Columbia River, an assessment of downstream reaches is required. In future phases of this study we hope to address these data gaps, in addition to gaining further understanding of how fish are currently utilizing the cold-water locations that were documented in this initial phase.

Table 8: Summary of potential thermal refuge zones for lower Columbia Gorge tributaries based on 2014–2015 summer temperature monitoring results and previously existing monitoring data.

a) Tributary confluence zones (cold-water plumes)

	[1]Temp. suitable for salmonids		[1]Size suitable for salmonids		[1]Depth suitable for salmonids		Suitable cold-water refuge		Notes
Tributary	**Juvenile**	**Adult**	**Juvenile**	**Adult**	**Juvenile**	**Adult**	**Juvenile**	**Adult**	
Bridal Veil Cr.	Y	Y	Y	N	Y	Y	Y	N	
Duncan Cr.	unk.	unk.	unk.	unk.	unk.	unk.	unk.	unk.	Logger lost.
Eagle Cr.	Y	Y	Y	Y	N	N	Y	Y	
Horsetail/ Oneonta Cr.	Y	Y	Y	N	N	N	Y	N	
Multnomah/ Wahkeena Cr.	Y	Y	Y	N	N	N	Y	N	
Tanner Cr.	Y	Y	Y	N	N	N	Y	N	

b) Upstream reaches, streams with floodplain zone present

	Floodplain Reach		**Alluvial Fan/Upstream Reach**			**Notes**
Tributary	**[2]Suitable temperature?**	**[3]Salmon Observed?**	**Surface streamflow**	**[2]Suitable temperature?**	**[3]Salmon observed?**	
Gibbons Cr.	N	N	Continuous	Y	[4]Juveniles	Temperature suitability based on prior LCEP monitoring data.
Hamilton Cr.	N	N	Intermittent in late summer	Y	[4]Juveniles	
Hardy Cr.	N	juveniles	Unknown	Y	Juveniles	Temperature data was recovered in 2016. Juveniles observed in floodplain slough and above floodplain.
Horsetail/ Oneonta Cr.	Y	Juveniles	Continuous	Y	[4]Juveniles	
Latourell Cr.	Unknown	Juveniles	Continuous	Unknown	[4]Juveniles	Upstream logger lost. Awaiting data from downstream logger.
Multnomah/ Wahkeena Cr.	Y	Juveniles	Continuous	Y	[4]Juveniles	

c) Upstream reaches without floodplain, relatively high flow

	Alluvial Fan/Upstream Reach			**Notes**
Tributary	**[5]Surface streamflow**	**[2]Suitable temperature?**	**[3]Salmon observed?**	
Bridal Veil Cr.	Continuous	Y	adult	
Eagle Cr.	Continuous	Y	adult / [4]juveniles	Observed adult fish may have been of local hatchery origin
Tanner Cr.	Continuous	Y	adult / [4]juveniles	Observed adult fish may have been of local hatchery origin

d) Upstream reaches without floodplain, relatively low flow

	Alluvial Fan/Upstream Reach			**Notes**
Tributary	**[5]Surface streamflow**	**[2]Suitable temperature?**	**[3]Salmon observed?**	
Duncan Cr.	Unknown	Unknown		logger lost.
Goodbear/ Archer Cr.	Dry for much of summer	Y		
Lawton Cr.	Continuous	Y	adult	Single adult was observed near confluence
McCord Cr.	Dry for much of summer	Y	juvenile	
Moffet Cr.	Continuous	Y		
Woodard Cr.	Intermittent in mid-late summer	Y		

Notes:

1) Criteria applied for defining a suitable ‘cold-water’ plume for salmonids are as follows: plume temperature ≤ Columbia R. mainstem temperature – 2°C, size ≥ 1 acre, depth ≥ 0.5 meter (juvenile salmon), depth ≥ 1–2 meters (adult salmon).

2) Suitable temperature for upstream reaches is defined as ≤ 18 °C at some point during the period of record. This may include daytime and/or nighttime stream temperatures. Applies mainly to juvenile salmonids using these areas.

3) Because this study was not specifically focused on monitoring fish use, a lack of observations does not necessarily indicate an absence of fish. We only note cursory observations here.

4) While not observed in this study, juveniles have been observed in these streams in summer during other LCEP studies.

5) Characteristics of the stream flow at our temperature logger locations. A number of streams were observed to have surface flow upstream of our loggers, which subsequently became subsurface flow as the streams transitioned to coarse, alluvial fan systems above their respective confluence zones.

PHASE 2 OF 3: LOWER COLUMBIA RIVER MAINSTEM AND LARGE TRIBUTARY CONFLUENCE MONITORING

Background, Phase 2

Phase 1 of this study characterized cold-water inputs to the lower Columbia River from 18 small tributaries in the Columbia River Gorge. While most streams were successfully monitored, data gaps remained afterwards due to loss or theft of monitoring equipment. Further down river, multiple larger tributaries enter the lower Columbia. While temperature data is available for many of these, the quality of thermal refuge that any might provide to summer migrating salmonids is not well documented. Furthermore, while the Columbia River mainstem has been found to be well mixed, with minimal vertical or horizontal temperature stratification, we were unable to locate information that confirms this for all river depths including the deepest sections. The goal of this second phase of the study then was to address data gaps that remained after Phase 1, as well as to better characterize the mainstem Columbia and its side channels with respect to potential cold-water refuges. Specific objectives during this phase included the following:

A) Redeploy temperature loggers at lower Columbia Gorge tributaries where 1) data was not obtained in Phase 1; and 2) additional data is desired to provide a multi-year record to allow for comparison to Phase 1 data, which was collected during an anomalous climate year (2015. See Phase 1 Discussion).
B) Extend temperature monitoring from confluence zones of lower Columbia Gorge tributaries into the mainstem to better investigate if cold water may be entering the mainstem subsurface via seepage through the alluvial fan or other groundwater sources versus surface water in the primary channels of these streams.
C) Characterize cold-water plumes at confluences of lower Columbia River tributaries downstream of the Phase 1 study area (lower Columbia River Gorge). Based on available resources, the downstream extent was limited to approximately Longview, Washington, at Columbia river mile (RM) 67. Between RM 67 and the lower Columbia Gorge, there are three large tributaries that were known prior to this study to form cold-water plumes at their confluences. These are the Cowlitz, Kalama, and Lewis Rivers, which are the focus of this objective. Confluences of other tributaries of significance in this reach were also evaluated for the presence of cold water.
D) Monitor lower Columbia River mainstem from RM 67-146 (Bonneville Dam), to locate possible additional cold-water inputs including topographic depressions, outfall sources, groundwater seeps, and zones of hyporheic flow.

The Phase 2 monitoring area (Figure 18) covers a significant length of the lower Columbia River. During typical summer conditions ocean tides force colder, higher salinity water up-estuary to approximately RM 21–23, in Cathlamet Bay. From this point to Bonneville Dam at RM 146, the river is well mixed, with water temperature governed by fluvial discharge from the dam. These ranges align closely with system zones defined by Jay et al. (2016), which were defined using extensive water level and inundation frequency data. Our study area monitored 79 miles (RM 67–146) of the total 123 miles of tidal-fluvial zone (RM 23-146) where water temperature during the summer is a concern for migrating salmon. In the remaining 44 miles (36% of the total tidal fluvial length) of river downstream of our survey area additional cold-water inputs may exist, and this reach should be monitored in a future study.

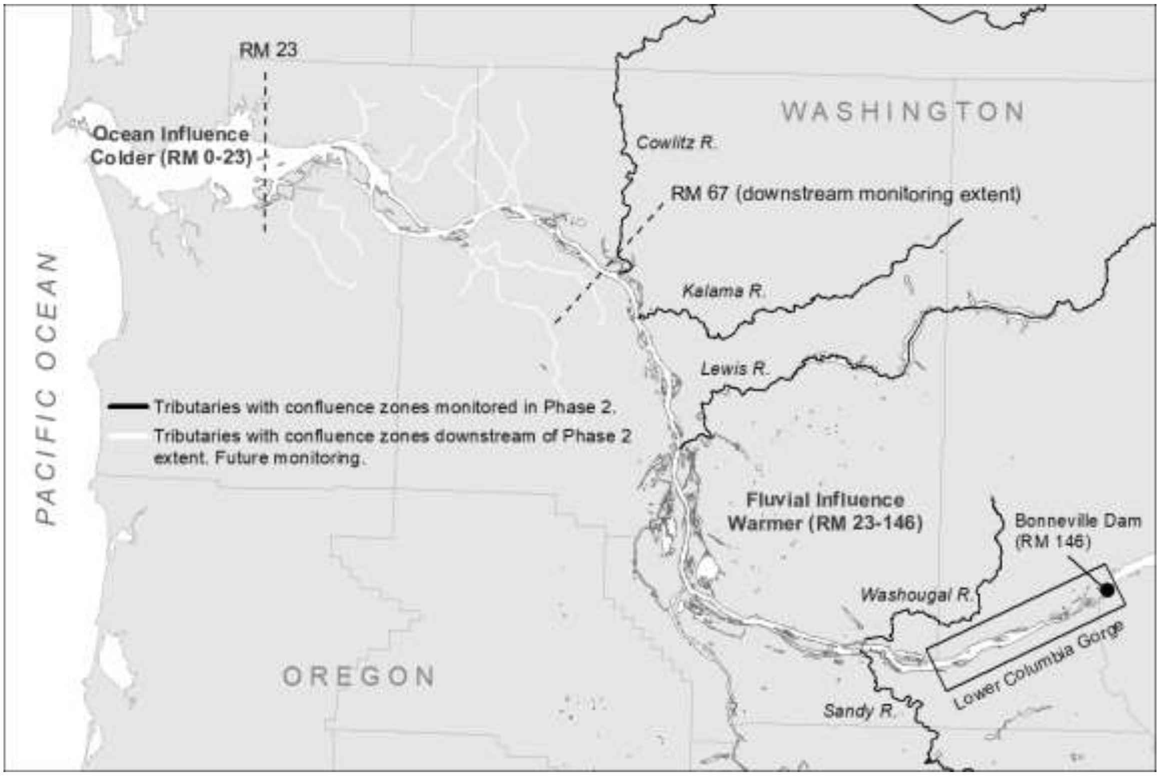


Figure 18. The lower Columbia River and estuary with place names and zones as related to Phase 1 and 2 monitoring. Lower Columbia Gorge tributary confluences were monitored in Phase 1. Phase 2 extended downstream to RM 67 and included mainstem and tributary confluence temperature monitoring. RM 0-23 receives colder, ocean tide influence. RM 23–146 temperature is governed by warmer upstream fluvial discharge. RM 23-44 tributary confluences should be monitored as part of a future study.

Methods, Phase 2

For redeployment of temperature loggers at selected lower Columbia Gorge tributaries (Objective A above) we used the same methods described for Phase 1. For mainstem and downstream tributary confluence temperature monitoring (Objectives B, C, D) we used two additional techniques (Figure 19): a custom temperature sensor configuration for multiple depths with an audio alarm; and a HOBO temperature logger deployed at depth for a limited period. The custom configuration allowed for rapid assessment of temperature over a large spatial area and throughout the water column, with an alarm triggered to alert the boat operator when temperature fell below a set value (20 °C) for any of the sensors. This configuration was operable over water depths to 35 feet. To test for stratification of deeper waters, we deployed HOBO loggers to instantaneously record water temperatures of the deepest portions (up to 70 feet) of the mainstem lower Columbia.

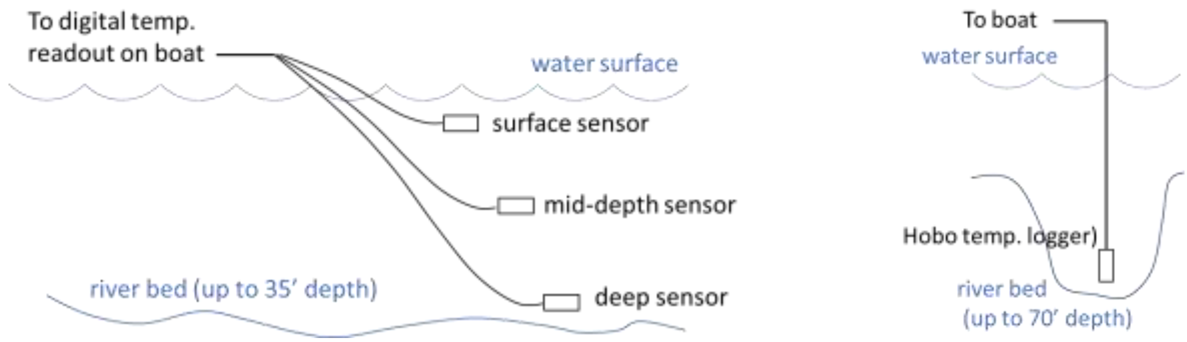


Figure 19. Schematics of temperature sensor deployment for Phase 2 mainstem Columbia and downstream tributary temperature monitoring. Left: custom sensors used for continuous monitoring of water column up to 35' depth. Right: HOBO data logger deployment at deep water locations.

Results, Phase 2

Table 9 summarizes data collected during summer 2016 Phase 2 monitoring. We re-deployed HOBO water temperature loggers at seven lower Columbia Gorge tributary locations that were monitored during Phase 1 (summer 2015), to fill data gaps and to provide records of comparison for the two summers. We then surveyed Columbia R. mainstem temperatures and mapped the extent of cold-water plumes at 5 larger downstream tributaries, during two days in late summer.

Table 9: Data collected for Phase 2 (summer 2016) of the lower Columbia River Thermal Refuge Study.

Site	Stream temperature monitoring interval	Instantaneous water temperature survey using towed sensors, and/or Hobo logger	Discharge	Bathymetry Survey	Notes
Bridal Veil Cr.	7/19/16 – 9/14/16	--	07/20/16, 08/05/16	08/05/16	Deployed to compare to 2015 conditions
Goodbear/Archer Cr.	No data (logger buried under fill)				Deployed to compare dry periods to 2015
Hamilton Cr.	6/22/16 – 9/14/16	--	--	--	Deployed to compare dry periods to 2015
Hardy Cr.	1/1/16 – 9/16/16	--	--	--	Deployed to compare to 2015 conditions
Horsetail/ Oneonta Cr.	--	--	07/20/16, 08/05/16	08/05/16	Fill 2015 data gap.
Tanner Cr. near Col. R. confluence	6/22/16 – 9/14/16	--	--	--	Deployed to fill 2015 data gap.
Tanner Cr. upstream of hatchery	No data (logger malfunction)				Deployed to compare to 2015 conditions
Woodard Cr.	6/22/16 – 9/14/16	--	--	--	Deployed to compare dry periods to 2015
Columbia R. mainstem	--	08/29/16 – 08/30/16	--	--	

Cowlitz R. confluence		8/30/16			
Kalama R. confluence		8/30/16			
Lewis R. confluence		8/30/16			
Sandy R. confluence		8/29/16			
Washougal R. confluence		8/29/16			

Lower Columbia Gorge tributary temperature monitoring results

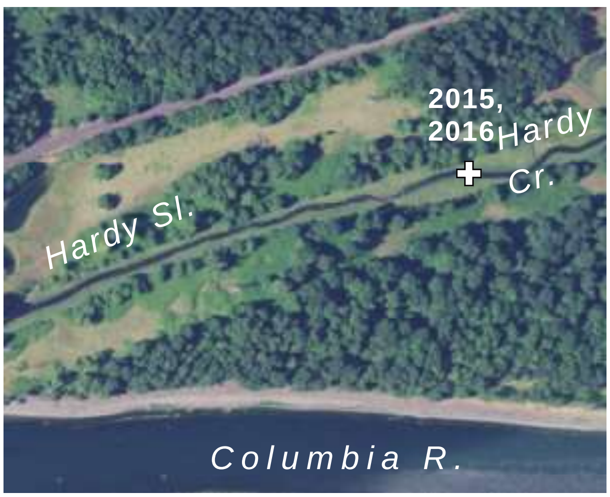
We re-deployed HOBO temperature loggers at seven locations, with specific objectives based on results of Phase 1 monitoring. We collected additional discharge and topographic elevation data at the Horsetail/Oneonta Cr. and Bridal Veil Cr. confluences with the Columbia R to support Phase 3 studies that were planned for these sites. The seven locations chosen for repeated stream temperature monitoring and their associated objectives are shown in Table 10. Temperature logger placement locations for Phase 1 (2015) and Phase 2 (2016) monitoring are shown in Figure 20. Temperature records, (with comparison to Phase 1 data if available) follow in Figure 21.

Table 10: lower Gorge tributary locations selected for repeated temperature monitoring during Phase 2 (2016).

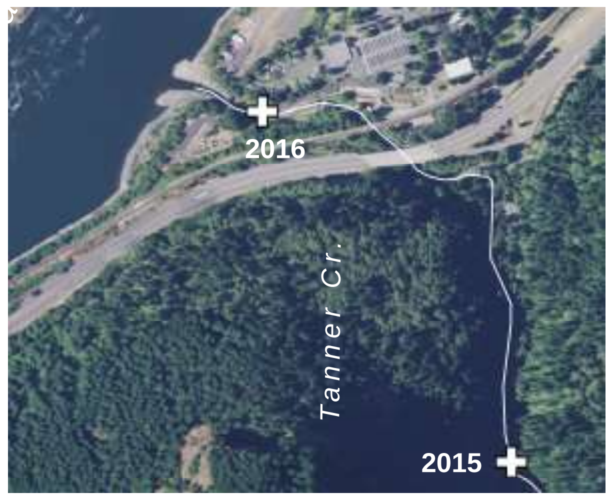
Bridal Veil Cr.	Additional data collected in Phase 2 due to inclusion in Phase 3 feasibility planning. Phase 2 logger was placed at the same location and depth (~ 2 ft.) as the Phase 1 logger.
Goodbear/ Archer Cr.	One of the lowest flow streams in the study group, with surface flow ceasing at the logger location on 7/28/2015. Phase 2 monitoring was intended to determine whether this is a typical summer characteristic or if the 2015 result was due to anomalous climate and hydrologic conditions (high temperatures and low springtime precipitation). Logger was subsequently buried under fill and not accessible, precluding this analysis.
Hamilton Cr.	Phase 2 logger was placed further upstream relative to the Phase 1 logger which was closer to the slough and was influenced by intermittent pulses of Columbia R. backwater. The upstream position was intended to provide an additional water temperature record in the floodplain section of the tributary.
Hardy Cr.	Logger could not be retrieved immediately after Phase 1 due to high water. As a result, a continuous temperature record was obtained from summer 2015 – summer 2016.
Tanner Cr. upstream	Tanner Cr. upstream of the Tanner Cr. fish hatchery was monitored again in Phase 2 to provide comparison of stream temperatures for the two years. Due to a logger malfunction, data was not logged in Phase 2, precluding this analysis.
Tanner Cr. downstream	Tanner Cr. downstream near the Columbia R. confluence was monitored again in Phase 2 to fill Phase 1 data gap (Phase 1 logger was lost or stolen).
Woodard Cr.	One of the lowest flow streams in the study group, with surface flow ceasing at the logger location from 8/25– 8/30 2015, and again after 09/29/2015. Phase 2 monitoring was intended to determine whether this is a typical summer characteristic or if the 2015 result was due to anomalous climate and hydrologic conditions (high temperatures and low springtime precipitation) or poor logger location. Phase 2 logger was placed in a deeper location (~2 ft.), to capture the lowest possible flow condition.

a. Bridal Veil Cr.

b. Hamilton Cr.



c. Hardy Cr.



d. Tanner Cr.

e. Woodard Cr.

Figure 20. Temperature logger locations for Phase 1 (2015) and 2 (2016) lower Gorge tributary monitoring.

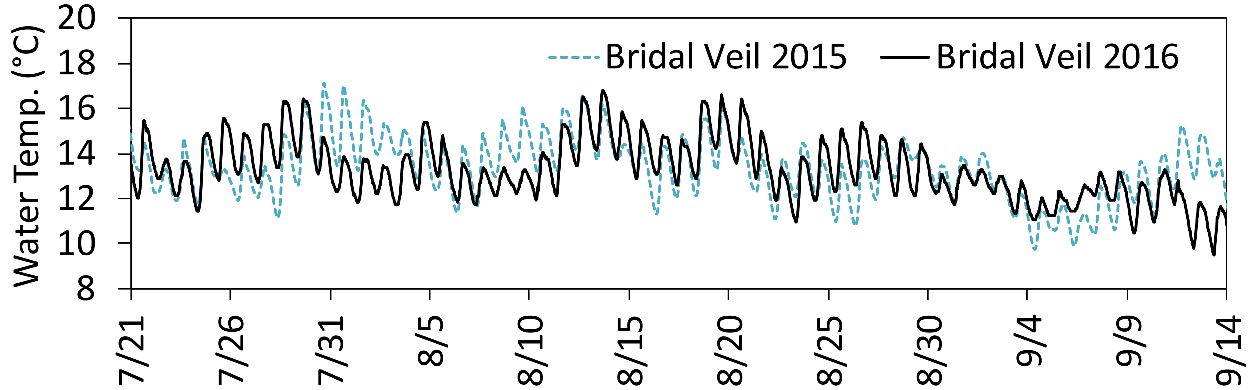


Fig. 21a. Bridal Veil Creek

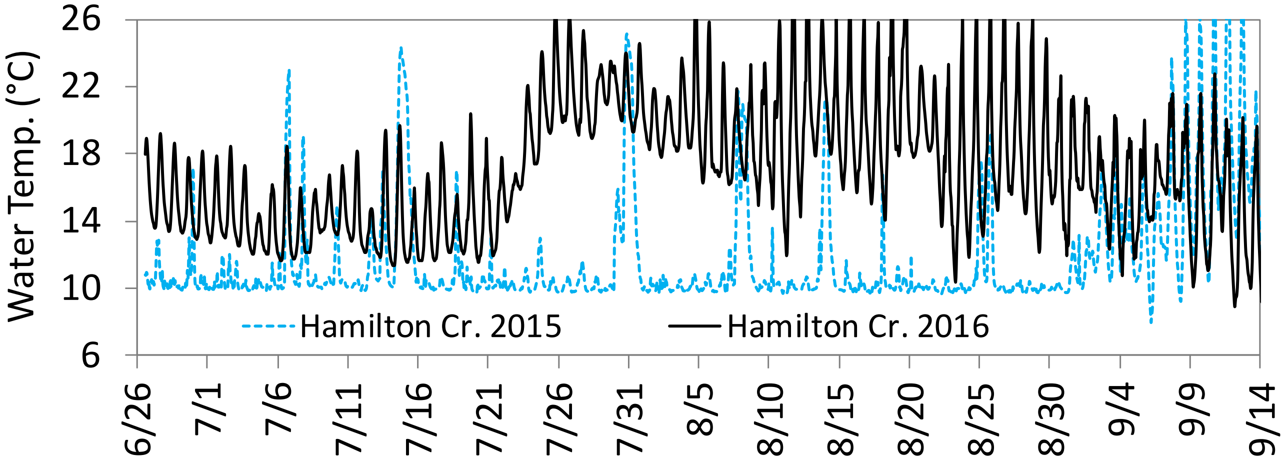


Fig 21b. Hamilton Creek

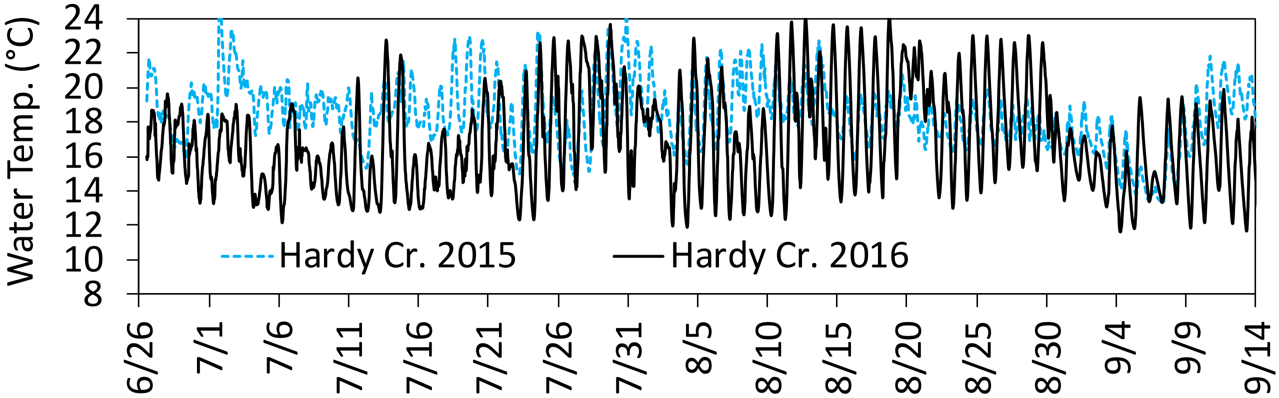


Fig. 21c. Hardy Creek

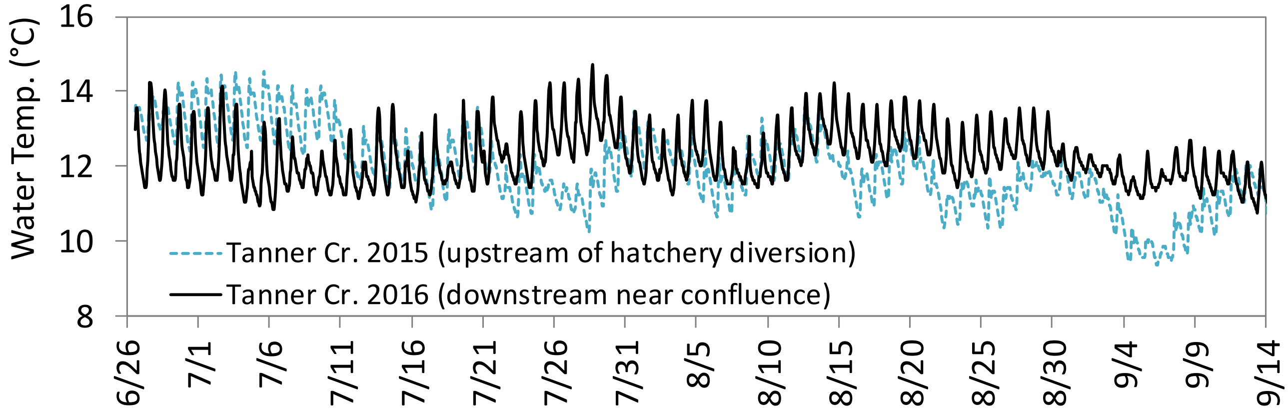


Fig. 21d. Tanner Creek

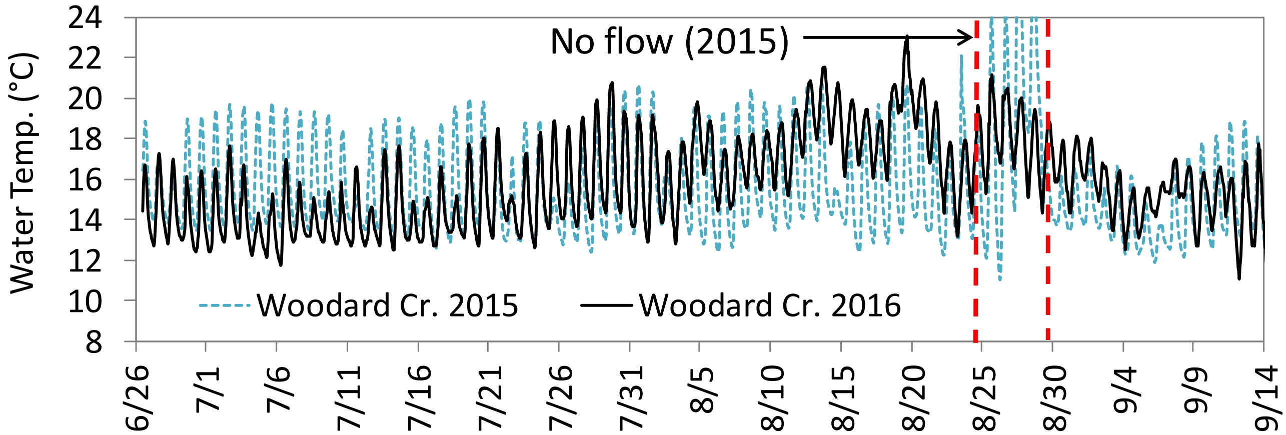


Fig. 21e. Woodard Creek

Figure 21. Hourly temperature logger records at lower Gorge tributary locations monitored in Phase 2. Phase 1 data included for comparison.

<u>Lower Columbia mainstem and large tributary confluence water temperature mapping</u>

We mapped water temperature in the mainstem and at confluences of major tributaries between Longview, WA and the lower Gorge during a three-day period (August 29–31) in late summer of 2016, using the towed temperature sensor configurations described above. The objectives included characterizing the extent of cold water at tributary confluences and documenting other unknown sources of cold-water inputs to the mainstem over as large of an extent as could be mapped given time and budget constraints. Potential inputs include groundwater seeps (particularly around alluvial fan features of lower Gorge tributaries), outfalls, and deep-water holes in the mainstem. Results of from the three-day survey are summarized in Figure 22.

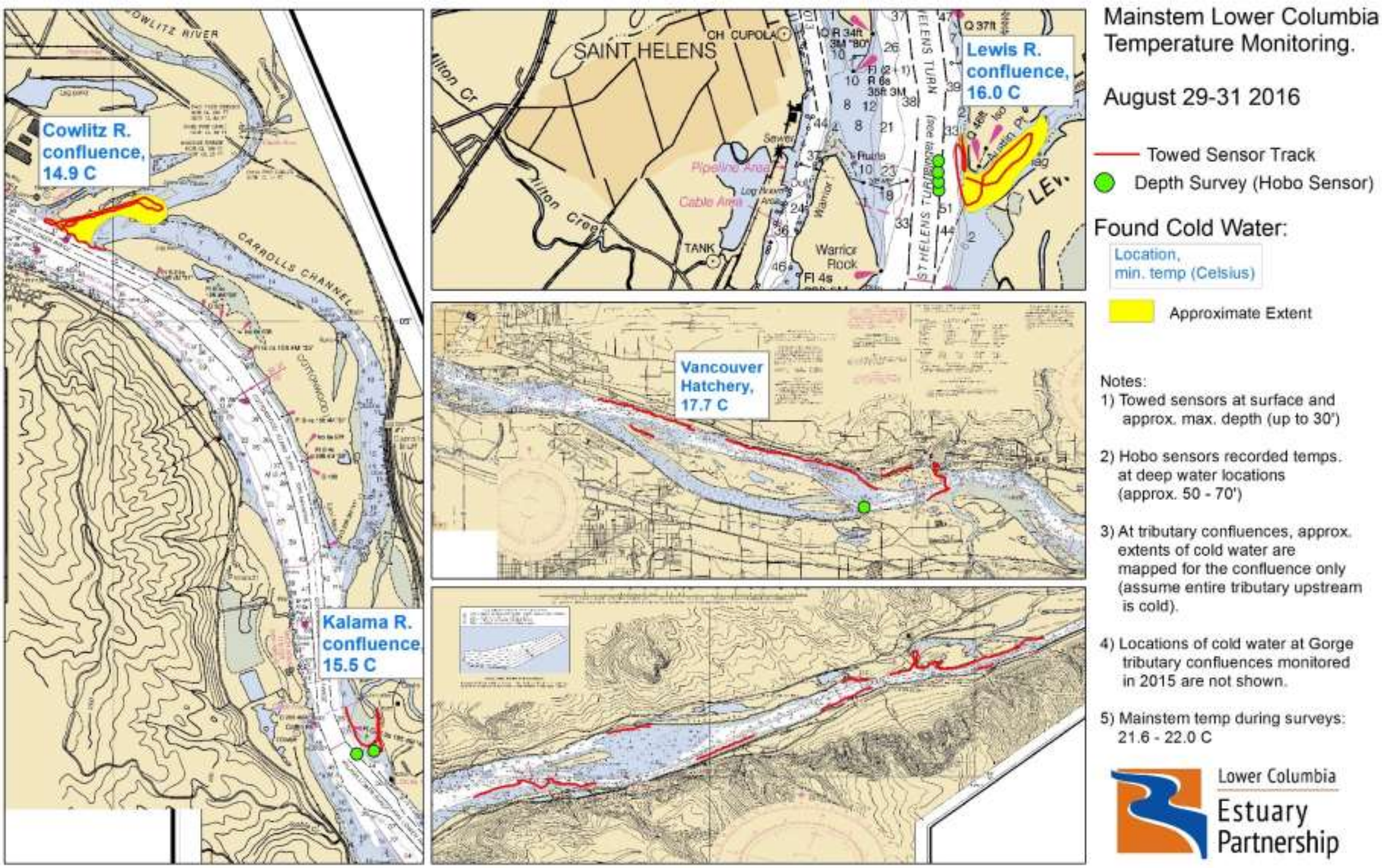


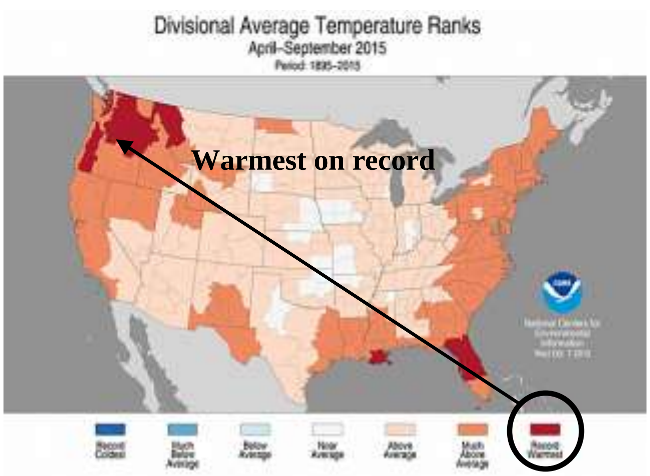
Figure 22. Monitoring results summary for Phase 2 lower Columbia mainstem and large tributary confluence temperature mapping.

Discussion, Phase 2

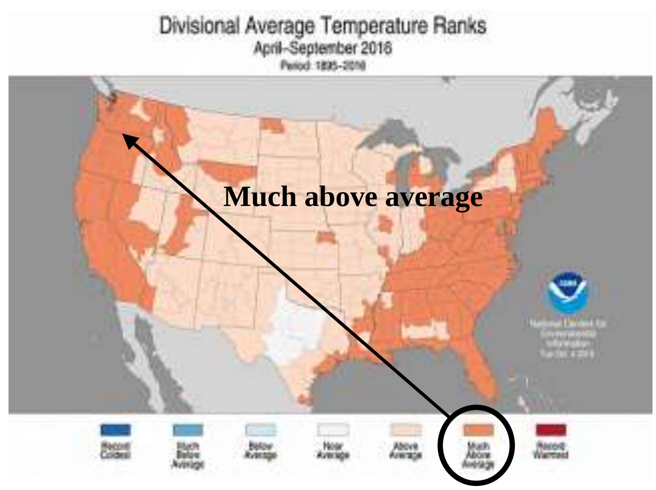
Lower Columbia Gorge tributary temperature monitoring

Temperature loggers were re-deployed at several lower Columbia Gorge tributaries that were monitored as part of Phase 1 (2015) to provide a comparison of conditions for each year, and to fill data gaps due to loggers being lost or stolen during Phase 1 (and thus data not being recovered). Loss, and logger malfunction, occurred again in Phase 2 for two of the seven loggers deployed. At the Goodbear/Archer Cr. confluence, the logger was buried with fill before data could be recovered. At the upstream Tanner Cr. location (above the fish hatchery water intake), the logger malfunctioned before data could be recovered. At both locations then, water temperature comparisons between summer 2015 and summer 2016 could not be obtained.

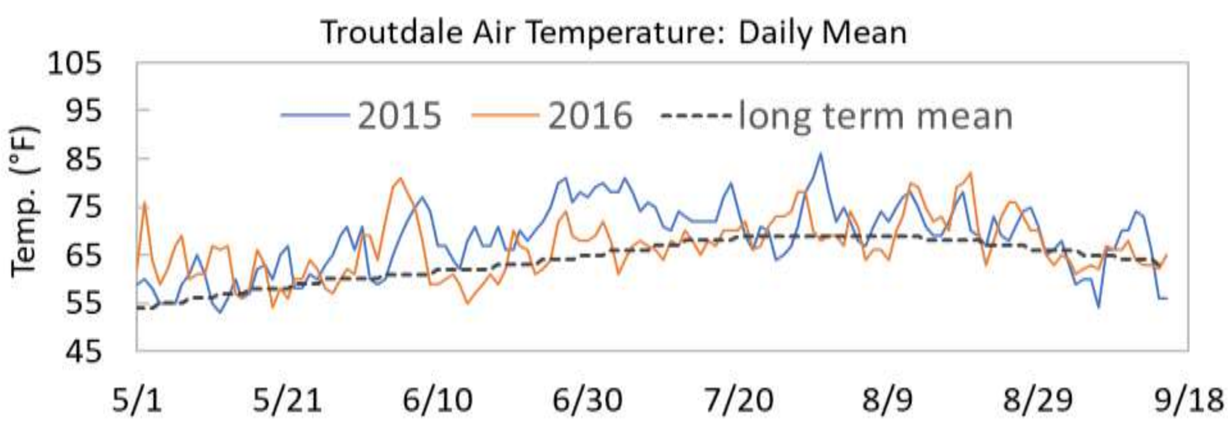
To compare Phase 1 (summer 2015) results to Phase 2 (2016) results, it is important to consider the underlying drivers that influence stream temperature, and thus our results. All temperature loggers where overlapping data was collected were placed in locations upstream of tributary confluences. At these locations, the primary physical parameters that act on stream temperature, and are subject to inter-annual variability, include air temperature and precipitation. Mainstem Columbia River flows, which could influence conditions at tributary confluences, are not a factor in these upstream locations. Figure 23 provides a comparison of air temperature, and Figure 24 provides a comparison of precipitation, for the 2015 and 2016 spring–summer periods.



a. regional daily average, 2015

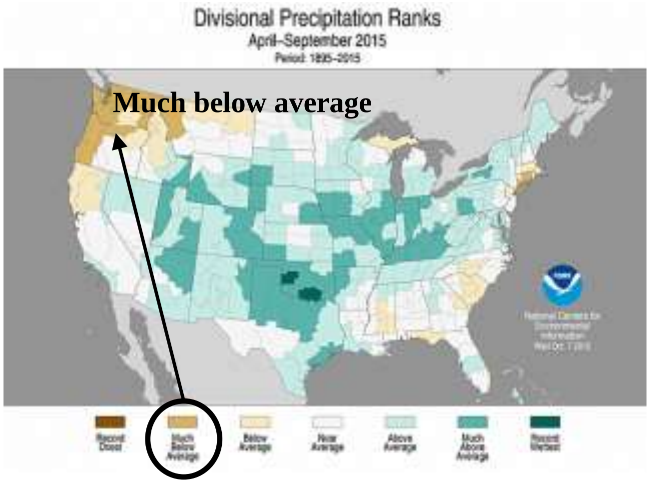


b. regional daily average, 2016

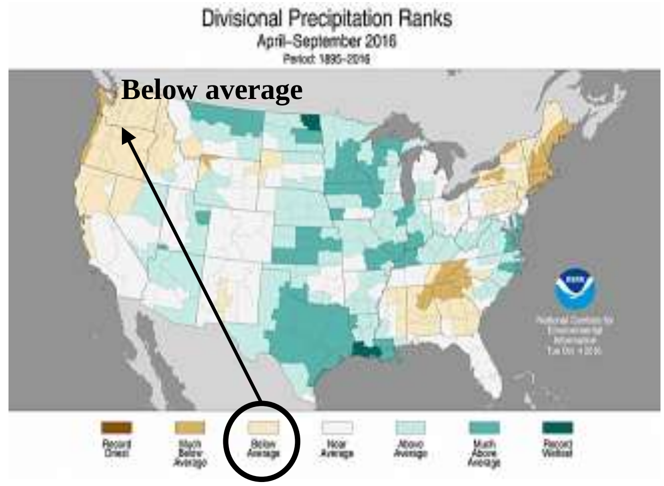


c. mean temperature records for Troutdale, OR

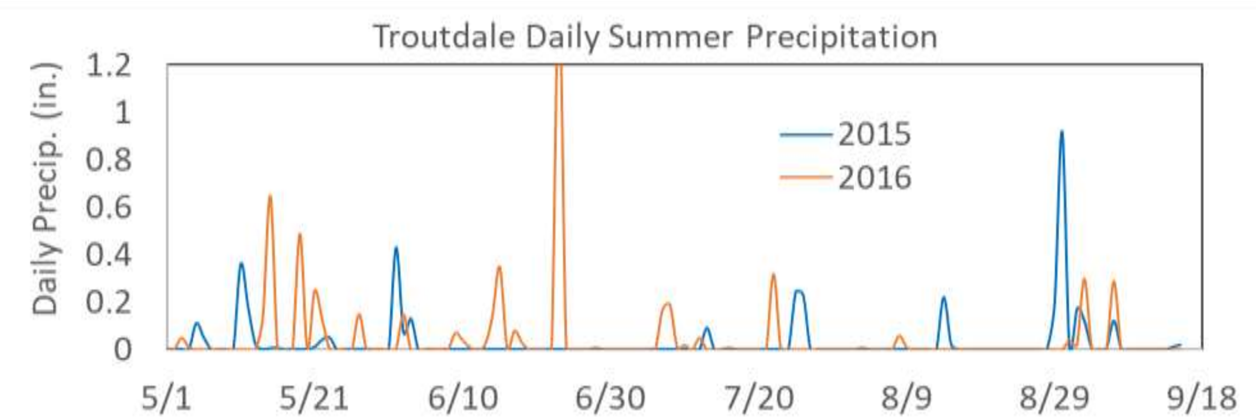
Figure 23. Air temperature comparison for summer 2015 versus summer 2016.



a. regional daily average, 2015



b. regional daily average, 2016



c. daily precipitation records for Troutdale, OR

Figure 24. Daily precipitation comparison for summer 2015 versus summer 2016.

As the figures suggest, climatic conditions during spring–summer 2016 were not unlike conditions during the same period in 2015 in the Pacific Northwest, with both years experiencing considerably warmer, and drier conditions relative to normal. We had hoped that 2016 conditions would be closer to long-term averages, allowing for a comparison of stream metrics during a highly anomalous summer (2015) to those that could be expected during a typical summer. Because the two summers were similar though, this was not possible, and we expect that the Phase 1 and Phase 2 results would likely be similar as well. The following are specific observations for streams that were monitored during Phase 1 and Phase 2:

Bridal Veil Creek

Data loggers were placed at the same location for both study phases, allowing for direct comparison of results. Due to late deployment in Phase 2 (July 19, 2016), overlapping records were not obtained for early summer. As expected, due to similarity in climatic conditions, stream temperature characteristics were similar for Phase 1 and Phase 2 (Figure 21a). Overall temperature range and diurnal variation remained relatively constant for the two summers, and being one of the larger flow streams surveyed, diurnal variation (approximately 3 °C max.) was small relative to lower flow streams.

Hamilton Creek

The Hamilton Creek Phase 1 temperature record (Figures 9e and 21b) showed consistently cold temperatures of 10–14 °C, with little diurnal variation but with intermittent warm pulses several days apart resulting from occasional Columbia R. backwatering events, until flow terminated and the logger became exposed to air on

9/1/2015. By placing the logger further upstream during Phase 2 (Figure 20b) we intended to characterize the floodplain reach of the stream, outside of Columbia R. influence. The result was somewhat unexpected, with flow appearing to terminate earlier at the upstream reach (~ 7/23/16 at the Phase 2 location), relative to the slough (9/1/2015 at the Phase 1 location). This suggests that the downstream slough portion of Hamilton Creek (or Hamilton Slough) may be fed by subsurface water that bypasses the portion of the channel monitored in 2016. This is further supported by the temperature records, which show consistently colder water at the slough location relative to upstream, suggesting a cooling effect of upstream water as it passes underground and re-emerges further downstream. This effect is consistent with the nature of this type of alluvial fan system.

Hardy Creek

At Hardy Creek, a single data logger was left in place for the duration of the two phases, allowing straightforward comparison of the two summers' records. The most notable difference between the two years is the significant difference in diurnal variation (~8 °C max for 2015, ~12 ° max for 2016). This was consistent throughout the summer, but more noticeable during certain periods beginning in August (Figure 21c). Because flow data was not collected for this stream, we cannot positively attribute the difference to changes in flow. We would also expect the opposite effect— more diurnal variation during the lower flow year of 2015— if flow was a factor. Since atmospheric effects can likely be ruled out due to the logger location remaining constant, the cause of this difference in diurnal temperature variation between 2015 and 2016 is unknown.

Tanner Creek

We were unable to obtain overlapping records for both the upstream and downstream Tanner Cr. locations due to logger loss/malfunction in both Phase 1 and Phase 2, however comparison of the Phase 1 (2015) upstream record to the Phase 2 (2016) downstream record shows little variation between the two years, as expected (Figure 21d). As at Bridal Veil, the other relatively high flow tributary, diurnal variations in the Tanner Cr. temperature records were smaller compared to the lower flow tributaries.

Woodard Creek

As with monitoring at Hamilton Creek, the Phase 2 logger at Woodard Creek was placed in a deeper location relative to Phase 1 (Figure 20e) to obtain a longer temperature record with no interruption of flow, if possible. Results were as expected, with a continuous temperature record (no dry out periods) seen for the duration of the 2016 summer, compared to a brief dry out period in late summer 2015. The 2016 record also showed considerably less diurnal variation compared to 2015 (Figure 21e), likely a result of the deeper water location in 2016 minimizing atmospheric heating and cooling effects.

Because of similar climatic conditions in summer 2015 and summer 2016, the Phase 1 and Phase 2 temperature characteristics from our monitoring of lower Gorge tributaries did not differ significantly. The additional monitoring did, however, confirm some of the findings from Phase 1, as well as reveal additional patterns. Overall, the larger flow streams showed smaller diurnal variations in temperature from atmospheric heating and cooling, relative to smaller streams. Within an individual stream, these same effects are variable over depth, with deeper water remaining consistently colder throughout the day (see Woodard Creek data, Figure 21e). Data also showed that, for streams flowing through alluvial fan systems, flow may be quite variable at different locations due to possible hyporheic flow, with water entering or exiting the ground at various locations (see Hamilton Creek data, Figure 21b).

Finally, a comparison of daily differences in water temperatures between summer 2015 and summer 2016 with two local climate variables— air temperature and precipitation— reveals the relative influence of these two factors on stream temperatures. Figure 25 shows a strong relationship between the difference in daily average air temperature and the difference in daily average water temperature for all tributaries monitored in Phase 1 and Phase 2. When 2015 air temperatures were higher (positive air temperature differential), 2015 water temperatures were generally higher as well, relative to 2016. When 2016 air temperatures were higher (negative air temperature differential), 2016 water temperatures were generally higher as well, relative to 2015. Figure 26 shows summer 2015 and summer 2016 precipitation events, combined with water temperature differential for the two years. This data does not show any clear response to precipitation events, particularly for the larger flow tributaries (Bridal Veil Creek, Tanner Creek). Because precipitation events are infrequent in the Pacific Northwest summer, their influence on stream temperature relative to air temperature would remain insignificant even if they were a stronger driver.

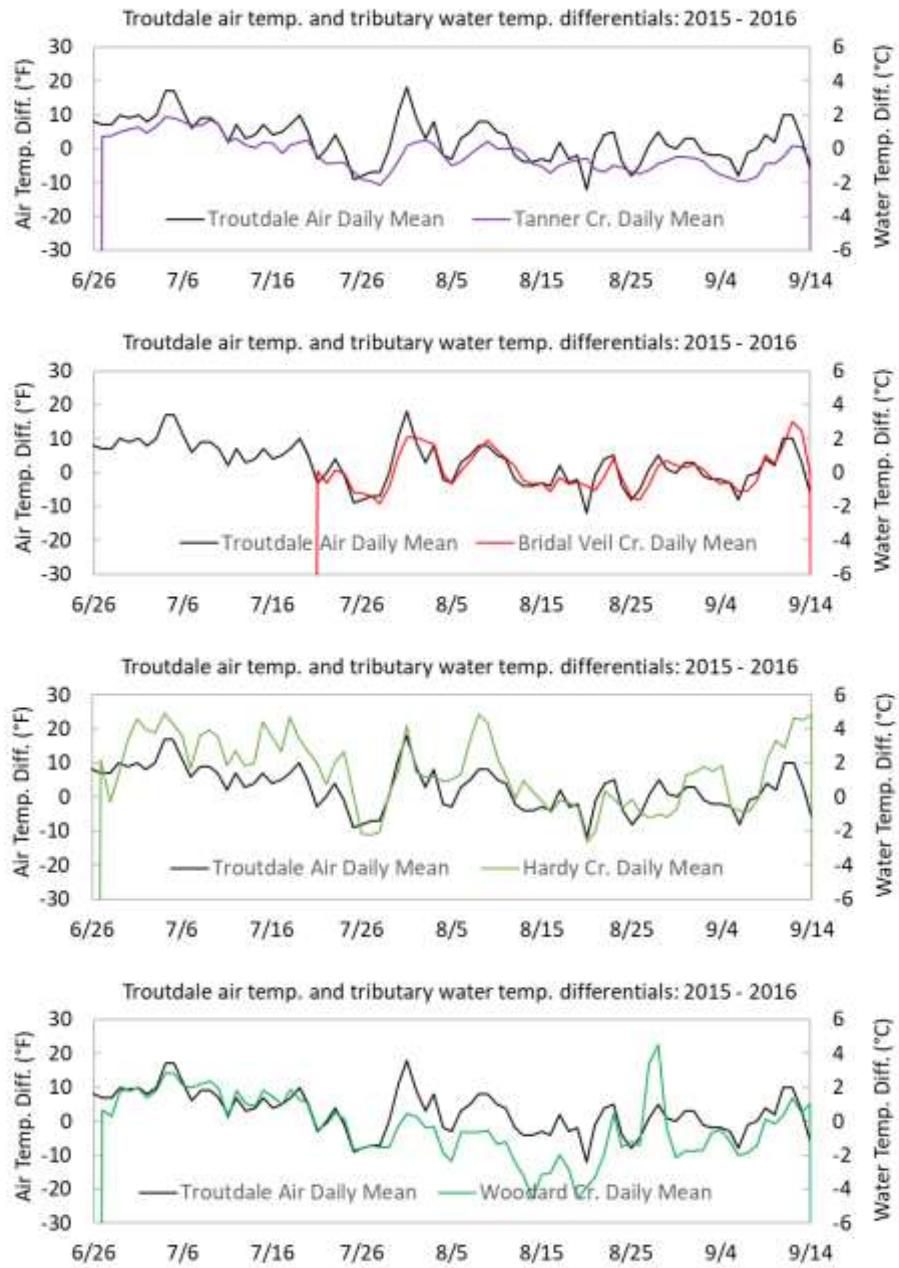


Figure 25. Difference in daily mean air temperature at Troutdale, OR, and difference in daily mean water temperature of lower Gorge tributaries, for 2015 versus 2016.

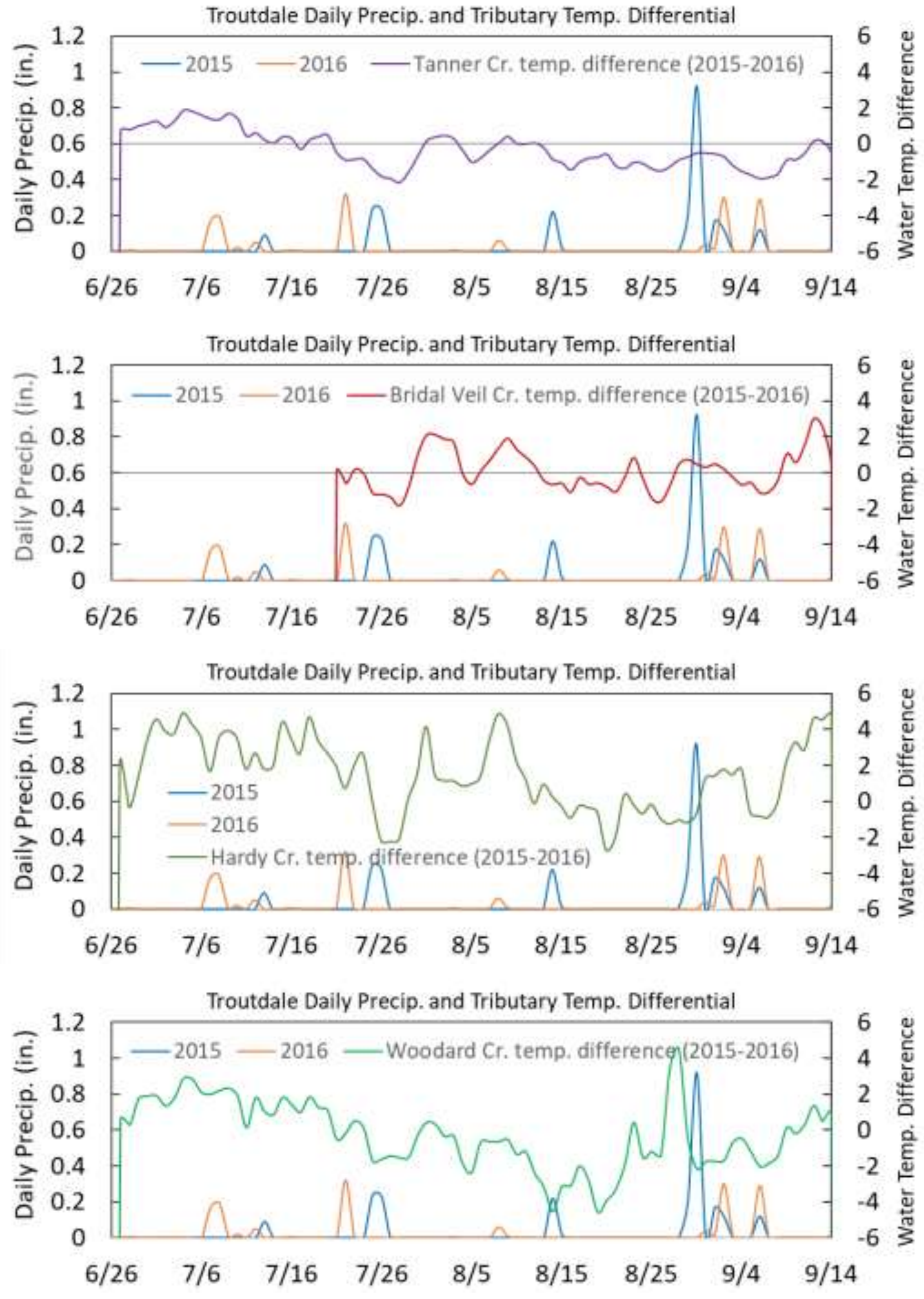


Figure 26. Difference in daily precipitation at Troutdale, OR, and difference in water temperature of lower Gorge tributaries, for 2015 versus 2016.

Lower Columbia mainstem and large tributary confluence water temperature mapping

We used towed temperature sensors, at three depths in the water column (surface, mid-depth, max.-depth), to map water temperature of the mainstem lower Columbia River and the confluences of major cold-water tributaries, from the Phase 1 lower Columbia Gorge study area downstream to approximately river mile 67 at Longview, WA (the approximate extent that time and budget would allow). The objective of this effort was not to intensively monitor water temperature at particular locations, but rather to qualitatively determine the extent of potential cold-water inputs to the lower Columbia over as large a spatial extent as possible. We focused on areas where we saw the highest potential for cold water to be located: at tributary confluences; adjacent to alluvial fan features where lower Gorge tributary confluences enter the Columbia; in the deepest holes of the mainstem; and adjacent to outfalls.

Of all areas surveyed, we only noted significant cold-water inputs at previously known locations (Figure 22): the confluences of three major downstream tributaries (the Cowlitz, Kalama, and Lewis Rivers), and at a very small discharge location for the Columbia Springs fish hatchery, immediately upstream of the I-205 bridge near Camas, Washington (where we also noted significant adult salmonid presence). We expected to see at least minimal cold-water signals at the confluences of the Sandy and Washougal Rivers, but did not detect any temperatures lower than the mainstem Columbia. This may have been a result of the relatively late date that monitoring took place, at which time flows from these tributaries are nearing their annual minimums. The monitoring at the Sandy River confluence was also confounded by a large presence of recreational fishing boats, however we were able to survey most of the area. Deep water pockets in the mainstem showed no deviation in temperature from surface and mid-depth waters, confirming that the river is completely mixed throughout the water column. Cold water was also observed at multiple outfall locations along the Washington shoreline around Camas, Washington, however these inputs are likely too small to provide cold-water refuge for salmonids, and therefore were not mapped, or addressed further.

At confluence zones of the three major cold-water tributaries, the Cowlitz, Kalama, and Lewis Rivers, we did not observe plumes of cold water extending into the mainstem. As with smaller tributaries in the lower Columbia Gorge, once these water sources enter the mainstem they are quickly dispersed, resulting in sharp temperature gradients when transiting from tributary to mainstem. Average observed water temperature values for each plume are shown in Figure 22. These values were observed to be quite uniform throughout each plume, particularly at the Lewis and Cowlitz R. confluences. The Cowlitz R. had the coldest temperature (14.9 °C), followed by the Kalama (15.5 °C), and the Lewis (16.0 °C) rivers. Approximate extents of observed cold water at these sources are shown in Figure 27, including the small location at the Columbia Springs hatchery outlet, near Camas, Washington. Scale is maintained in all figures, to illustrate relative plume sizes.

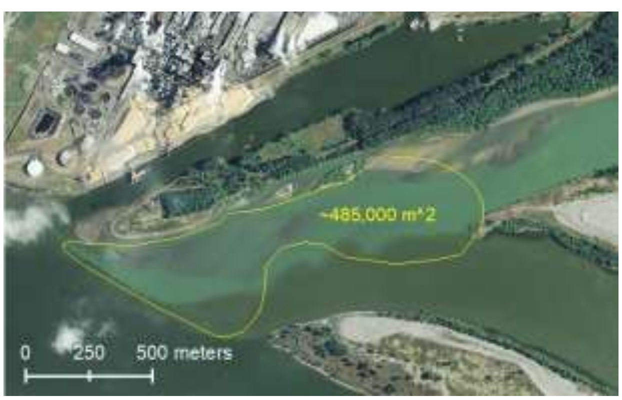


Fig. 27a: Cowlitz R.

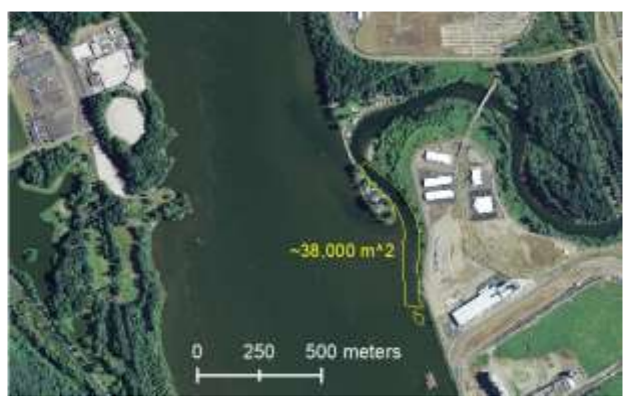


Fig. 27b: Kalama R.

Fig. 27c: Lewis R.

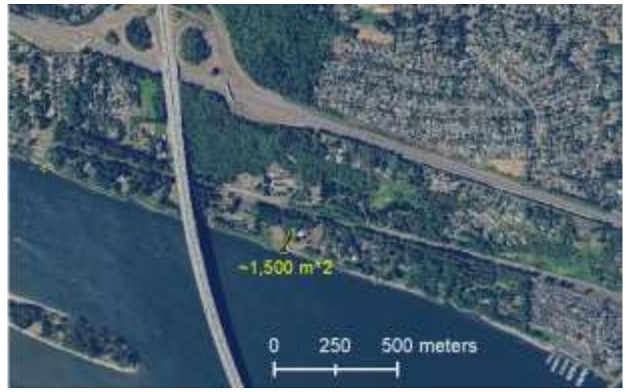


Fig 27d. Columbia Springs hatchery outlet

Figure 27. Approximate extent of cold-water 'plume' areas at the locations where cold water was observed during Phase 2 monitoring.

We estimated volumes of available cold water to adult salmonids for each of the three tributary confluences, based on the best available bathymetric data (U.S. Army Corps of Engineers Digital Terrain Model, 2010). Because river levels fluctuate considerably at multiple time scales due to tidal and fluvial effects, we calculated these volumes using both average high and average low water values, obtained from NOAA historical water level data from nearby gages. It should be noted that for each tributary, the distinction between the plume area at the confluence and the remaining upstream reach was made arbitrarily. Water temperature of the entire tributary upstream from the plume remains constant, and it is likely that areas further upstream are also being used by migrating salmonids as thermal refuge. Because there were no clear defining features from which to demarcate a distinct plume zone, we used a best guess approach for each tributary. Furthermore, the confluence zones of these tributaries are highly energetic, and resulting morphologic changes (shifting sandbars, channels, etc.) are frequent and can significantly influence calculated volumes of available cold-water habitat. It is likely that topography at all these confluence zones has changed significantly since bathymetric data was last obtained, and so our estimates of volume, while still useful, likely do not exactly reflect current conditions. Estimated volumes are shown in Table 11. These values are derived as shown in Figure 28, assuming that adult salmonids require a minimum 1–2 meter water depth for suitable thermal refuge, based on our established preliminary criterion outlined in Phase 1.

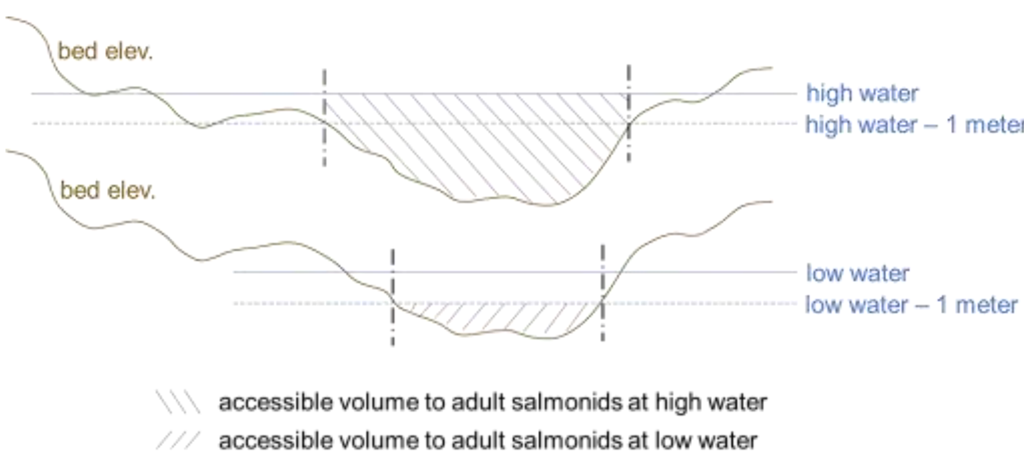


Figure 28. Estimation of the volume of cold water available to migrating adult salmon in a cold-water 'plume' at a tributary confluence. Method assumes that adult salmon require a minimum 1–2 meter water depth.

Table 11. Estimated volumes of cold-water volumes available to adult salmonids at tributary confluence plumes.

Tributary Plume	[1]Average high/low water levels (m)	Available cold-water area at average high water (m^2)	Available cold-water area at average low water (m^2)	Available cold-water volume at average high water (m^3)	Available cold-water volume at average low water (m^3)	Mean available cold-water volume (m^3)	[2]EPA estimate of available volume of cold-water (m^3)
Cowlitz R.	3.6/1.6	650,000	318,500	2,456,000	1,067,000	1,762,000	1,554,230
Kalama R.	3.6/1.6	31,500	5,400	64,800	8,400	36,600	71,089
Lewis R.	3.5/1.9	209,000	130,300	653,000	285,000	469,000	613,455

Notes:

1. Average high and low water levels (in meters relative to NAVD88) were estimated from NOAA water level gage data (Longview, WA and St. Helens, OR) during July and August, for the years 2009–2017.
2. Source: EPA Technical memorandum, December 12, 2017, from John Palmer: Volume of Cold Water Refuge Associated with the 26 Tributaries Providing CWR in the Lower Columbia River.

The Phase 2 assessment of cold-water inputs to the lower Columbia River confirmed several important observations regarding the availability of cold water to salmonids in the lower Columbia River. Most notable is the fact that cold-water inputs are limited, and that large spatial gaps exist between them along the migratory path of salmonids, requiring them to travel significant distances during summer to find refuge from warmer mainstem waters. From the Lewis River confluence at Columbia river mile 87 (the last sizeable refuge zone below Bonneville Dam for upstream migrating adult salmonids) to Eagle Creek (the next sizeable refuge zone, just above Bonneville Dam at Columbia river mile 147), adult salmonids must navigate 60 miles without significant access to cold water (Figure 29). While the lower Columbia Gorge tributaries (as well as the small outlet at the Columbia Springs hatchery) do provide cold water to the lower Columbia, their limited flows, as well as their morphologic characteristics, greatly limit the extent to which they can be detected by and serve as effective thermal refuge for significant numbers of adult salmon. Our observations and results do, however, indicate that these sources may currently be providing effective habitat for juvenile salmonids.

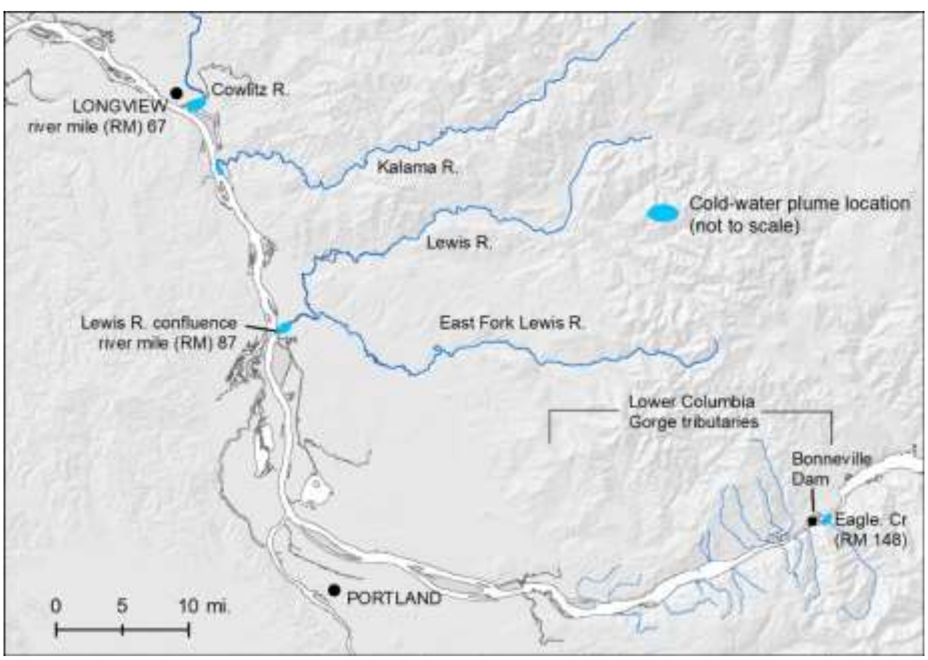


Figure 29. Separation of existing cold-water plumes at tributary confluences in the lower Columbia River

Based on these findings, a third phase of this study was added to investigate methods of enhancing lower Columbia Gorge tributaries so that they can provide increased thermal refuge to both adult and juvenile summer migrating salmonids. To date, the Estuary Partnership has undertaken multiple restoration projects at lower Gorge tributaries, which partially address this issue through actions such as revegetation, passage improvements, restoration of instream flow, and targeted large wood placement to encourage beaver activity and hyporheic exchange. These actions have largely taken place in upstream and floodplain reaches of these streams, away from the confluence zones. In Phase 3, we use data and results obtained from initial phases of this study, coupled with hydrodynamic modeling, to assess the feasibility of various methods of enhancing cold-water plumes at the confluence zones to increase the detection and capacity of cold-water habitats at these locations.

PHASE 3 OF 3: ENHANCEMENT OF COLD-WATER REFUGE PLUMES AT LOWER COLUMBIA GORGE TRIBUTARY CONFLUENCES. FEASIBILITY ASSESSMENT.

Background, Phase 3

For several Columbia River tributaries located above Bonneville Dam, plumes of cold water that form during summer months at their respective confluences with the Columbia River have been shown to be used by adult salmonids returning to their natal streams when peak Columbia River temperatures regularly exceed 21°C (Keefer et al. 2011). Water temperatures of these tributaries range from 2–7 °C cooler than the mainstem, and their combination of discharge, thermal, and topographical characteristics allow for the formation of cold-water plumes of adequate size and depth to be utilized by migrating adult salmonids. These confluence zones are typically characterized by a tributary entering a natural or man-made embayment (Figure 30). Partial, or in some instances, nearly complete isolation from mainstem currents that is provided by the local topography minimizes entrainment of warmer mainstem water into colder tributary water, keeping the embayment at or close to tributary temperatures. With continuous tributary flow, colder water is forced out of the embayment and into the mainstem along the migratory path of adult salmonids, where they can detect it and move into the embayment to seek refuge from warmer mainstem waters. Previous studies (Keefer et al. 2008, Keefer et al. 2011) have shown that when temperatures exceed threshold levels (typically 19-20°C) migrating steelhead will utilize these features for weeks at a time, while residence times for Chinook salmon are typically on the order of days to 1 week for a given location.

Figure 30. Confluence zones of four mid-Columbia River tributaries which provide thermal refuge for migrating salmonids. All are characterized by a cold-water tributary entering an isolated embayment. Top left: Eagle Creek; top right: Herman Creek; bottom left: Wind River; bottom right: Little White Salmon River.

Phase 2 of this study showed similar cold-water zones at three major Columbia River tributary confluences located several miles below Bonneville Dam: the Cowlitz, Kalama, and Lewis Rivers. Additional Phase 1 and 2 monitoring of lower Columbia Gorge tributaries revealed them to also have mean temperatures at least 2°C lower than the Columbia River. However, due to their smaller relative flows and topographical characteristics, their outputs are quickly subsumed upon entering the mainstem Columbia, thereby limiting cold-water plume formation and the associated benefits to salmonids that are seen at confluence zones further upstream and downstream. Of the five lower Columbia Gorge tributary confluences where cold-water plumes were observed to form, only the Eagle Creek confluence, located above Bonneville Dam at Columbia River mile 147, meets all our preliminary criteria, outlined in Phase 1, for providing suitable thermal refuge to both adult and juvenile salmonids. This leaves a gap of approximately 60 miles, from the Lewis R. confluence at river mile 87 to the Eagle Creek confluence at river mile 147, where migrating salmon have no access to cold water in the lower Columbia River (Figure 31).

This project phase assessed the feasibility of modifying nearshore topography of selected lower Gorge tributary confluences to enhance cold water retention at existing plume locations, thereby making them more beneficial to summer migrating salmon. Potential design techniques include the placement of diversion structures to deflect mainstem river flows around the tributary confluences, thereby encouraging plume formation. The outcome identified cost-effective methods of implementing these techniques into habitat restoration actions for species recovery to more fully address the anticipated effects of climate change on Columbia River salmonids.

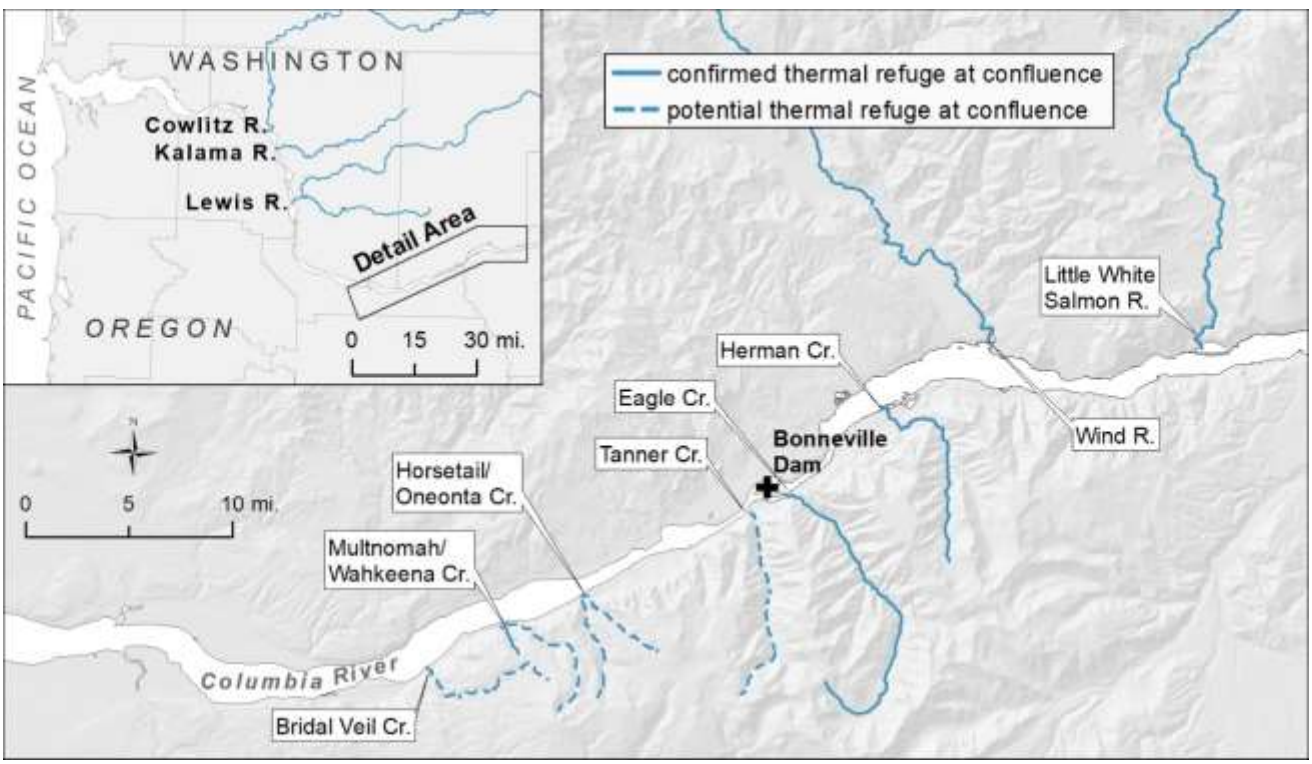


Figure 31. Lower and mid-Columbia Gorge tributaries with confirmed and potential thermal refuges for adult salmonids at their confluence zones. Inset map shows additional lower Columbia tributaries with thermal refuges at confluences zones confirmed in Phase 2 monitoring. The gap in thermal refuge zones between the Lewis R. and Eagle Creek is approximately 60 miles. Note: additional cold-water refuge confluence zones not on map exist further upstream and downstream in the Columbia R.

Phase 1 and 2 monitoring showed limited cold-water plume formation at four lower Gorge tributary confluence zones other than Eagle Creek where enhancement techniques could potentially be employed to increase plume sizes and make them more suitable as thermal refuges (Figure 31). In this study phase we examined plume enhancement at three of these tributaries: Bridal Veil Creek, Multnomah/Wahkeena creeks, and Horsetail/Oneonta creeks. Due to potential social constraints at Tanner Creek (proximity to navigation channel, high public use, hatchery operation, among others), we did not include it in this analysis. To assess plume enhancement at the three selected tributary complexes, we used a high resolution hydrodynamic and water quality (temperature) model to simulate existing plume formations and compared these to simulated plume dimensions resulting from various topographical modifications. We chose to use a three-dimensional model (3D), to capture the temperature stratification that was observed in the water column during Phase 1 monitoring of these confluence zones. The modeling process involved the following steps:

- Create model mesh representation of existing physical topography, using existing elevation data and higher resolution elevation data collected during Phase 1 and 2 monitoring.
- Determine the period of interest for running model simulations (length of time, and specific window within the summer months).
- Create time series representations of boundary forcing conditions that control hydrodynamics and water temperature in the lower Columbia Gorge, for the period of interest. These include Columbia River stage (water surface elevation), Columbia River and tributary discharges, Columbia River and tributary temperatures, and atmospheric conditions (air temperature, solar radiation, wind speed, and rainfall).
- Run existing conditions model with applied boundary condition data. Calibrate and validate model performance, by comparing observed plume sizes and temperatures (obtained from Phase 1 field monitoring) to simulated plume sizes and temperatures and adjusting model parameters until good agreement is obtained.
- Re-run model simulations with applied boundary condition data (river and tributary discharge and temperature, etc.) and altered physical topography representing desired enhancement actions.
- Compare plume extents for the existing condition to those with altered topography, to determine the effectiveness of selected enhancement actions in increasing plume size and quality.

Methods, Phase 3

We used the Tuflow FV modeling engine for all model simulations. Tuflow FV is a finite volume, flexible mesh numerical model that can simulate hydrodynamic processes in oceans, coastal waters, estuaries, and rivers. Its accompanying AD (advection/dispersion) module allows for simulation of water quality parameters, including temperature, and its 3D capability allows for simulation of outputs in the vertical as well as horizontal planes. The model also allows input of atmospheric forcing parameters such as wind, air temperature, rainfall, and solar radiation, which may be important drivers of water temperature at the scale and locations of interest.

<u>Elevation inputs and model mesh</u>

The primary source of elevation data used to generate the model mesh is the U.S. Army Corps of Engineers (COE) 2010 Lower Columbia River Digital Terrain Model (U.S. Army Corps of Engineers, 2010). This 1-meter resolution data set includes the most complete and up to date collection of bathymetric and topographic data for the lower Columbia River mainstem and surrounding floodplain. Resolution of bathymetric data within the Columbia Gorge is quite low for this data set however (15 meter transect spacing), and because preliminary 2D model results showed a high sensitivity of plume dynamics to bathymetry we supplemented this data set with higher resolution bathymetric data collected at the tributary confluences of interest during Phase 1 and Phase 2 of this study (Figure 32), to improve model performance.

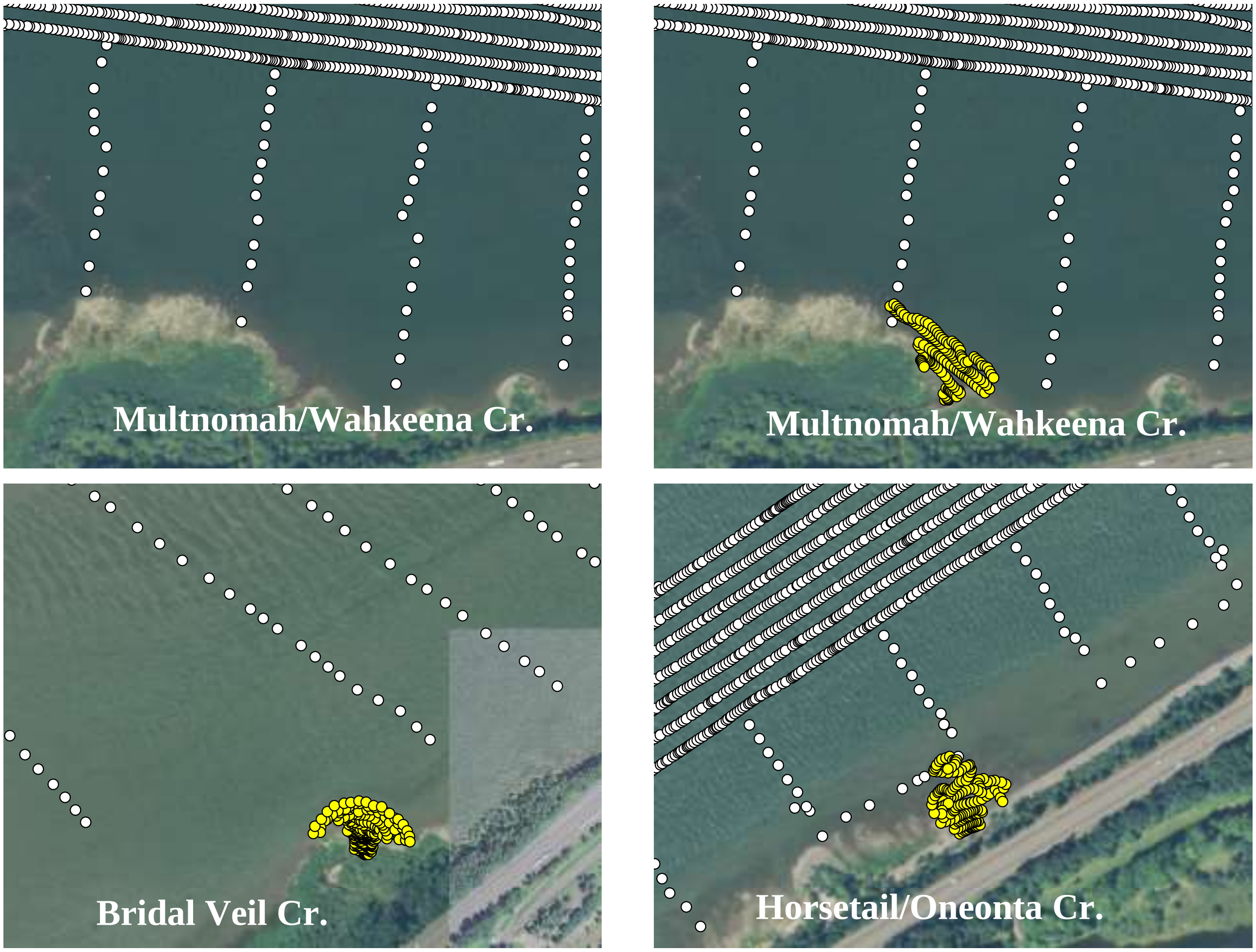


Figure 32. Bathymetric data sources for hydrodynamic model mesh generation near modeled tributary confluences: US Army Corps of Engineers 2010 Lower Columbia Digital Terrain Model bathymetric data (white circles); LCEP Phase 1 and 2 elevation data (yellow circles) collected at higher resolution to improve mesh resolution.

To apply real-time physical forcing at model boundaries as accurately as possible, the model mesh was extended upstream and downstream to locations where gage data is available. The downstream boundary, where water surface elevation (WSE) is applied as the primary boundary input, extends to Sand Island, where WSE data was collected in 2008 as part of another monitoring program. The upstream boundary, where river discharge is applied as the primary boundary input, extends nearly to Bonneville Dam, where discharge and WSE data are available from gages maintained by the COE and U.S. Geological Survey. Both boundaries were also placed far enough away from the tributary confluences of interest to ensure that possible boundary effects do not influence model results. The final model mesh extent, along with mesh detail at two of the three confluences modeled (Bridal Veil Cr. and Multnomah/Wahkeena Cr), are shown in Figure 33.

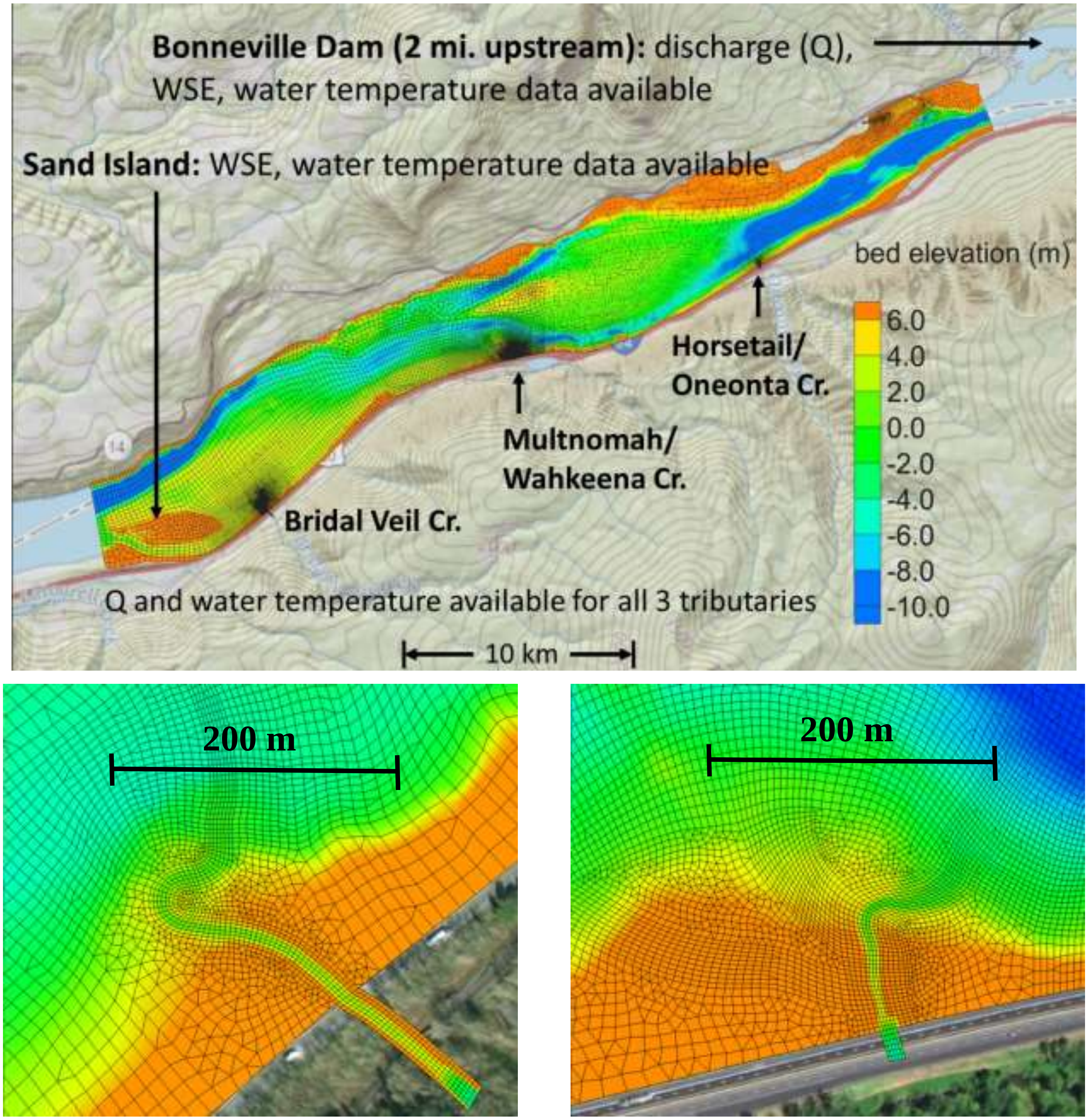


Figure 33. Tuflow model mesh generated for cold-water plume analysis. Top: mesh extent in lower Columbia River Gorge; bottom left: mesh detail at Bridal Veil Cr. confluence; bottom right: mesh detail at Multnomah/ Wahkeena Cr. confluence. The same elevation scale applies to all images.

<u>Period of interest</u>

The time segment selected for running model simulations was governed by three factors: a) the summer migration window for adult and juvenile salmonids; b) availability of model forcing data; and c) model simulation run time requirements. Figure 3 (Phase 1 section above) overlays run timings for different salmonid species with average Columbia River temperatures. Our period of interest extends from July 10–September 10, when peak run timings for most species coincide with river temperatures higher than 20 °C. Practical constraints of data availability and model run times limited the specific period and duration of time that could be modeled within this window. Because we chose to apply real-time forcing data for our modeling, we were limited to time periods for which it is available. The limiting factor for model forcing data was WSE applied at the downstream boundary (upstream boundary conditions were obtained from Bonneville gage data, whose period of record extends back several years). WSE data at the downstream boundary was collected at Sand Island from July 25, 2008–July 26, 2009. Duration of time modeled was limited by the required computation time of the model. We limited model run times, as a practical consideration of analyzing several different enhancement strategies. With available computing resources this allowed us to simulate approximately 4 days of real time conditions. To best balance the three controlling factors in selecting a simulation period, we selected a 4-day period near the middle of the migration run time of concern. We then compared daily WSE at Bonneville for 2008 and 2009 (the two summers for which WSE data is available from the Sand Island record) to long-term 50% exceedance values and determined that 2008 is a slightly better representation of average hydrologic conditions relative to 2009, for this period (Figure 34). The final period of interest selected for model simulations then was July 31–August 3, 2008.

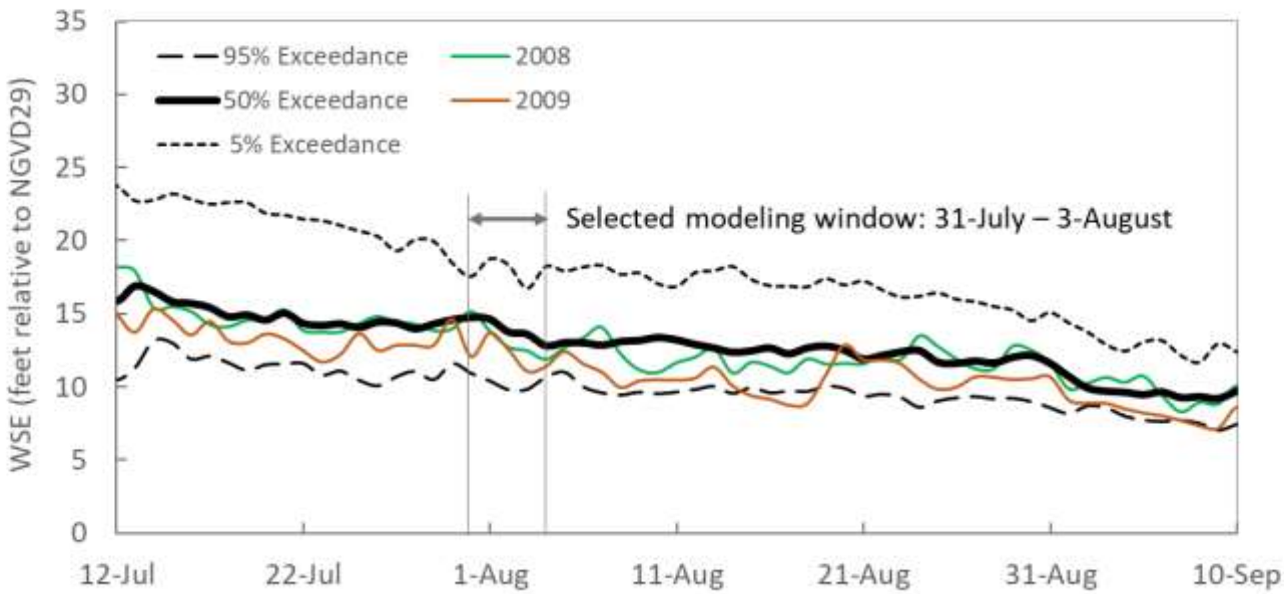


Figure 34. Summertime daily Columbia River level (WSE) below Bonneville Dam for selected years and percent exceedances for 1990–2017 period of record. This data was used to select between 2008 and 2009 for chosen modeling period.

<u>Model boundary inputs (physical forcing parameters)</u>

The primary drivers of hydrodynamics and resulting water temperature in the lower Columbia Gorge include ocean tide forcing from the Pacific Ocean and discharge (flow) from the Bonneville Dam immediately upstream. As confirmed in Phase 2 monitoring, the mainstem Columbia River is well mixed downstream of Bonneville Dam, resulting in highly uniform temperatures over that length of river and throughout the water column. Water temperatures at tributary confluences are further influenced by tributary temperatures and discharges. In shallow areas, atmospheric forcing, including air temperature, relative humidity, solar radiation, and wind, can have a significant effect on water temperatures. To evaluate existing conditions (i.e. plume formation at confluence zones under the existing topographical conditions) these forcing factors were applied as unsteady (time varying) inputs to the existing conditions model mesh. WSE and water temperature were applied at the downstream boundary, discharge and water temperature were applied at the upstream boundary, and discharge and water temperature were applied at each of the three tributary inputs. Atmospheric inputs were applied globally, at the surface of all mesh cells. The following data sources were used for model boundary condition inputs:

Columbia R. WSE (applied to downstream boundary): As mentioned above, Sand Island hourly WSE data collected as part of an earlier LCEP monitoring program was used for the downstream model boundary forcing.

Columbia R. discharge (applied to upstream boundary): Hourly discharge data was obtained from the gage at Bonneville Dam. This gage is maintained by the U.S. Army Corps of Engineers, and recorded data is available from the Fish Passage Center (www.fpc.org).

Columbia River WSE and discharge values applied at the model boundaries are shown in Figure 35. WSE varies by approximately 0.6 meters maximum daily, and 1 meter over the modeled period. As indicated in the figure, Columbia River WSE in this reach of the river, during summer months, is strongly tied to diurnal variations in Bonneville discharge. This cyclical discharge pattern is associated with hydropower generation, which is coupled to daytime power demands in the region. Model simulations have shown this power peaking cycle to have a significant effect on the size of cold-water plumes at the tributary confluences studied. Thus, in addition to natural factors including tides and atmospheric influences, human control of river discharge is an additional factor controlling plume dynamics at these locations.

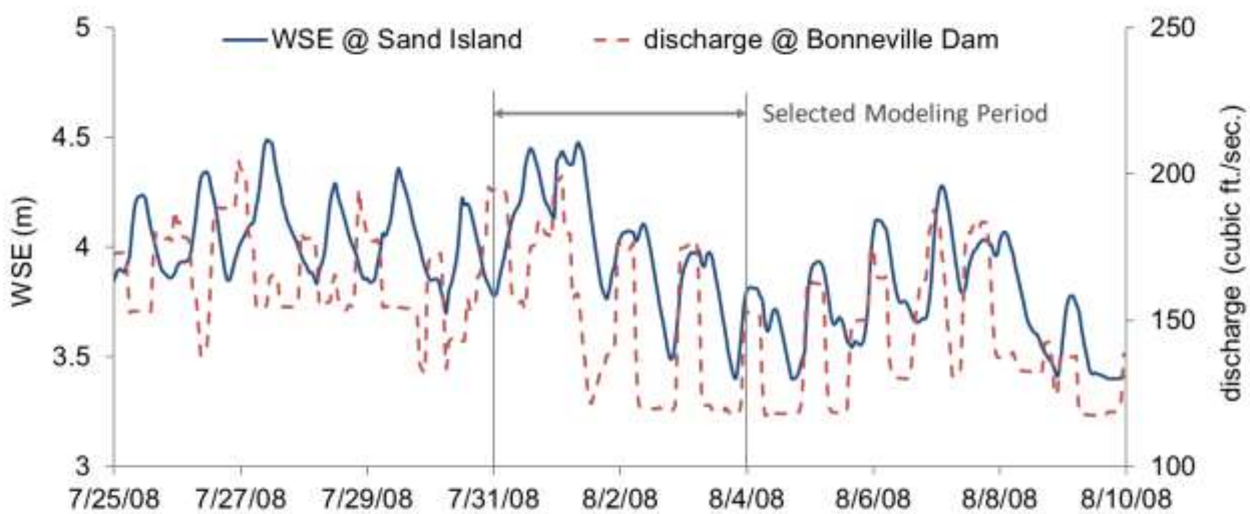


Figure 35. Downstream (WSE) and upstream (discharge) boundary forcing data applied to model simulations.

Columbia R. temperature (applied to downstream and upstream boundary): Columbia River water temperature data was obtained from the gage at Washougal, WA. This gage is part of the Saturn Observation Network (Saturn-08), a network of physical and biogeochemical observation stations in the lower Columbia River and estuary that is owned and maintained by the Oregon Health and Sciences University Center for Coastal Margin Observation and Prediction (www.stccmop.org).

Tributary discharge and temperature (applied to tributary boundaries): Tributary data was obtained from data collected during Phase 1 of this study (Lower Columbia Gorge Tributary Monitoring). Although we did not collect continuous discharge data, results indicate that flows in these tributaries remain quite uniform throughout the mid-summer. Based on this assumption we used the discrete values we measured at each tributary and applied a gradually declining trend to obtain continuous discharge estimates for each tributary.

Atmospheric inputs (applied globally): Climate records including air temperature, cloud cover, rainfall, relative humidity and wind speed were obtained from the Weather Underground Strawberry Meadows (KORTROUT20) station at Troutdale, OR (https://www.wunderground.com/weather/us/or/troutdale/97060). Solar radiation (longwave and shortwave) input values were obtained from standard curves for solar irradiance incident upon the Earth's surface.

Model calibration and validation

We compared model simulation output results to field observed data to validate model operation. Flow and WSE outputs were analyzed to validate hydrodynamics, and water temperatures were analyzed to validate advection/dispersion (water quality) results. Due to a lack of observed WSE data within the model domain for the 2008 period modeled, a direct comparison of model results to field observations of WSE, to validate hydrodynamics, is not possible. Although WSE data extending back several years is available from the gage immediately below Bonneville Dam, the steep elevation gradient between the gage location and the upstream model boundary precludes application of this data for any useful comparison. To validate hydrodynamics, we instead used continuity of flow as a measure of model integrity and compared simulated flow at an upstream model cross section to that at a downstream location. We also compared simulated WSE elevation at the model upstream boundary to WSE applied at the downstream boundary to confirm surface slope was consistent with predictions and measurements from other studies.

We were also limited in our ability to validate temperature results for the existing conditions model, due to the different time frames between plume temperature observations (2014–2016), and simulated model results (2008). We made this comparison indirectly, by selecting a window during the 2008 simulation where hydrologic and atmospheric conditions were analogous to those at the date and time when plume temperature mapping occurred and comparing the simulated plume size and temperature at that model timestep to the observed plume size and temperature. Though our plume observations were limited to a handful of spot measurements, we concluded that this rough comparison of modeled to observed plume characteristics was a sufficient level of verification.

Simulate plume dynamics for enhancement scenarios and compare results to existing conditions

Selection of strategies to enhance cold-water plume formation at selected tributaries was guided by the following objectives: maximizing use for both salmon life stages (outmigrating juveniles and returning adults); minimizing cost; and minimizing geomorphic risks. For maximizing salmonid use, we applied access criteria for juvenile and adult fish. For juveniles, we presumed that since all confluences are presently providing suitable refuge based on criteria outlined in Phase 1, any additional enhancement would only further this existing benefit. The limiting factor then was to select enhancement strategies that would increase benefits to adult salmonids, allowing them to both detect plumes along their migratory path, and reside in plumes for extended periods of time. For detection criteria, we assumed salmon migrate upstream within the 2–10 meter depth contour range (Figure 36. Values obtained through personal communication with Matt Keefer, 2017). For residence time we applied a minimum plume depth of 1 meter, based on a criterion of 1–2 meters outlined in Phases 1 and 2.

To maximize the cost-effectiveness of potential structures, we selected alignments that would minimize the length of required diversion structures while maximizing resulting plume area. This included consideration of existing landform locations and how they are influencing local hydrodynamics, when evaluating different structure orientations. Where possible, we looked at incorporating these landforms into the overall diversion mechanism at each confluence, to minimize lengths of necessary constructed features.

While the study did not include an extensive analysis of geomorphic risks associated with placement of diversion structures at the selected sites, we did take into consideration general factors when selecting various structure orientations for analysis, including exposure to Columbia River flows and stability of current tributary alignments. Future phases will include a more detailed analysis of risks associated with these and other factors, including risk of infilling due to mainstem and tributary derived sediments.

Guided by the above objectives, we selected several potential enhancement alternatives, each with a unique combination of diversion structure orientations and tributary alignments, for each site. For each alternative, we adjusted model mesh elevations accordingly, so that diversion structures were modeled as continuous, non-permeable landforms. We ran model simulations for each scenario using the same boundary conditions that were applied in the existing conditions simulations. We compared model output results for each enhancement scenario to the existing conditions model output by evaluating relative differences in overall plume size and plume temperature.

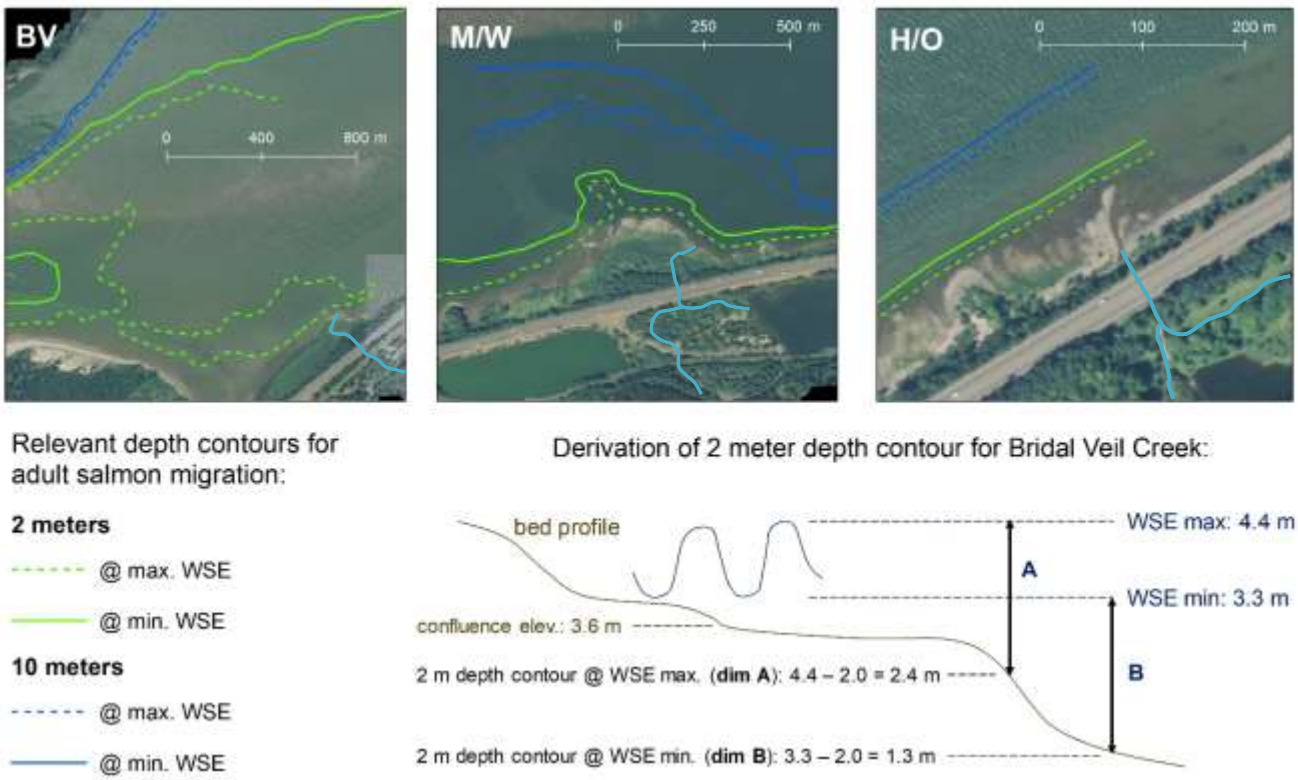


Figure 36. Applied criteria for detection of cold-water plumes by summer migrating adult salmon. Shown are the 2- and 10-meter depth contours at each tributary confluence (Bridal Veil (BV), Multnomah/Wahkeena (M/W), and Horsetail/Oneonta (H/O)). Assuming adult salmon migrate within this depth range, diversion structures must be designed to extend cold-water zones into this range to allow for detection by passing adults. Graphic at bottom right illustrates the process of deriving relevant depth contours.

Results, Phase 3

Model calibration and validation

The methods above describe the limitations in obtaining a thorough validation of model performance, for both hydrodynamics and water temperature predictions. For hydrodynamics, we verified consistent magnitude of flow and appropriate water surface slope throughout the model domain. Results are shown in Figure 37 and are taken to be an indicator of proper model operation, in lieu of comparison of simulated results to field observed values, which are not available. The observed WSE slope of ~1e-05 (m/m) is appropriate for this reach of the river. Based on these comparisons of flow and WSE we concluded that the model hydrodynamics, which were obtained with minimal calibration, are sufficiently accurate for its intended purpose of examining plume dynamics at the selected tributary confluences.

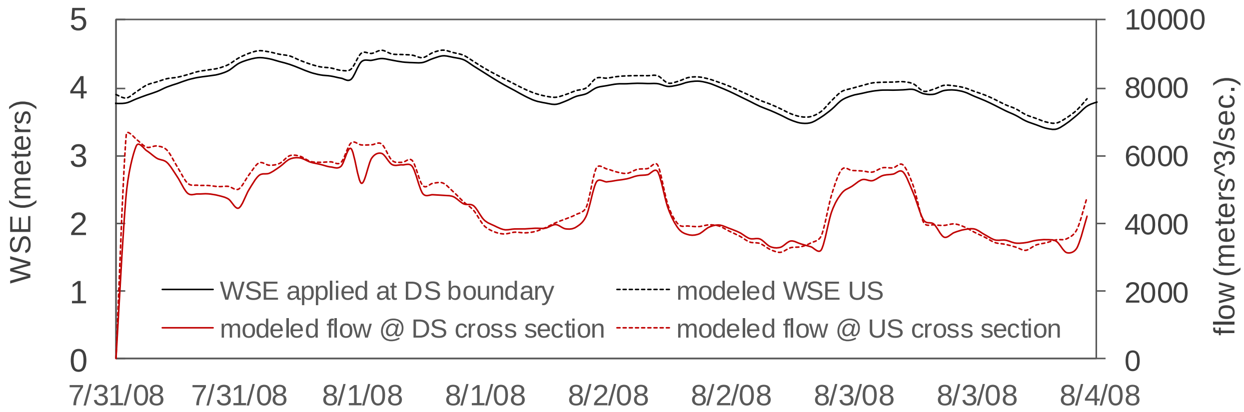


Figure 37. Verification of model hydrodynamics. WSE and flow at upstream (US) and downstream (DS) mesh locations.

Validation of water temperature results is illustrated in Figure 38. We compared model results to field observations from different times but attempted to select model time periods that had similar hydrologic conditions as occurred during the observation period (Table 11). For Bridal Veil Creek, comparison was done at the water surface only, due to lack of sufficient observations at depth. For Multnomah Creek, measurements were taken at the surface and at depth, allowing for comparison at both locations. Water temperatures at the Horsetail/Oneonta confluence were observed to be relatively uniform throughout the water column, and so were recorded at mid-depth only. Because absolute tributary temperatures likely varied between the two time periods, we did not expect modeled temperatures to exactly match the observed values. This was particularly true at the Horsetail/Oneonta confluence, where observed tributary temperature at the confluence was colder than the value applied in the 2008 model run (15.5 °C versus 17.2 °C), and at Multnomah/Wahkeena, where observed tributary temperature at the confluence was significantly warmer than the value applied in the 2008 model run (17.8 °C versus 13.8 °C). At the Multnomah/Wahkeena confluence a small secondary channel to the north of the main channel was not captured in the model but is evident in the plot of observed results. Despite the entrainment of virtually all sediment within manmade features located in the floodplain, the alluvial fan feature at this confluence is still somewhat dynamic. The channel is currently migrating out of its existing, constructed alignment and creating a new channel that flows due north. This feature formed sometime after collection of elevation data at this location (2010 LiDAR data acquisition), and thus was not incorporated into model topography. Despite the limitations in comparing observations to model results from differing time periods, overall the results indicate good prediction of plume sizes by the model, at all confluences. Temperature stratification over the water column, which was also noted in field observations at the Bridal Veil and Multnomah/Wahkeena confluences, was also well predicted by the 3D model simulations.

Table 11. Values of primary physical parameters affecting water temperature, at the time of plume temperature mapping in the field (observed period) versus at selected model time step for comparison of modeled to observed results. Model time steps for comparison were selected to best minimize differences relative to the observed period, for each confluence.

	value during:					
	BV obs. period (8/15/15 13:00)	BV model step (8/3/08 14:00)	MW obs. period (7/29/14 12:00)	MW model step (8/1/08 09:00)	HO obs. period (8/5/16 10:30)	HO model step (8/3/08 06:00)
Columbia R. WSE (ft)	12.2	12	15.5	14.8	13.3	13.5
Columbia R. discharge (kcfs)	130.8	118.7	168.1	158.9	129	157.5
Columbia R. temperature (°C)	21.7	21.1	21.4	20.9	21.5	20.5
Tributary temperature (°C)	14.0	13.2	17.8	13.8	15.5	17.2

Observed temperature　　Modeled temperature

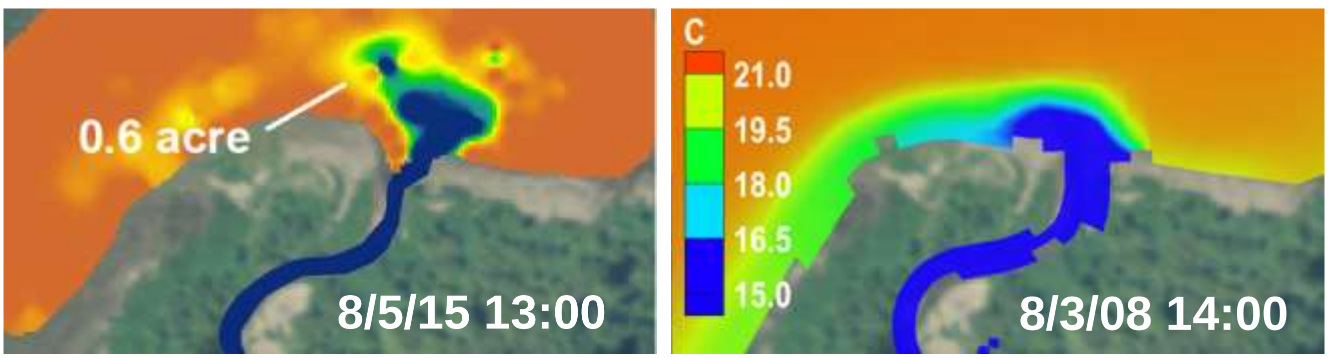


Figure 38a. Bridal Veil confluence temperature, at water surface

Observed temperature　　Modeled temperature

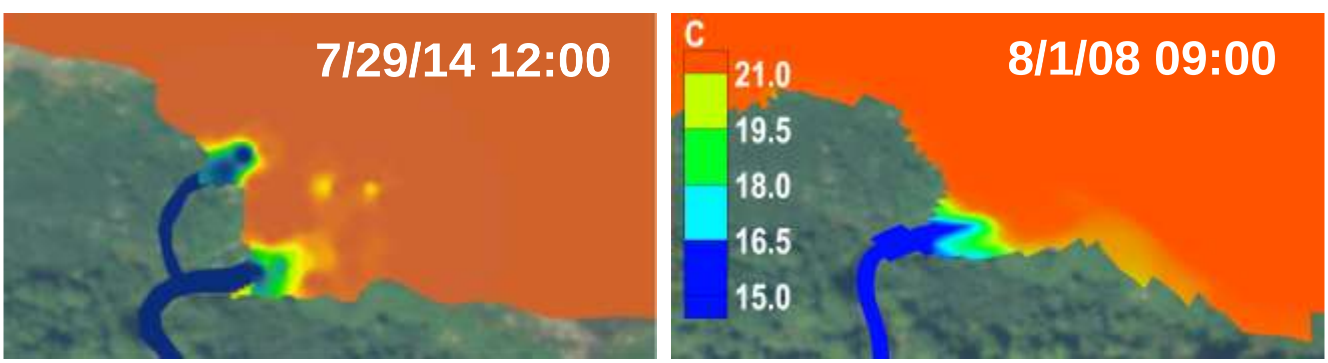


Figure 38b. Multnomah/Wahkeena confluence temperature, at water surface

Observed temperature　　Modeled temperature

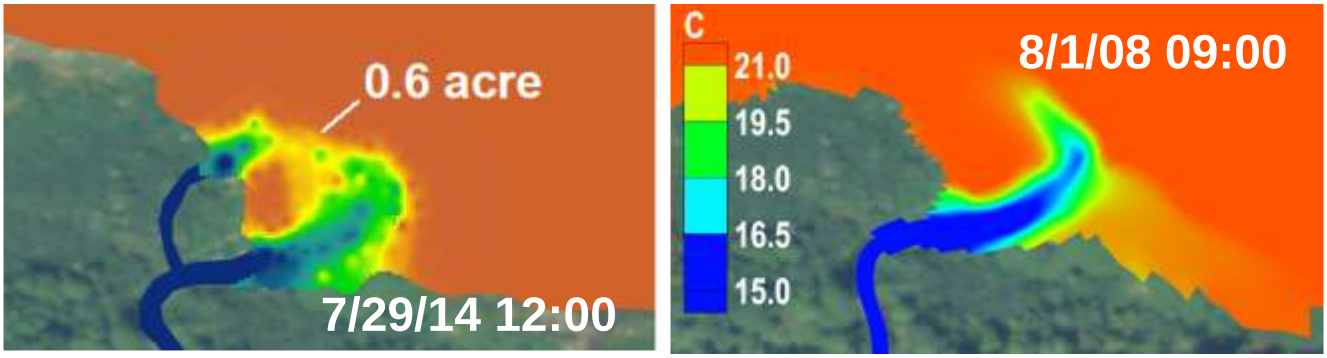


Figure 38c. Multnomah/Wahkeena confluence temperature, at maximum depth

Observed water temperature　　Modeled water temperature

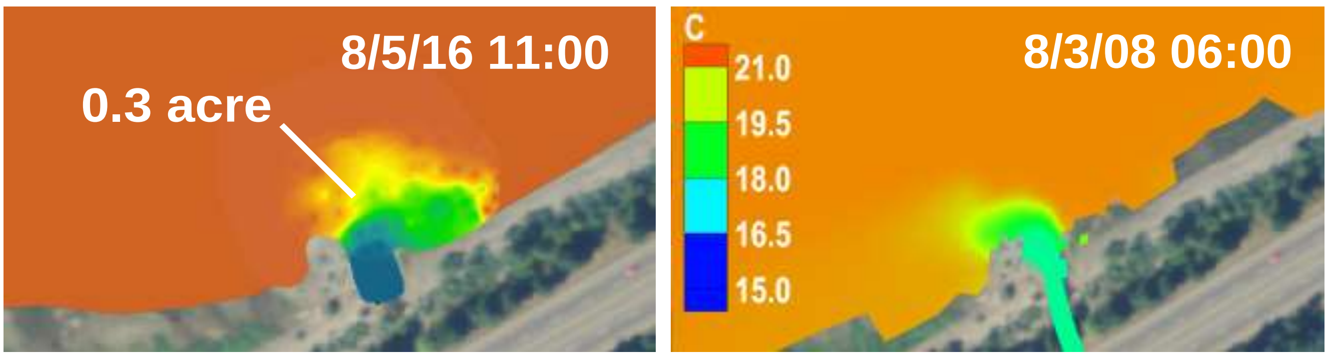


Figure 38d. Horsetail/Oneonta confluence temperature, at mid-depth

Figure 38. Verification of model water temperatures at tributary confluences.

<u>Simulated plume enhancement scenario results: comparison to existing conditions simulation</u>

We examined flow patterns from the preliminary 2D model, and existing landforms, to guide placement of diversion structures and manipulation of landforms at tributary confluences. Strategies were iterative, wherein the effectiveness of cold-water plume enhancement for a given tested scenario informed placement of structures and manipulation of landforms in subsequent scenarios.

A. Horsetail/Oneonta confluence

Flow patterns revealed small scale eddy formation upstream and downstream of the existing confluence, resulting from interaction with lateral landforms (Figure 39). Diversion structures were placed with the objective of minimizing backwatering effects of these warmer, mainstem eddies into the confluence zones.

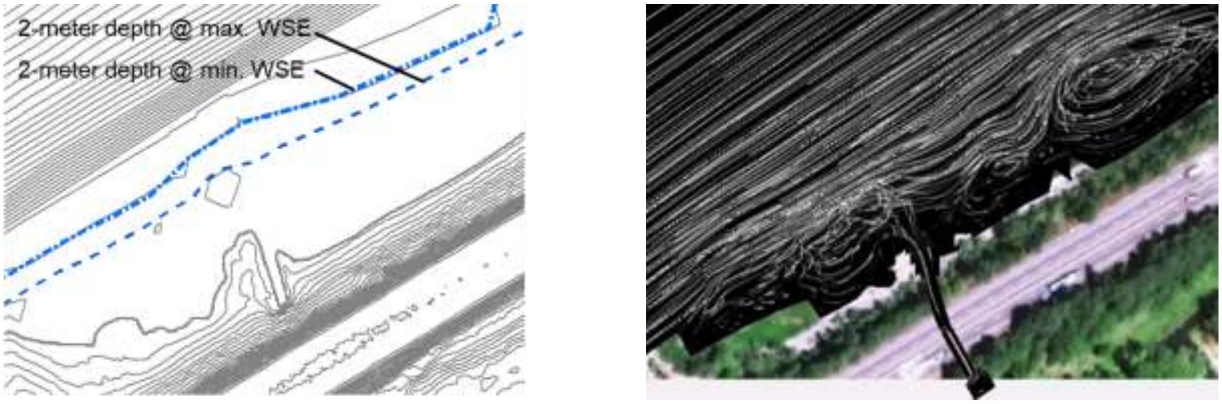


Figure 39. Elevation contours (left), and simulated 2D flow patterns (right) at the Horsetail/Oneonta tributary confluence. Small scale eddy formation influenced by landforms normal to the shoreline are evident (right), and guided structure placement. Also shown at left, in blue, are the 2-meter depth contours at max. and min. WSE during the simulation period (see Figure 34).

The following strategy was followed for testing the effectiveness of plume enhancement at the Horsetail/Oneonta confluence. Because existing depth is relatively shallow around the confluence zone, we included excavation of material behind diversion structures for each scenario, to maintain a minimum depth of 2 meters, consistent with our depth criterion for thermal refuge for salmonids.

1. Scenario 1: single upstream structure angled along shoreline (Figure 40, left). This structure begins downstream of the major eddy seen in 2D simulations and extends to the 2-meter depth contour, to maximize access for migrating adult salmonids. Placement at an angle alleviates stress imparted by mainstem flows and provides a low energy zone for a longer distance where cold tributary water can concentrate, relative to a perpendicular structure. Because of the added length, however, associated costs would be higher relative to a perpendicular structure.

2. Scenario 2: single upstream structure perpendicular to shoreline (Figure 40, right). Because cost would presumably be lower for this shorter structure relative to the angled structure of Scenario 1, its effectiveness in enhancing plume formation was evaluated.

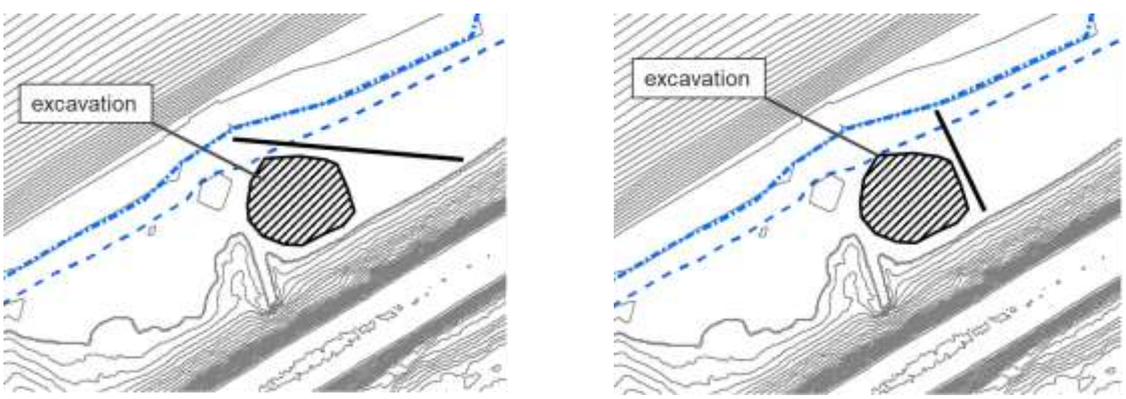


Figure 40. Scenario 1 (left) and 2 (right) structure placements for the Horsetail/Oneonta confluence, with excavation to 2-meter depth.

3. Scenario 3: single upstream structure + removal of downstream landform (Figure 41, left). This scenario tests the added effectiveness of cold-water plume enhancement through removal of the existing downstream landform, which as noted in the 2D simulations, enhances warm-water eddy formation downstream of the confluence. We tested this in combination with the angled upstream structure of Scenario 1, which proved more effective relative to the perpendicular structure of Scenario 2 (see results in Figure 42).

4. Scenario 4: full structure placement (Figure 41, right). We tested the effectiveness of more fully enclosing the confluence through placement of a downstream structure and upstream structure. Again, we used the angle upstream structure of Scenario 1 due its more effective results relative to the perpendicular structure of Scenario 2 (see results in Figure 42).

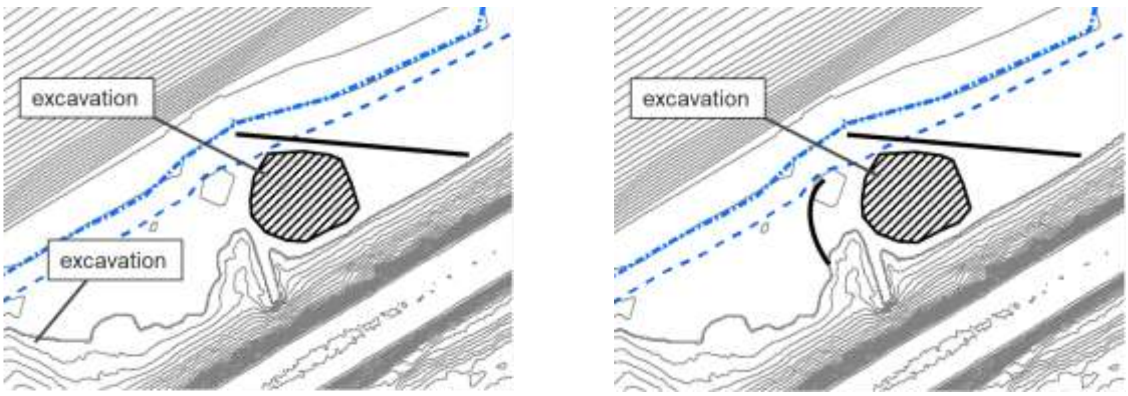


Figure 41. Scenario 3 (left) and 4 (right) structure placements for the Horsetail/Oneonta confluence, with excavation to 2-meter depth.

Simulated water temperatures at the Horsetail/Oneonta confluence for given plume enhancement scenarios and the existing condition are shown in Figure 42. Because no significant difference was noted for Scenario 3 relative to Scenario 1, results for Scenario 3 are not included. Because plume extents and plume temperatures were seen to be highly dynamic in response to changing forcing factors, all outputs shown are taken from the same model timestep, to provide effective comparison.

Model Scenario 1 proved most effective at enhancing cold-water plume formation at the Horsetail/Oneonta confluence, relative to existing conditions. The maximum overall extent of water colder than 20 °C for the full simulation period increased from approximately 550 m^2 for the existing condition to 4,100 m^2 for Scenario 1, an eight-fold increase. It is likely that this value would increase further with additional length of structure added, but this was not evaluated in this study phase. Scenario 2 produced a maximum extent of cold water (20 °C max.) of approximately 2,100 m^2. This is a four-fold increase from existing conditions, but just 51% of the Scenario 1 extent. However, if structure length becomes a limiting cost factor, Scenario 2 may provide adequate benefits at a reduced cost relative to Scenario 1.

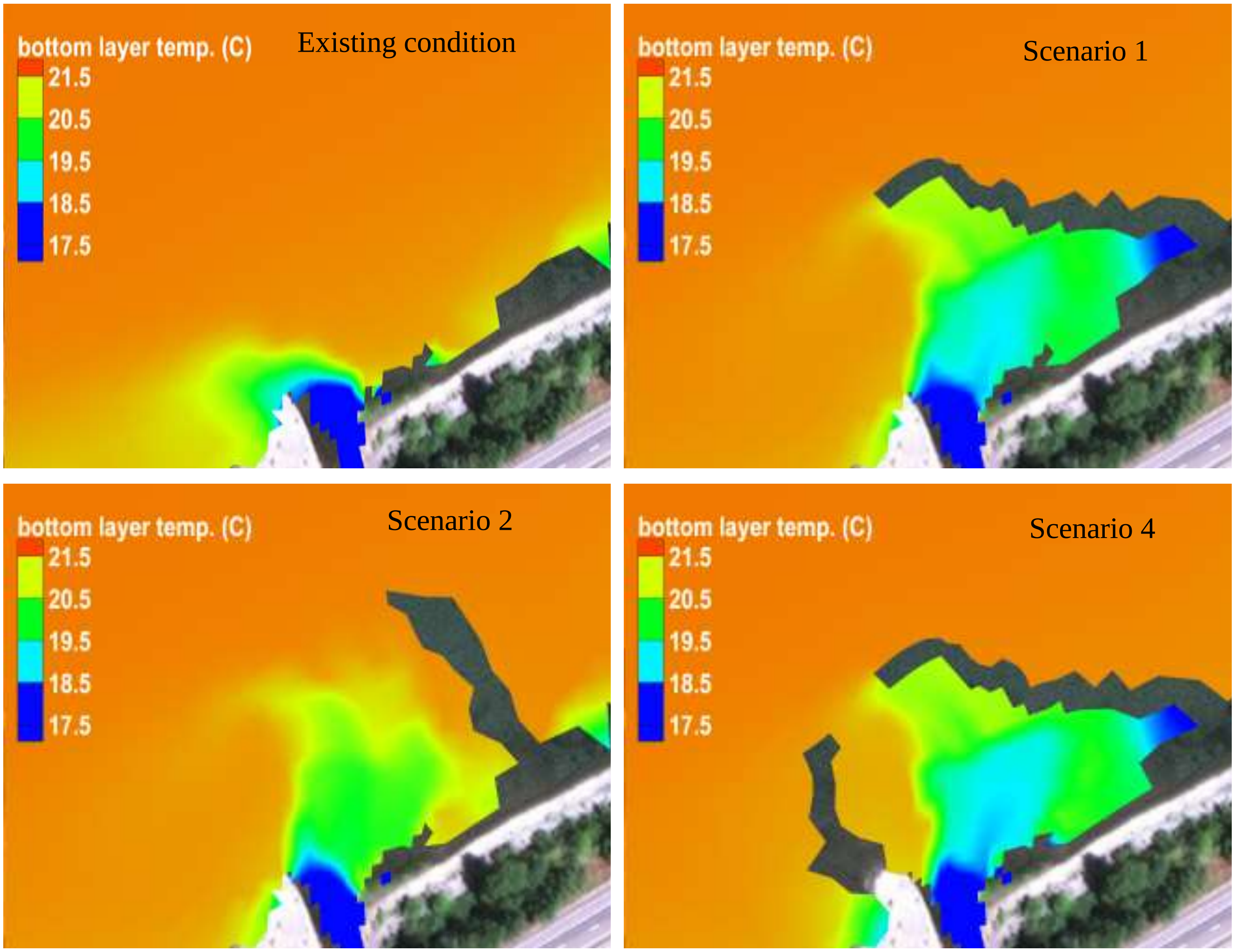


Figure 42. Simulated water temperatures at the Horsetail/Oneonta confluence, taken at a single model timestep, for the existing conditions model and plume enhancement scenarios 1, 2 and 4. Because Scenario 3 showed no change relative to Scenario 1, its results are not included.

At the model timestep used for output results shown in Figure 42, the plume extent for Scenario 4 appears nearly identical to that for Scenario 1, indicating no additional benefit of including the downstream structure. However, comparison of water temperature results over time provides additional insight. Figure 43 compares time series of water temperature for scenarios 1 and 4, at two locations (Figure 44). Results indicate slightly colder temperatures for Scenario 4 relative to Scenario 1 for both locations. This slight difference may not be enough to justify additional cost of adding the downstream structure. However, further analysis of the effect of varied boundary condition forcing shows that under some conditions, this structure may provide additional benefit. Figure 45 shows simulated water temperatures for Scenario 4 under three different wind forcing conditions: the recorded (true) gage wind; no wind; and two times the recorded gage wind. Results indicate different temperature response for the three conditions. While the scope of this project did not allow for a full analysis of these types of effects, these results indicate that such factors should be taken into consideration in future design phases.

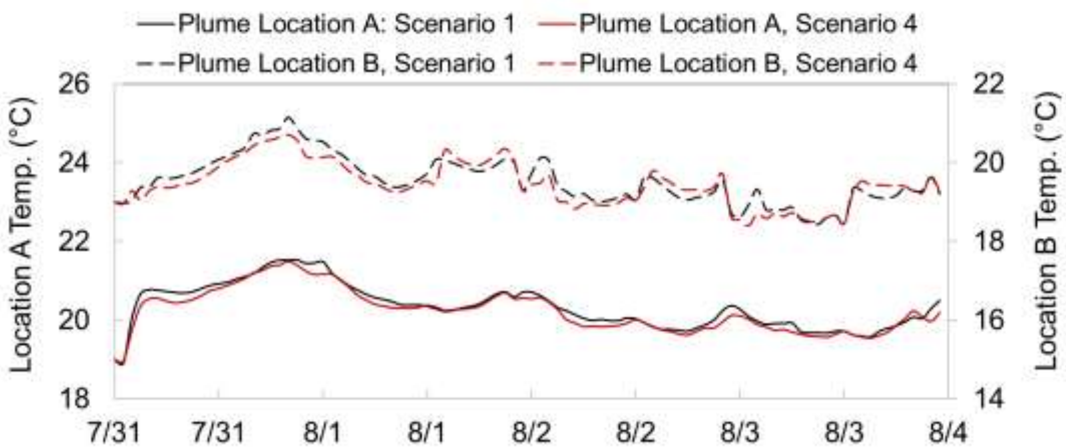


Figure 43. Simulated water temperature measured at two discrete locations, for Scenario 1 (black lines) vs. Scenario 4 (red lines). Results are plotted on separate axes for simplification of viewing.

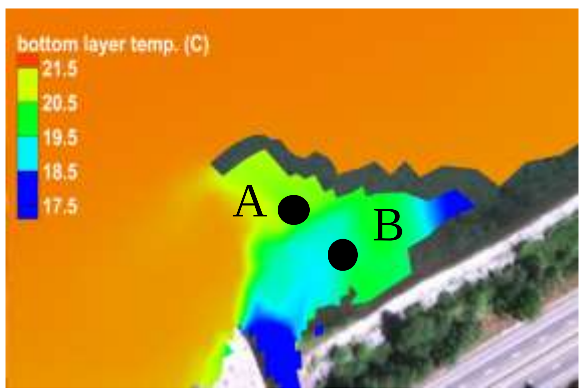


Figure 44. Water temperature measurement locations for results shown in Figure 40 (Scenario 1 shown).

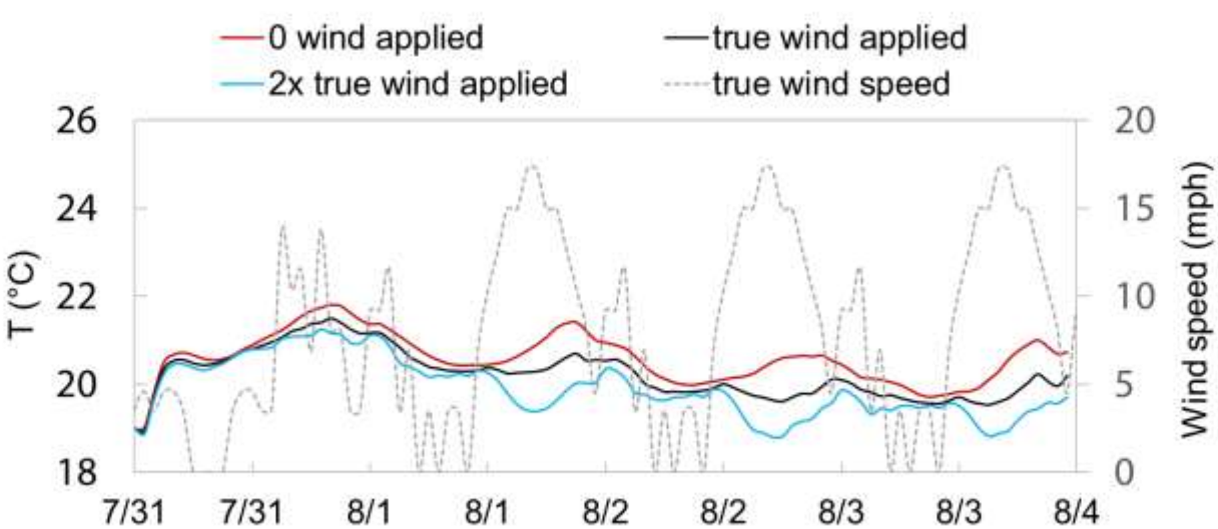


Figure 45. Effect of applied wind speed on simulated confluence temperature for Scenario 4. Simulated temperatures were coldest during periods of maximum wind speed.

B. Multnomah/Wahkeena confluence

Flow patterns from the 2D model also revealed eddy formation upstream and downstream of the existing Multnomah/Wahkeena confluence due to interaction with lateral landforms (Figure 46). As with the Horsetail/Oneonta simulations, a strategy of isolating the confluence from entrainment of warm water by these eddies was followed. The alluvial fan feature present at this confluence is moderately dynamic (despite an altered sediment regime), and ample evidence exists that the stream is relocating to the north. Currently, the outlet has begun to deviate from its eastern outlet, having cut a secondary outlet to the northeast (Figure 38b). It likely will inhabit both of these channels for some period. Because of this, we evaluated scenarios with two alternate channel outlets - to the north; and to the west - as part of the strategy for this confluence.

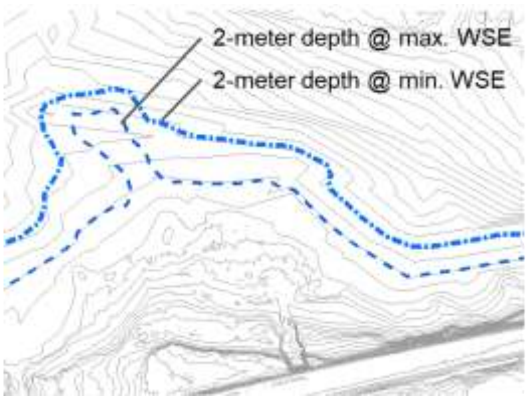
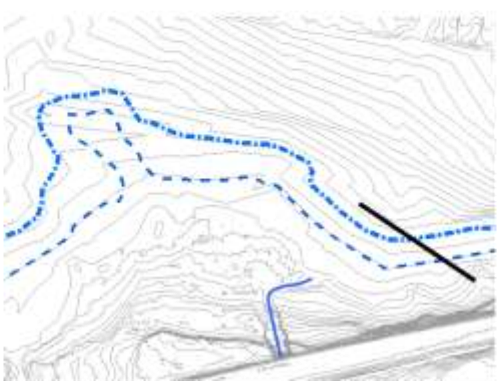


Figure 46. Elevation contours (left), and simulated 2D flow patterns (right) at the Multnomah/Wahkeena tributary confluence. Eddy formations influenced by landforms normal to the shoreline are evident, and guide structure placement. Also shown on the left, in blue, are the 2-meter depth contours at max. and min. WSE during the simulation period (see Figure 35).

The following strategy was used to test the effectiveness of plume enhancement at the Multnomah/Wahkeena confluence.

1. Scenario 1: single upstream structure angled along shoreline (Figure 47, left). This structure begins at a small protruding landform located upstream of the confluence and extends downstream roughly parallel to the 2-meter depth contour range, to just beyond the confluence.

2. Scenario 2: full structure placement surrounding the confluence. Additional placement of the downstream structure further isolates the confluence zone from mainstem flows, relative to Scenario 1.



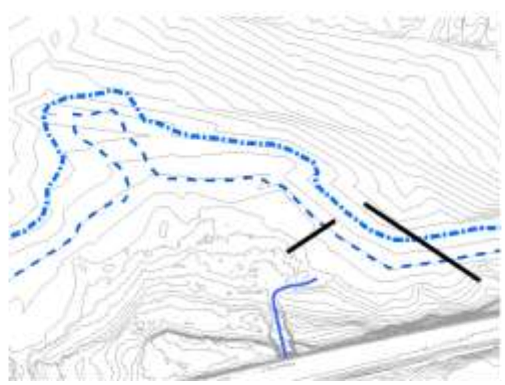


Figure 47. Scenario 1 (left) and 2 (right) structure placements for the Multnomah/Wahkeena confluence.

3. Scenario 3: tributary outlet oriented to the west, no structures (Figure 48, left). This scenario tests the effectiveness of enhancing cold-water plume formation through utilization of an existing landform (in this case, the alluvial fan), with no additional structure placement. In this orientation the existing alluvial fan potentially shields the confluence from the energy of mainstem flows and promotes retention of cold water at the confluence.

4. Scenario 4: tributary outlet oriented to the west + added downstream structure (Figure 48, center). Placement of the small structure downstream of the re-located confluence further isolates the confluence zone from the large eddy formation downstream of the alluvial fan.

5. Scenario 5: tributary outlet oriented to the west + full structures (Figure 48, right). Additional placement of the structure upstream of the re-located confluence fully isolates the confluence zone from the mainstem. For this scenario, the natural alluvial fan feature is no longer acting as the upstream barrier.

Figure 48. Scenario 3 (left), 4 (center), and 5 (right) structure placements for the Multnomah/Wahkeena confluence.

6. Scenario 6: tributary outlet oriented to the north, full structures (Figure 49, left). This scenario was tested due to the natural trajectory of the tributary outlet, which has been trending north from its current eastern orientation. It was assumed that full structures would be required for this scenario, due to exposure to mainstem flows at this location.

7. Scenario 7: tributary outlet oriented to the north, full structures extended, (Figure 49, right). This scenario increases isolation from mainstem flows, by extending the length of the upstream structure.

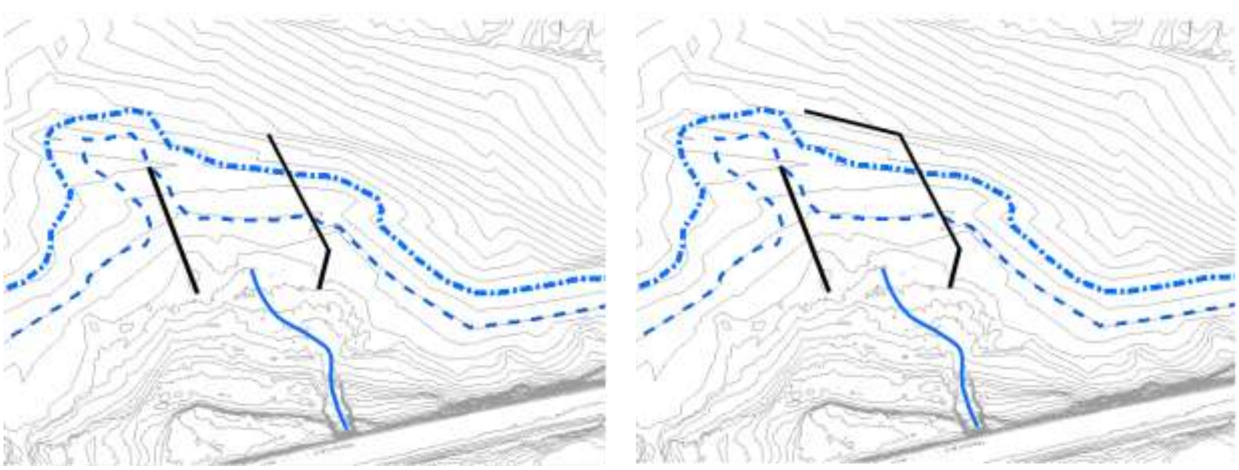
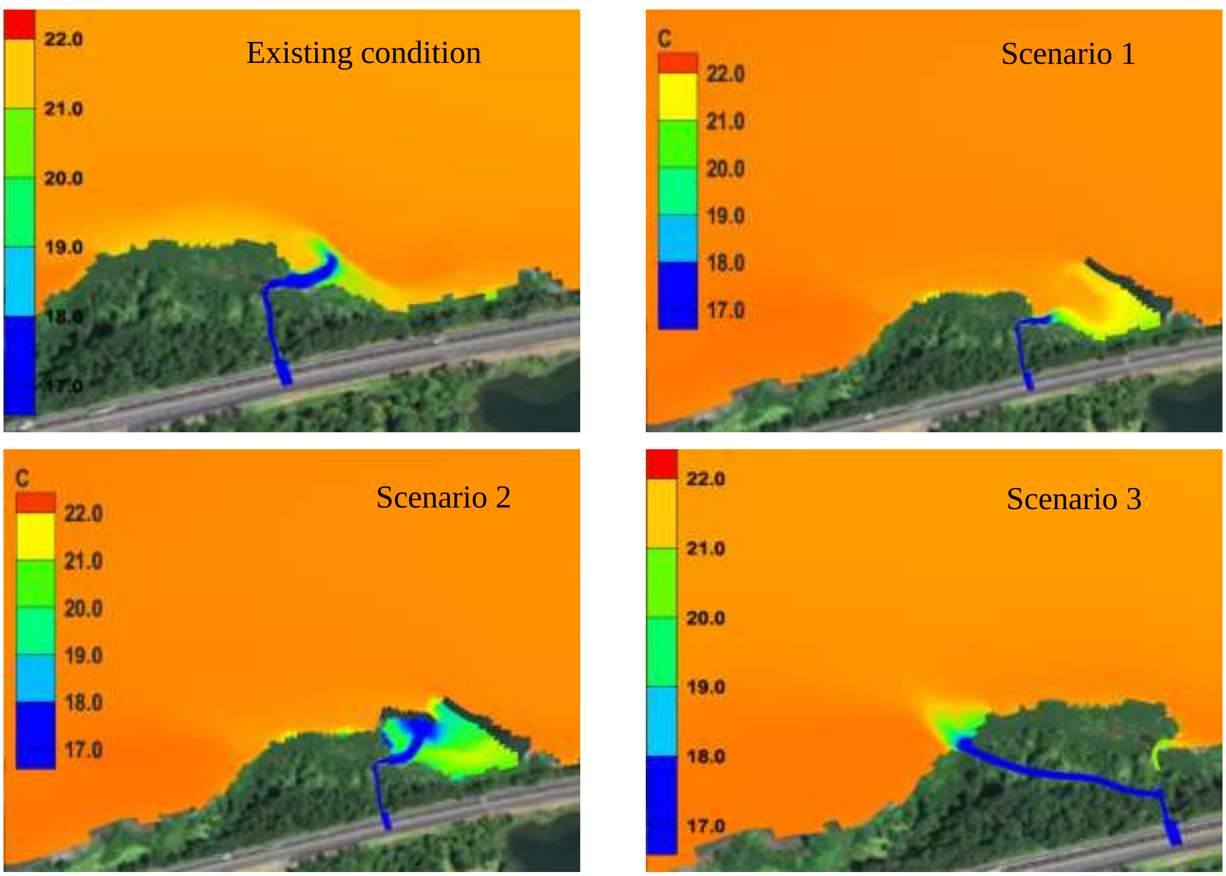


Figure 49. Scenario 6 (left) and 7 (right) structure placements for the Multnomah/Wahkeena confluence.

Simulated water temperatures at the Multnomah/Wahkeena confluence for given plume enhancement scenarios and the existing condition are shown in Figure 50. As seen in the Horsetail/Oneonta simulations, plume extents and temperatures were highly dynamic in response to changing forcing factors, and so all outputs shown are from the same model timestep, to maintain consistency for comparison.

Based on model results, all three tributary outlet orientations exhibited significant plume enhancement given adequate shielding from mainstem flows. For the existing (eastern) orientation, a single upstream structure (Scenario 1) was seen to be inadequate to maintain cold plume temperatures. Rather, the confluence must be more fully shielded with the inclusion of a downstream structure (Scenario 2), to allow plume formation. Project scope did not allow for fully evaluating the maximum potential plume size, however the structures that were modeled resulted in an increase of the extent of water colder than 20°C from approximately 2,500 m^2 for the existing condition to 14,800 m^2 for Scenario 2.

Both alternate outlet orientations (west and north) also required an upstream and downstream structure to promote cold-water plume formation. Again, the maximum potential plume size was not tested for either scenario, but the structures that were tested resulted in plume sizes of approximately 23,300 m^2 and 24,200 m^2 respectively for Scenarios 5 and 7 (the measured extent of water colder than 20°C). Both are significantly larger than plume formation under the existing condition (~2,500 m^2). Scenario 6 showed limited plume formation (6,800 m^2 max. area), indicating that the fully extended upstream structure tested in Scenario 7 is necessary for this stream outlet orientation.



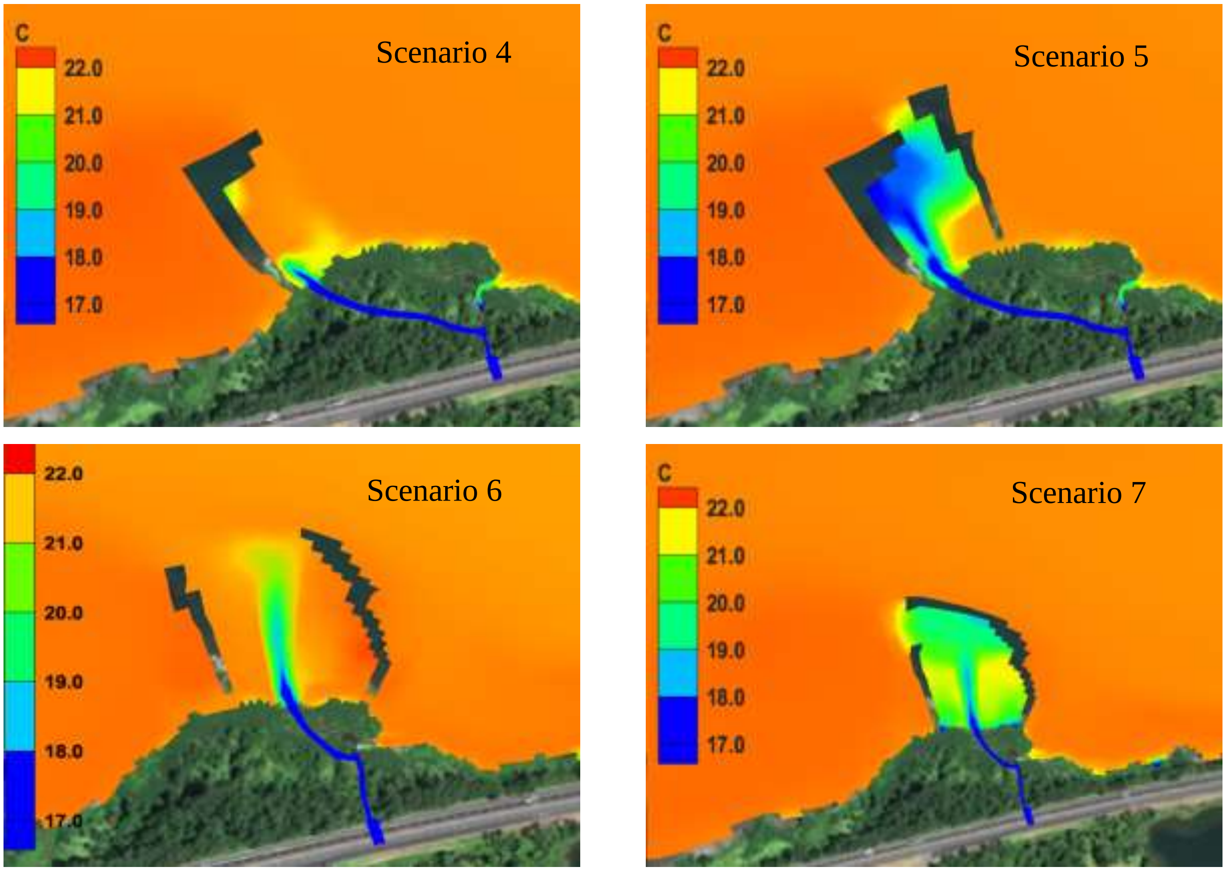


Figure 50. Simulated water temperatures at the Multnomah/Wahkeena confluence, taken at a single model timestep, for the existing conditions model and Scenarios 1–7 as described above.

C. Bridal Veil Creek confluence

Flow patterns from earlier 2D simulations did not indicate significant eddy formation near the alluvial fan feature where the Bridal Veil Creek confluence is located. (Figure 51). Based on this observation the enhancement strategy for this confluence was aimed at minimizing length of structures and using existing landforms for mainstem shielding. We evaluated plume formation at the existing confluence location and an alternate orientation with the outlet re-directed to the north. Although the current orientation appears stable, re-routing to the north eliminates the sharp bend near the confluence and the resulting potential for future natural relocation.

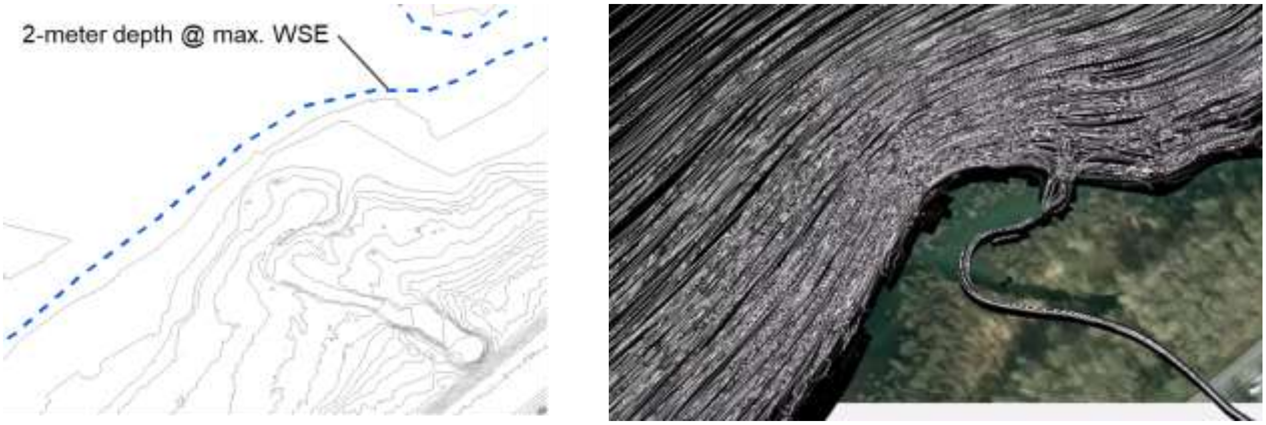


Figure 51. Elevation contours (left), and simulated 2D flow pattern (right) at the Bridal Veil Creek tributary confluence. Also shown on the left, in blue, is the 2-meter depth contour at max. WSE during the simulation period. The 2-meter depth contour at min. WSE is beyond the map extent (see Figure 36).

The following strategy was followed for testing the effectiveness of plume enhancement at the Bridal Veil Creek confluence.

1. Scenario 1: single upstream structure angled along shoreline (Figure 52, left). This structure begins at an existing small protruding landform located upstream of the confluence and extends out and slightly downstream to the 2-meter depth contour, just beyond the existing confluence.

2. Scenario 2: full structure placement surrounding confluence (Figure 52, right). Additional placement of the downstream structure further isolates the confluence zone from mainstem flows, relative to Scenario 1.

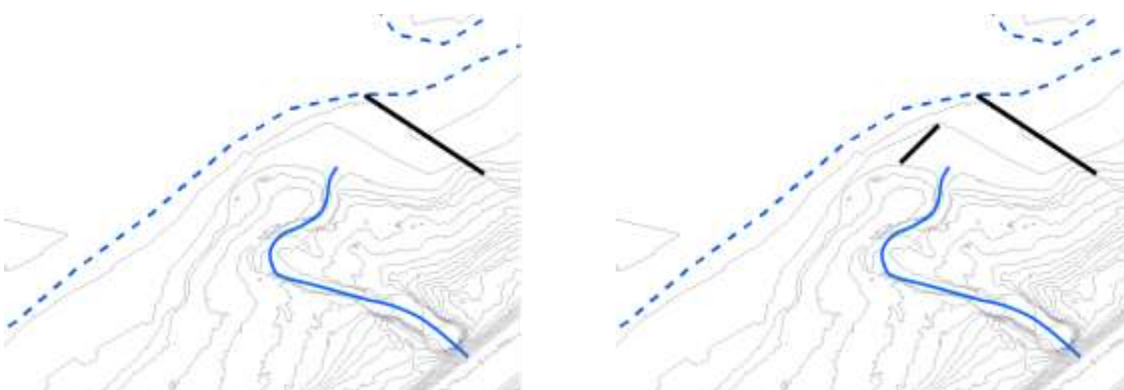


Figure 52. Scenario 1 (left) and 2 (right) structure placements for the Bridal Veil Creek confluence.

3. Scenario 3: tributary outlet oriented to the north, no structures (Figure 53, left). This scenario tests the effectiveness of enhancing cold-water plume formation through utilization of the existing alluvial fan to potentially shield the confluence from the energy of mainstem flows and promote retention of cold water.

4. Scenario 4: tributary outlet oriented to the north + upstream structure (Figure 53, right). Shielding provided by the existing alluvial fan is further enhanced with addition of a single diversion structure.

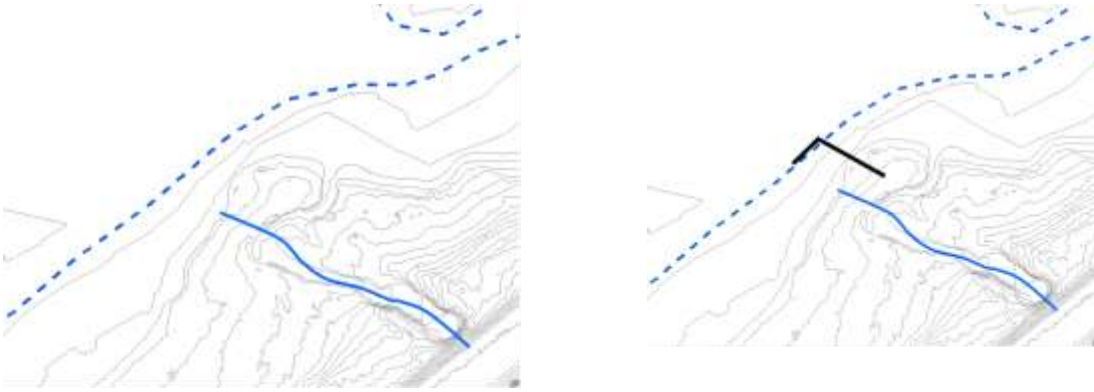


Figure 53. Scenario 3 (left) and 4 (right) structure placements for the Bridal Veil Creek confluence.

5. Scenario 5: tributary outlet oriented to the north + full structures (Figure 54, left). Provides maximum shielding from mainstem energy, for the re-located outlet.

6. Scenario 6: tributary outlet oriented to the north + full structures, larger embayment (Figure 54, right). Relative to Scenario 5, the size of the potential cold-water embayment is increased by placing structures further apart. This limited test for increasing plume size through enlargement of the created embayment size was only performed at this confluence location.

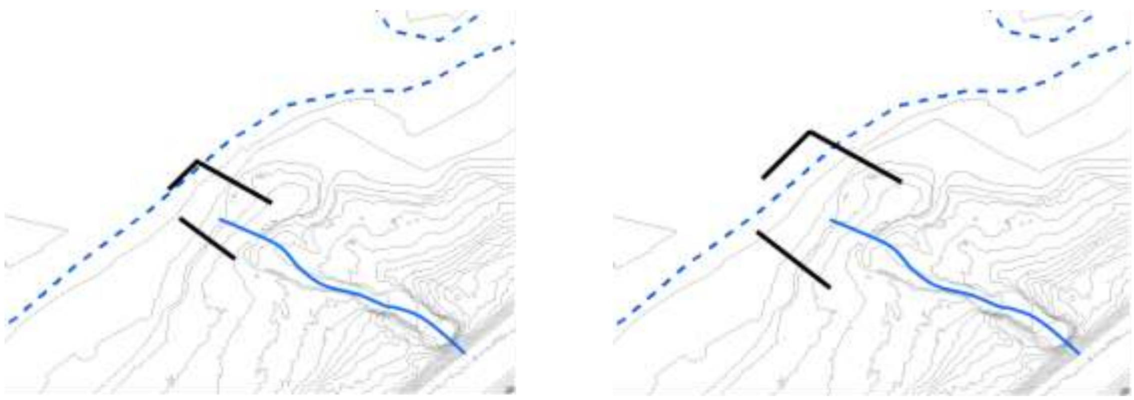
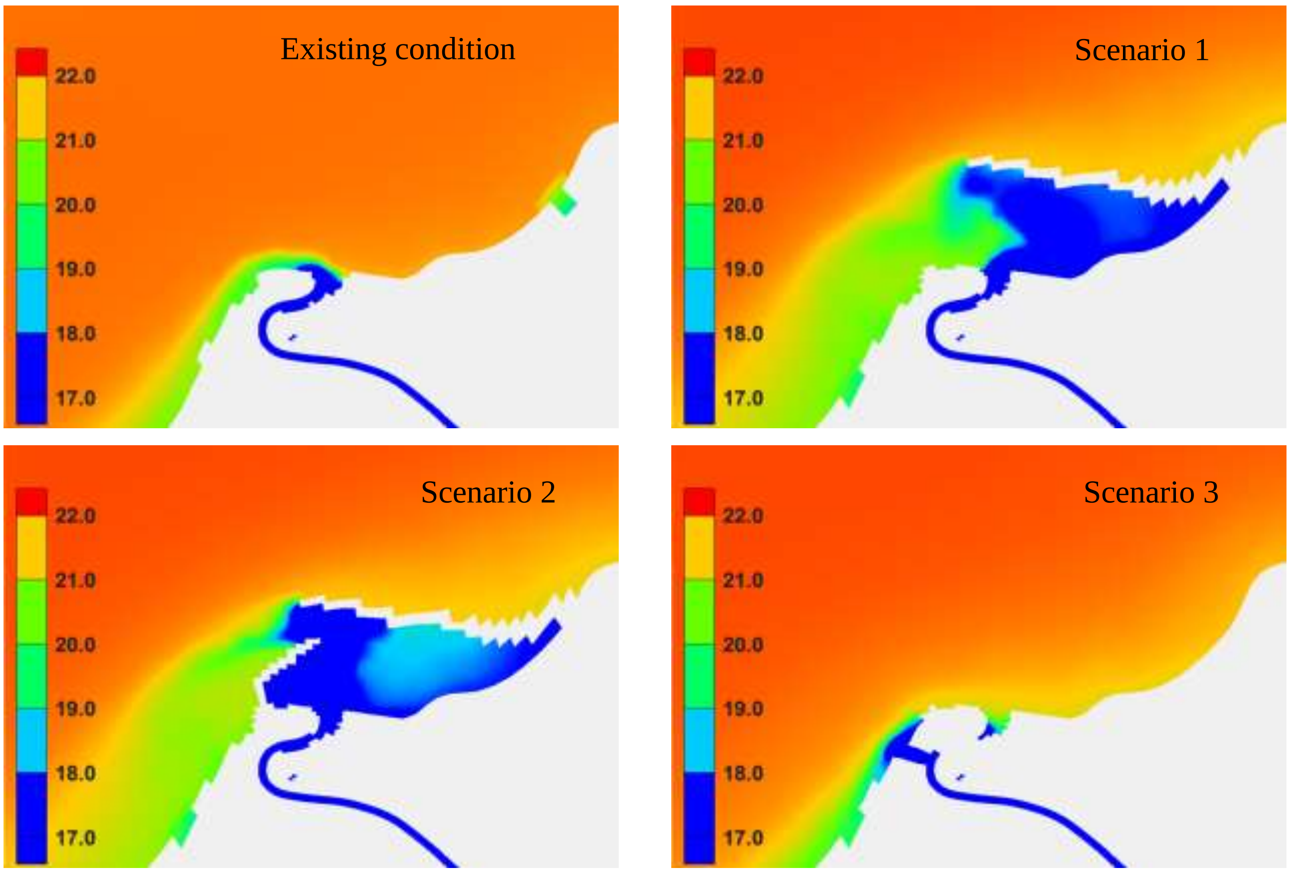


Figure 54. Scenario 5 (left) and 6 (right) structure placements for the Bridal Veil Creek confluence.

Simulated water temperatures at the Bridal Veil Cr. confluence for given plume enhancement scenarios and the existing condition are shown in Figure 55. As seen in the Horsetail/Oneonta and Multnomah/Wahkeena simulations, plume extents and temperatures were highly dynamic in response to changing forcing factors, and so all outputs shown are from the same model timestep, to maintain consistency for comparison.

Based on model results, both tributary outlet orientations exhibited significant plume enhancement given adequate shielding from mainstem flows. For the existing (eastern) orientation, a single upstream structure (Scenario 1) was seen to be adequate to promote cold-water retention at the confluence. Addition of the downstream structure (Scenario 2) did not significantly enhance plume size or duration relative to Scenario 1. Maximum plume size (defined as the extent of water < 20°C) for Scenario 1 was approximately 15,100 m^2, compared to 15,800 m^2 for Scenario 2. Both are considerably larger than the maximum plume size of 4,200 m^2 seen for the existing condition.

For the north-oriented channel outlet, the alluvial fan by itself (Scenario 3) was seen to be inadequate for promoting cold-water plume formation. Further placement of an upstream structure (Scenario 4) resulted in some cold water retention (max. area of 10,000 m^2), and subsequent addition of a downstream structure (Scenario 5) increased enhancement (max. area of 15,500 m^2). A final simulation (Scenario 6) was performed for the north-oriented outlet to test the potential for increased plume size as the embayment size is increased. By placing diversion structures further apart, the resulting larger embayment retained cold water over its full extent, expanding the maximum plume size to 24,300 m^2. It is likely that plume sizes could be increased further in this manner at all tributary confluences included in this project, however the analysis was outside our scope. Furthermore, doing so may require longer structures, at higher cost. Finding the correct balance of structure length and plume size relative to cost will be addressed in future phases.



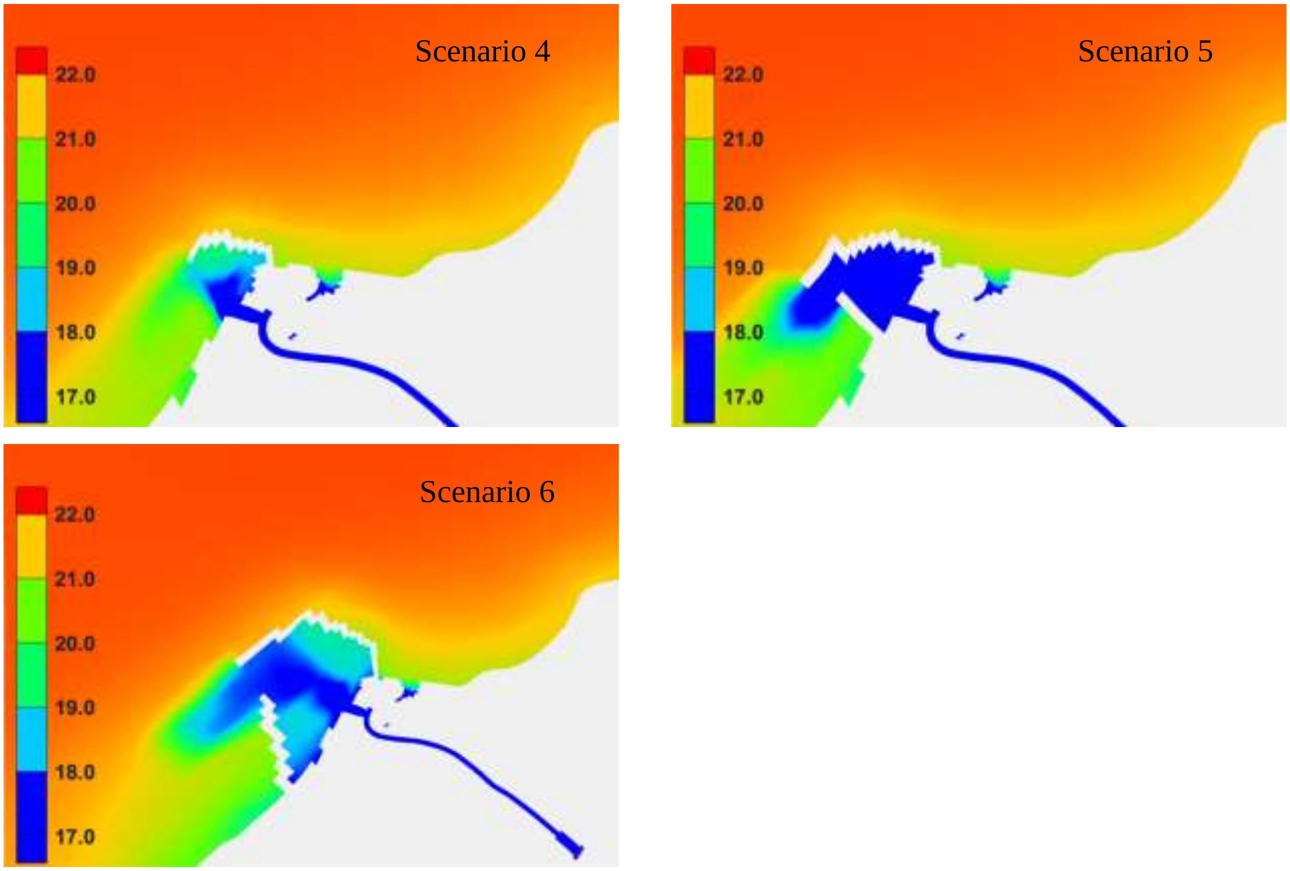


Figure 55. Simulated water temperatures at the Bridal Veil Creek confluence, taken at a single model timestep, for the existing conditions model and Scenarios 1–6 as described above.

Table 12 summarizes the effectiveness of simulated restoration scenarios in enhancing cold-water plume formation at the three tributary confluences evaluated in this study. Model results show that each confluence has the potential for a significant increase in cold water retention relative to existing conditions, given adequate shielding from mainstem flows. At the Horsetail/Oneonta and Bridal Veil confluences, a single upstream structure may be adequate in promoting cold water retention, while at Multnomah/Wahkeena it appears that the confluence must be further isolated by an additional downstream structure, for all stream outlet orientations tested.

Table 12. Summary of maximum cold-water plume extents[1] at modeled tributary confluences, for existing conditions and all restoration scenario simulations.

Confluence	Condition	Approximate maximum cold-water plume area (m^2)	Approximate maximum cold-water plume volume[2] (m^2)
Horsetail/Oneonta	Existing condition	550	11,800
	Scenario 1	4,100	61,300
	Scenario 2	2,100	32,400
	Scenario 4	4,000	58,100

Multnomah/Wahkeena	Existing condition	2,500	45,400
	Scenario 2	14,800	266,100
	Scenario 5	23,300	438,300
	Scenario 6	6,800	125,300
	Scenario 7	24,200	478,000
Bridal Veil	Existing condition	4,200	71,800
	Scenario 1	15,100	246,500
	Scenario 2	15,800	254,800
	Scenario 4	10,000	187,500
	Scenario 5	15,500	279,000
	Scenario 6	24,300	414,000

Notes:

1. Maximum plume extent is defined as the area (or volume) of water < 20°C at any given model time step.
2. Measured plume volumes are based on limited bathymetric information in the model and should only be considered relative to other model conditions.
3. Results for scenarios that did not result in significant cold-water plume enhancement are not included.
4. It is likely that for scenarios where cold-water plume enhancement was seen, larger areas and volumes would result with diversion structures spaced further apart to form larger embayments. This was only evaluated on a limited basis in this study.

Discussion, Phase 3

This phase of the Lower Columbia River Thermal Refuge Study evaluated strategies for enhancing cold-water retention at selected lower Columbia Gorge tributary confluences, to provide thermal refuge for summer migrating salmonid species. Previous phases of the study highlighted a significant lack of accessible thermal refuge habitat in the lower Columbia, with a gap of nearly 60 miles between the Lewis River and Eagle Creek, the next accessible upstream refuge zone. Enhancing cold-water habitat at these lower Gorge tributary confluences would provide critical respite to salmonid species migrating during summer months when mainstem Columbia River temperatures are increasingly exceeding critical levels for these species, due to many factors, including climate induced warming.

Results of 3D hydrodynamic and water temperature modeling show that selected restoration scenarios have the potential to significantly increase the size of cold-water plumes at the three tributary confluences studied. Restoration scenarios that were tested resulted in increases in cold-water plume sizes ranging from 3–10 times larger than current extents under existing conditions. Techniques tested for increasing cold-water plume sizes involved isolating the confluence zones from warmer mainstem flows through a combination of placed flow diversion structures and manipulation of existing landforms where possible. At each confluence zone, a series of scenarios, each with a different combination of structures and landforms, were modeled, and resulting water temperatures were compared to those from the existing conditions simulation, to evaluate the effectiveness of the scenario in increasing cold-water plume size. Selected scenarios were iterative, with structure placements guided by results of prior scenarios tested.

While model results indicate promise for enhancing thermal refuge zones at lower Gorge tributary confluences through the placement of flow diversion structures, several key aspects related to the feasibility of constructing such structures were either not considered, or addressed on a limited basis, in this study. These must be addressed in future phases of development, and include the following:

- Structure Type

  All flow diversion structures that were tested as part of various restoration scenarios were represented as continuous, solid (non-porous) features in the hydrodynamic model, analogous to a levee, or wall. While fulfilling the primary intent of modifying local hydraulics to enhance plumes of cold water, other potential habitat benefits to salmonids, as well as potential cost savings, may not be realized through actual implementation of this structure type. The benefit of large wood and riparian vegetation to stream and river ecosystems is well documented. Less well documented, but known, is that the lower Columbia River historically contained large (even channel spanning) wood jams and other complex physical features. The modern river is a homogenous system that almost completely lacks these features. Therefore, secondary objectives of project design will be to provide physical habitat features such as hydraulic refugia, cover from predators, and overhanging vegetation. This will be very important, particularly when considering the potential of these structures to *attract* predators such as sea lions and piscivorous birds.

  Evaluating the effectiveness of different structure types in diverting summertime mainstem flows and enhancing cold water retention at confluences, as well as in withstanding the erosive forces of mainstem flows year-round, was largely outside of the scope of this modeling study and will need to be considered as part of future design. We were able to begin some preliminary simulations of segmented structures, which upon initial inspection appear to have minimal negative impact on plume dynamics relative to the solid landforms. While this seems encouraging, further testing of this and other structure types such as dense wood jams will be required as part of future feasibility and design phases.

  Appendix B provides conceptual drawings of potential structure types and orientations which have been considered thus far in this study. As indicated, structures would be designed to serve multiple functions, including diversion of mainstem flows to allow plume formation, habitat creation for juvenile refuge, and overtopping to allow sediment scour behind structures. These concepts will be refined in future phases, as practical considerations for project implementation, as discussed herein, are addressed.

- Stability

  In addition to structural stability in withstanding high energy Columbia River flows, as related to structure type, we did not assess geomorphic stability associated with sediment infilling or channel avulsion as part of this study. All three confluence areas exhibit complex sediment dynamics with deposition from the tributary interfacing with the transport capacity of a major river. Future project phases will need to consider this complex dynamic, along with the effect that potential structures will have on it. The operating assumption is that these structures must be designed such that they will not require maintenance, e.g., dredging.

- Boundary Effects

  Based on limited simulation results, plume dynamics and resulting water temperatures were highly sensitive to variations in boundary forcing, including atmospheric effects. For example, we noted significant variations in plume temperatures for different wind forcing that was applied. The magnitude of response varied based on the selected scenario, and throughout the water column. This study allowed for only a limited assessment of such effects.

- Bathymetric Effects

  Field observations and model results indicate that bed topography (bathymetry) strongly influences plume dynamics and resulting plume temperatures. While we collected some bathymetric data at the tributary confluences chosen for this analysis, overall spatial resolution of the bathymetric model was low, and likely not fully representative of actual conditions. Although the model validation process did show good reproduction of observed water temperature at each confluence, for future analysis an updated, high resolution bathymetric survey of each confluence and surrounding mainstem zone is recommended.

- Cost

  A detailed cost assessment for feature types that could potentially be employed as flow diversion structures was outside the scope of this study phase. If, however, structure length is used as a proxy for approximate cost, model results can provide a rough estimate of the cost (i.e. structure length) to benefit (size and quality of cold-water plume) ratio of different restoration scenarios that were tested. Table 13 summarizes the approximate maximum cold-water plume areas measured for each scenario, along with the structure lengths modeled and resulting ratio of structure length to plume area. The lowest values are indicative of the highest benefit per unit structure length. For example, despite having similar maximum plume areas of ~4,000 m^2, Horsetail Oneonta Scenario 1 provides more benefit per unit length relative to Scenario 4 (0.029 versus 0.042) due to the shorter structure length required (120 m versus 170 m). Because our suite of selected restoration scenarios was limited by the scope of this study, it is possible that increased cost-benefit ratio could be obtained through other structure locations that were not tested. If similar length structures can be placed further apart to further increasing embayment sizes, while at the same time maintaining cold temperatures throughout, additional benefits will be obtained at no further cost. Other minor adjustments to the assessed alignments also may yield improved cost-benefit ratios. Maximizing the cost-benefit ratio in this, and other, manners will be assessed in future phases of this study.

Table 13. Relationship between maximum plume area[1] and relative length of modeled structures for restoration scenario simulations.

Confluence	Condition	Total structure length (m)	Approximate maximum cold-water plume area (m^2)	Ratio: structure length/ plume area
Horsetail/Oneonta	Scenario 1	120	4,100	0.029
	Scenario 2	70	2,100	0.033
	Scenario 4	170	4,000	0.042
Multnomah/Wahkeena	Scenario 2	160	14,800	0.011
	Scenario 5	260	23,300	0.011
	Scenario 6	400	6,800	0.058
	Scenario 7	270	24,200	0.011
Bridal Veil	Scenario 1	180	15,100	0.012
	Scenario 2	240	15,800	0.015
	Scenario 4	65	10,000	0.007
	Scenario 5	130	15,500	0.008
	Scenario 6	300	24,300	0.012

Notes:

1. Maximum plume area is defined as the area (or volume) of water < 20°C at any given model time step.
2. Results for scenarios that did not result in significant cold-water plume enhancement are not included.

While a detailed cost assessment was not done, rough cost estimates from prior, similar project types can be applied to derive conceptual cost estimates for these construction Scenarios. Table 14 outlines concept costs at two of the sites, for various scenarios.

Table 14. Concept cost estimates for selected scenarios from Table 13.

Horsetail/Oneonta confluence: Scenario 1 landform

Item	Qty	Unit $	Item $	Notes
Mobilization	1	$ 53,000	$ 53,000	~ 8% of fixed costs
Access, Diversion, De-watering, Env. Control	1	$ 99,000	$ 99,000	~15% of fixed costs
Earthwork	12,000 yds^3	$ 30	$ 360,000	
Large Wood	300 pcs.	$ 1,000	$ 300,000	200 roots, 100 piles
Contingency (30%)			$ 243,600	
		Subtotal =	**$ 1,055,600**	

Horsetail/Oneonta confluence: Scenario 4 landform

Item	Qty	Unit $	Item $	Notes
Mobilization	1	$ 84,000	$ 84,000	~ 8% of fixed costs
Access, Diversion, De-watering, Env. Control	1	$ 158,000	$ 158,000	~15% of fixed costs
Earthwork	20,000 yds^3	$ 30	$ 600,000	
Large Wood	450 pcs.	$ 1,000	$ 450,000	300 roots, 150 piles
Contingency (30%)			$ 387,600	
		Subtotal =	**$ 1,679,600**	

Multnomah Wahkeena confluence: Scenario 5 landform

Item	Qty	Unit $	Item $	Notes
Mobilization	1	$ 66,000	$ 66,000	~ 8% of fixed costs
Access, Diversion, De-watering, Env. Control	1	$ 124,000	$ 124,000	~15% of fixed costs
Earthwork	15,000 yds^3	$ 30	$ 450,000	
Large Wood	375 pcs.	$ 1,000	$ 375,000	250 roots, 125 piles
Contingency (30%)			$ 304,500	
		Subtotal =	**$ 1,319,500**	

Multnomah Wahkeena confluence: Scenario 5 creek re-route

Item	Qty	Unit $	Item $	Notes
Mobilization	1	$ 50,000	$ 50,000	~ 15% of fixed costs
Access, Diversion, De-watering, Env. Control	1	$ 50,000	$ 50,000	~15% of fixed costs
Earthwork	4,000 yds^3	$ 30	$ 120,000	
Large Wood	210 pcs.	$ 1,000	$ 210,000	140 roots, 70 piles
Contingency (30%)			$ 129,000	
		Subtotal =	**$ 559,600**	

Notes:
Unit costs are based on construction costs from previously constructed project types.

Next Steps

In view of current and predicted future summer temperatures in the Columbia River exceeding critical thresholds for migrating salmonids, combined with a significant lack of existing thermal refuge areas and a demonstrated potential for increasing these in the lower River, as outlined in this study, LCEP plans to initiate a pilot enhancement project at the Horsetail/Oneonta confluence. Of the three confluence zones that were assessed in Phase 3, this location is most suitable to initiate a project to test the effectiveness of placing flow diversion structures to enhance cold water plume formation, for the following reasons:

- Cost – Of the three sites evaluated, required structure lengths for suitable plume formation are shortest at Horsetail/Oneonta (Table 13) and therefore this site has the potential to be most cost-effective.

- Access – Relative to the other two confluences, the Horsetail/Oneonta confluence has the shortest distance to adult salmonid migratory depth contours of 2–10 meters, as communicated by Matt Keefer (Keefer 2017). While structures at each of these locations would be designed to access this migratory path, the short distance afforded by the Horsetail/Oneonta site puts it in the most direct path and requires the shortest length (i.e. less expensive) structures.

- Stability – Unlike the other confluences which occur at more active alluvial fan locations, the Horsetail/Oneonta channel location is relatively stable, which minimizes risk of project failure due to potential channel avulsion. Based on aerial photography interpretation the channel location, which is fixed by an outlet culvert under the I-84 interstate crossing, has remained in a stable location for several decades.

- Cumulative effects – LCEP has completed a suite of restoration actions in the floodplain reach of Horsetail/Oneonta creeks over the last decade, which have resulted in significant habitat improvements for juvenile salmonids and improved water quality at this site. Additional creation of thermal refuge habitat at the confluence zone would complement this work and provide cumulative benefits to multiple species and life stages of salmonids at the site.

In addition to addressing the technical aspects outlined in the Discussion above, several other practical considerations of project implementation (cost, permitting, hazard risk, construction access, etc.) will be addressed in the next stage of feasibility and design. Assuming project implementation achieves the intended benefit of increasing thermal refuge, as predicted by the Phase 1 study, the other sites will be evaluated for project implementation in future years.

This study has highlighted the importance of cold-water habitat to summer migrating Columbia River salmonids, and the present lack of it throughout a large portion of the lower river. We present a potential enhancement technique for using the limited existing sources of cold water to create zones of thermal refuge that would be suitable for use by these endangered stocks. If the technique proves successful, and if mainstem temperatures continue to increase as predicted, the habitats they create will fill a significant gap in the lower River, providing critical areas of refuge that function similar to larger upriver zones where significant salmonid use has been documented.

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APPENDIX A

Site Maps of Lower Columbia Gorge Tributaries Monitored During the Lower Columbia River Gorge Thermal Refuge Study Phases 1 and 2

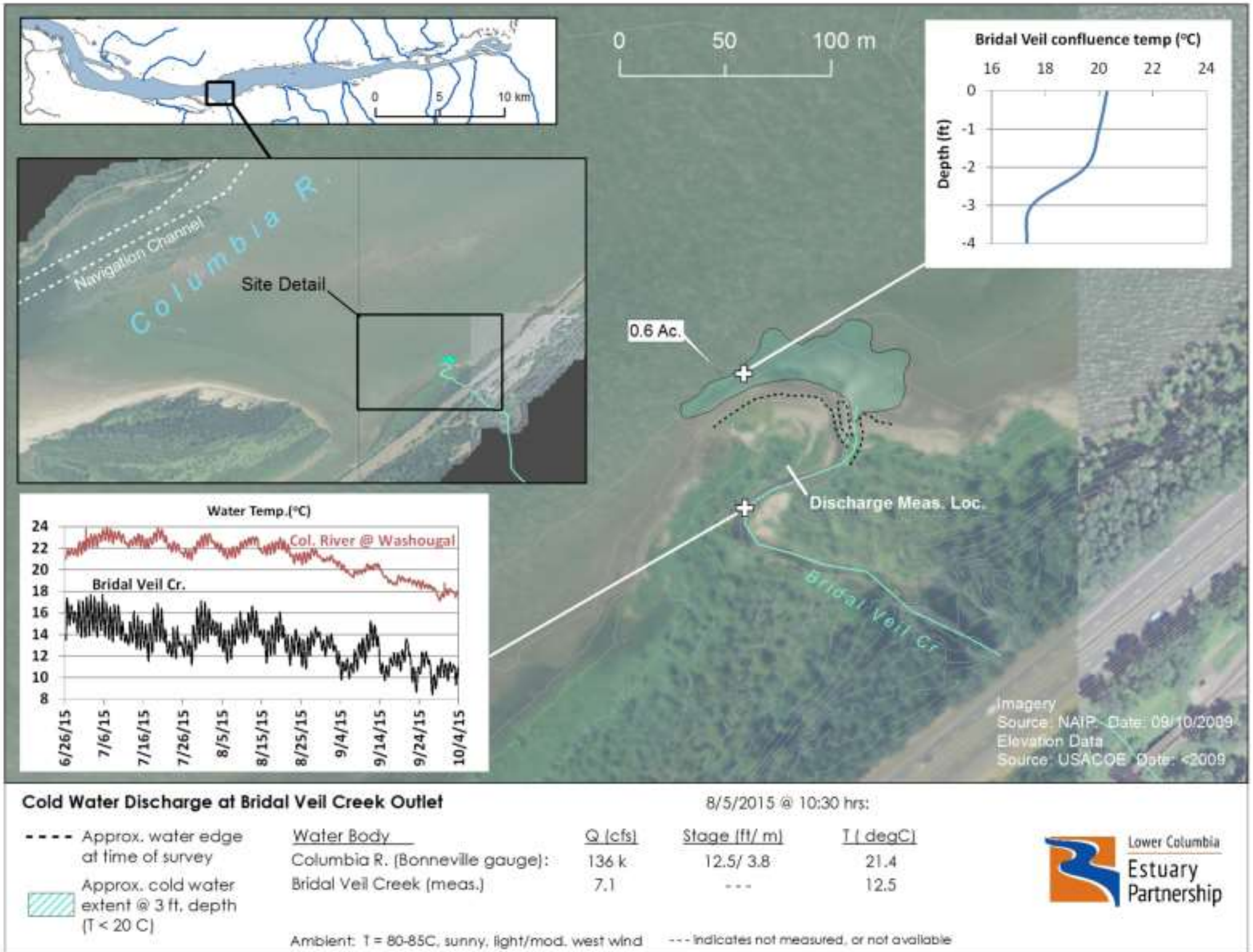


Figure A-1: *Bridal Veil Creek: Site map and results.*

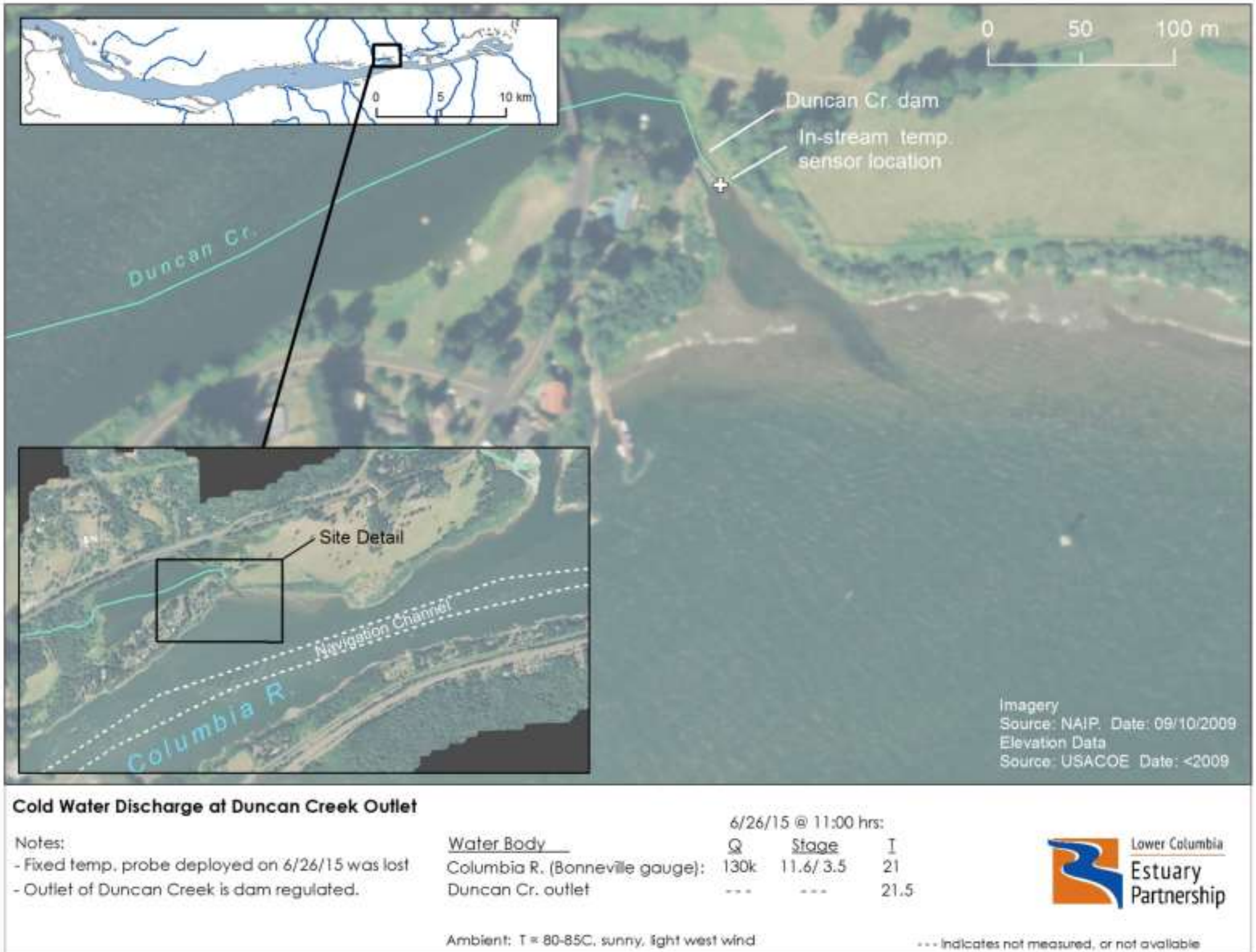
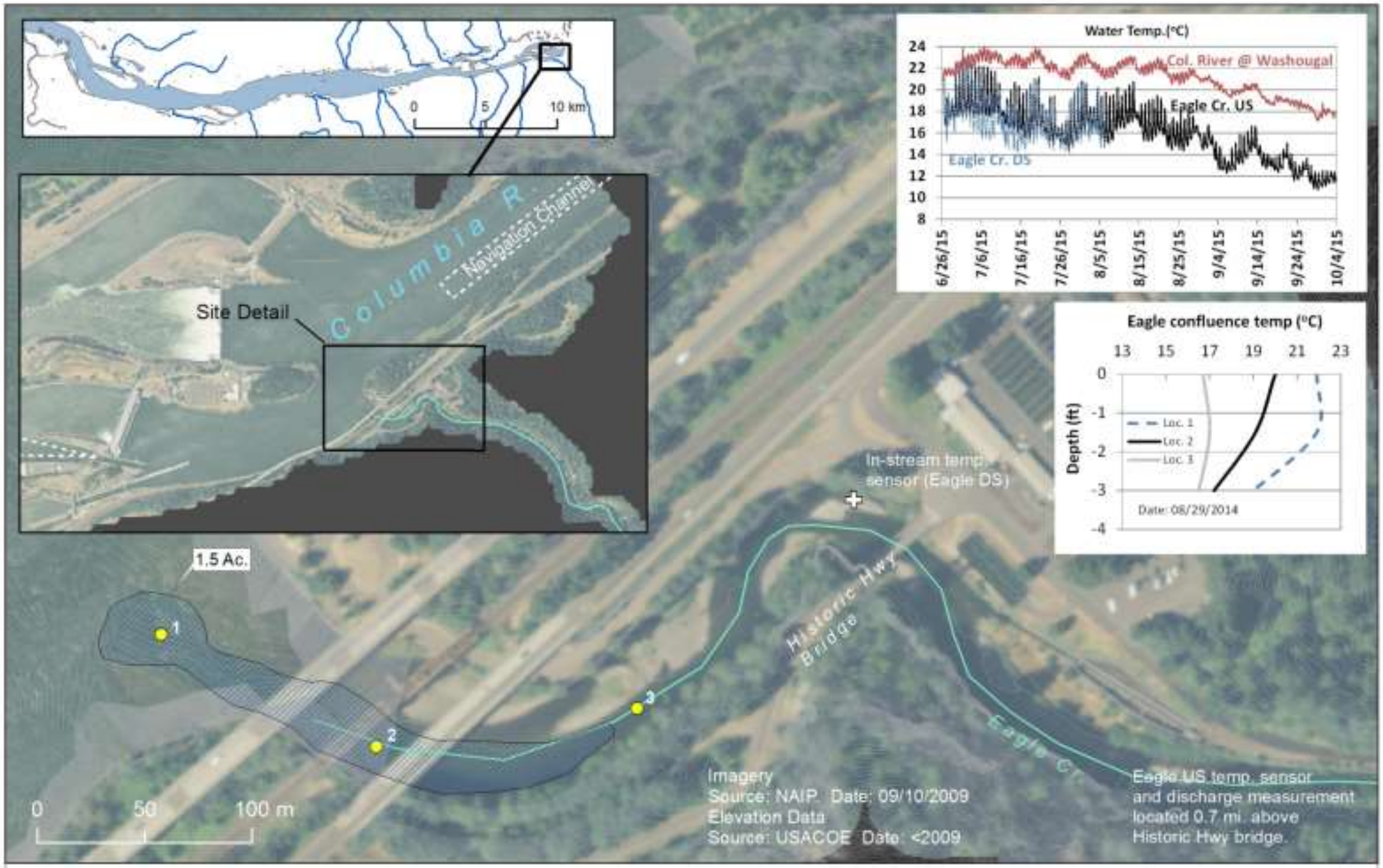


Figure A-2: *Duncan Creek: Site map and results.*



Cold Water Discharge at Eagle Creek Outlet

Approx. cold water extent @ 3 ft. depth (T < 20 C)

		8/29/14 @ 10:30 hrs:		8/11/15 @ 10:00 hrs:		
Water Body	Q (cfs)	Stage (ft/ m)	T (C)	Q	Stage	T
Columbia R. (Bonneville gauge):	---	74.6/ 22.7	24	---	74.8/ 22.8	22.2
Eagle Creek (meas.)	---	---	16.5	13.9	---	---

Ambient: T = 80-85C, sunny, light west wind

--- indicates not measured, or not available

Lower Columbia Estuary Partnership

Figure A-3: *Eagle Creek: Site map and results.*

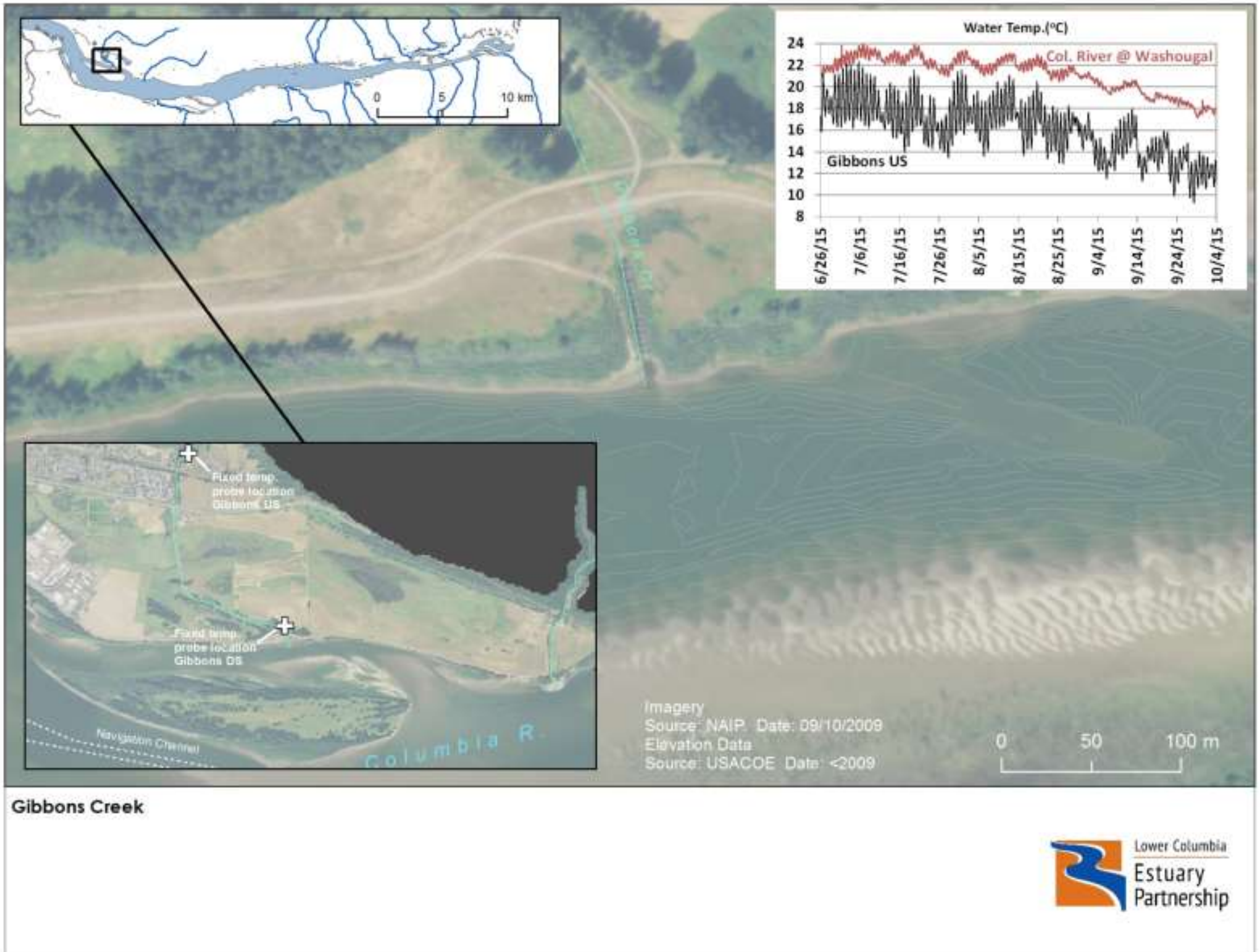
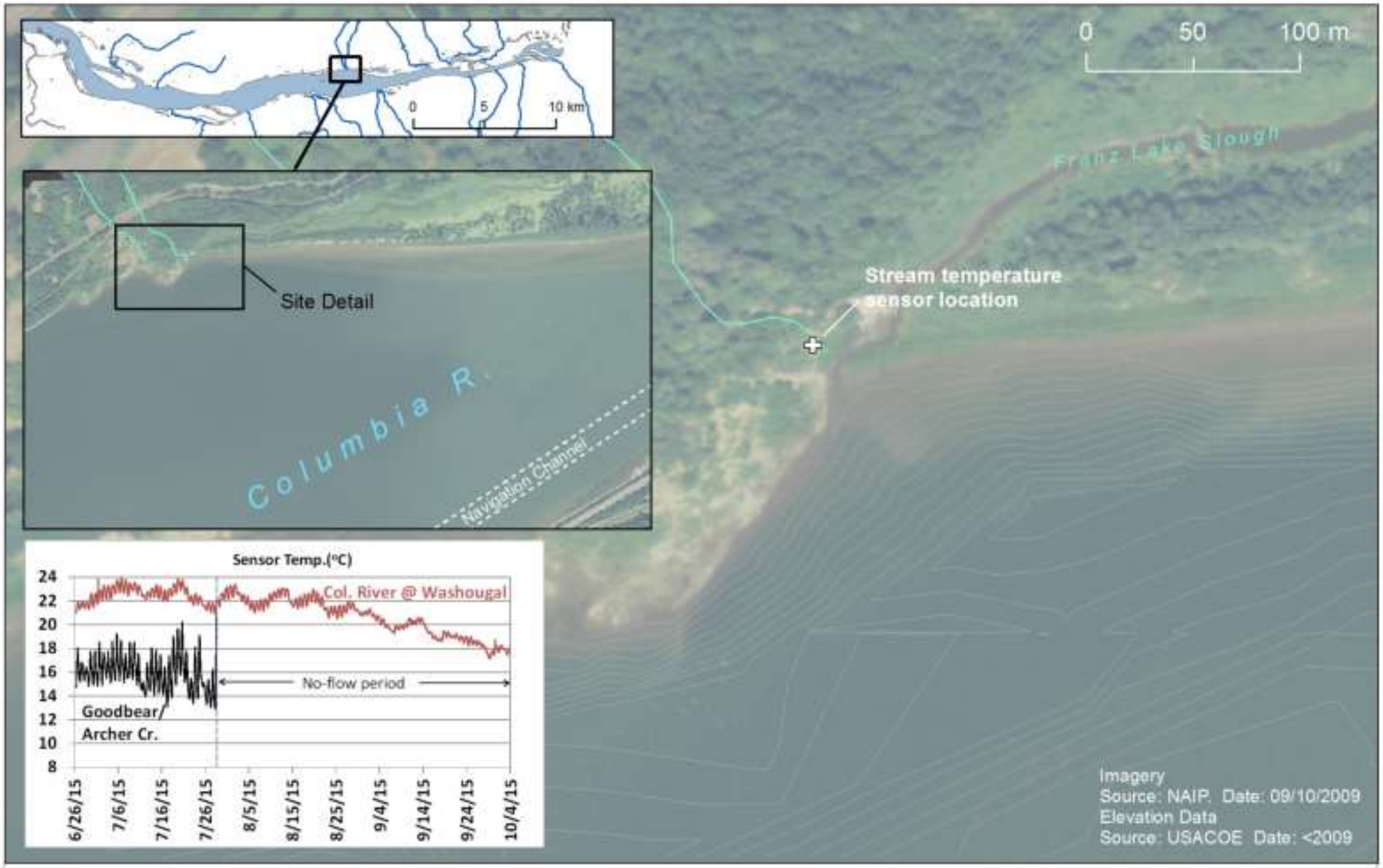


Figure A-4: *Gibbons Creek: Site map and results.*



Goodbear/Archer Creeks

Notes:
- Fixed temp. probe deployed 6/26/15.
- No stream flow detected during 8/7/15 survey. Sensor removed.

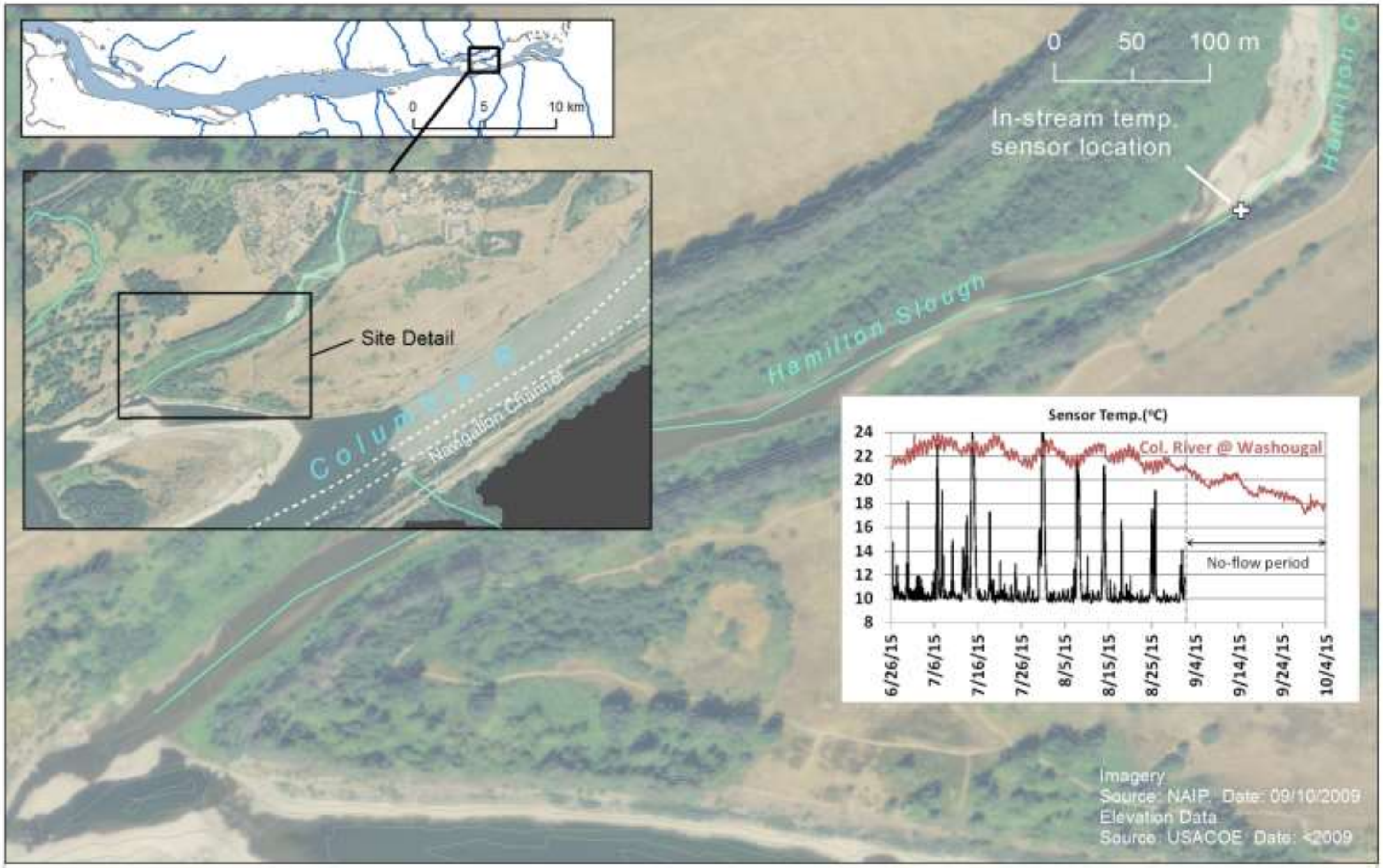
	6/26/15 @ 10:30 hrs:			8/7/15 @ 10:00 hrs:		
Water Body	Q	Stage	T	Q	Stage	T
Columbia R. (Bonneville gauge):	130k	11.6/ 3.5	21.1	140k	12.3/ 3.7	21.5
Goodbear Cr.	---	---	14.4	0	---	---

Ambient: T = 80-85C, sunny, light west wind

--- Indicates not measured, or not available

Lower Columbia Estuary Partnership

Figure A-5: *Goodbear/Archer Creek: Site map and results.*



Cold Water Discharge at Hamilton Creek Outlet

Notes:

- Hamilton Slough backwaterd by Columbia R.
- No measurable cold water plume at confluence of Hamilton Cr. and Hamilton Sl.

6/26/15 @ 13:00 hrs:

Water Body	Q	Stage	T
Columbia R. (Bonneville gauge):	142k	12.2/ 3.7	21
Hamilton Slough	---	---	21
Hamilton Creek	---	---	12.4

Ambient: T = 80-85C, sunny, light west wind

--- indicates not measured, or not available

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Figure A-6: *Hamilton Creek: Site map and results.*

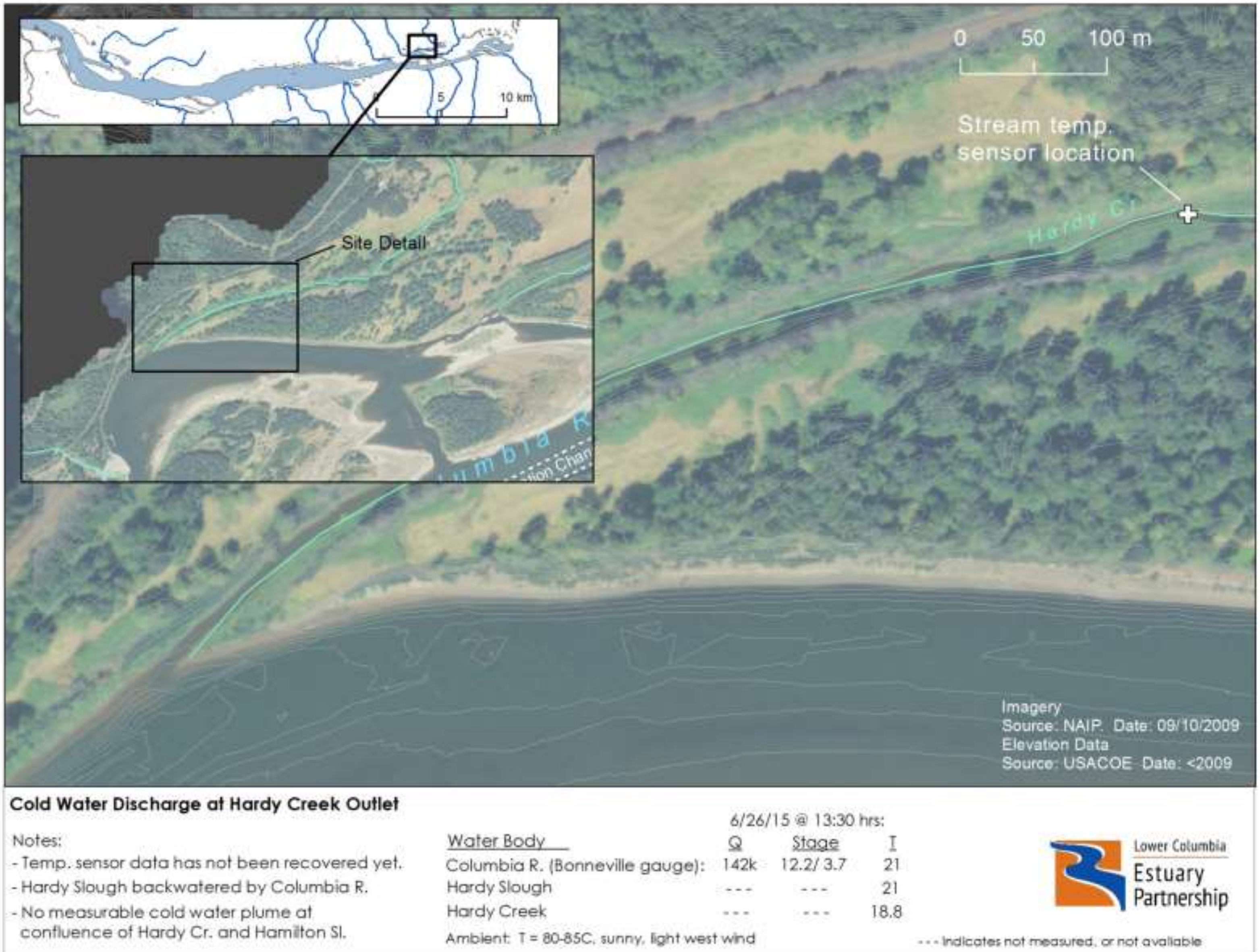


Figure A-7: *Hardy Creek: Site map and results.*

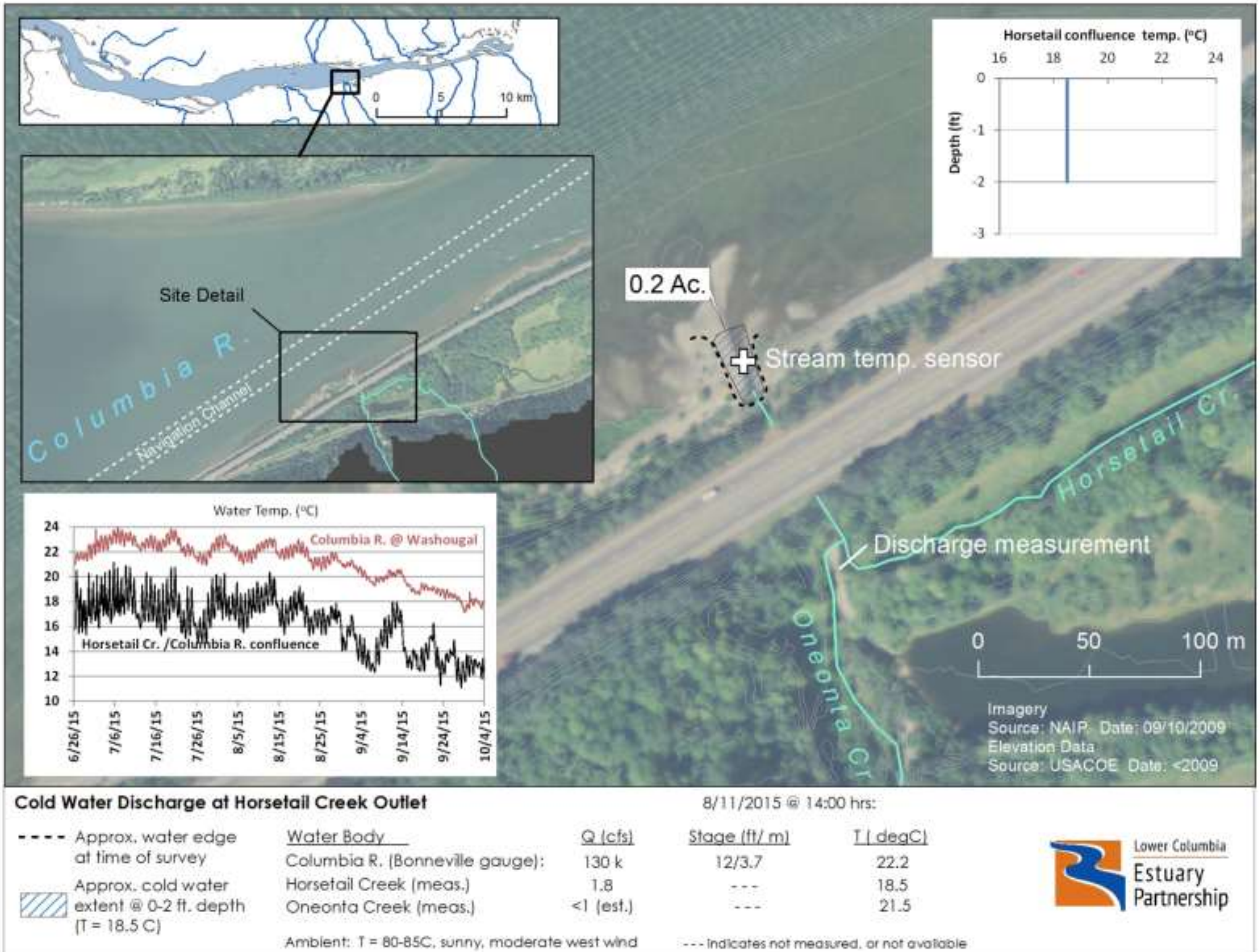


Figure A-8: *Horsetail/Oneonta Creek: Site map and results.*

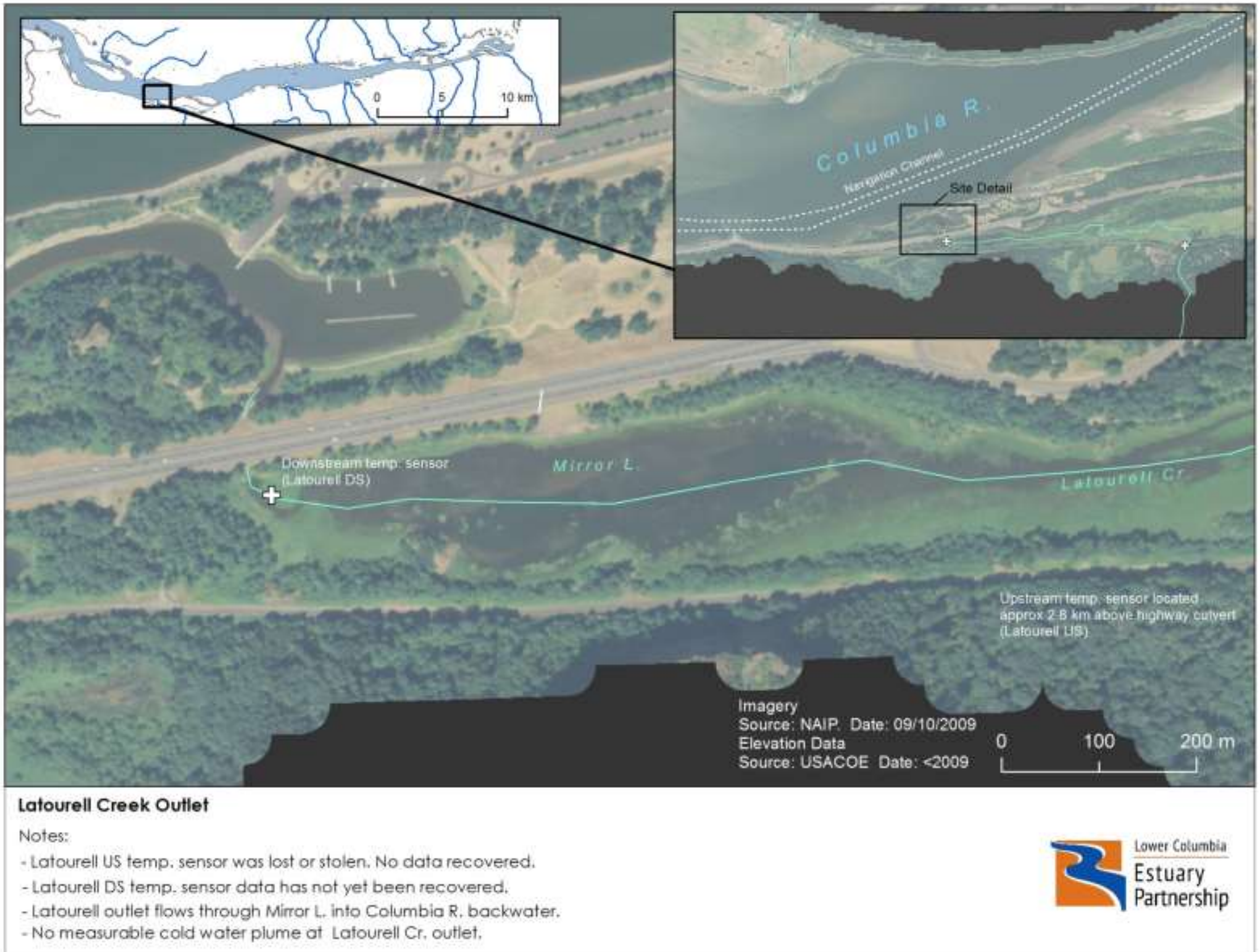
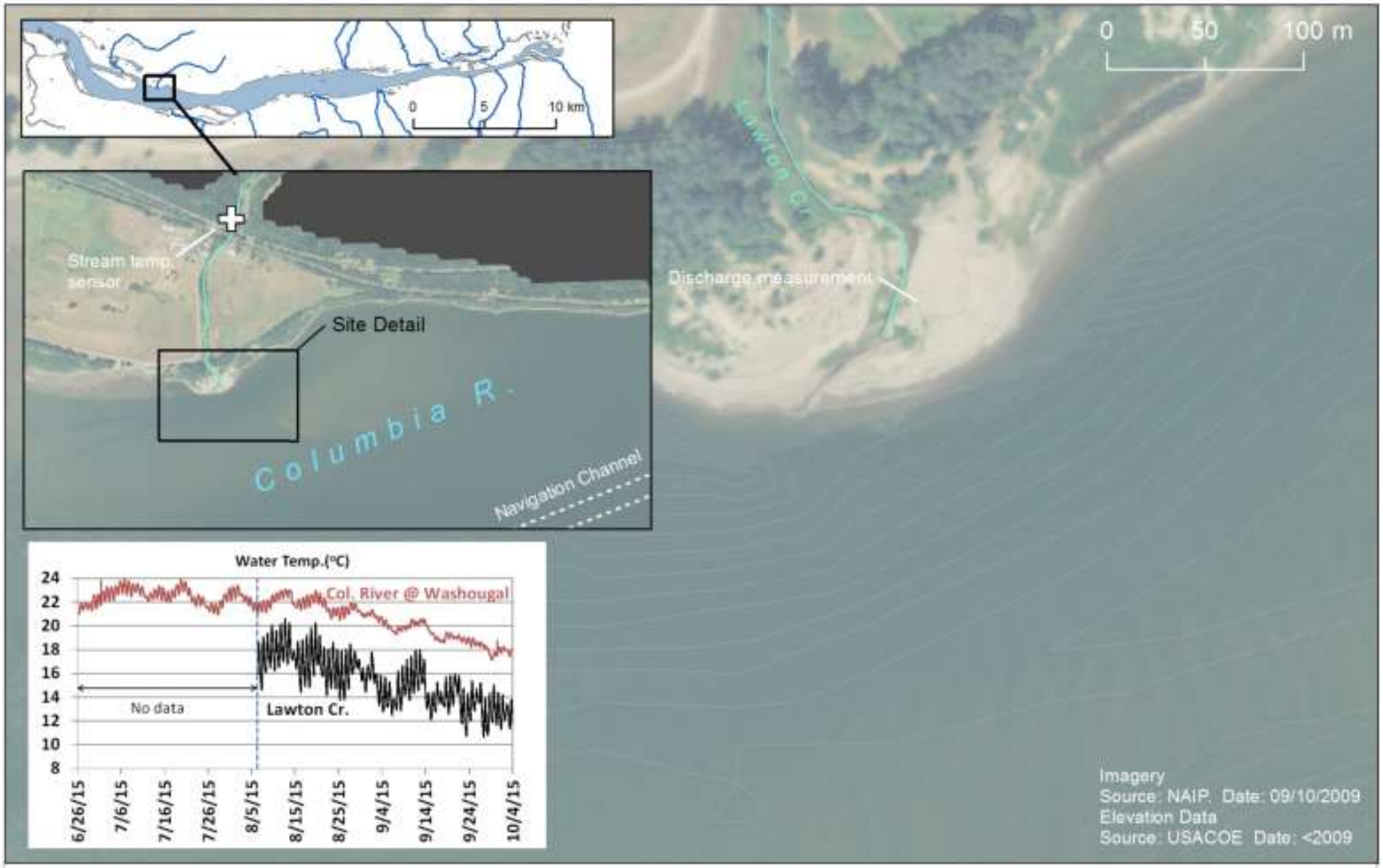


Figure A-9: *Latourell Creek: Site map and results.*



Lawton Creek

Notes:

- Fixed temp. sesnsor deployed on 6/26/15 was lost. Deployed second sensor on 8/6/15.

	6/26/15 @ 10:30 hrs:			8/6/15 @ 10:00 hrs:		
Water Body	Q	Stage	T	Q	Stage	T
Columbia R. (Bonneville gauge):	130k	11.6/ 3.5	21.1	140k	12.3/ 3.7	21.5
Lawton Cr.	- - -	- - -	15.7	1.5	- - -	15.5

Ambient: T = 80-85C, sunny, light west wind

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- - - Indicates not measured, or not available

Figure A-10: *Lawton Creek: Site map and results.*

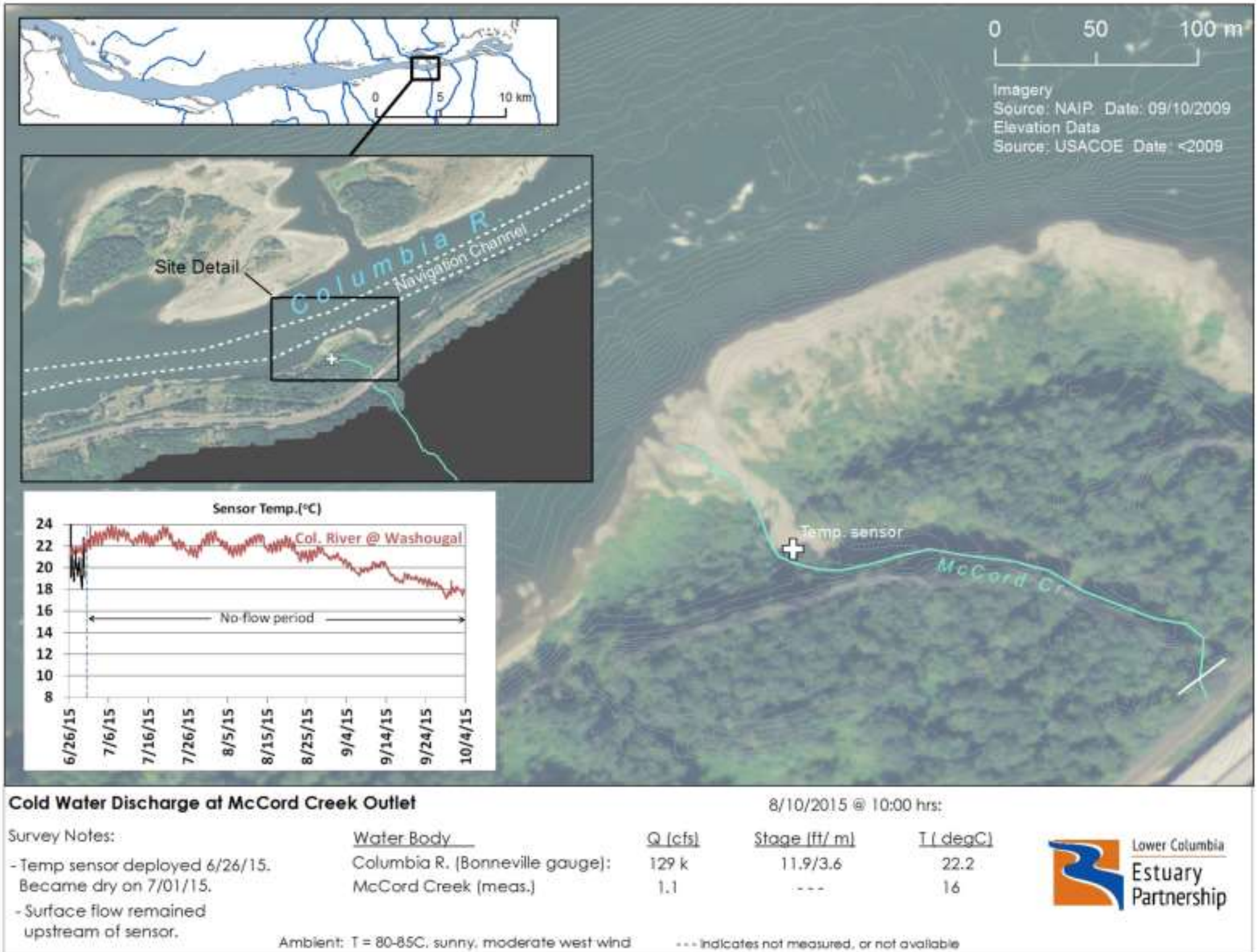
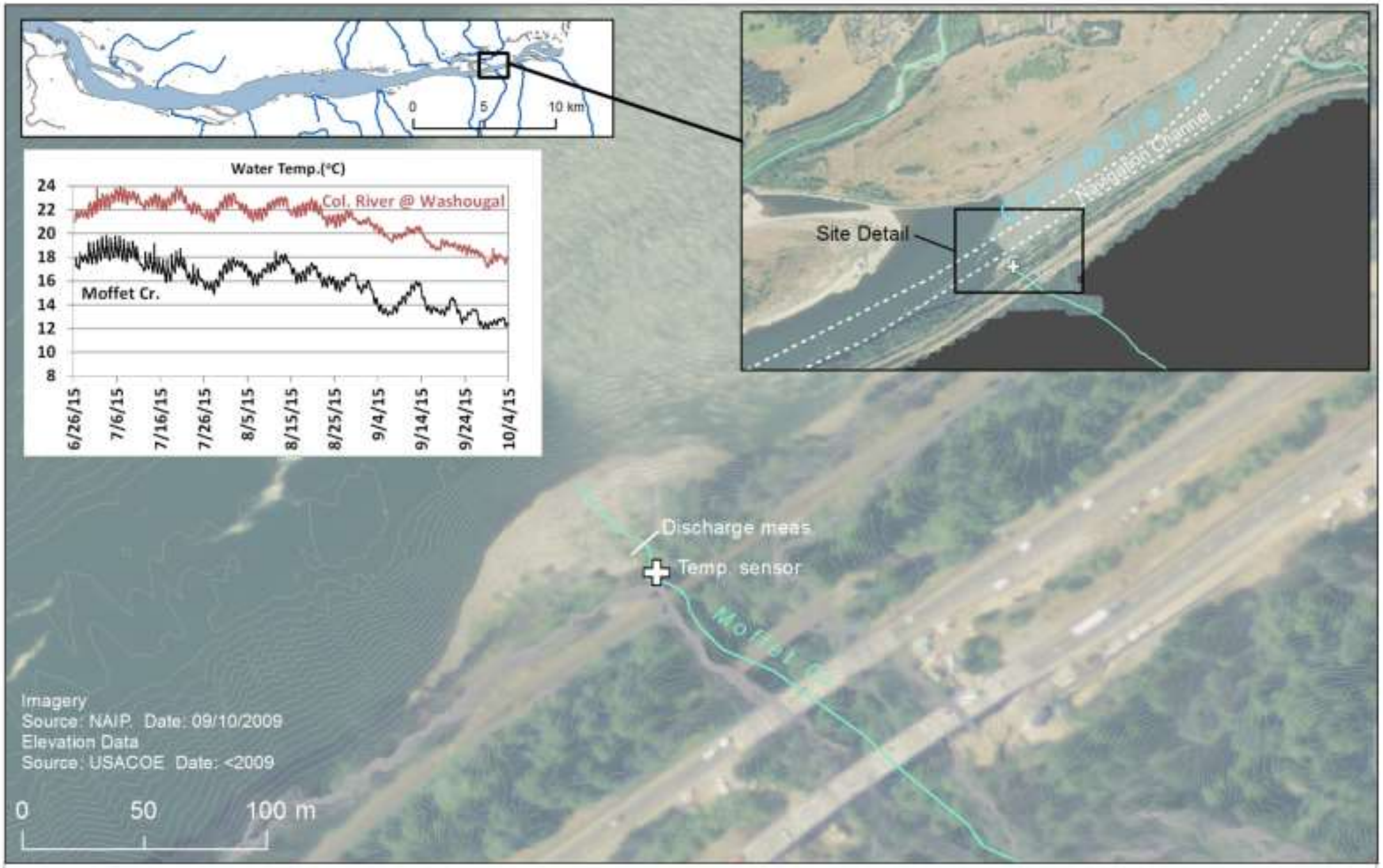


Figure A-11: *McCord Creek: Site map and results.*



Cold Water Discharge at Moffet Creek Outlet

8/11/2015 @ 11:00 hrs:

Survey Notes:
- No detectable cold water plume at Columbia River confluence

Water Body	Q (cfs)	Stage (ft/ m)	T (degC)
Columbia R. (Bonneville gauge):	130 k	12.6/3.8	22.2
Moffet Creek (meas.)	0.4	- - -	16

Lower Columbia Estuary Partnership

Ambient: T = 80-85C, sunny, moderate west wind

- - - indicates not measured, or not available

Figure A-12: *Moffet Creek: Site map and results.*

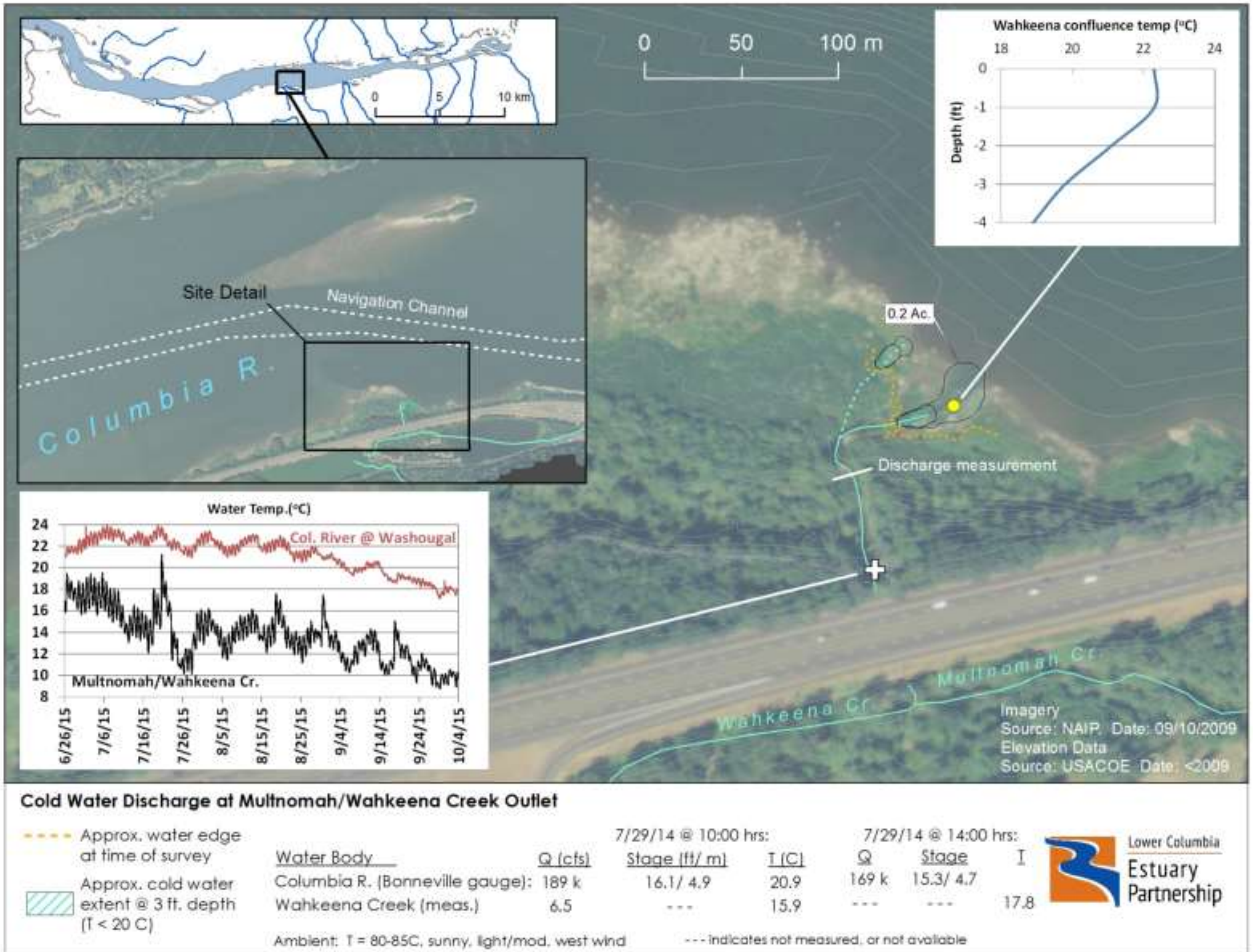


Figure A-13: *Multnomah/Wahkeena Creek: Site map and results.*

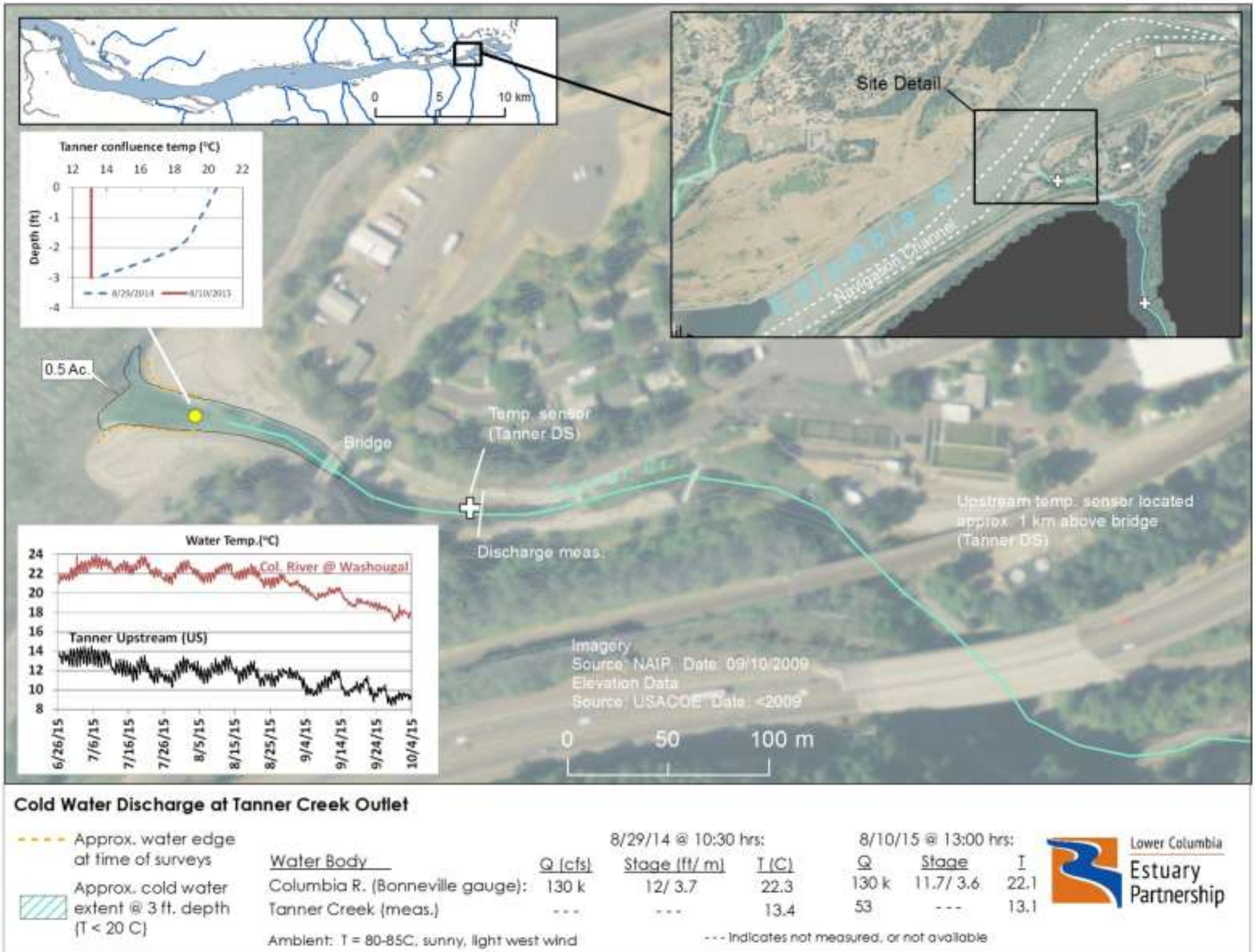
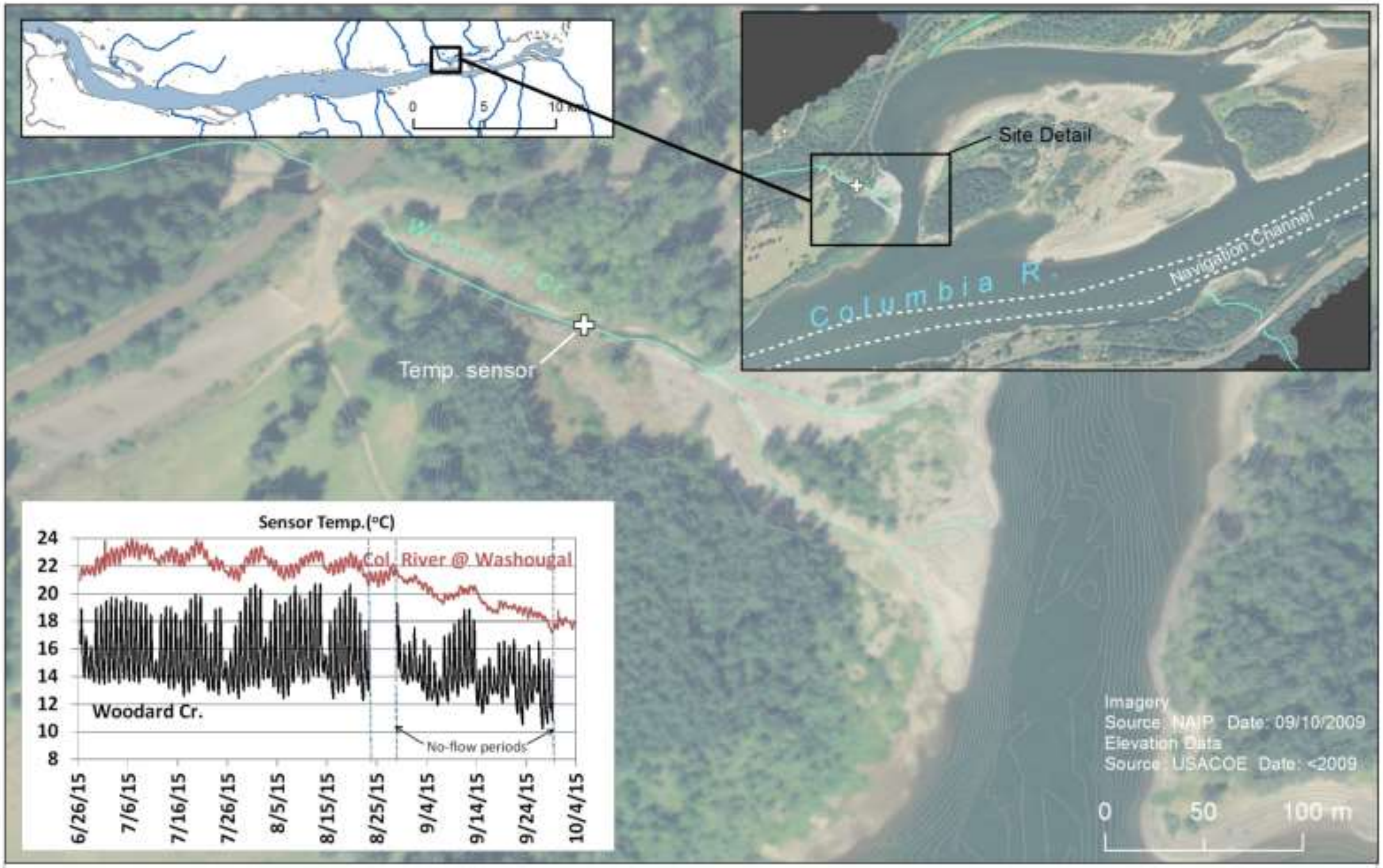


Figure A-14: *Tanner Creek: Site map and results.*



Cold Water Discharge at Woodard Creek Outlet

Notes:

- Fixed temp. probe deployed 6/26/15.
- No surface flow into Columbia R. on 8/7/15 survey

	6/26/15 @ 12:00 hrs:			8/7/15 @ 11:00 hrs:		
Water Body	Q	Stage	T	Q	Stage	T
Columbia R. (Bonneville gauge):	130k	11.6/ 3.5	21.1	142k	12.2/ 3.7	21.5
Woodard Cr.	---	---	15.9	<1	---	17.9

Ambient: T = 80-85C, sunny, light west wind

--- indicates not measured, or not available

Lower Columbia Estuary Partnership

Figure A-15: Woodard Creek: Site map and results.

APPENDIX B

Conceptual Drawings of Proposed Structures for Enhancing Cold-Water Plume Formation at Selected Tributary Confluences (Study Phase 3)

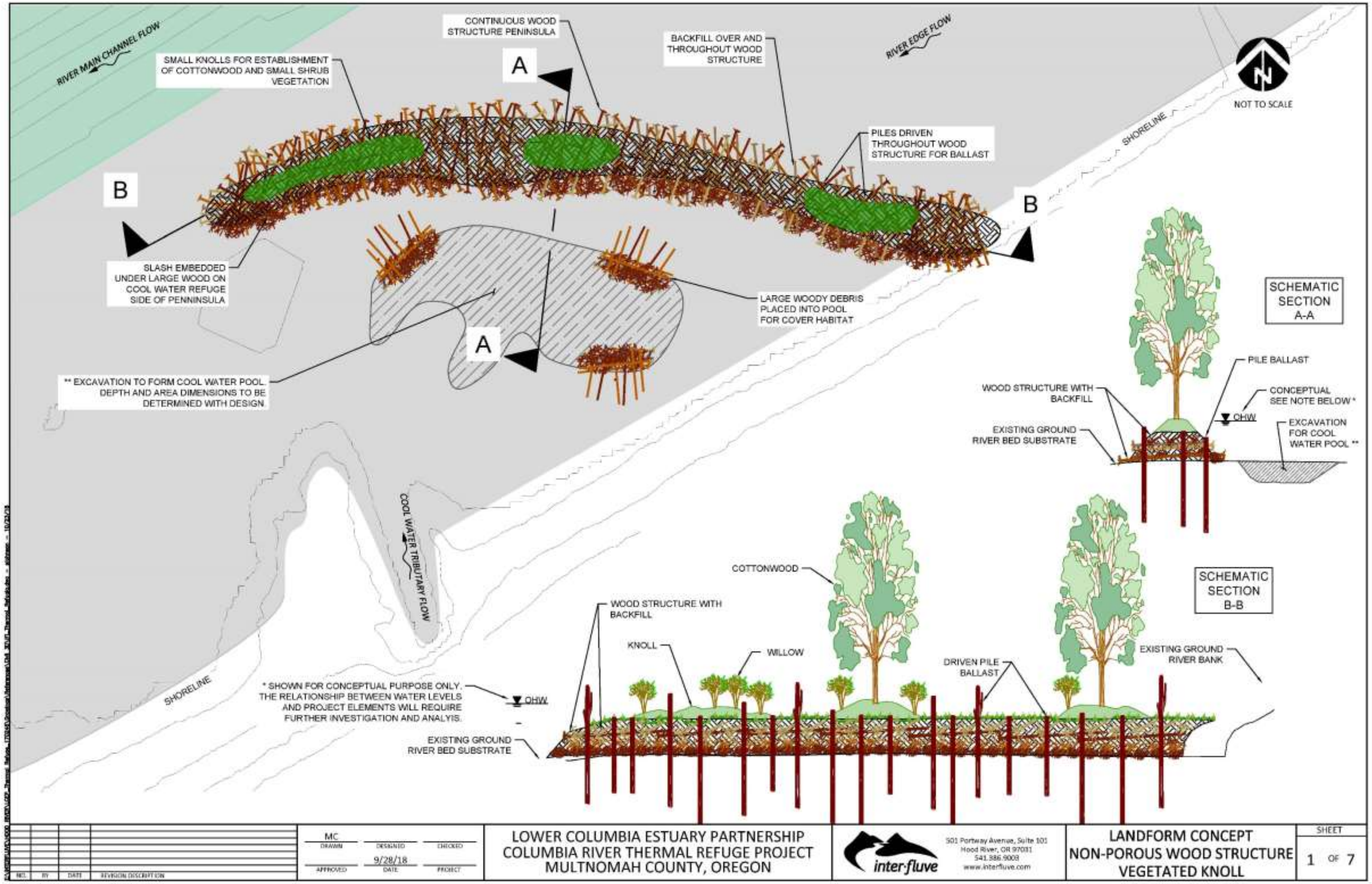


Figure B-15: Conceptual approach for thermal refuge enhancement structure placement at selected tributary confluences (Study Phase 3). Sketch 1 of 7.

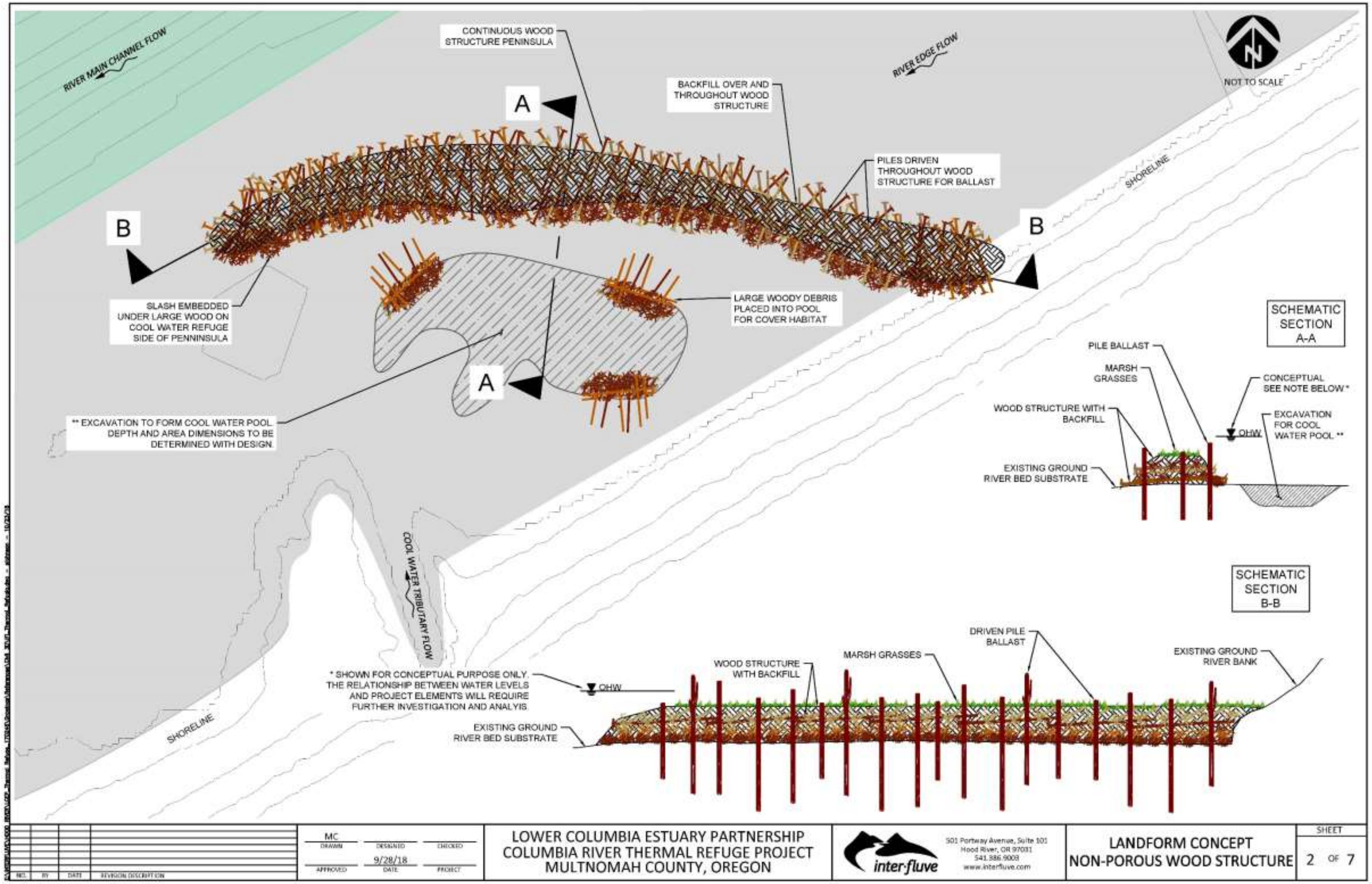


Figure B-15: Conceptual approach for thermal refuge enhancement structure placement at selected tributary confluences (Study Phase 3). Sketch 2 of 7.

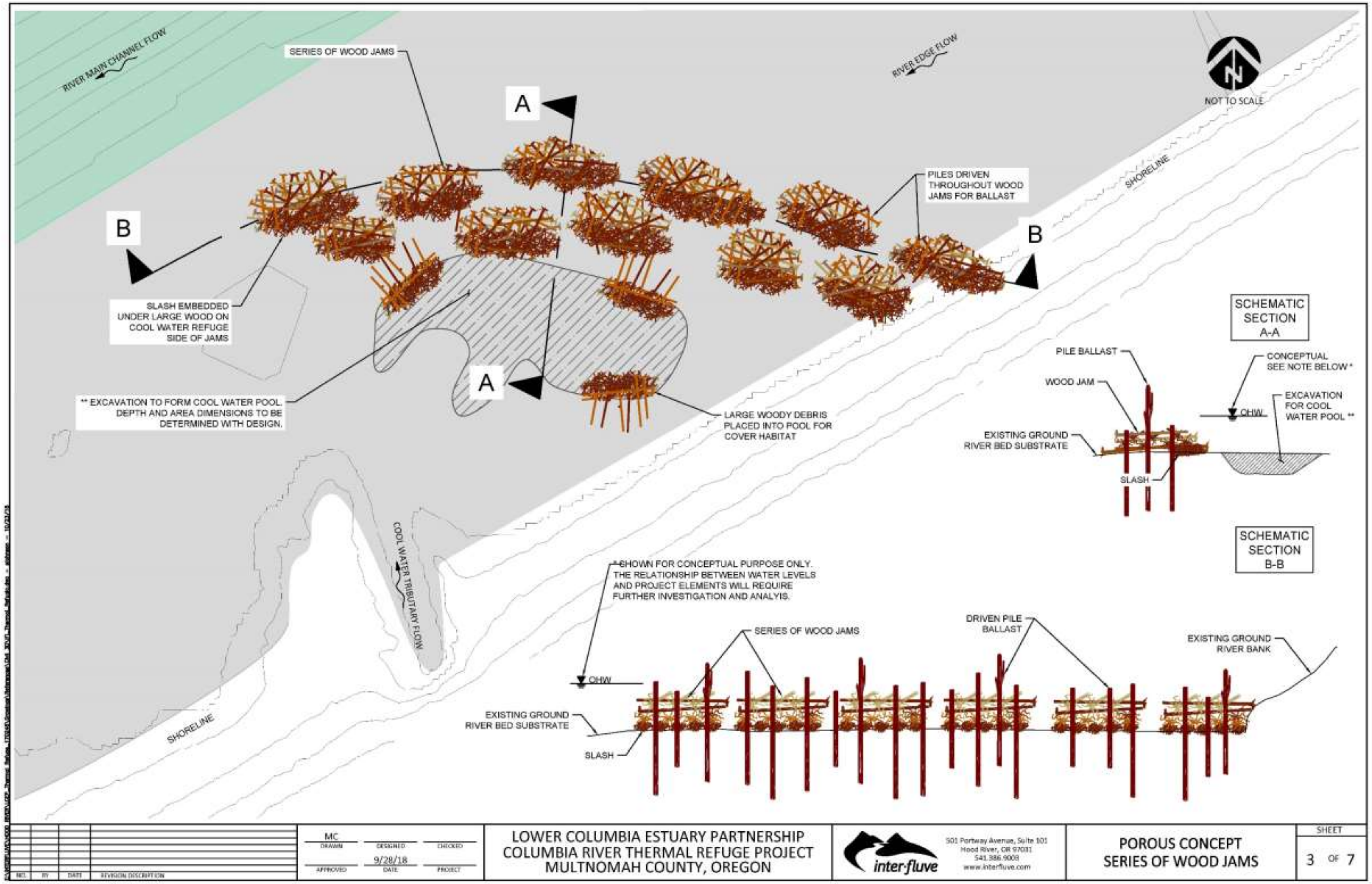


Figure B-15: Conceptual approach for thermal refuge enhancement structure placement at selected tributary confluences (Study Phase 3). Sketch 3 of 7.

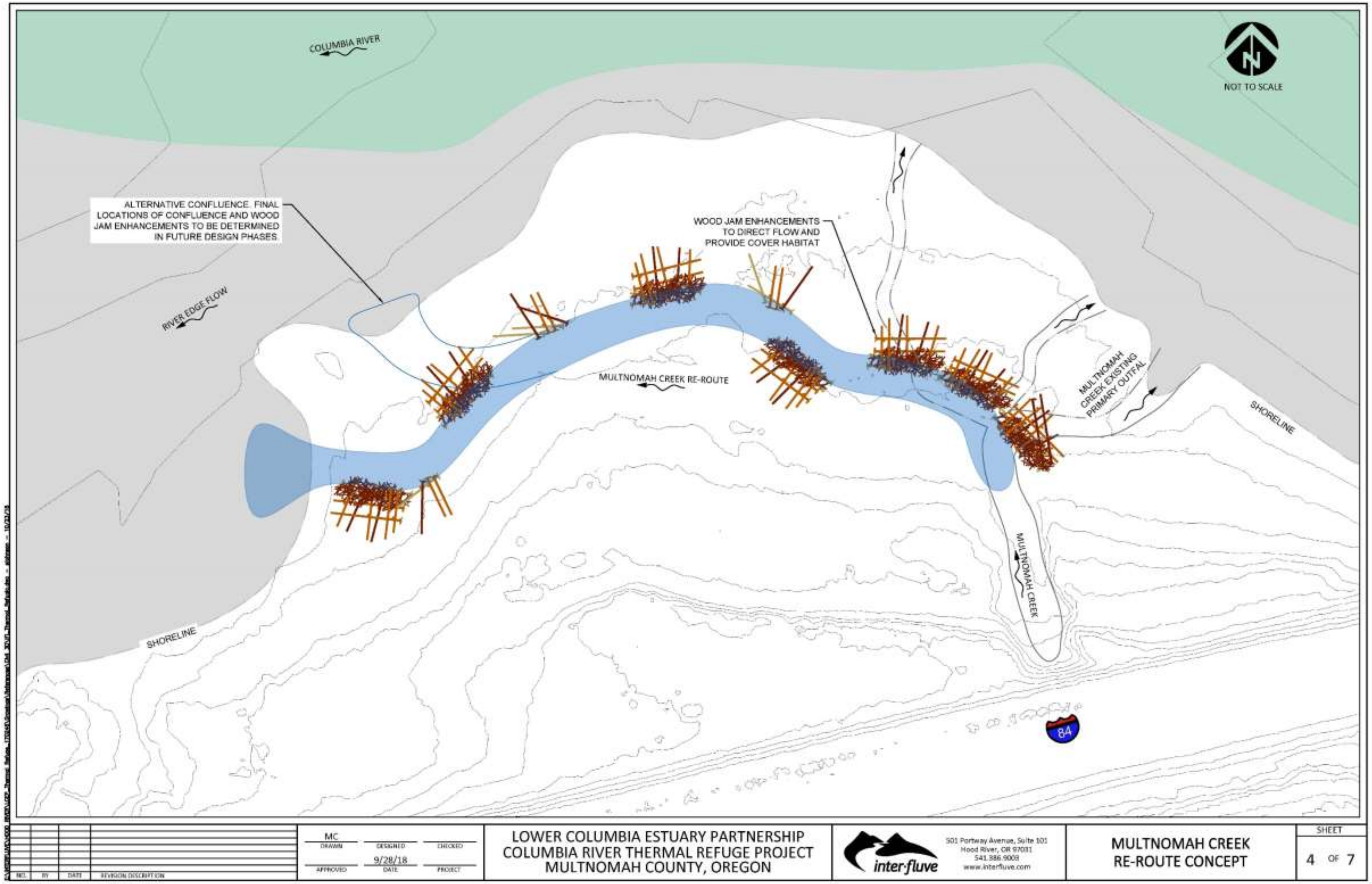


Figure B-15: Conceptual approach for thermal refuge enhancement structure placement at selected tributary confluences (Study Phase 3). Sketch 4 of 7.

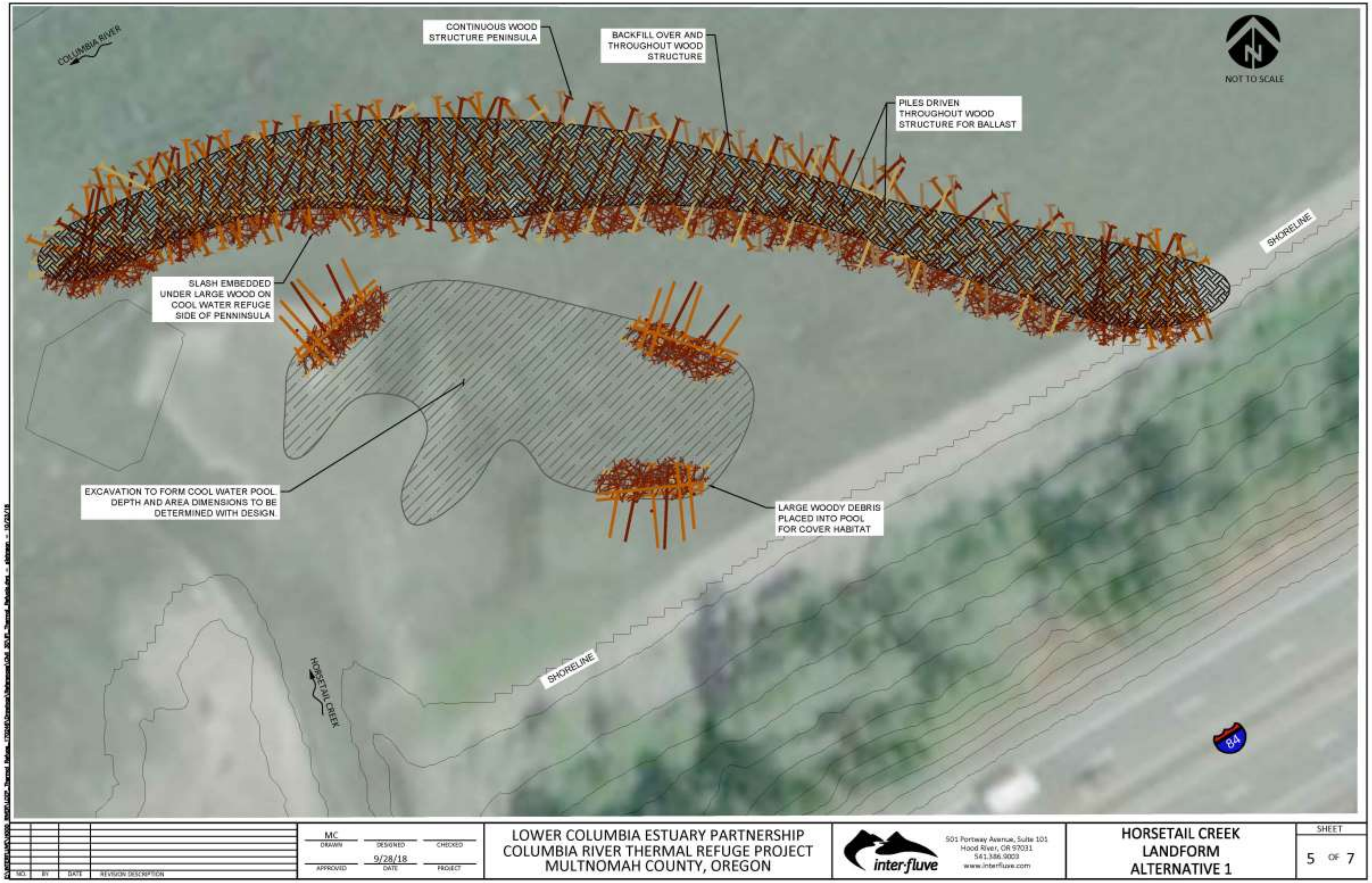


Figure B-15: Conceptual approach for thermal refuge enhancement structure placement at selected tributary confluences (Study Phase 3). Sketch 5 of 7.

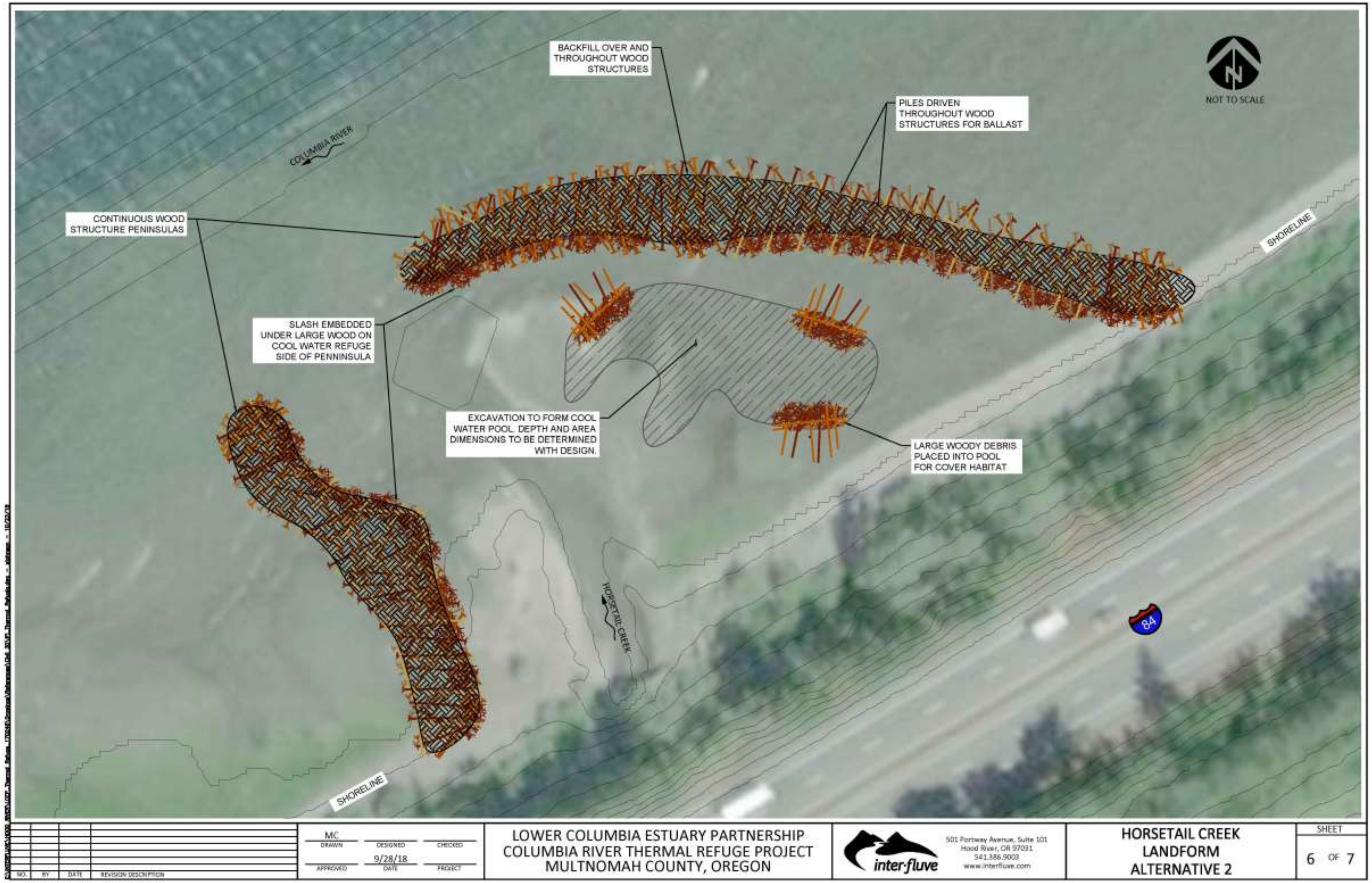


Figure B-15: Conceptual approach for thermal refuge enhancement structure placement at selected tributary confluences (Study Phase 3). Sketch 6 of 7.

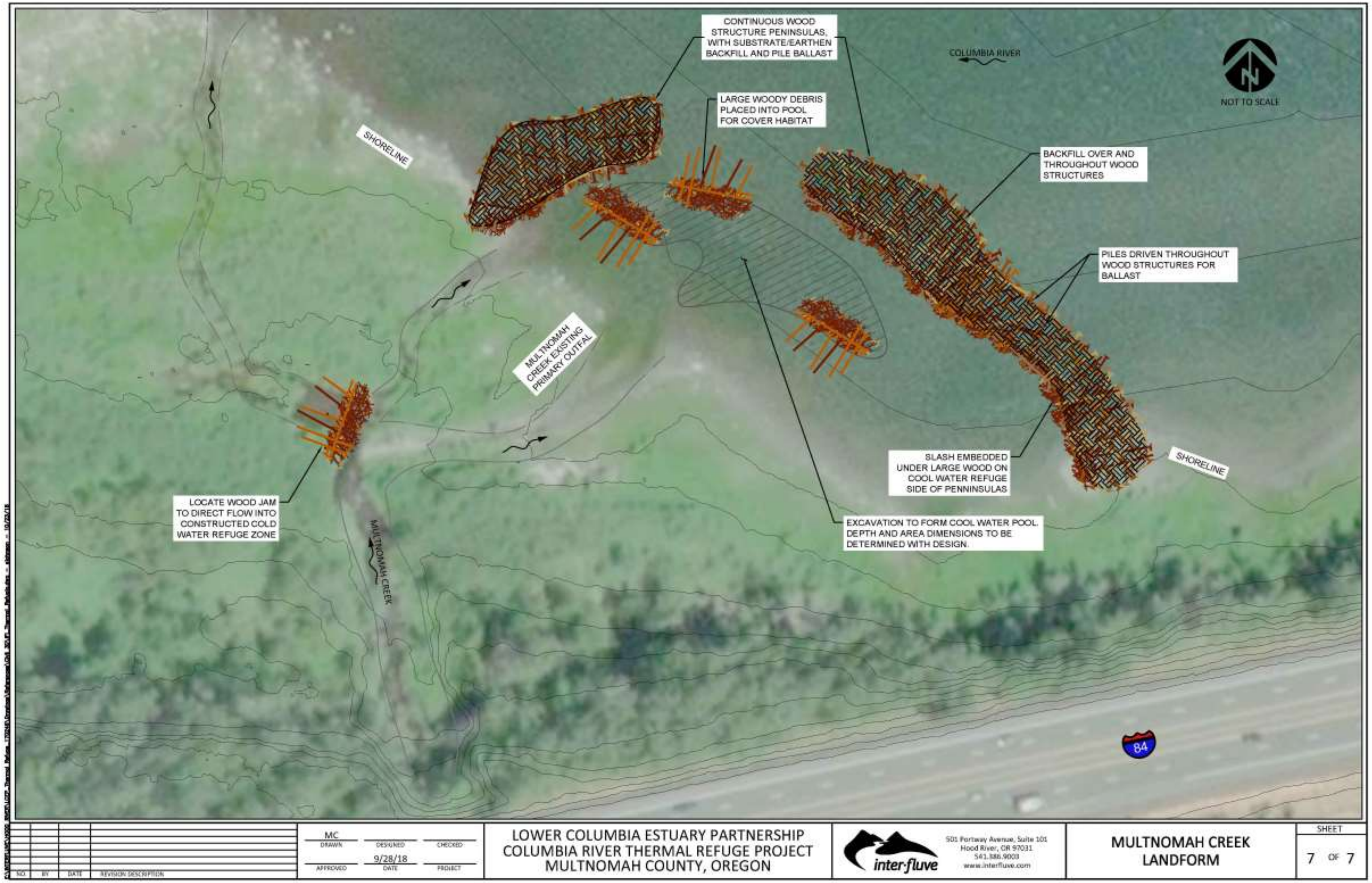


Figure B-15: Conceptual approach for thermal refuge enhancement structure placement at selected tributary confluences (Study Phase 3). Sketch 7 of 7.