DEPARTMENT OF THE ARMY
CORPS OF ENGINEERS, NORTHWESTERN DIVISION
PO BOX 2870
PORTLAND OR 97208-2870

REPLY TO
ATTENTION OF

FEB 13 2013

Planning, Environmental Resources,
Fish Policy and Support Division

Mr. Barry Thom
NOAA Fisheries Service
1201 NW Lloyd Blvd., Suite 100
Portland, OR 97232

Dear Mr. Thom:

Please see the enclosed report titled, "Location and Use of Adult Salmon Thermal Refugia in the Lower Columbia and Lower Snake Rivers" which was prepared to fulfill the requirements of Amendment 1 of the 2010 Supplemental FCRPS BiOp.

This report provides a comparison of existing tributary and lower Columbia and lower Snake River temperature data; a summary of the Snake and Clearwater River confluence study/modeling operations and Dworshak project releases; and a compilation of the University of Idaho studies of temperature regimes during upstream migration and the use of thermal refugia by adult salmon and steelhead in the Columbia River Basin.

The document was developed by the Corps in coordination with the other Action Agencies and was provided in draft for review and comment to NOAA and to our partners in the Regional Implementation Oversight Group (RIOG). Our responses to comments received from the RIOG are attached to the enclosed report.

I am forwarding a copy of this letter to Ms. Kathryn Puckett, Columbia Snake Salmon Recovery Office, Bureau of Reclamation, PN Region, 1150 N. Curtis Road, Suite 100, Boise, Idaho 83706; Mr. Duane Mecham, Office of the Regional Solicitor, 805 SW Broadway, Suite 600, Portland, Oregon 97205; Ms. Sarah McNary and Mr. Paul Majkut, Bonneville Power Administration, PO Box 3621, Portland, Oregon 98708; and Mr. Bruce Suzumoto, NOAA Fisheries Service, 1201 NW Lloyd Blvd., Suite 100, Portland, Oregon 97232.

If you have any questions, please contact Mr. Rock Peters of my staff at 503-808-3723 or Ms. Kim Johnson at 503-808-4060.

Sincerely,

David L. Combs
Chief, Planning, Environmental Resources,
Fish Policy and Support Division

Enclosures

Location and Use of Adult Salmon Thermal Refugia in the Lower Columbia and Lower Snake Rivers

Federal Columbia River Power System
Amendment 1 of the Supplemental FCRPS BiOp

February 2013

US Army Corps of Engineers®
Northwestern Division

Introduction

In 2009, after a review of the 2008 Federal Columbia River Power System (FCRPS) BiOp by the Obama Administration, the Action Agencies (U.S. Army Corps of Engineers, Bonneville Power Administration, and Bureau of Reclamation) proposed, and NOAA Fisheries endorsed, the jointly-developed Adaptive Management Implementation Plan (AMIP) which identified specific measures implementing NOAA Fisheries' 2008 Reasonable and Prudent Alternative (RPA). The AMIP accelerates and enhances implementation of RPA actions, collecting more data and improving analytic tools to better inform future adaptive management decision-making, and adding new biologic triggers for contingency action within the RPAs adaptive management provisions. The AMIP called for a more precautionary approach to address uncertainties about the future condition of the affected salmon and steelhead, particularly out of concern for how climate change may affect these species and their habitat. One such measure (included as Amendment 1 of the 2010 Supplemental FCRPS BiOp) called for the U.S. Army Corps of Engineers (Corps) to identify the use and location of adult salmon thermal refugia in the lower Columbia and lower Snake rivers using existing information on adult migration, temperature monitoring data, and modeling efforts. Amendment 1 of the 2010 Supplemental FCRPS BiOp states:

> Under RPA Action 55 the Action Agencies will undertake selected hydrosystem research to resolve critical uncertainties. As part of this action, by June 2012, the Corps will complete a report to identify the use and location of adult salmon thermal refugia in the lower Columbia and lower Snake rivers using existing information on adult migration, temperature monitoring data, and modeling efforts. Additional investigation or action may be warranted based on the results of this report.

This report provides existing information in response to Amendment 1 and is presented in three sections:

(1) a comparison of existing tributary and lower Columbia and lower Snake River temperature data from the Corps' Water Management System database and the USGS National Water Information System database (http://waterdata.usgs.gov/nwis);
(2) lower Snake River temperature conditions which includes the use of the Dworshak project releases for downstream temperature moderation and the Snake and Clearwater River confluence study/modeling operations and water temperatures within the lower Snake River reservoir system; and,
(3) temperature regimes during upstream migration and the use of thermal refugia by adult salmon and steelhead in the Columbia River Basin (University of Idaho).

Temperature Monitoring Data

The Corps tracks temperature monitor data along the Clearwater River from the mouth to Dworshak Dam, the lower Snake River from the mouth to Anatone gauge, and the Columbia River from Astoria to the border with Canada. However, limited information is available from monitors on the smaller tributaries along the lower Snake and Columbia rivers (see Sheets 1-3). This document identifies and analyzes the temperature data that is publically available in the Corps Water Management System and the USGS National Water Information System near the confluences of the tributaries and the lower Snake and lower Columbia rivers. The existing data shows that the Clearwater (at Spalding), Umatilla and Deschutes rivers are cooler during the adult fish migration period; the Clearwater (at Orofino) and the Yakima River are substantially warmer during this timeframe and the Willamette River is about the same. The temperature data used in this analysis identifies broad thermal refugia areas along the lower Columbia and lower Snake rivers.

Lower Snake River Temperature Modeling and Operations

Significant work has been completed to develop and implement a CE-QUAL-W2 temperature model for the lower Snake River. This report documents that the current cool water releases from Dworshak, based on modeling information, provides cooler deep water available in the lower Snake River down to the forebay of Lower Granite Dam to aid adult salmon and steelhead during upstream migration.

CE-QUAL-W2 temperature models are also currently being developed for the lower Columbia River from Pasco, Washington to the forebay of Bonneville Dam, including McNary, John Day and The Dalles reservoirs. Once completed, these CE-QUAL-W2 models will have the capability of producing hourly longitudinal in-reservoir temperature profiles for each reservoir and hourly tailwater temperature estimates. The CE-QUAL-W2 temperature models for the lower Columbia River reservoirs are expected to be completed by the end of 2012.

Use of Thermal Refugia by Salmon and Steelhead

Use of thermal refugia by radio tagged adult salmon and steelhead along the lower Snake and lower Columbia rivers is well documented through the work done by the University of Idaho's Cooperative Fish and Wildlife Research Unit. This information is presented in Section 3. However, aside from the sites discovered along the margins of the Bonneville and The Dalles reservoirs, there has been little systematic mapping of thermal refugia along the Columbia-Snake River migration corridor or in spawning tributaries. Important gaps along the migration route include downstream from Bonneville Dam, in the mid-Columbia upstream from Priest Rapids Dam, and in the Snake River upstream from the Clearwater River confluence.

Adult salmonid use of thermal refugia potentially has both positive and negative effects on upstream migrants. Presumed benefits of refugia use include reduced metabolic costs, reduced physiological stress, reduced negative temperature effects on maturation and gamete quality, and increased survival. Indirect negative effects of refugia use include migration delay, exposure to pathogens, permanent straying (i.e., loss from the source population), predation risk, and delayed effects from fisheries contact (i.e., catch and release, gill net fallout, etc.).

Next Steps

In this report, the Corps identifies the use and location of adult salmon thermal refugia in the lower Columbia and lower Snake rivers using existing information regarding adult migration, temperature monitoring data, and modeling efforts. University of Idaho identified a list of information gaps (Section 3) that the region could consider pursuing.

In the future, climate change may affect water temperatures throughout the Columbia River Basin. By applying the model findings of the anticipated climate changes in the Pacific Northwest, potential water temperature changes could be forecasted for the lower Columbia and lower Snake rivers. This information could provide a framework to define actions needed to conserve thermal refugia which benefit the fish that use these sites during upstream migration.

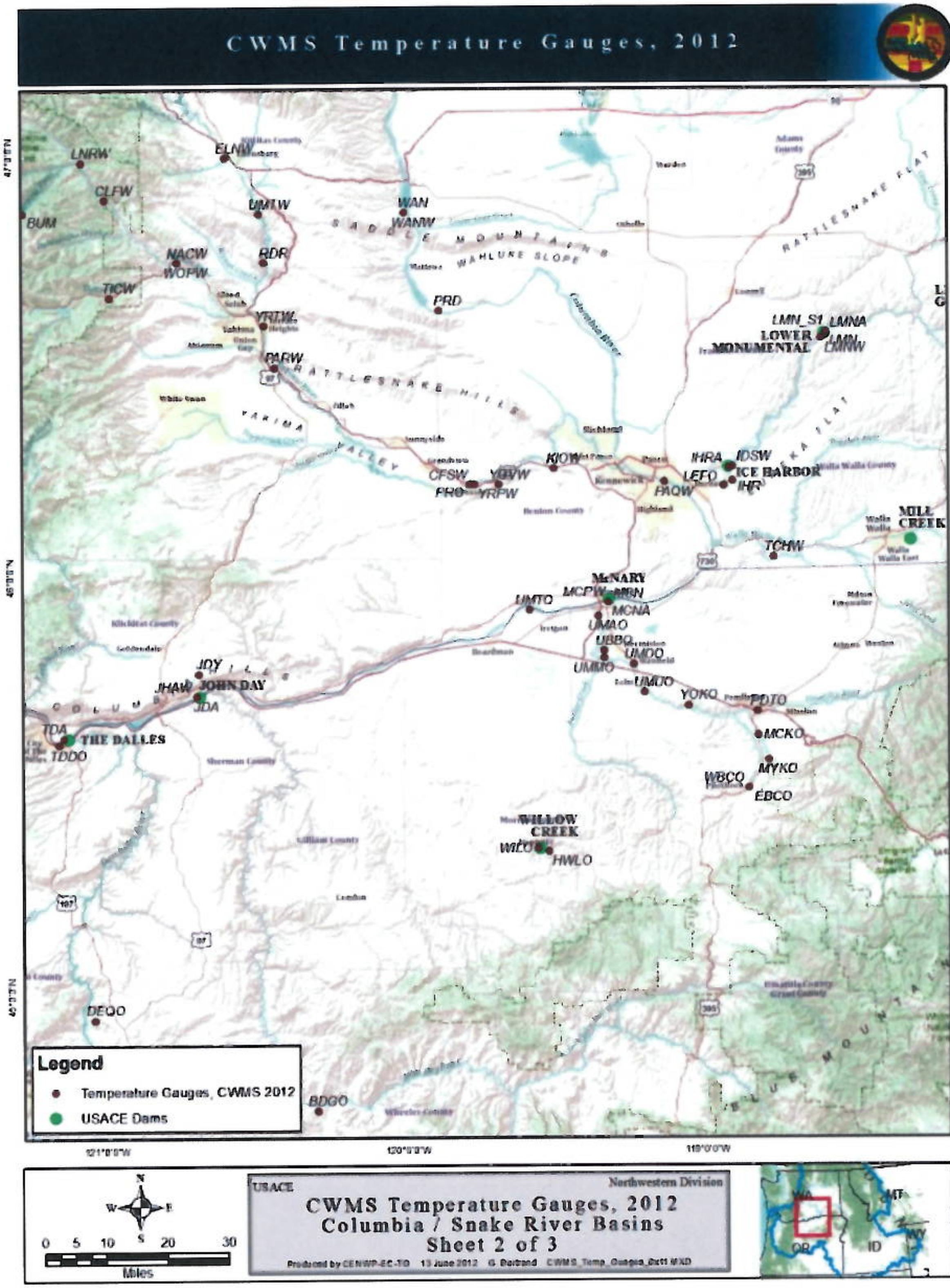
Section 1: Comparison of Existing Tributary and Lower Snake and Lower Columbia River Temperature Data

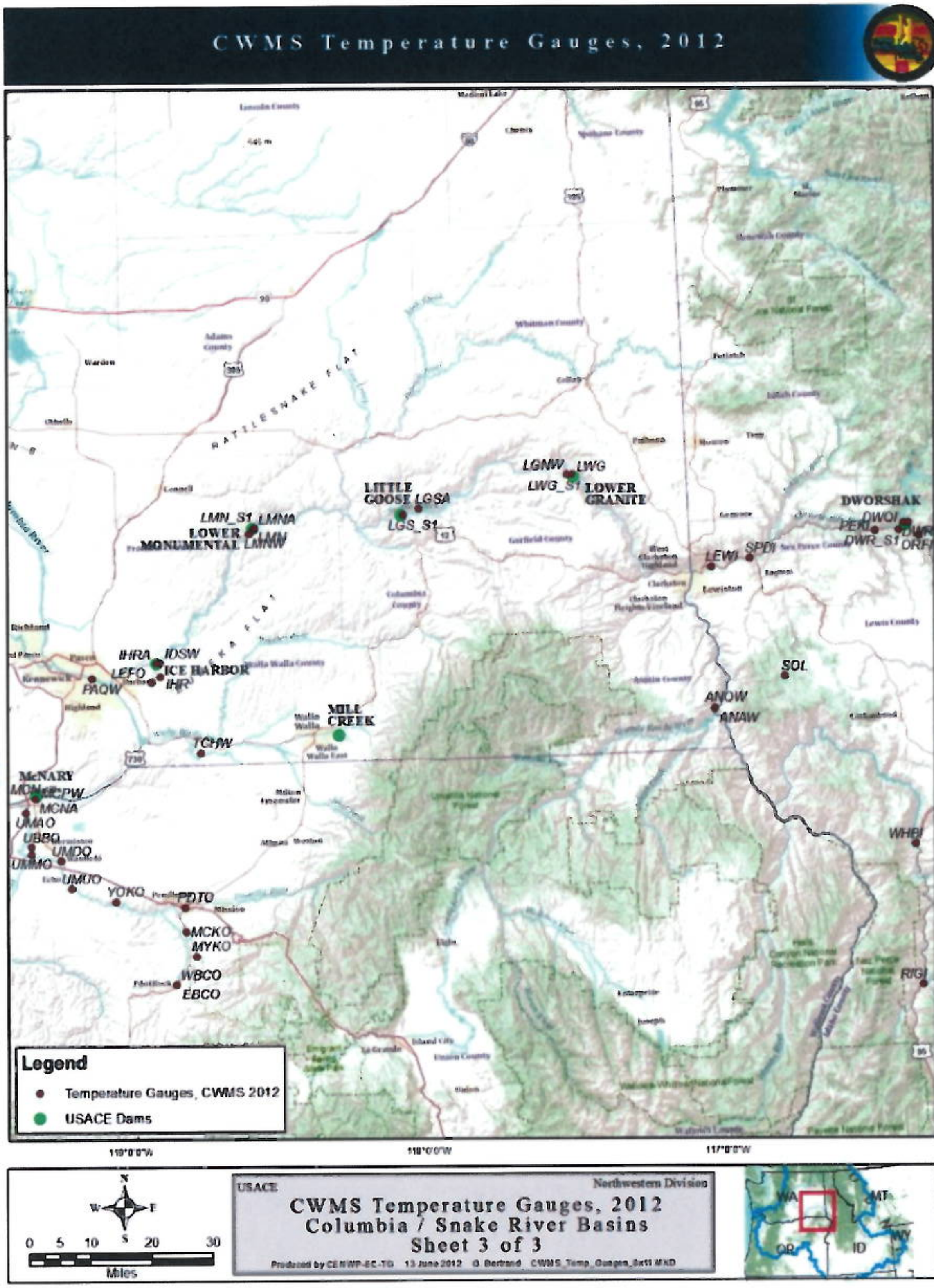
The purpose of this section is to identify potential thermal refugia areas as adult salmon migrate upstream by evaluating existing temperature data at the confluences of tributaries in comparison with the lower Snake and lower Columbia rivers. For this report, a list of water temperature gauges in the Corps Water Management System (CWMS) database used in 2012 was plotted on ArcGIS maps (see Sheets 1 through 3).

Although extensive temperature monitoring exists along the Clearwater River from the mouth to Dworshak Dam, the lower Snake River from the mouth to the Anatone gauge, the Columbia River from Astoria to the border with Canada, limited data is available in the CWMS database for the smaller tributaries.

The temperature data criterion was established to provide a high-quality representation of recent conditions. The preferred data set was a five-year average (2007-2011) of daily maximum temperatures measured year-round or at a minimum during the June-October timeframe. The temperature monitors in the CWMS database that were selected for evaluation met these criteria.


CWMS Temperature Gauges, 2012
LNRW
CLFW
DEPW
CRWW
PACW
SRS
BAKW
CASW
ASTO
LOPW
SLTW
BOMO
BON
BONNEVILLE
THE DALLES
TDA
TDDO
CWMW
Portland
SYCO
SCLO
NBRO
FCBO
BFLO
SCOO
DLLO
GSTO
TLBO
WILLAMETTE FALLS LOCKS
GOVO
KZRO
GOSO
SALEM
LAMO
DEOO
LSEO
MEHO
LSCO
NSMO
LSMO
BIG CLIFF
BRBO
RCMO
DETROIT
BCKO
JEFO
ALBO
MNFO
QCCO
SBCO
TRGO
Legend
Temperature Gauges, CWMS 2012
USACE Dams
Columbia River Basin
124°0'0"W
123°0'0"W
122°0'0"W
121°0'0"W
0 5 10 20 30
Miles
USACE
Northwestern Division
CWMS Temperature Gauges, 2012
Columbia / Snake River Basins
Sheet 1 of 3
WA
OR
ID
MT
WY


CWMS Temperature Gauges, 2012
LNRW
CLFW
BUM
ELNW
UMTW
WAN
WANW
NACW
WOPW
RDR
TICW
PRD
YRTW
PARW
LMN_S1
LMNA
LOWER MONUMENTAL
LMNW
KIOW
IHRA
IDSW
ICE HARBOR
LEFO
IHR
PAQW
CFSW
YGVW
PRO
YRPW
MILL CREEK
TCHW
McNARY
MCPW
MCNA
UMTO
UMAO
UBBO
UMDO
UMMO
UMUO
YOKO
PDTO
MCKO
MYKO
WBCO
EBCO
JDY
JHAW
JOHN DAY
JDA
TDA
THE DALLES
TDDO
WILLOW CREEK
WILO
HWLO
DEQO
BDGO
Legend
Temperature Gauges, CWMS 2012
USACE Dams
121°0'0"W
120°0'0"W
119°0'0"W
47°0'0"N
46°0'0"N
45°0'0"N
N
W
E
S
0 5 10 20 30
Miles
USACE
Northwestern Division
CWMS Temperature Gauges, 2012
Columbia / Snake River Basins
Sheet 2 of 3
WA
MT
OR
ID
WY

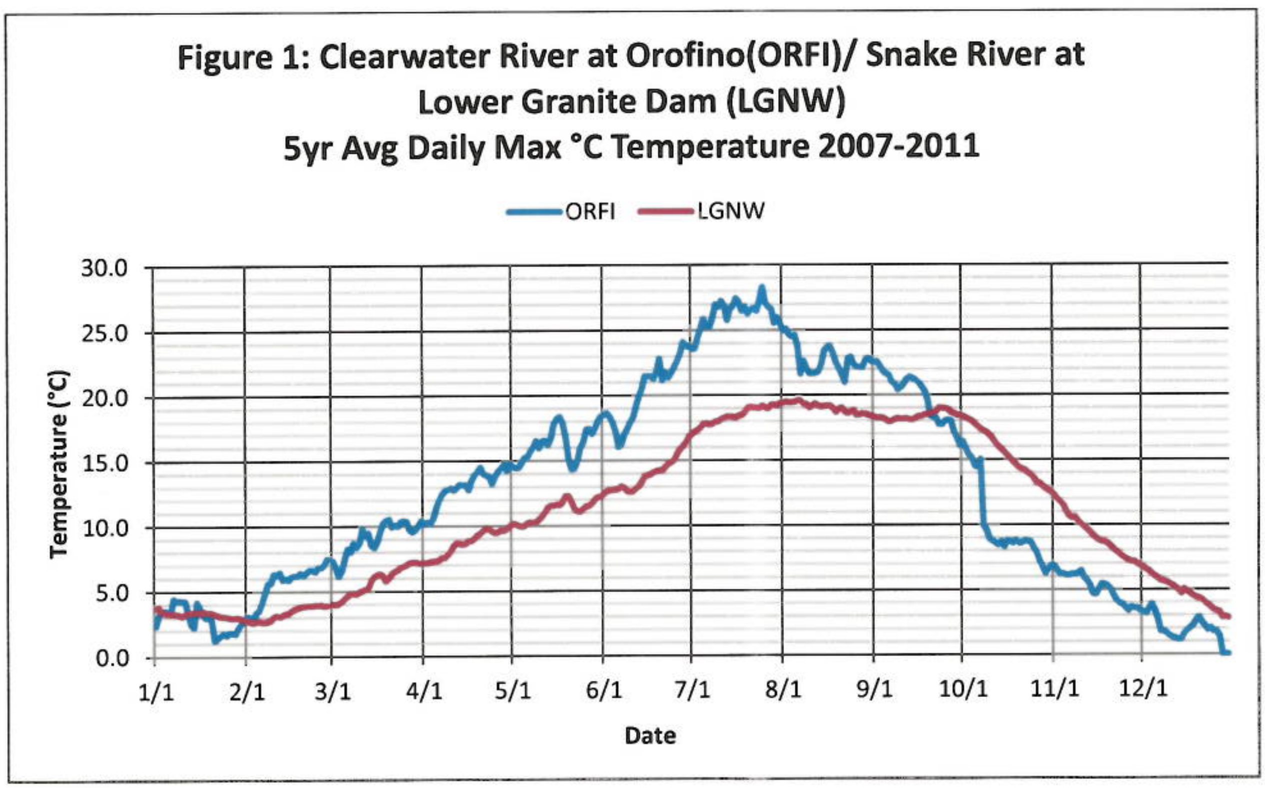

CWMS Temperature Gauges, 2012
LITTLE GOOSE
LGSA
LGS_S1
LGNW
LWG
LWG_S1
LOWER GRANITE
LMN_S1
LMNA
LOWER MONUMENTAL
LMNW
DWORSHAK
DWQI
DWR_S1
LEWI
SPDI
IHRA
IDSW
LEFO
ICE HARBOR
IHR
PAQW
MILL CREEK
TCHW
SOL
ANQW
ANAW
McNARY
MCPW
MCNA
UMAO
UBBO
UMDO
UMMO
UMUO
YOKO
PDTO
MCKO
MYKO
WBCO
EBCO
WHBI
RIGI
Legend
Temperature Gauges, CWMS 2012
USACE Dams
119°0'0"W
118°0'0"W
117°0'0"W
47°0'0"N
46°0'0"N
0 5 10 20 30
Miles
USACE
Northwestern Division
CWMS Temperature Gauges, 2012
Columbia / Snake River Basins
Sheet 3 of 3
WA
MT
OR
ID
WY

Where Corps temperature data was available, the tributary and mainstem gauge on the lower Snake or Columbia rivers were identified and selected for comparison (Table 1).

Table 1: Selected Tributary and Mainstem Gauges for Comparison

Tributary Gauge	Station ID	Mainstem Gauge	Station ID	Mainstem River
Clearwater at Orofino	ORFI	Lower Granite Tailwater	LGNW	Snake
Clearwater at Spalding	SPDI	Lower Granite Tailwater	LGNW	Snake
Snake River Near Anatone	ANQW	Clearwater near Lewiston	LEWI	Clearwater
Yakima River near Kiona	KIOW	Pasco on the Columbia	PAQW	Columbia
Umatilla River near Umatilla	UMAO	McNary Forebay	MCNA	Columbia

Figures 1 through 5 show the five year average daily maximum temperatures (2007 – 2011) for the selected tributary gauges compared to the mainstem gauge on the Columbia or Snake rivers. The daily values represent the maximum hourly temperature reading each day averaged over five years. In general, during the adult fish migration period the tributaries were cooler than the mainstems for the Clearwater, the lower Snake and the lower Columbia rivers except for the Clearwater at Orofino from the February to the end of September (Figure 1) and the Yakima River from the middle of March to the middle of September (Figure 4). Note that Orofino (Figure 1) is upstream of the confluence of the North Fork of the Clearwater River and Spalding (Figure 2) is downstream of the confluence. The difference between Figure 1 and Figure 2 illustrate the effect of reduced temperature from Dworshak releases.



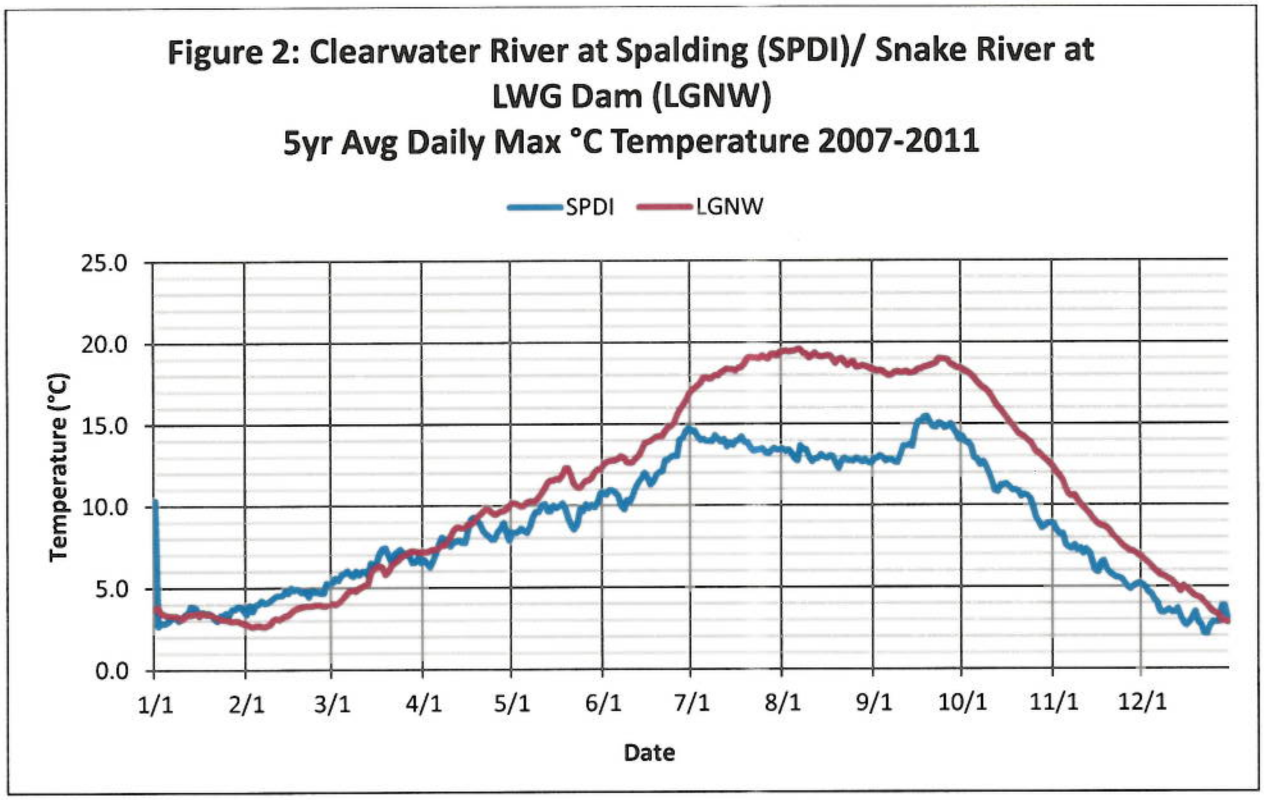


Figure 2: Clearwater River at Spalding (SPDI)/ Snake River at LWG Dam (LGNW)
5yr Avg Daily Max °C Temperature 2007-2011
SPDI
LGNW
25.0
20.0
15.0
10.0
5.0
0.0
Temperature (°C)
1/1
2/1
3/1
4/1
5/1
6/1
7/1
8/1
9/1
10/1
11/1
12/1
Date

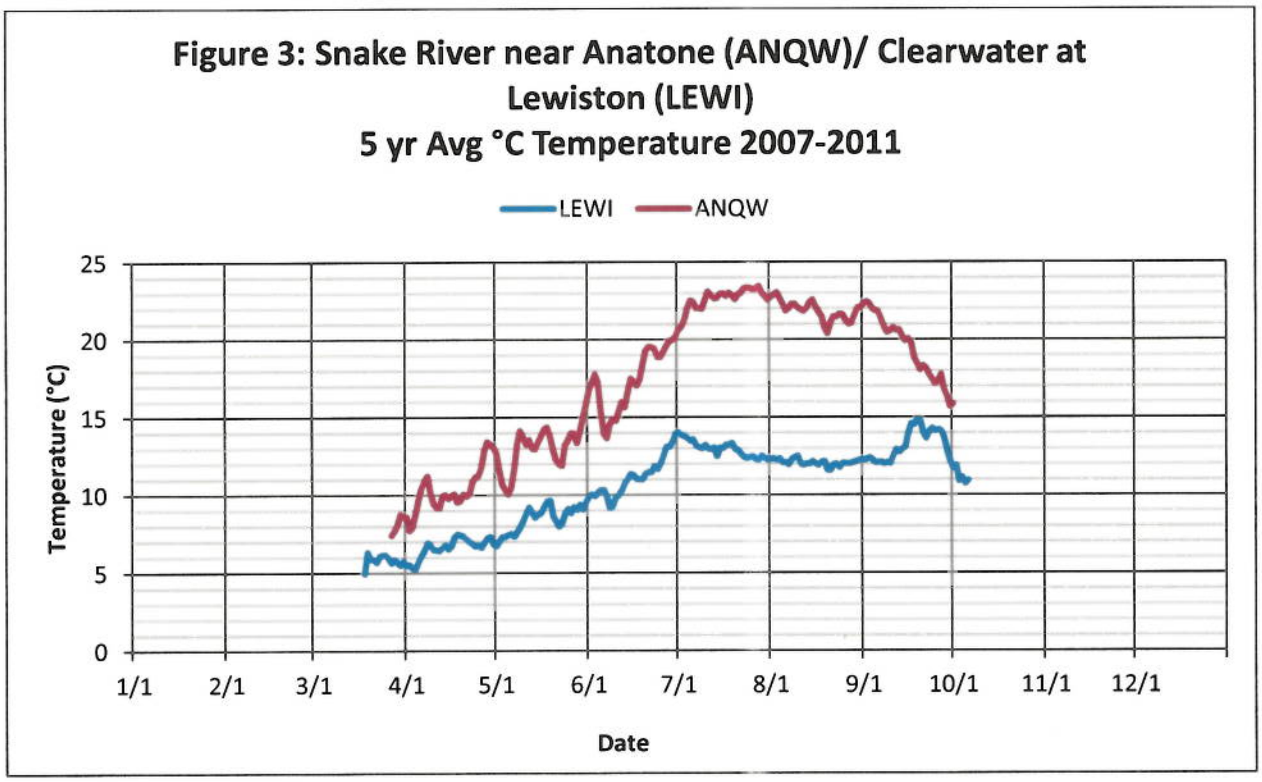


Figure 3: Snake River near Anatone (ANQW)/ Clearwater at Lewiston (LEWI)
5 yr Avg °C Temperature 2007-2011
LEWI
ANQW
25
20
15
10
5
0
Temperature (°C)
1/1
2/1
3/1
4/1
5/1
6/1
7/1
8/1
9/1
10/1
11/1
12/1
Date

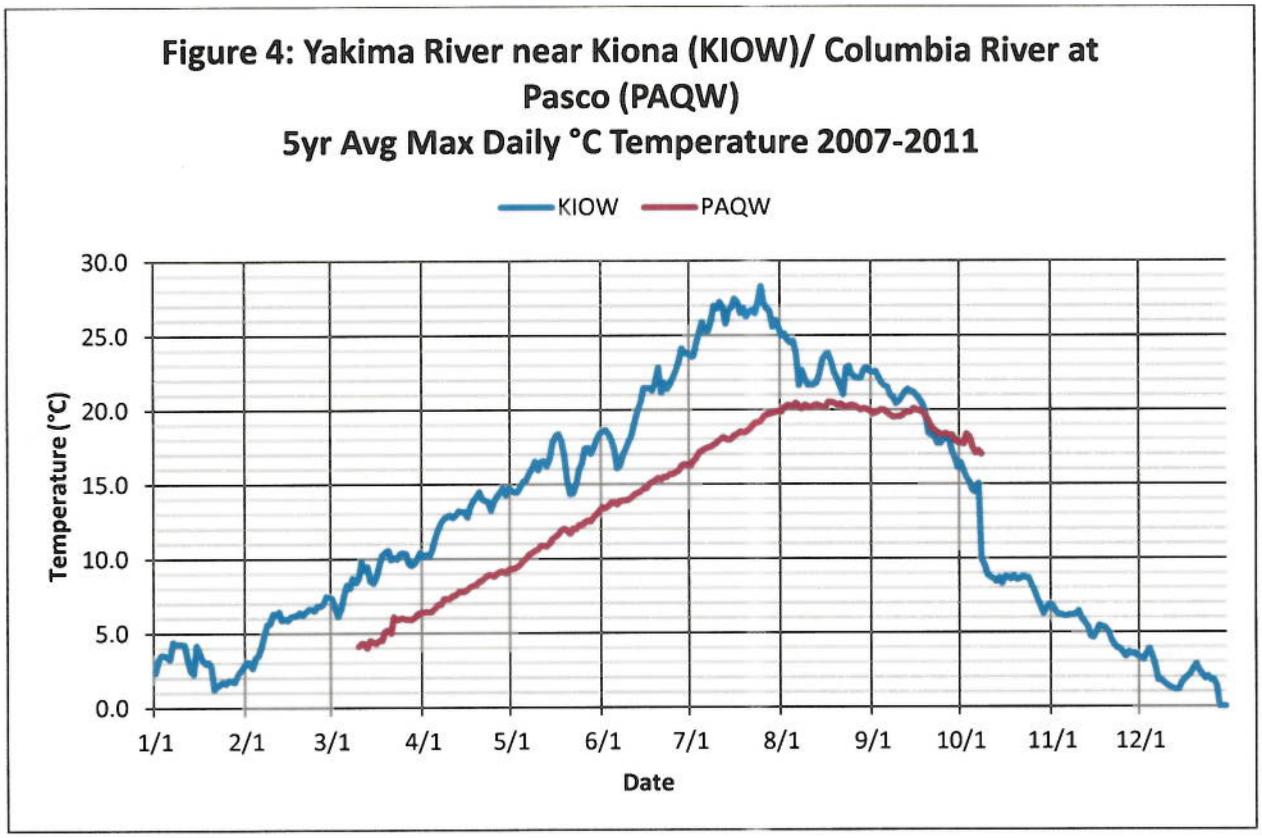


Figure 4: Yakima River near Kiona (KIOW)/ Columbia River at Pasco (PAQW)
5yr Avg Max Daily °C Temperature 2007-2011
KIOW
PAQW
Temperature (°C)
30.0
25.0
20.0
15.0
10.0
5.0
0.0
1/1
2/1
3/1
4/1
5/1
6/1
7/1
8/1
9/1
10/1
11/1
12/1
Date

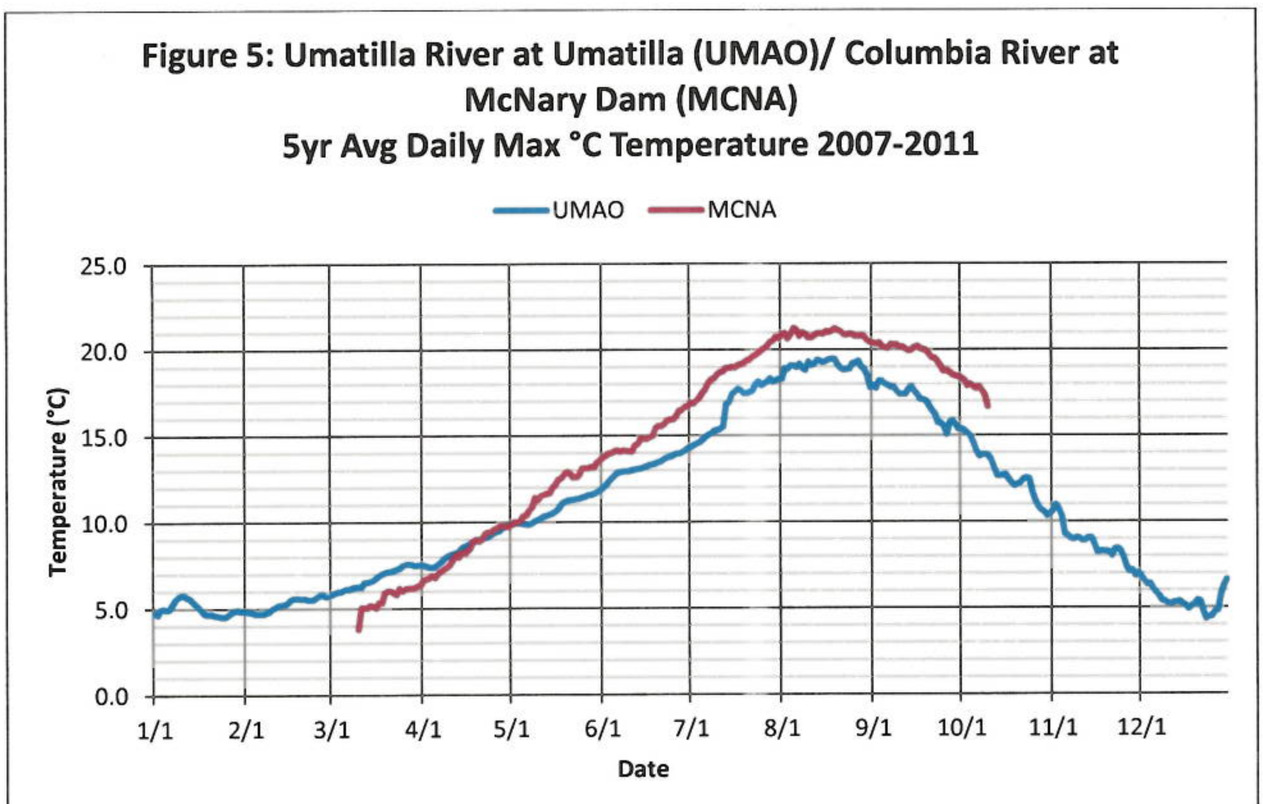


Figure 5: Umatilla River at Umatilla (UMAO)/ Columbia River at McNary Dam (MCNA)
5yr Avg Daily Max °C Temperature 2007-2011
UMAO
MCNA
Temperature (°C)
25.0
20.0
15.0
10.0
5.0
0.0
1/1
2/1
3/1
4/1
5/1
6/1
7/1
8/1
9/1
10/1
11/1
12/1
Date

Other tributary gauges shown on the CWMS map were evaluated for comparison, but did not provide five years of current data for analysis. For example, the Walla Walla River near Touchet gauge (TCHW) has not recorded temperature since 2006 and the Cowlitz River at Castle Rock gauge (CASW) has only recorded temperature data since 2011.

Due to the limited tributary data available in the CWMS data base, we investigated temperature data available from the USGS National Water Information System Data at http://waterdata.usgs.gov/nwis. Table 2 list the USGS lower Columbia and lower Snake River tributary gauges starting at the mouth and moving up river. Consistent with the CWMS data base, limited temperature data was available for the tributaries. The Willamette River at Portland, OR gauge (14211720) and the Deschutes River at Moody, near Biggs gauge (1410300) were the only two USGS gauges at the lower Columbia and Lower Snake river tributaries that provided additional information.

Table 2: USGS Lower Columbia and Lower Snake River Tributary Water Quality Gauges (National Water Information System Aug 2012)

Gauge	Description	Temperature Data
14243000	Cowlitz River at Castle Rock, WA	2011
14220500	Lewis River at Ariel, WA	No data
14211720	Willamette River at Portland, OR	1975-2012
14142500	Sandy River BWL Bull Run River, NR Bull Run	No data
14137500	Sandy River Below Revenue Bridge, Near Sandy	No data online
	Wind River	No monitor
14120250	Hood River Below Powerdale Dam NR Hood River, OR	No data online
14123500	White Salmon River near Underwood, WA	No data
14113000	Klickitat River near Pitt, WA	No data
14103000	Deschutes River at Moody, Near Biggs, OR	1951-2012
14048000	John Day River at McDonald Ferry, OR	1978 - 1981
14033500	Umatilla River near Umatilla, OR	No data
14018500	Walla Walla River near Touchet, WA	2002-2005
12511900	Yakima River at I-182 Hwy Bridge at Richland, WA	No data
13351000	Palouse River at Hopper, WA	No data
13344500	Tucannon River near Starbuck, WA	No data
13342450	Lapwai Creek NR Lapwai, ID	1998-2003
13341570	Potlatch River Below Little Potlatch Cr NR Spalding	No data
12462500	Wenatchee River at Monitor, WA	No data
12452500	Chelan River at Chelan, WA	No data
12450500	Methow River at Pateros, WA	No data

Figure 6 shows the average daily maximum temperature readings from 2009-2011 at the USGS Willamette River at Portland gauge compared to the Columbia River at Washougal gauge. Only three years of temperature data were available (March to October) at the Willamette gauge, even though the USGS data mapper listed temperature data from 1975-2012. The graph shows little temperature difference between the Willamette and the Columbia rivers except for when the Willamette is warmer in March and mid-July and cooler in early June.

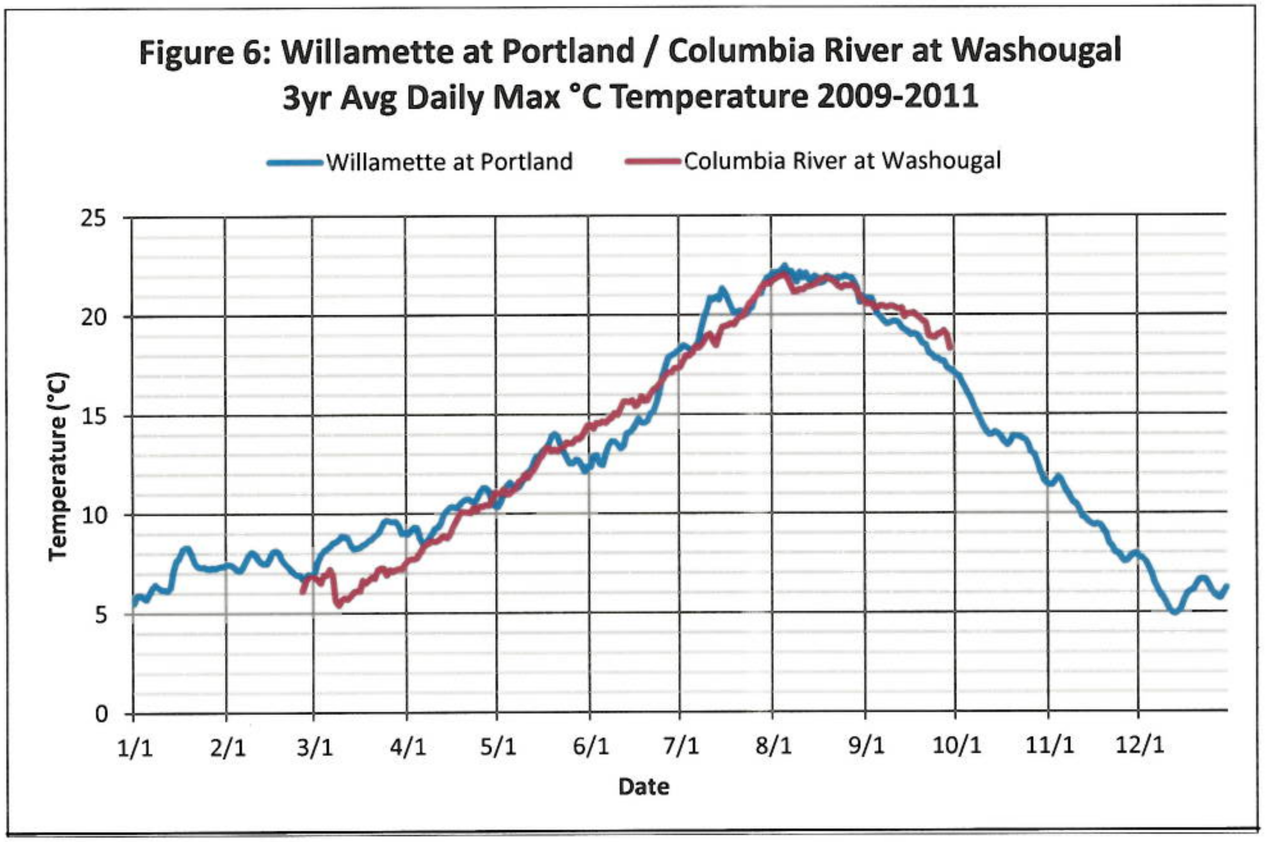
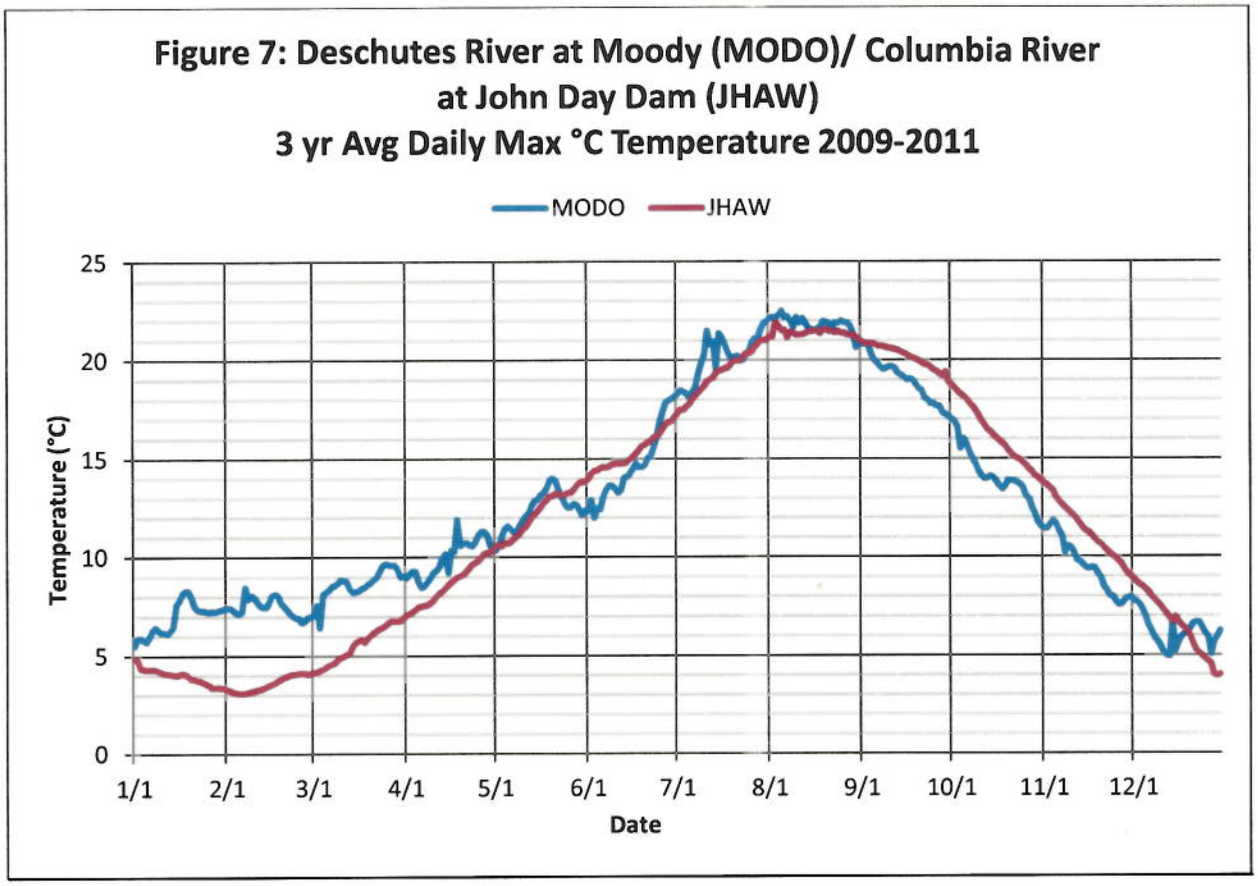


Figure 7 shows the average daily maximum temperature readings from 2009-2011 at the Deschutes River at Moody gauge compared to the Columbia River at the John Day Dam tailrace gauge. This graph portrays an interesting trend where the Deschutes River is consistently warmer than the Columbia River from January to the beginning of June and cooler from September through mid-December.

Note the Deschutes River temperatures changed after the Round Butte Fish Passage Facility came on line in April 2010. The 273-foot underwater tower mixes warm water from the top of Lake Billy Chinook with cold water at the bottom, adjusting the mixture by computer. This facility may be able to ensure that the Deschutes River provides cooler temperatures during the adult fish migration season.



Although this report focuses on current readily available temperature data in the lower Columbia and lower Snake Rivers, historical and modeling evaluations have been completed for some other tributaries. . For example, in December 2010, Cramer Fish Sciences prepared the Temperature Characteristics of Herman Creek Cove and its function as a Cool-Water Refuge for Adult Salmon and Steelhead in the Columbia River. This report was a result of a proposal by Nestle Water North America to substitute 0.5 cfs of well water in exchange for 0.5 cfs of spring water. The study measured temperature on August 5 and again on September 1, 2010 at four foot depth increments from about 16 stations spaced along transects extending about 250 ft both north and south of the Creek mouth and about 300 to 500 ft across the width of the Cove. The study found that "The persistence of a large cool water pool at depth in Herman Creek Cove that is generally about 4 °C cooler than surface water and 6 °C cooler than the Columbia River."

During July 2003 June 2004, the Underwood Conservation District, White Salmon, Washington, measured water temperature at several sites along the White Salmon River as part of an effort to assess current and potential salmonid production in Rattlesnake Creek associated with restoration efforts. The methods included using a hand held digital thermometer while collecting the general water chemistry data and using continuous-reading temperature loggers placed at sixteen (16) sites. The study found that "the White Salmon was noticeably cooler and provided a cool refuge for various fish species. All of the tributaries (Buck Creek, Rattlesnake Creek, Gilmer Creek and Trout Lake Creek) contributed higher temperatures."

In April of 1999, a report was prepared for Portland General Electric to study water temperature in the Lower Deschutes River, Oregon (Huntington and Hardin April 1999) to assess the Pelton Round Butte Project (PRB) on thermal regimes in the lower Deschutes River, Oregon. For this analysis, a SNTEMP model was used to simulate PRB's effects on water temperatures along the 100 mile length of the lower Deschutes River. The simulations suggest that during the period modeled, the PRB effect at 4.0 miles above the river's mouth, raised temperatures by an average of 0.5 °C from early August to mid-December and decreased temperatures by approximately 0.6 °C during the remainder of the annual cycle.

Section 2: Lower Snake River Temperature Conditions

Introduction

The focus of this section is temperature conditions in the four lower Snake River reservoirs (Lower Granite, Little Goose, Lower Monumental, and Ice Harbor) and how thermal refugia is created in the lower Snake River by operational releases of cool water from the upstream Dworshak Project. Dworshak is essentially the only high head reservoir that is stratified and has high utility for potential temperature management near Lower Granite.

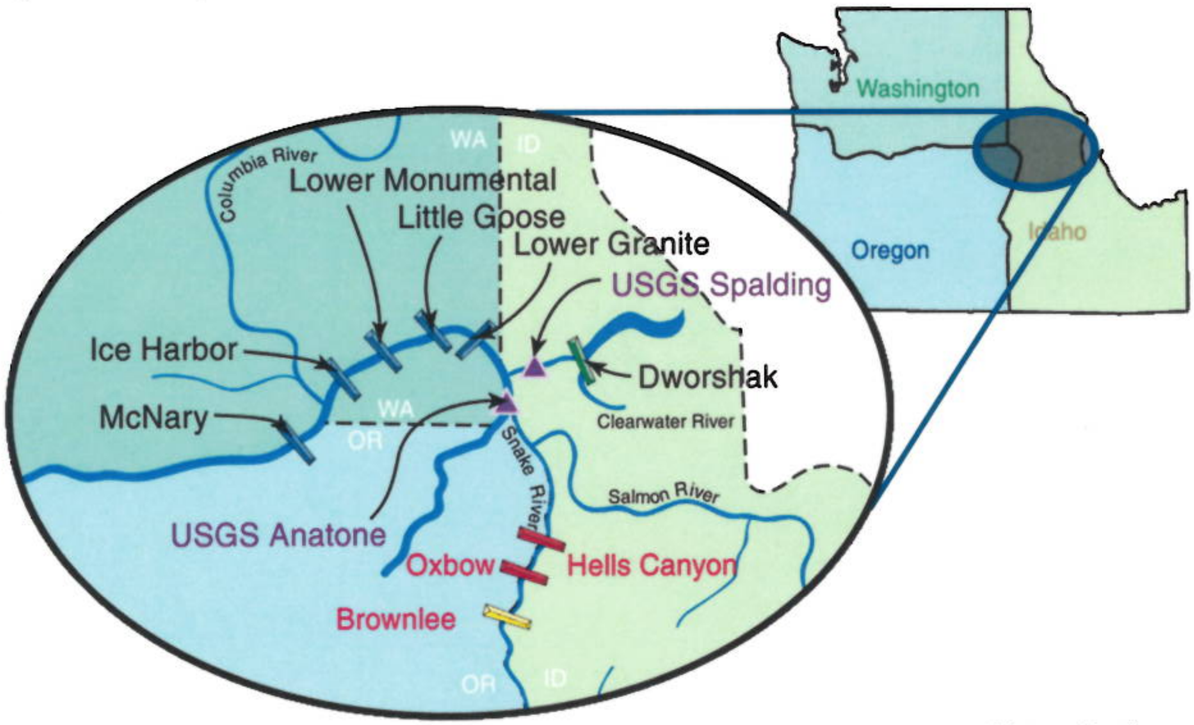


Figure 8. Locations of Dworshak Dam, the four lower Snake River Dams, McNary Dam, USGS fixed monitor stations, and the Hells Canyon Complex.

Temperature Standards - The State of Idaho incorporates aquatic life designations in their water quality standards (Idaho Administrative Code IDAPA 58.01.02). The temperature criterion for the Clearwater River is influenced by salmonid spawning. During the time of year when salmon are spawning and the eggs are incubating, the maximum water temperature is set at 13 °C (55 °F) with a maximum daily average no greater than 9 °C (48.2 °F). The standard reverts to the cold-water criteria of a maximum water temperature of 22 °C (72 °F) with daily averages no greater than 19 °C (66 °F) to provide cold water for optimum health during other life stages. The Idaho cold-water standard of 22 °C (72 °F) also applies to the mainstem of the Snake River above the confluence of the Clearwater River (river mile 139.3).

The State of Washington's Water Quality Standards (Washington Administrative Code [WAC] 173-201A; Rev: November 20, 2006) are also based on designated uses. The designated aquatic life use for the lower Snake River from its mouth at the Columbia River to the Oregon border (river mile 176.1) is salmonid spawning, rearing and migration. The water quality standards specify that water temperatures in the lower Snake River shall not exceed 20 °C (68 °F) within the study reach as a result of human activity. In addition, temperature increases due to human activity in the lower Snake River (*i.e.*, below the Clearwater River) shall not exceed:

$t = 34/(T+9)$, where
t = change in temperature, and
T = background temperature (°C)

For example, if the background temperature were 20 °C (68 °F), then the maximum allowable temperature increase due to human activity would be 1.17 °C (2.1 °F). Above the confluence with the Clearwater River, increases over 0.3 °C (0.5 °F) caused by human activity from a single source are not allowed, and increases over 1.1 °C (2 °F) from all activities are not allowed when the background stream temperature is over 20 °C (68 °F).

The Washington water temperature standards for the lower Columbia River from the mouth to river mile 391.1 are similar to the ones described above for the lower Snake River.

Use of Dworshak Project Releases for Downstream Temperature Moderation

The occurrence of water temperatures greater than 20 °C (68 °F) in the lower Snake River have been documented since at least the 1950s (Peery et al., 2003) and resource managers have considered utilizing cold-water releases from the Dworshak project for many years as a means of moderating these conditions for the benefit of salmonids. Dworshak Dam is a high-head cold-water storage project located on the North Fork of the Clearwater River, Idaho, and operated by the U.S. Army Corps of Engineers (USACE). The project was completed in 1973, is 717 feet tall, and has over 2 million acre feet of usable storage. In addition, the project has several features that provide flexibility for temperature control. First, the project has 3 turbine units, and each of these units has a selector gate that can be moved vertically to control tailwater temperatures (Figure 9). Total powerhouse capacity is about 10,000 cfs and additional discharges can be released from the spillway and/or the regulating outlets that are located about 250 feet below full pool. Total discharge is normally limited to approximately 14 kcfs to avoid exceeding Idaho's total dissolved gas standard of 110%. Second, because the forebay is about 650 feet deep, there is a considerable amount of cold water available during the summer even though the thickness of the warmer surface layer increases as the season progresses (Figure 10). Depending on where the selector gates are positioned, water can be withdrawn in overshot mode (i.e., it enters over the top of the gate), undershot mode, (i.e., it enters at the base of the gate) to tap into a specific thermal layer, or a combination of the two. Additional water can be released from the spillway at the beginning of the summer or the deep regulating outlets where the water is close to 4 °C (33.8 °F). These features facilitate blending deep cold water with warmer surface water through the summer.

Summer cold-water releases to aid migration of adult salmon and steelhead have occurred since 1991. The early releases were conducted on an experimental basis, but have since become a part of the operational program within existing authorities and other limitations. The amount of cold water currently available from Dworshak Dam for flow augmentation is the volume of water in the reservoir between elevation 1,600 ft (full pool) and 1,520 ft. This volume is approximately 1.2 million acre-feet (1.5 billion m^3).

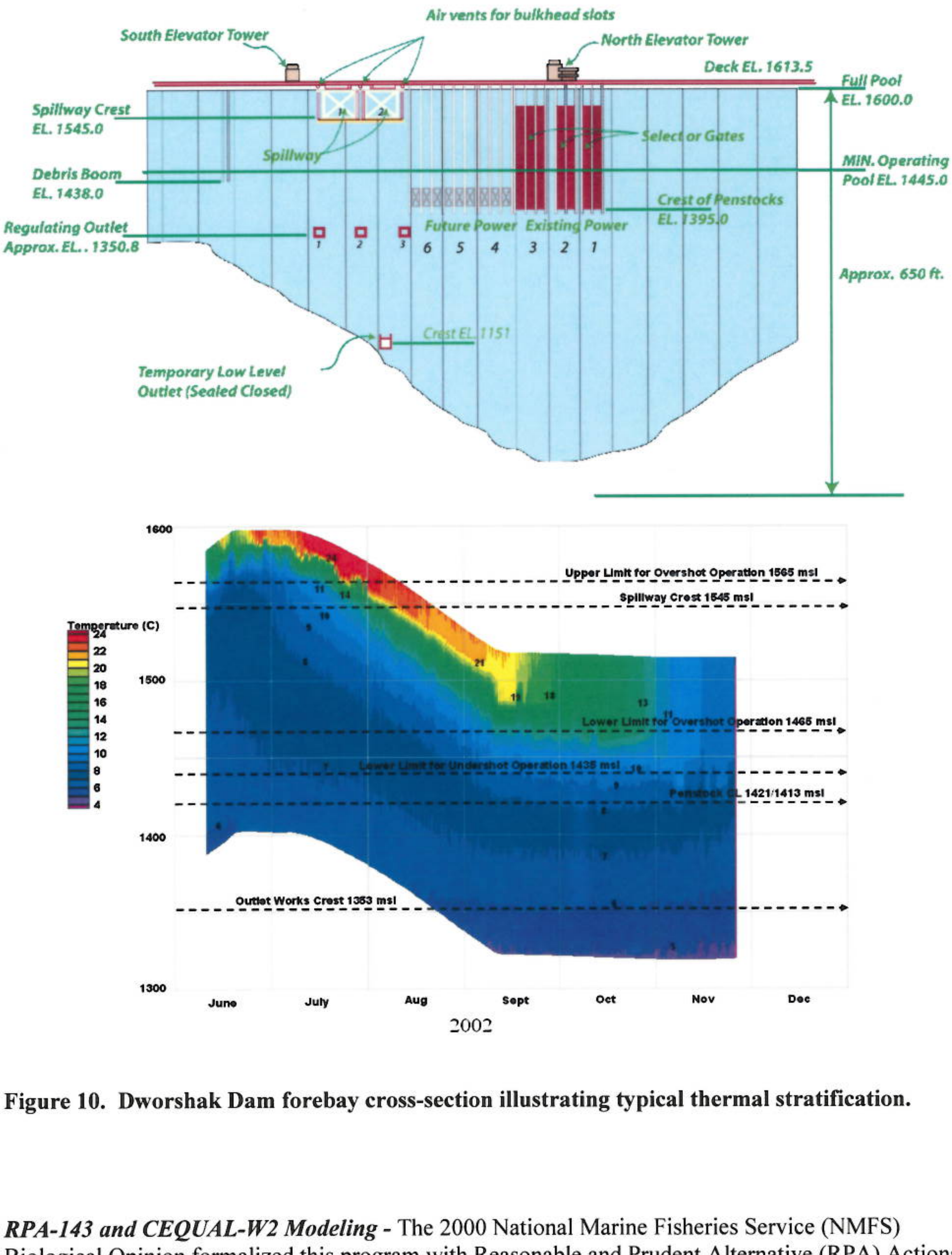


Figure 10. Dworshak Dam forebay cross-section illustrating typical thermal stratification.

RPA-143 and CEQUAL-W2 Modeling - The 2000 National Marine Fisheries Service (NMFS) Biological Opinion formalized this program with Reasonable and Prudent Alternative (RPA) Actions 33, 34, and 143. RPA Action 143 states, "[t]he Action Agencies shall develop and coordinate with NOAA Fisheries and EPA on a plan to model the water temperature effects of alternative Snake

River operations. The modeling plan shall include a temperature data collection strategy developed in consultation with EPA, NOAA Fisheries and state and tribal water-quality agencies. The data collection strategy shall be sufficient to develop and operate the model and to document the effects of project operations." To address this RPA action in a collaborative manner, the Regional Water Quality team established a technical workgroup to develop the plan called for by the action item. The team was composed of numerous agencies including: Bonneville Power Administration (BPA), Columbia River Inter-Tribal Fish Commission (CRITFC), the Environmental Protection Agency (EPA), Idaho Power Company, Idaho Department of Environmental Equality (IDEQ), Idaho Water Resources Department, Nez Perce Nation, NOAA Fisheries, Oregon Department of Environmental Quality (ODEQ), Fish Passage Center, US Army Corps of Engineers (USACE) and Washington Department of Ecology (WDOE).

The team recommended the CE-QUAL-W2 model because of its capability to simulate the exchange and transport of thermal energy in rivers and reservoirs where vertically stratified conditions may develop. The model has the ability to simulate a wide range of outlet structures, different physical reservoir characteristics, and water quality constituents through a complex network of water bodies. The coupled interaction between water temperature and density stratified flow conditions are readily simulated by the model and are critical for the accurate simulation of thermal budgets in storage reservoirs.

The Corps has been using CE-QUAL-W2 since 2005 to model environmental flow augmentation and temperature moderation releases from Dworshak Dam to the lower Snake River. Operations have been implemented based on the results of the modeled information to reduce temperature at Lower Granite Dam. These actions provide cooler deep water that adult fish utilize during upstream migration.

Water Temperatures in the Inflowing Snake and Clearwater Rivers - Water temperature data in the lower Snake River upstream of the reservoirs have been collected through routine monitoring programs since at least 1959. Construction of the lower Snake River reservoir projects began in 1956 at the Ice Harbor Dam site. To support construction and future project data requirements, the US Geological Survey (USGS) began collecting water temperature data at the following fixed monitor stations:

- The Snake River fixed monitor station near Anatone, Washington (river mile 167.2, approximately 8 miles east of Anatone)
- The Snake River fixed monitor station near Clarkston, Washington (river mile 134)
- The Clearwater River fixed monitor station near Spalding, Idaho (river mile 11.6, approximately 11 miles above Lewiston, Idaho).

Hourly water temperature data are transmitted via the Geostationary Operational Environmental Satellite (GOES) system in near real-time. The data collected by the USGS at these three stations are published in its annual Water Resources Data Report for Washington and Idaho. The quality of these data is controlled by the USGS using its standards, and the record is considered to be very good and representative of the river at these locations. The Snake River station near Clarkston was discontinued in 1964; therefore, only the Anatone and Spalding station data are used in this evaluation. The annual USGS publications list maximum and minimum temperatures for each day of the period. During this period of record, there were a number of changing reservoir conditions upstream from both the Anatone and Spalding gauges. Construction of the Idaho Power Company's Hells Canyon reservoir complex (i.e., Brownlee, Oxbow, and Hells Canyon) was completed on the

Snake River in 1967. Dworshak Dam construction was completed in 1973 on the North Fork of the Clearwater River (approximately 35 miles above the Spalding station). By 1974, upstream reservoir development above Lewiston, Idaho, was completed on both the Snake and Clearwater rivers and the upstream reservoirs were being operated under their normal operating criteria (as defined before special reservoir operations began for threatened and endangered fish species).

Where possible for this evaluation, data graphs are plotted beginning in 1975 to best represent the current level of upstream reservoir development. Data are analyzed by comparing each year in the record and also by preparing period averages for each record.

The average daily maximum water temperatures at the USGS Anatone station for the periods 1975 through 1991 and 1992 through 2010 are very similar (Figure 11). Maximum daily temperatures exceeded 20 °C (68 °F) each year for 35 to 91 days (an average of 56 percent of the time) between 1 June and 1 October.

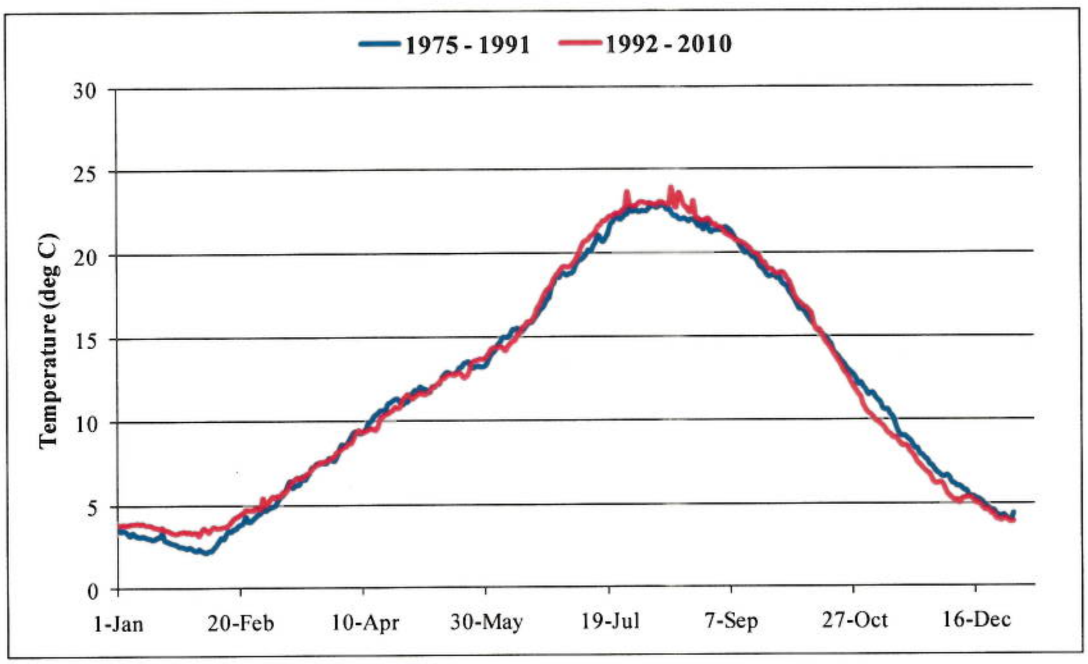


Figure 11. Average daily maximum water temperatures for the USGS fixed monitor station at Anatone, 1975 through 1991 and 1992 through 2010.

The analogous graph for daily maximum water temperatures recorded at the USGS fixed monitor station at Spalding on the Clearwater River shows a different pattern (Figure 12). This shift to colder temperatures during the 1992 - 2010 period is because of summer cold-water releases from Dworshak Reservoir. The temperature of these supplemental releases, during July, August, and September, range from 6 °C (43 °F) to 12 °C (54 °F). The purposes for these below-equilibrium temperature releases are to improve water temperature regimes and increase velocities in the four lower Snake River reservoirs; conditions thought to aid emigration of juvenile salmonids, reduce the occurrence of pathogenic diseases, and provide cooler water for returning adults. The augmentation flow usually begins in early July so that temperatures in the Lower Granite Dam tailrace (the compliance point used to evaluate temperature conditions in the lower Snake River) do not exceed a daily maximum of 20°C (68 °F). The 1992-2010 trace in Figure 12 shows that average maximum water temperatures peak in late June near 17 °C (62.6 °F) and the mean July and August temperatures were less than 20 °C (68 °F). In fact, the average maximum daily water temperatures were up to 6 °C (10.8 °F) less in July and August during the 1992 - 2010 interval.

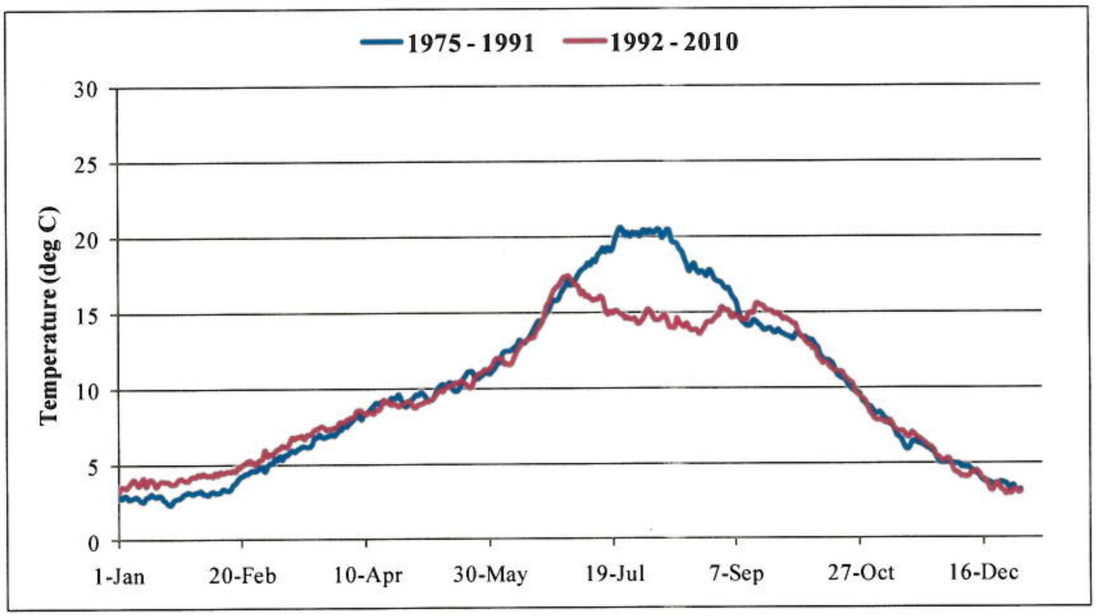


Figure 12. Average daily maximum water temperatures for the USGS fixed monitor station at Spalding, 1975 through 1991 and 1992 through 2010.

<u>Snake and Clearwater River Confluence Study/Modeling</u>

The Pacific Northwest National Laboratory completed a study from 2002 to 2005 to assess and model hydrodynamics and temperature conditions in the lower Snake River (Cook et al., 2006). The 2005 field work included an intensive effort to collect temperature and acoustic Doppler current profile (ADCP) information near the confluence of the Snake and Clearwater rivers. Four results from this study are of interest. First, if the differences between temperature and discharge in the two rivers are relatively small, then the two rivers will parallel each other downstream of the confluence for at least two miles (Figure 13). This scenario is typical of early spring conditions when the temperature differences are less than 2 °C (3.6 °F). Second, when the temperature difference is relatively small but the discharge difference is large; the two rivers can mix within two miles of the confluence. This set of conditions often occurs later in the spring when the temperature differences are 3-4 °C (5.4-7.2 °F) while the Clearwater River discharge ranges from 30-40 kcfs and the Snake River is between 55-60 kcfs. The third scenario, and one that typically occurs during the summer when cold water is released from the Dworshak project, is when there are relatively large (8-12 °C [14.4-21.6 °F]) temperature differences between the rivers. In this case, the cold Clearwater River water plunges beneath the warmer Snake River at the confluence (Figure 14). Fourth, the cold water from the Clearwater River can migrate upstream along the bottom of the Snake River. The extent of this intrusion depends on the differences in density and momentum of the two rivers but can extend approximately one mile upstream.

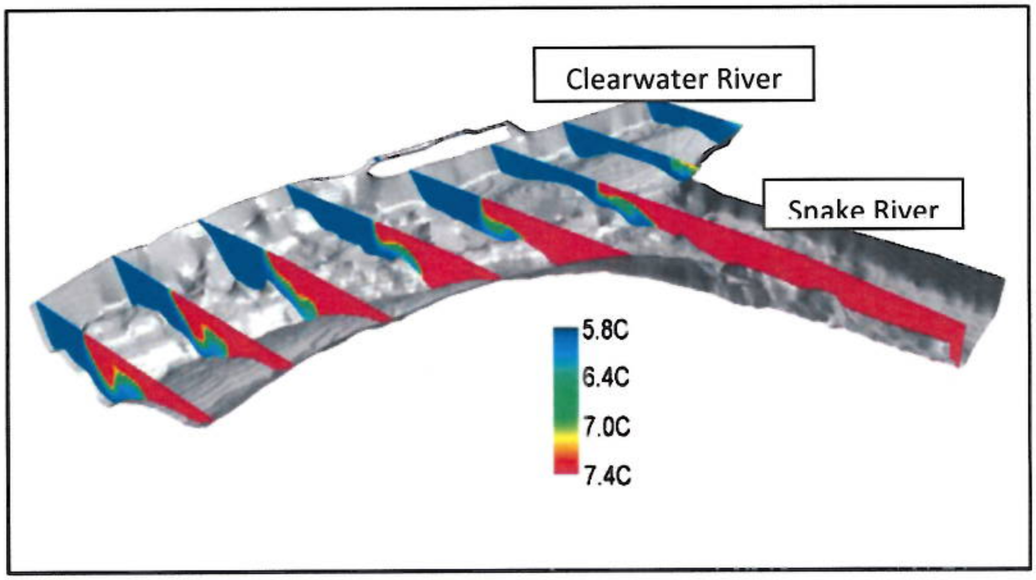


Figure 13. Lateral temperature differences at the confluence of the Snake and Clearwater Rivers when the temperature and discharge differences are relatively small (Cook et al., 2006)

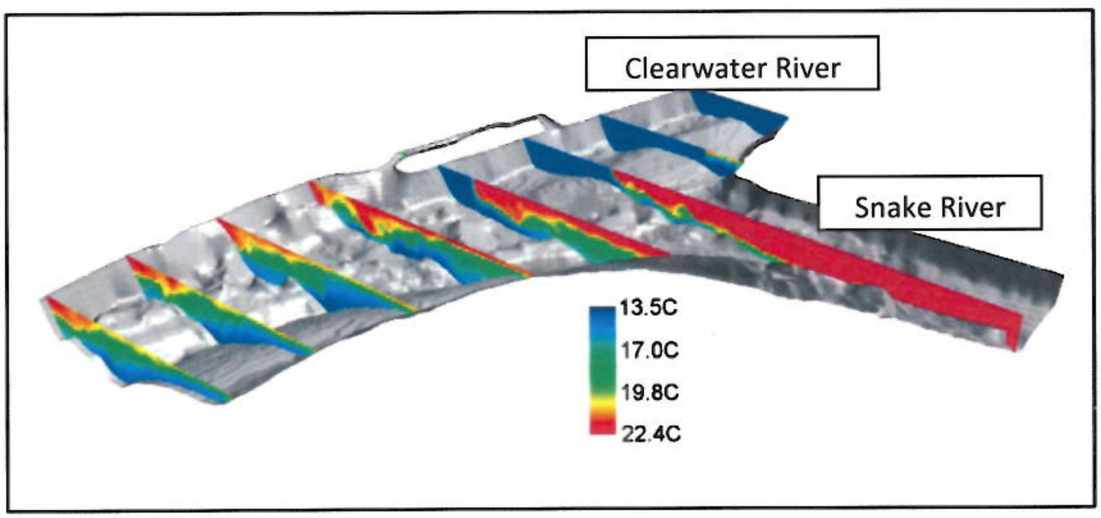


Figure 14. Temperature gradients at the confluence of the Snake and Clearwater Rivers when the temperature differences are relatively large (Cook et al., 2006)

***Water Temperatures at Lower Granite Dam Tailwater* -** Lower Granite tailwater is the compliance point that the Regional Technical Management Team (TMT) considers with regards to the 20 °C (68 °F) temperature standard. The effect of releasing cooler Dworshak Reservoir water during the summer is very apparent in Figure 15. The 1978 through 1991 period is represented by available project scrollcase temperatures. These temperatures were recorded at the projects prior to the current real-time in-river sensors and were recorded once or twice a day. Because the turbine intakes are located relatively deep in the water column, this data does not represent maximum thermal conditions, but rather something closer to average. However, it is the only historic time series project data available and does show that water temperatures were greater than 20 °C (68 °F) between the beginning of July and the first part of September at Lower Granite Dam. The 1995 through 2010 trace shows that the average of the daily maximum temperatures recorded at the Lower Granite Dam fixed monitoring system (FMS) tailwater station were less than 20 °C (68 °F). During the time the CEQUAL-W2 model has been used, the occurrence of hourly temperature exceedances at Lower Granite Dam have ranged from 0-5 percent.

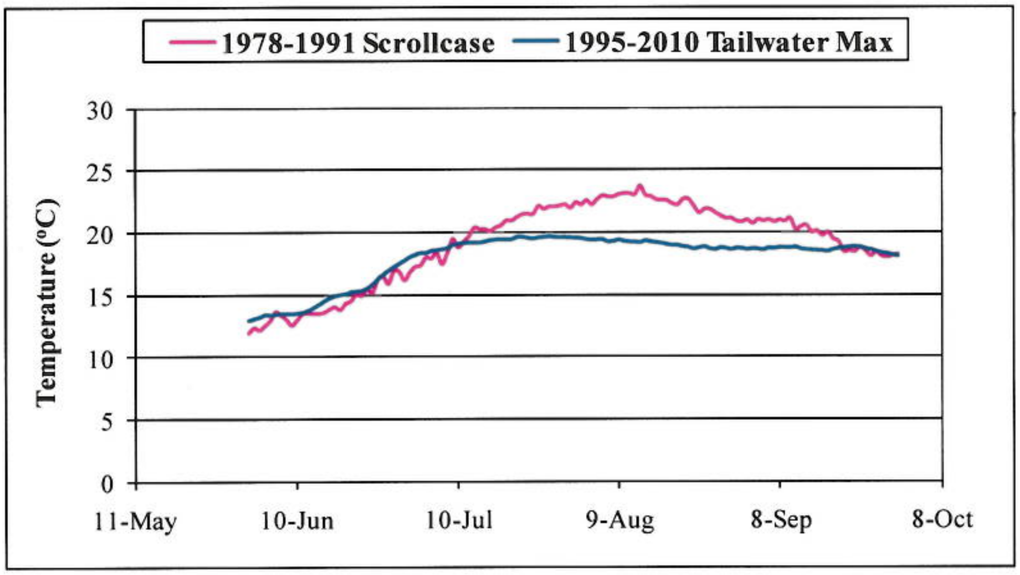


Figure 15. Comparison of the 1978-1991 and 1995-2008 scrollcase temperatures wiht the 1995-2010 tailwater FMS station temperatures at Lower Granite Dam.

Water Temperatures Within the Lower Snake River Reservoir System

The lower Snake River reservoirs do not stratify thermally to the extent that Dworshak Reservoir and other deep lakes typically do. Significant temperature differences between the surface and bottom waters are generally rare in flowing waters. A frequently used rule-of-thumb is that a water body has to have a mean depth greater than 10 m (33 ft) and a mean annual hydrologic residence time in excess of 20 days before strong thermal stratification develops. The mean depths of the lower Snake River reservoirs are greater than 10 m (33 ft), but the average annual residence time for each pool is about five days. The calculated retention time can approach 20 days during the summer and fall of low-flow years and facilitate the development of vertical temperature differences. However, wind- and flow-induced turbulent diffusion, along with convective mixing historically prevented thermal stratification from happening most of the time.

However, with the advent of the summer augmentation flows described above, vertical thermal gradients are more pronounced in the lower Snake River now than they were in the past. The summer thermal gradient is more apparent in that forebay of Lower Granite Dam than other Corps projects on the lower Snake River because it is the upper most project. Based on hourly data (2005-

2010) from temperature stings that were installed in the forebays of each lower Snake River dam in 2004 as part of the RPA Action 143 program, the average temperature difference during 15 July through 31 August at 1 m (3.3 ft) and 30 m (98 ft) was 4.1 °C (7.4 °F). This difference has been as high as 8 °C (14.4 °F). The thermal influence of summer cold-water releases from Dworshak Dam decreases downstream (Figure 16) and varies from year-to-year, but the average difference at Little Goose Dam for the same time period was 2.1 °C (3.8 °F) and 1.6 °C (2.9 °F) at Lower Monumental Dam and Ice Harbor dams.

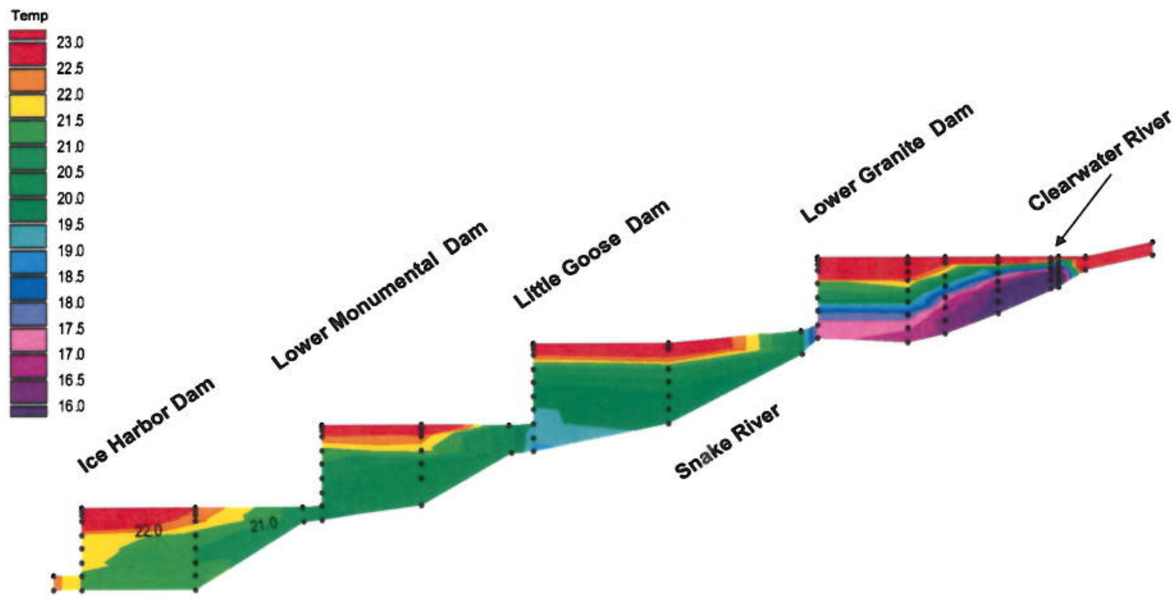


Figure 16. Average water temperature gradients in the four lower Snake River reservoirs from 15 July through 31 August 2006.

One consequence of stronger vertical thermal gradients in the forebays of the four lower Snake River projects, especially Lower Granite Dam, is temperature differentials in the adult fish ladders. A study completed by USACE between 2000 and 2002 as a response to RPA Action 114 investigated water temperature differences between the exit and entrance of the fish ladders at the four projects (USACE, 2004). The results showed that the number of hourly temperature differentials that exceeded 2.7 °C (5 °F) between 1 June and 30 September was greatest at Lower Granite Dam, ranging from 378 in 2002 to 1,046 in 2001. The average number of exceedances decreased at downstream projects, ranging from 71 to 371 at Little Goose Dam, 29 to 65.5 at Lower Monumental Dam and 1.5 to 68.5 at Ice Harbor Dam. These differences can hinder upstream migrations, and there are on-going investigations aimed at creating more uniform ladder temperatures.

Comparison Between Above and Below the Lower Snake River Reservoir System - Another perspective of the thermal benefits of the summer flow augmentation program can be seen by comparing water temperature conditions above the lower Snake River reservoir system to selected tailwater stations. Figure 17 displays an upstream versus downstream temperature summary comparison using mean daily maximum temperatures measured from 1995 through 2010. During

July, August, and part of September, the maximum temperatures were greatest at the inflowing Snake River at Anatone, least at Lower Granite Dam tailwater, and Ice Harbor Dam tailwater was intermediate. The mean difference between maximum daily temperatures at Anatone and Lower Granite Dam tailwater was 3.5 °C (6.3 °F), but was as high as 4.9 °C (8.8 °F). The maximum and mean temperature differences between Anatone and Ice Harbor Dam tailwater were less at 2.4 °C (4.3 °F) and 1.3 °C (2.3 °F), respectively.

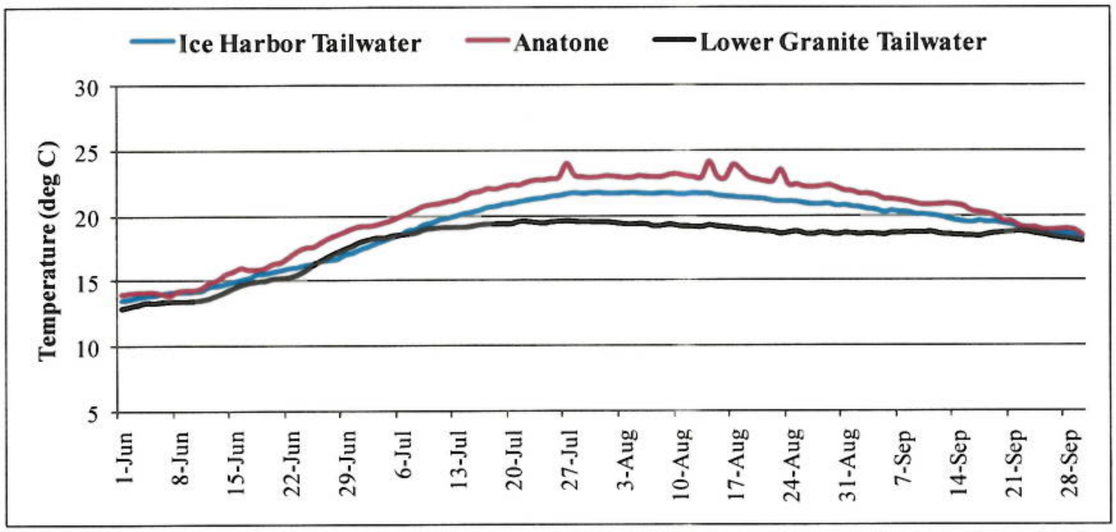


Figure 17. Average maximum temperatures measured at Anatone, Lower Granite Dam tailwater and Ice Harbor Dam tailwater between 1995 and 2010.

Summary

This section of the report documents the extensive information currently available regarding the lower Snake River temperature conditions including the Corps' implementation of the CE-QUAL-W2 temperature model, how Dworshak project releases provide for cooler deep water (thermal refugia) in the lower Snake River for fish use during upstream.

Section 3: Temperature regimes during upstream migration and the use of thermal refugia by adult salmon and steelhead in the Columbia River basin. (University of Idaho - December 2011.)

Introduction

Summertime water temperatures in the lower Columbia River have steadily increased over the last several decades (Figure 18). Annual peak temperatures have exceeded 21 °C in most recent years and have been as high as 24 °C. The warmest period typically occurs in late July to early September, coincident with late-migrating summer Chinook and sockeye salmon and with substantial portions of the fall Chinook salmon and summer steelhead runs (Figure 19). Water temperatures in the 19-22 °C range, like those that routinely occur in the Columbia River main stem, are a significant management concern for adult migrants because large proportions of adults currently can experience thermal conditions considered to be stressful. Such temperatures have been associated with behavioral changes and a variety of sub-lethal effects on physiology, disease susceptibility, reproductive development, gamete quality (i.e., over-ripening), survival, and fitness (e.g., Flett et al. 1996; Lee et al. 2003; Naughton et al. 2005; Richter and Kolmes 2005; Wagner et al. 2005; King et al. 2007; Mann 2007; Reid 2007; Farrell et al. 2008; Keefer et al. 2008a, 2010; Eliason et al. 2011). Based on these and other studies, we assume that temperatures above ~18-19 °C induce stress in adult migrants and that higher temperatures are associated with stronger negative consequences. This issue may become more acute if warmer regional temperatures predicted by climate models come to pass.

Many adult salmon and steelhead temporarily use thermal refugia when Columbia and Snake River water temperatures are high (Goniea et al. 2006; Keefer et al. 2009). These sites appear to be critically important mid-migration holding habitats for some populations. A series of cool-water refugia are located along the migration corridor at tributary confluences with the main stem rivers. Many of the most-used refugia sites are located between Bonneville and John Day dams in the lower Columbia River, where cool-water tributaries draining the Cascade Range enter reservoirs. These sites are often 2-7 °C cooler than the main stem (High et al. 2006; Goniea et al. 2006). Additional sites that may be thermal refugia for adult migrants include tributary confluence areas downstream from Bonneville Dam, upstream from the Columbia River-Snake River confluence in the mid-Columbia River, and in the Snake River upstream from Lower Granite reservoir. The lower Snake River contains little in the way of cool water refugia but there is evidence that fish will use the limited cool water sources when available. In addition, managers have seasonally reduced Snake River reservoir water temperatures by releasing cool water from Dworshak reservoir on the Clearwater River, and adult migrants do use the cooler water (Clabough et al. 2007a, 2007b). Salmonid use of specific refugia sites other than in the Bonneville-John Day reach has not been well documented, but there is anecdotal evidence that adult aggregations occur seasonally at several locations. Groundwater-based refugia in the main stem have not been identified, but may be present in reaches not dominated by bedrock. Potential locations include areas downstream of dams such as tailraces where there is a potential for groundwater input (above the dam) and expression (below the dam). The ecological significance of such areas would depend on the discharge rate and temperature of groundwater. The latter would be strongly influenced by groundwater residence time.

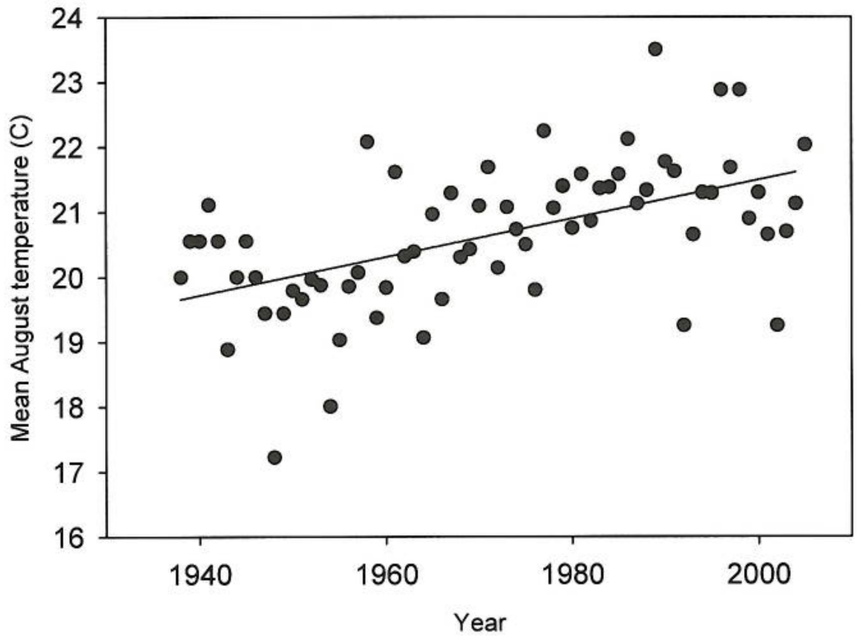


Figure 18. Mean August water temperature (°C) at Bonneville Dam, 1938-2005. Source: Columbia River DART.

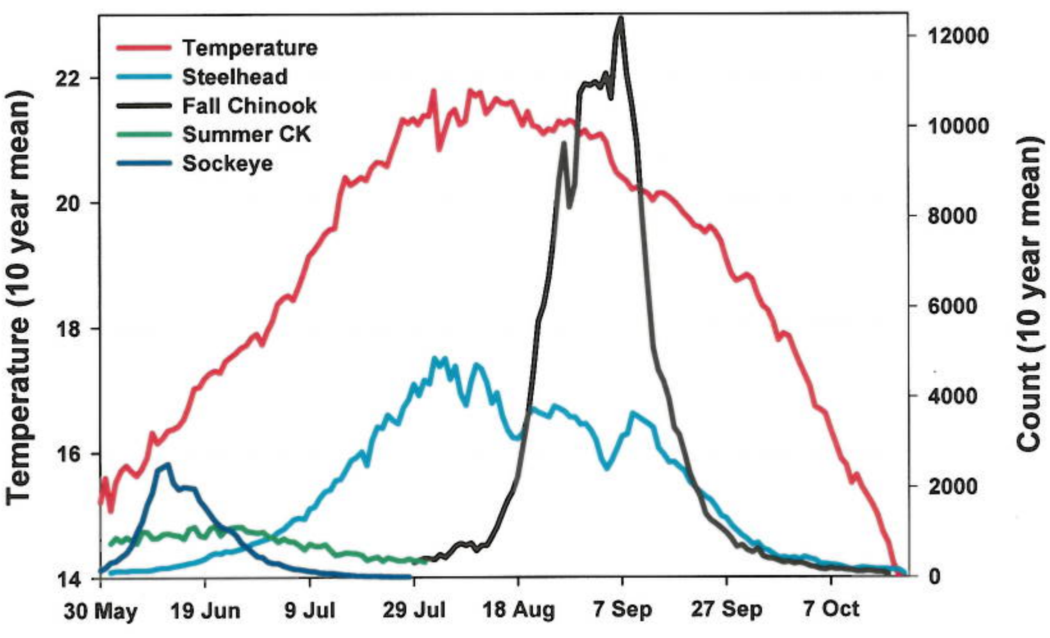


Figure 19. Ten-year (1996-2005) mean lower Columbia River water temperature (°C) and mean run size and timing of adult summer Chinook salmon, fall Chinook salmon, sockeye salmon, and summer steelhead at Bonneville Dam. Thermal refugia use by many adult populations has been associated with water temperatures greater than 19-20 °C.

Much of what is known about adult salmon and steelhead use of thermal refugia in the Columbia basin has been gleaned from the large-scale radiotelemetry studies funded by the USACE and conducted by the UI and NMFS. While these studies focused on monitoring adult salmonid behavior at dams, most major tributaries were also monitored to help estimate hydrosystem escapement and identify individual populations. The antenna arrays at tributary confluence areas and adjacent reservoir sites allowed us to collect behavioral data at several of the critical refugia sites. The following summary describes some of the basic results of this research.

Thermal Refugia Summary

Spatial distribution – The thermal refugia sites that have been most studied are located at tributary confluences in the Bonneville and The Dalles reservoirs (Figure 20). These include Herman and Eagle creeks and the Wind, Little White Salmon, White Salmon, Hood, Klickitat, and Deschutes rivers. The most-used among these have been Herman Creek and the Little White Salmon, White Salmon, and Deschutes Rivers. Upstream from John Day Dam, tributaries draining primarily high-desert landscapes like the John Day, Umatilla, and Yakima rivers may provide periodic cool water refugia, but lower reaches of these rivers are often as warm as or warmer than the Columbia River during summer. A large temperature gradient often exists at the confluence of the Snake River measured at Ice Harbor and the Columbia River measured at Ice Harbor, with the Snake typically being warmer in summer and fall. Some Snake River adults temporarily hold in the cooler mid-Columbia water during warm periods (e.g., Stuehrenberg et al. 1978; Quinn et al. 1997). For example, some fall Chinook salmon and steelhead tagged at Ice Harbor Dam with thermal recorders delayed reascending the Snake River for 2 to 3 weeks and had noticeably cooler thermal profiles than adults that did not delay their migrations through the lower Snake River (Mann and Peery 2005).

Likely thermal refugia downstream from Bonneville Dam include the confluence areas of the Cowlitz, Lewis, Washougal, and Sandy rivers as well as several smaller tributaries fed by Cascade Range snowmelt or glaciers. Adult use of these sites for thermal refuge is largely anecdotal. Similarly, we are unaware of any quantitative summaries of refugia use in the mid-Columbia River upstream from Priest Rapids Dam, though confluence areas of the Wenatchee, Methow, and Entiat rivers may be seasonally important when main stem Columbia River temperatures reach stressful levels. In the impounded lower Snake River, there are known thermal refugia frequented by fall Chinook salmon and steelhead migrants (Mann 2007) at the outfall from Lyons Ferry hatchery and periodically at the Tucannon River confluence. In Lower Granite reservoir, Chinook salmon and steelhead will select to migrate in cooler water layers that result from releases from Dworshak reservoir when available (Clabough et al. 2007a, 2007b). At the head of Lower Granite reservoir, the confluence of the Clearwater and Snake rivers is an important refugium site for adults *en route* to the Hells Canyon reach of the Snake and to the Salmon, Grande Ronde, and Imnaha rivers. Thermal refugia have also been identified in several Snake River tributaries (e.g., Ebersole et al. 2003; Howell et al. 2010), but these studies have focused on resident salmonids and juvenile anadromous fish. We have observed adult salmon using thermal refugia near spawning grounds in some Salmon River tributaries (e.g., the South Fork Salmon River), but these behaviors have not been quantified. We are also currently examining the relationship between water temperature, adult behavior in relation to water temperature, and prespawn mortality during the migration and prespawn periods for Chinook salmon in the Willamette River basin (Mann et al. 2010; Keefer et al. 2010).

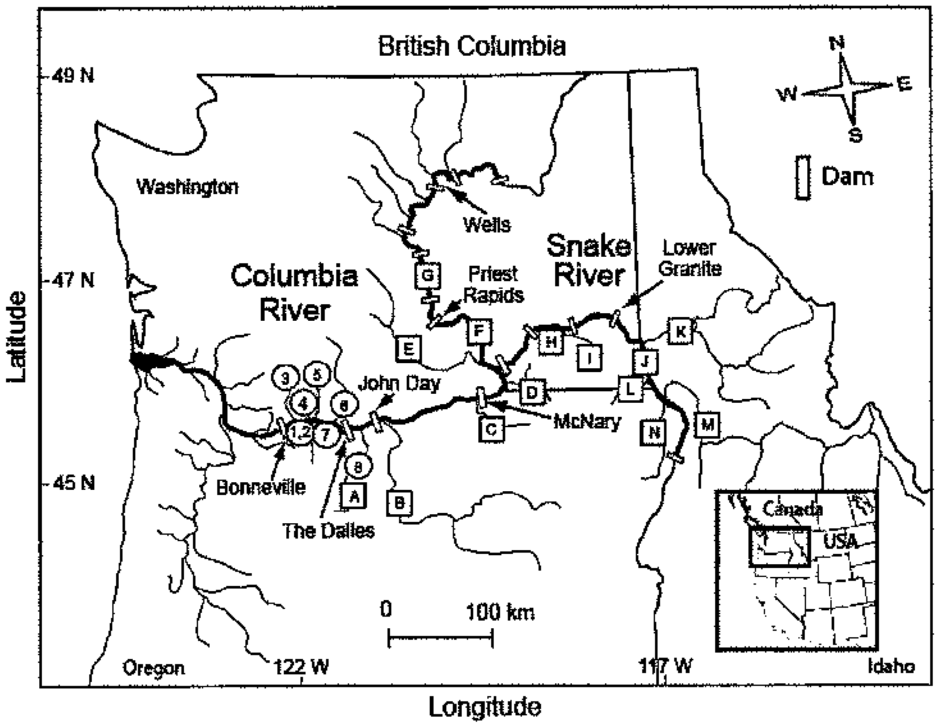


Figure 20. Map of the Columbia and Snake River basins, where radio-tagged adult salmon and steelhead were monitored at dams, in reservoirs, and while using cool water tributaries during migration through the lower Columbia River. Thermoregulatory behaviors were monitored at eight sites: (1) Herman Cr., (2) Eagle Cr., (3) Wind R., (4) Little White Salmon R., (5) White Salmon R., (6) Klickitat R., (7) Hood R., and (8) Deschutes R. Sites A-N were tributary populations used in the steelhead study described in Keefer et al. (2009).

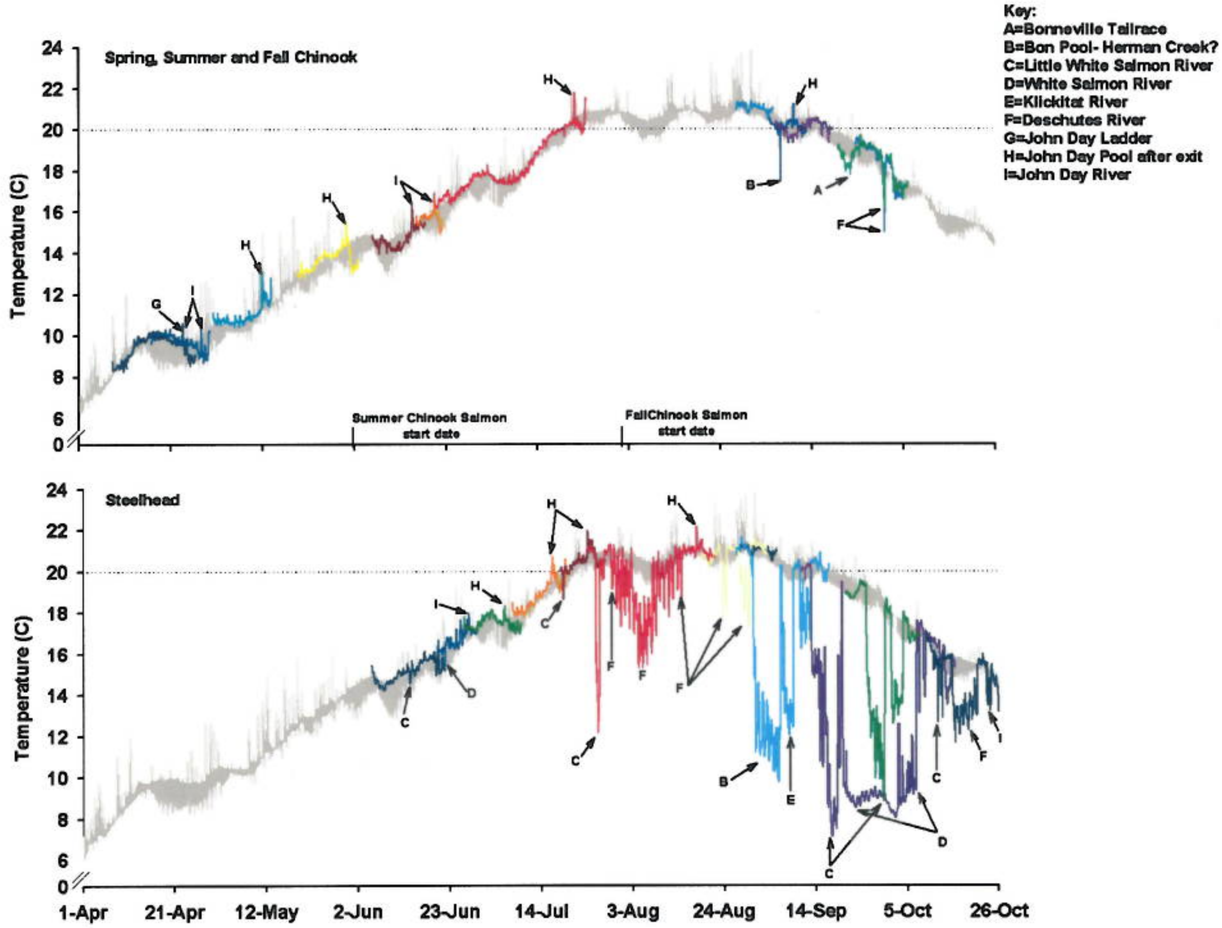


Figure 21. Examples of migration temperatures adult Chinook salmon (top) and steelhead (bottom) experienced during their migration from Bonneville Dam to McNary Dam, 2002. Gray bars represent the range (min to max) of daily mean water temperatures recorded at the four lower Columbia River dams. Colored lines represent fish body temperatures as recorded by internal temperature tags. (Each color represents an individual fish.) Body temperatures below the gray bars indicate thermal refugia use: specific migration locations are noted in the key at the upper right. Figure from Caudill et al. *in prep*. Also see Clabough et al. (2008).

Refugia use by summer steelhead – The incidence and duration of thermal refugia use differs widely among species as a function of migration timing and basic life history. In our research, summer steelhead had both the greatest incidence (~70%) and longest duration (up to several weeks or more) of refugia use among species studied in the lower Columbia River (Figure 21).

Initiation of thermal refugia use by steelhead in the lower migration corridor has been associated with main stem water temperatures of about 19 °C (Figure 22). For example, only about 10% of steelhead that entered the Bonneville reservoir when temperatures were <19 °C were detected on antennas at refugia sites, and these fish only briefly used the sites. In contrast, almost half the steelhead that entered the reservoir when temperature were 19-21 °C used refugia tributaries, and >70% used tributaries when temperatures were > 21 °C (Keefer et al. 2009). Duration of use rapidly increased as temperature increased, and extended to weeks during the warmest times (Figure 22). The summary of refugia use by upper Columbia River steelhead shown in Figure 23 is typical of the observed behavior in the Bonneville-John Day reach: fish that entered the reservoirs during warm periods quickly moved into cool-water tributaries and many remained until the onset of fall cooling.

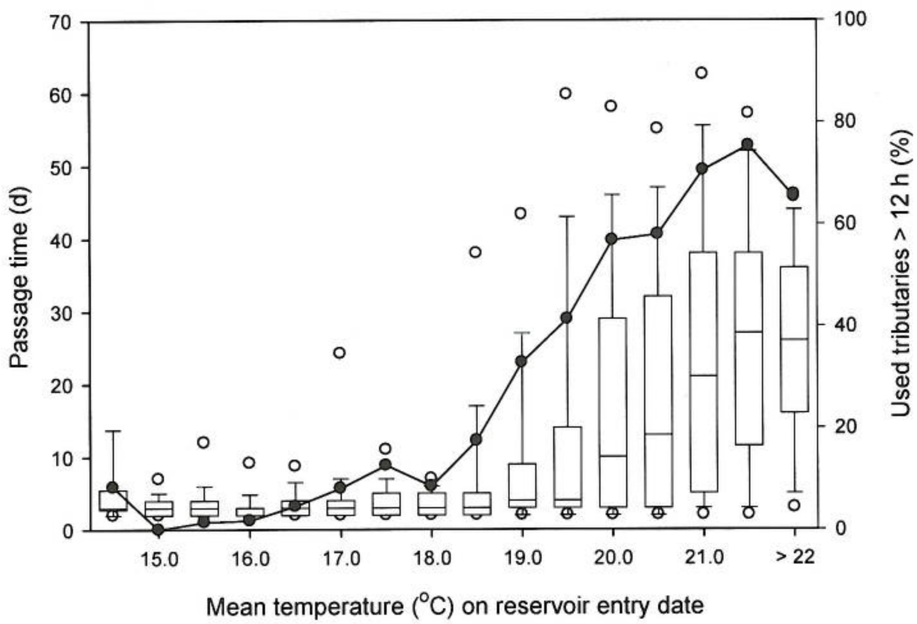


Figure 22. Steelhead passage times (d) from the top of Bonneville Dam to the top of The Dalles Dam, by water temperature at the Bonneville WQM site on the date each fish entered the Bonneville reservoir. Box plots show median, quartile, 10th, and 90th percentiles, pooled across study years; 5th, and 95th percentiles are marked by open circles. Solid line with solid circles shows the percent of steelhead recorded in cool water Bonneville reservoir tributaries for > 12 h. Figure from Keefer et al. (2009).

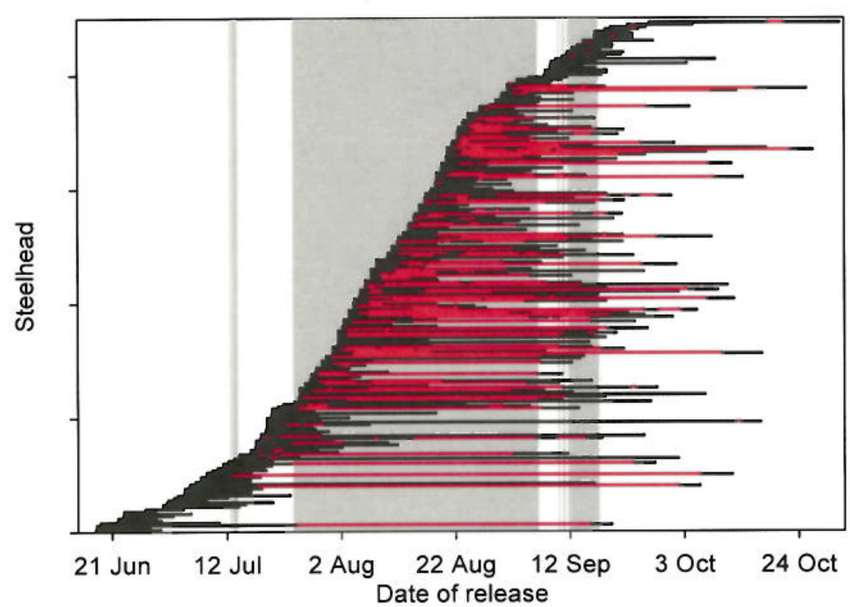


Figure 23. Cool-water refugia use recorded in the lower Columbia River (Bonneville Dam-John Day Dam) for 235 summer steelhead that eventually migrated to the upper Columbia River in 2001. Gray shading represents days when the mean Columbia River water temperature was ≥20 C. Each horizontal line represents an individual fish. Black sections of each line represent time when steelhead were in the main-stem Columbia River and red sections represent time in refugia tributaries.

Notably, individual steelhead often exited refugia tributaries into the main stem, but then quickly re-entered either the same refugia or another cool-water site if the main stem was warm. There did not appear to be differences in which tributaries were used that were associated with main stem temperatures or refugia-main stem temperature differentials, though these hypotheses were not explicitly tested.

In the Bonneville reservoir reach, radio-tagged steelhead were most likely to use the Little White Salmon (i.e., Drano Lake), White Salmon, and Wind rivers along with Herman Creek (Figure 24). Eagle Creek was also frequented by steelhead, though monitoring at that site was limited. Use of the Klickitat and Hood rivers was less than at the other tributaries, perhaps because of the extensive shallow flats near the mouths of these rivers (High et al. 2006). Above The Dalles Dam, about 25% of steelhead that passed John Day Dam were recorded in the Deschutes River. Fewer steelhead used the Deschutes (relative to the combined Bonneville sites) primarily because steelhead entered The Dalles reservoir about three weeks later, on average, than they entered the Bonneville reservoir and therefore encountered cooler main stem temperatures.

In all of the monitored lower Columbia River tributary refugia sites, rates of use and temporary residence times varied among steelhead populations (Figure 25). Population-specific refugia use was predictably associated with migration timing (Figure 26), with early- and late-timed populations less likely to use the cool-water sites. Groups with lower use included Hanford Reach, Tucannon, Clearwater and some Salmon River populations. The highest use rates and residence times were for populations that migrated during the warmest period, including Grande Ronde, Imnaha, Umatilla, Yakima, and John Day River populations (Figure 25).

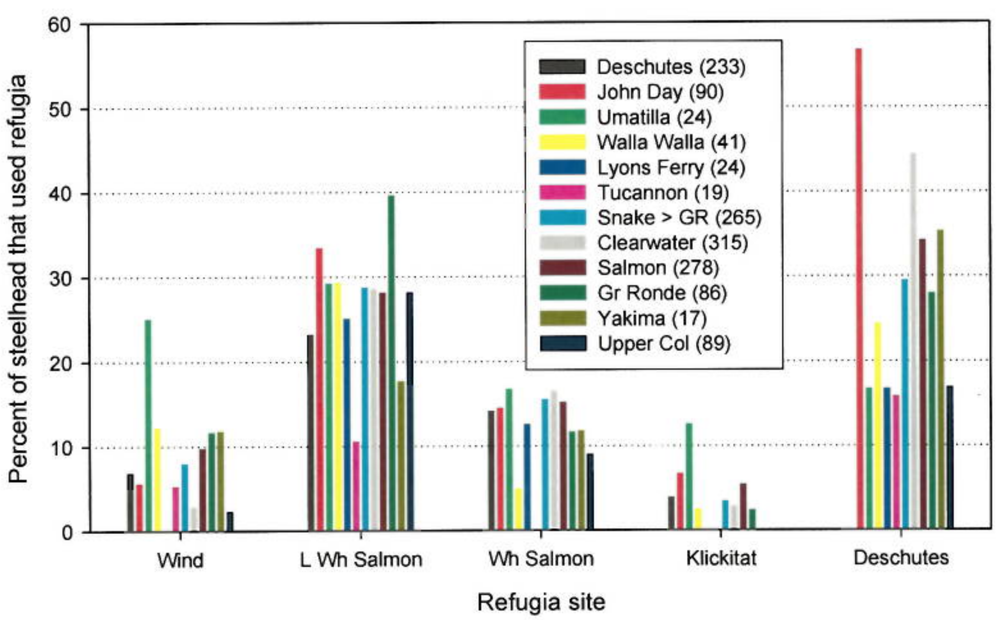


Figure 24. Population-specific use of selected cool-water refugia tributaries in the Bonneville-John Day reach by radio-tagged summer steelhead in 1996-1997 and 2000. Bar colors represent upriver populations, with sample sizes in parentheses. Steelhead additionally used Herman and Eagle creeks, but these small sites were inconsistently monitored in these study years. A small number of steelhead temporarily used the Hood River (not shown).

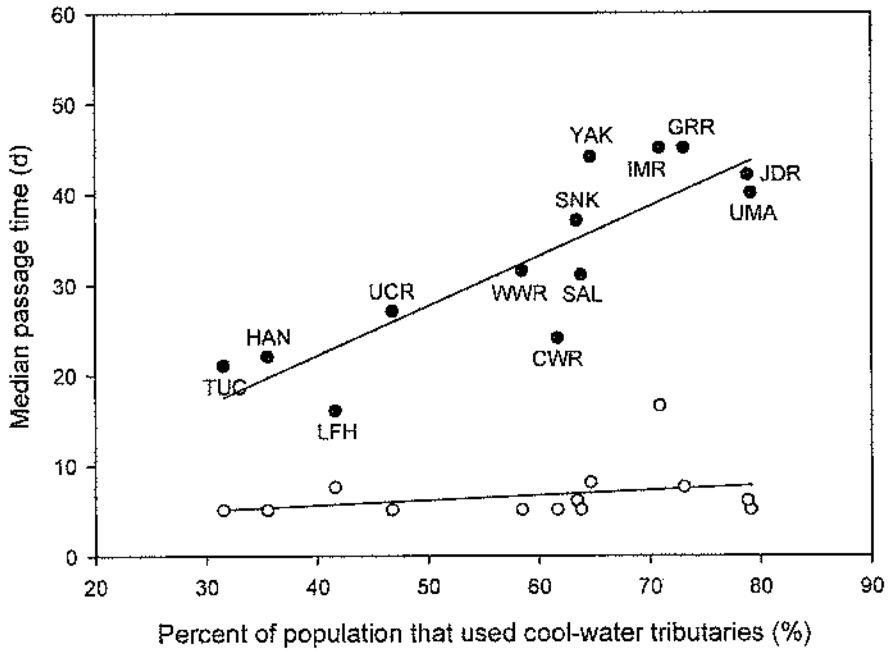


Figure 25. Relationships between median population-specific steelhead passage times from the top of Bonneville Dam to the top of John Day Dam and the percentages of steelhead that were (•) or were not (○) recorded in cool-water tributaries for > 12 h. Labels represent specific upriver populations. From Keefer et al. (2009).

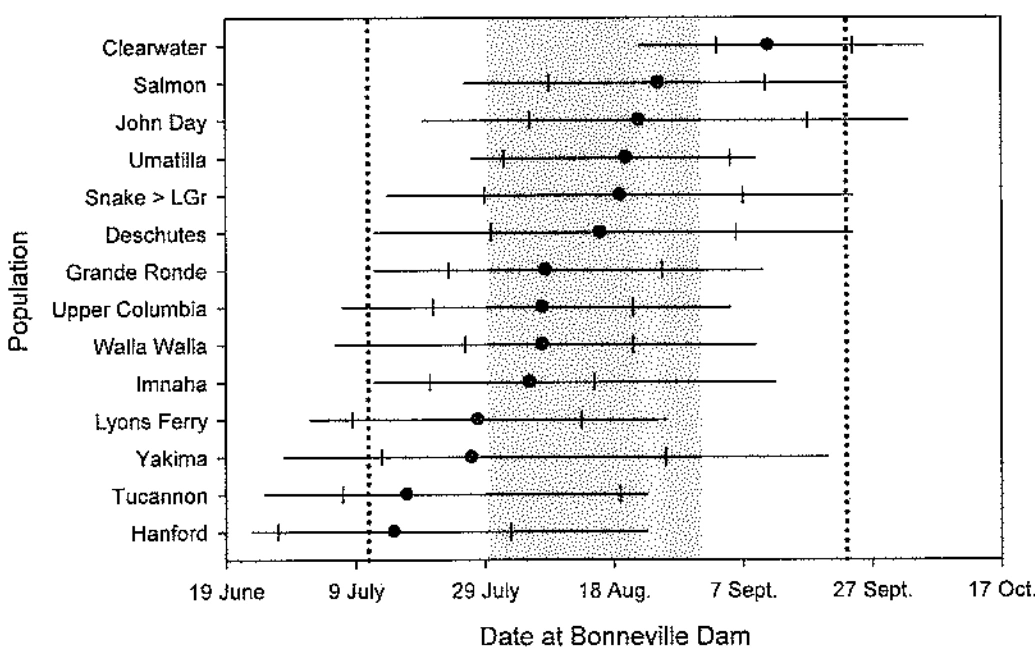


Figure 26. Migration timing distributions (median, quartiles, and 10th and 90th percentiles) at Bonneville Dam for steelhead that successfully returned to tributaries or hatcheries across study years. Vertical dotted lines show mean first and last dates that Columbia River water temperature was 19 °C; the shaded area shows dates with mean temperature ≥21 °C. From Keefer et al. (2009).

Extended refugia residence times for summer steelhead resulted, at least in part, from the relatively flexible migration timetable for steelhead. Many of the summer-run fish enter the Columbia River study area at the warmest time but have 6-10 months to reach springtime spawning areas. In our research, steelhead populations with relatively early (i.e., May) and relatively late (i.e., late September to October) migration past Bonneville Dam tended to encounter lower main stem temperatures and used lower Columbia River refugia at substantially lower rates than populations that migrated in mid-summer. It is certainly plausible – even probable – that the early-timed groups used other, unmonitored cool water sites further upstream, including sites in secondary tributaries. We have anecdotal evidence for this behavior, but temperature monitoring outside the lower Snake and lower Columbia rivers was not an objective of the original research.

Refugia use by Chinook salmon – In contrast with summer steelhead, about 20% of fall Chinook salmon and 15% of late summer Chinook salmon were recorded in one or more lower Columbia refugia sites in the radiotelemetry studies (e.g., Goniea et al. 2006). Summer and fall Chinook salmon have typically used refugia sites on a scale of days rather than weeks and mostly when main stem temperatures were highest (Figure 24). Even shorter temporary residence times in refugia sites were recorded for spring and early summer Chinook salmon (i.e., minutes to hours), suggesting to us that many of these populations enter lower river tributaries while searching for olfactory or other orientation cues (i.e., 'proving'), or as a result of conspecific behavior rather than as a result of thermoregulatory activity. Keefer et al. (2008b) includes a summary of temporary, non-natal tributary use by spring–summer Chinook salmon.

Initiation of thermal refugia use in the lower Columbia River by upriver fall Chinook salmon was associated with main stem water temperatures between 20 and 21 °C and rapidly increased as temperatures rose above 21°C (Figure 27). In our studies, 9% of radio-tagged fall Chinook salmon used migration corridor refugia for ≥12 h and the mean residence time for this group was 5.1 d (median = 2.9 d; Goniea et al. 2006). A fairly distinct temperature threshold was evident in both the initiation of refugia use (Figure 27) and the reduction in salmon passage rates through the Bonneville-John Day migration reach (Figure 28).

The Little White Salmon and White Salmon rivers were the most-used refugia sites for upriver fall Chinook salmon (i.e., those that passed John Day Dam), followed by the Deschutes and Klickitat rivers. Detections at antennas near the mouths of the Wind and Deschutes rivers also indicated that many salmon used the cool-water plumes from these rivers without moving out of the main stem and passing the in-stream antennas.

The upriver bright fall Chinook salmon run is numerically dominated by Hanford Reach fish, with additional populations in the Snake, Yakima, Deschutes, and upper Columbia rivers (Jepson et al. 2010). As with summer steelhead, among-population differences in run timing among the upriver bright Chinook salmon results in differences in temperature exposure and refugia use patterns among populations. On average, stocks that return to spawning areas upstream from Priest Rapids Dam and Deschutes river stocks are relatively abundant in August (Figure 29).

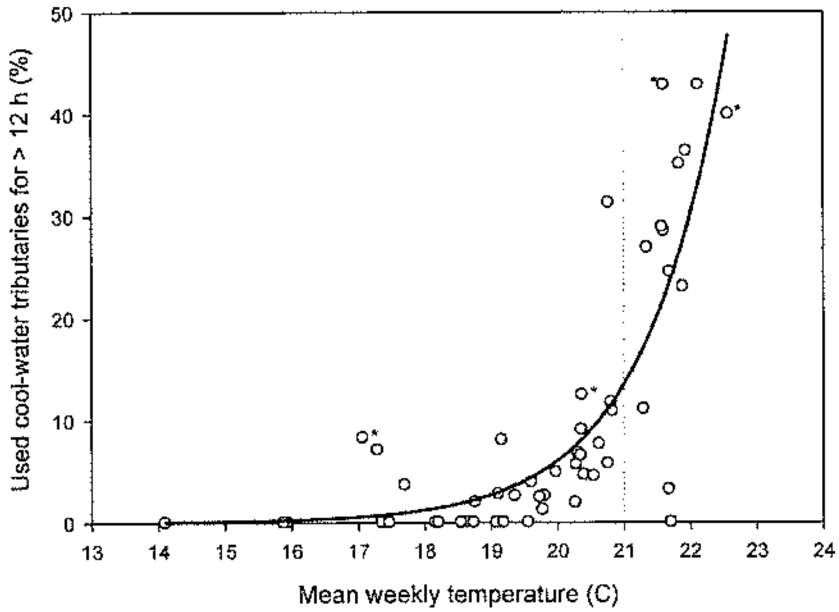


Figure 27. Relationship between the percent of fall Chinook salmon that used (> 12 h) cool-water tributaries and mean weekly water temperatures at Bonneville Dam. Symbols (○) represent 52 weekly bins (*mean* = 41 fish/bin; *range* = 4-122 fish/bin). Curve (—) is the exponential regression line that best fits the data (r^2 = 0.80; P < 0.0001; percent = $6.558^{-7}e^{0.802*\text{temperature}}$. Asterisk indicates data point with < 10 fish. Figure from Goniea et al. (2006).

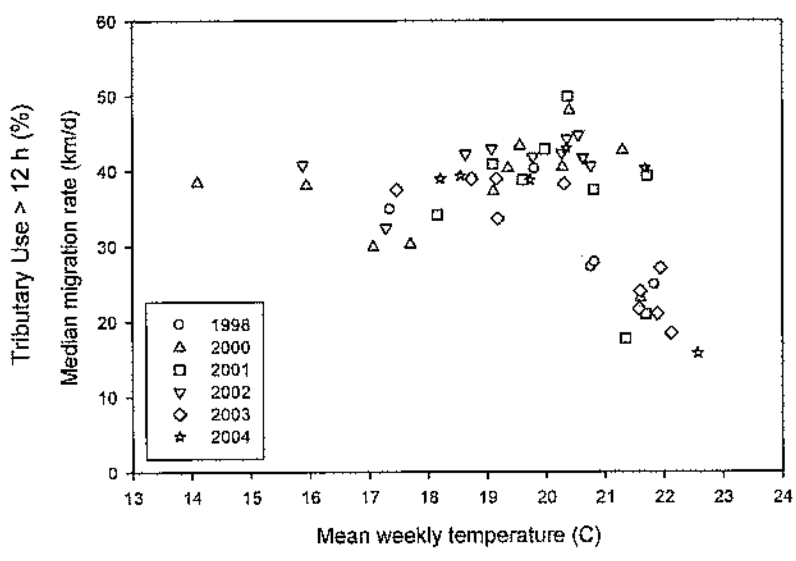


Figure 28. Relationship between median fall Chinook salmon migration rates (Bonneville to John Day Dam and mean weekly water temperatures at Bonneville Dam. Symbols represent week bins (*mean* = 41 salmon/bin; range = 4-122 salmon/bin). From Goniea et al. (2006).

Snake and Yakima River populations pass through the lower river corridor at low levels through much of August and September, while the Hanford Reach group increases in relative abundance as the fall season progresses. Refugia use by the radio-tagged fall Chinook salmon reflected these among-population differences in abundance and migration timing. A total of 161 salmon used refugia sites in the lower river for ≥12 h and could be confidently assigned to an upriver population. Of these, 80 (50%) were Hanford Reach fish, 30 (19%) were upper Columbia River fish, 18 (11%) returned to Priest Rapids Hatchery, 16 (10%) entered the Snake River, and 11 (7%) entered the Yakima River. Small numbers were last recorded in the Deschutes, Umatilla, and White Salmon rivers and at the Little White Salmon Hatchery, all after passing John Day Dam (i.e., some fell back downstream). Overall, the upriver fall Chinook salmon that used refugia sites were in approximate proportion to the overall escapement for these populations. We also note that Chinook salmon from headwater-spawning spring and summer runs have been recorded using thermal refugia in secondary tributaries to the Columbia and Snake rivers (e.g., Berman and Quinn 1991; Pinson 2005; Mann et al. 2008).

The comparatively limited thermal refugia use by Chinook salmon (versus summer steelhead) is presumably because salmon must reach spawning areas by late summer or fall. It is also likely that Chinook salmon populations that have historically migrated through the lower Columbia River corridor during the summer and fall have adapted to higher temperatures. Population-specific thermal tolerances have been explicitly quantified in Fraser River salmon populations (e.g., Lee et al. 2003; Eliason et al. 2011) and are probable in the Columbia River basin as well.

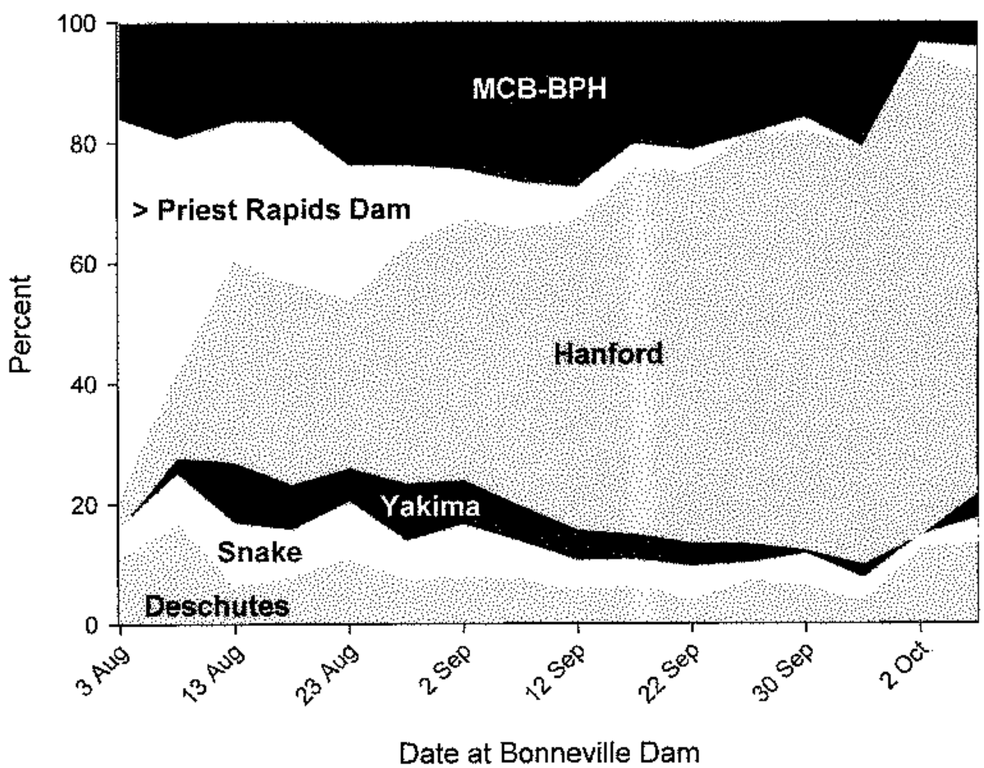


Figure 29. Mean composition of upriver bright fall-run Chinook salmon at Bonneville Dam using 5-day intervals based on release dates of radio-tagged fish, 1998 and 2000-2004. MCB-BPH = mid-Columbia River bright–Bonneville Pool hatchery stock. From Jepson et al. (2010).

Refugia use by sockeye salmon – Sockeye salmon, which mostly pass through the lower Columbia River prior to the warmest temperatures, have had the most limited refugia use in our research, though we emphasize that sockeye salmon have been the least-studied species. About 8% of sockeye salmon that passed through the lower river corridor were recorded in cool water tributaries in our single basin-wide study year (1997). We also recorded limited use of thermal refugia in a small-scale evaluation of Snake River sockeye salmon collected and radio-tagged at Lower Granite Dam in 2000. A few sockeye in that study entered the Clearwater River refugium when the main stem Snake River was > 20.5 °C (Keefer et al. 2008a).

In other river systems, sockeye salmon have shown thermoregulatory behavior in lakes (Newell and Quinn 2005; Roscoe et al. 2009), and Columbia River populations do occasionally stop migration when they encounter high Columbia River temperatures (Major and Mighell 1967; Hyatt et al. 2003). These examples suggest that sockeye salmon may use thermal refugia along the migration corridor to a greater degree than we have identified in our studies. Notably, we have found evidence for temperature-dependent mortality in sockeye salmon related to late run timing and high temperature exposure (Naughton et al. 2005). This temperature-survival relationship has been confirmed for Columbia River sockeye salmon in more recent studies (e.g., Crozier et al. 2011), and warrants further investigation.

General effects of refugia use – Adult salmonid use of thermal refugia potentially has both positive and negative effects on upstream migrants. These effects have rarely been quantified in field studies because fish fate, reproductive success, survival of progeny, and other fitness measures are difficult to measure and to link to thermoregulatory behavior or thermal experience. Presumed benefits of refugia use include reduced metabolic costs, reduced physiological stress, reduced negative temperature effects on maturation and gamete quality, and increased survival. An obvious direct negative effect is increased harvest risk because fish are spatially and temporally concentrated in refugia, attracting intensive fisheries. We found that Snake River and upper Columbia River steelhead that used refugia in the lower Columbia River were significantly less likely to survive to spawning tributaries, primarily because harvest rates in and near the refugia sites were high (Keefer et al. 2009). We have been unable to assess this harvest effect in Chinook salmon because the proportions using refugia were lower and relatively few fish were of known origin (i.e., with juvenile PIT tags that identified natal sites). The latter distinction is necessary to differentiate harvest of returning local fish from harvest of upstream migrants taken while holding in refugia.

Potential indirect negative effects of refugia use include migration delay, exposure to pathogens, permanent straying (i.e., loss from the source population), predation risk, and delayed effects from fisheries contact (i.e., catch and release, gill net fallout, etc.). Refugia sites are typically shallow, and intensive human use of the sites presumably can elevate fish stress levels. With the exception of estimating migration delay, these effects have not been measured.

Typical migration delays for fall Chinook salmon using refugia sites have ranged from hours to about 5 d, though some salmon used refugia for several weeks (Goniea et al. 2006). For most Chinook salmon, upstream passage delays on the order of several days likely have limited negative biological consequences, though this has not been explicitly tested with Columbia River populations. The delays potentially affect arrival timing at spawning grounds and consequently may have fitness effects, but it is certainly possible that the physiological benefits of refugia use outweigh potential negative effects of migration delay.

It is less clear what constitutes a migration "delay" for summer steelhead given the considerable flexibility in migration timing and rate exhibited by fish in this run. The mean refugia residence times for steelhead in the radiotelemetry studies have ranged from 5-15 d (High et al. 2006; Keefer et al. 2009), but times have varied widely among populations and many fish use refugia sites for 3-4 weeks (see Figures 22 and 23). As with Chinook salmon, it is not clear whether steelhead migration delays in refugia affect migration success or fitness (except for the harvest effects mentioned above).

Overall, it is currently unclear whether thermal refugia occasionally function as ecological traps for adult salmonids, where holding was adaptive under historic conditions but now results in a net mortality cost due to increased mortality factors (e.g., fishing), or whether they primarily provide fitness benefits.

Potential for reducing negative harvest effects in thermal refugia – As shown in Keefer et al. (2009), the concentration of summer steelhead in lower Columbia River refugia sites (e.g., at Drano Lake at the Little White Salmon confluence and the Deschutes River mouth) can result in high exploitation rates. Harvest impacts on upriver populations are also probable for Chinook salmon (especially summer and fall runs) and at sites other than those studied by the UI and NMFS. Harvest management at these sites may become increasingly important, particularly if impacts on threatened populations are determined to significantly reduce escapement.

The temperature thresholds shown in Figures 22 and 27 may be useful as predictors of refugia use by upriver populations in the lower Columbia River corridor. Importantly, the timing and duration of warm water periods in the main stem varies considerably among years (Figure 29). If managers seek to reduce harvest of upriver populations in lower river refugia sites or in the cool-water plumes created by these tributaries, main stem temperature thresholds may be useful for identifying times of greatest risk. The among-year differences shown in Figure 29 suggest that temperature-based management criteria would more effectively balance protection of thermoregulating fish with harvest of local stocks than would date-based restrictions.

Temperature-related harvest management that is population- specific or ESU-specific will require relatively detailed estimates of migration timing. Figures 26 and 28 show some of the best current migration timing data for summer steelhead and fall Chinook salmon. Population-specific migration timing distributions are also available for spring–summer Chinook salmon (Keefer et al. 2004) and sockeye salmon (e.g., Fryer 2009). We expect that lower river refugia use for these earlier migrants is most likely for upper Columbia River summer-run Chinook salmon, relatively late-timed Snake River Chinook salmon populations like those from the South Fork Salmon River and Imnaha River, and late-timed sockeye salmon.

Temperature variation in the main stem Columbia and Snake rivers

Adult salmon and steelhead can also exploit spatial heterogeneity in water temperature within the migration corridor. In addition to the cool-water plumes associated with tributaries, areas of cooler summer temperatures occur as a result of thermal stratification. Because most of the lower Columbia and lower Snake River reservoirs are flow-through projects, stratification is limited relative to some managed river systems, but vertical temperature gradients routinely occur. Lower Granite reservoir has some of the most heterogeneous temperature profiles in the lower Snake and lower Columbia hydrosystem, with summer temperatures ranging from >23 °C at the surface to ~11 °C at depth (Clabough et al. 2007b; Tiffan et al. 2009). This variability is related, in large part, to different temperature profiles from the Snake River (~20-24 °C in much of the summer and early fall) and the much cooler Clearwater River (~10-14 °C during the same time frame). Fish managers have utilized this temperature differential by increasing cold (~6 °C) water releases from Dworshak reservoir on the North Fork Clearwater River during the warmest summer periods in an effort to reduce temperatures in lower Snake River reservoirs. The Dworshak temperature effect is most pronounced in the Lower Granite reservoir but does extend to downstream reaches in some cases. The research by Clabough et al. (2007a, 2007b) demonstrated that adult migrants preferentially use the cooler layers in the Lower Granite reservoir.

Thermal layering in reservoirs is most typically characterized by the warmest water at the surface due to solar heating and wind events. This can directly affect the water temperature inside

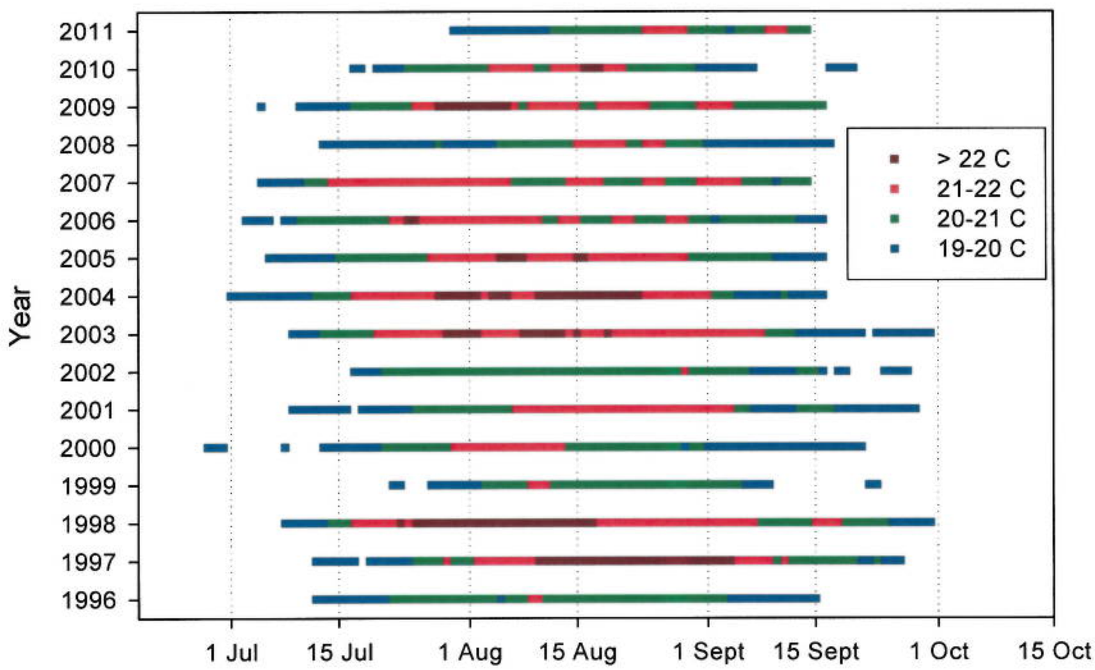


Figure 30. Columbia River water temperature data collected from early July to mid-October, 1996-2011. Colors show dates when mean water temperature was 19-20, 20-21, 21-22, and > 22 °C. Data source: Bonneville Dam water quality monitoring (WQM) site.

fishways at the main stem dams. Peery et al. (2003), Keefer et al. (2003), and Caudill et al. (2006) reported significant temperature discontinuities (>1-2 °C) between upper and lower sections of fishways at Snake River dams and at John Day and McNary dams. This pattern develops when warm reservoir surface water is pumped or gravity fed into the upper fishways while cooler tailrace and turbine outflow water is pumped into the lower fishways. Adult salmonids have responded to the abrupt temperature gradients by exiting fishways more frequently and holding in the cooler water in dam tailraces (often overnight). The overall effect has been slowed dam passage rates and produced migration delays on a temporal scale similar to the thermal refugia use described above for Chinook salmon (i.e., hours to days).

One of the most effective ways to characterize temperature exposure of adult salmonids has been the use of combined radiotelemetry and data storage transmitters (RDST). In 2000 and 2002, two relatively cool years, we monitored several hundred spring–summer and fall Chinook salmon and summer steelhead using RDST tags that collected temperature and depth data (Clabough et al. 2008). These studies confirmed that many adult migrants experience physiologically stressful temperatures. For example, 81% of fall Chinook salmon and 75% of steelhead encountered temperatures >20 °C and these estimates were conservative as a result of tagging restrictions and limits to data storage capabilities. Data from recovered transmitters also corroborated many of the behaviors described in this report, including adult use of tributary refugia, use of cool-water plumes below refugia sites, elevated temperature exposure inside dam fishways, and use of deep water in reservoirs and tailraces (Clabough et al. 2008; Johnson et al. 2005, 2010). The RDST data provided no compelling evidence for cold, groundwater-based refugia (i.e., springs) or that adults found or exploited upwelling hyporheic flows in the main stem rivers.

Information Gaps *(recommended by University of Idaho)*

• ***Spatial distribution*** – Aside from the sites along the margins of the Bonneville and The Dalles reservoirs, there has been little systematic mapping of thermal refugia along the Columbia-Snake River migration corridor or in spawning tributaries. Important gaps along the migration route include downstream from Bonneville Dam, in the mid-Columbia upstream from Priest Rapids Dam, and in the Snake River upstream from the Clearwater River confluence. The presence of potential ground-water inputs to the migration corridor that may provide refuge have been speculated on but not verified or disproven. Tributary refugia may be equally or even more important at upstream sites given the lower overall condition of fish at this stage in the migration.

• ***Temporal distribution*** – Temperature gradients between tributary refugia sites and adjacent migration corridors fluctuate seasonally and make the refugia more or less attractive to adult migrants. Temporal patterns in temperature differentials have not been well described, even for the relatively better studied sites. Similarly, seasonal and daily variability in vertical temperature profiles in reservoirs have not been well described.

• ***Population differences*** – As most clearly demonstrated for steelhead, the incidence and duration of refugia use differs among populations within runs. For steelhead this was largely a function of run timing, but there may be other factors that affect refugia use behavior, including among-population differences in metabolic performance, temperature preferences, or other factors. We still only have a rudimentary understanding of population-specific use of refugia for steelhead. Identifying population-specific refugia use patterns for Chinook, sockeye, and coho salmon may also help prioritize management strategies.

• ***Physiological benefits*** – Although refugia use is presumably adaptive and confers fitness benefits on adult salmonids, these benefits have not been quantified. Basic physiological metrics such as metabolic rate, stress levels, and reproductive hormone levels have not been measured.

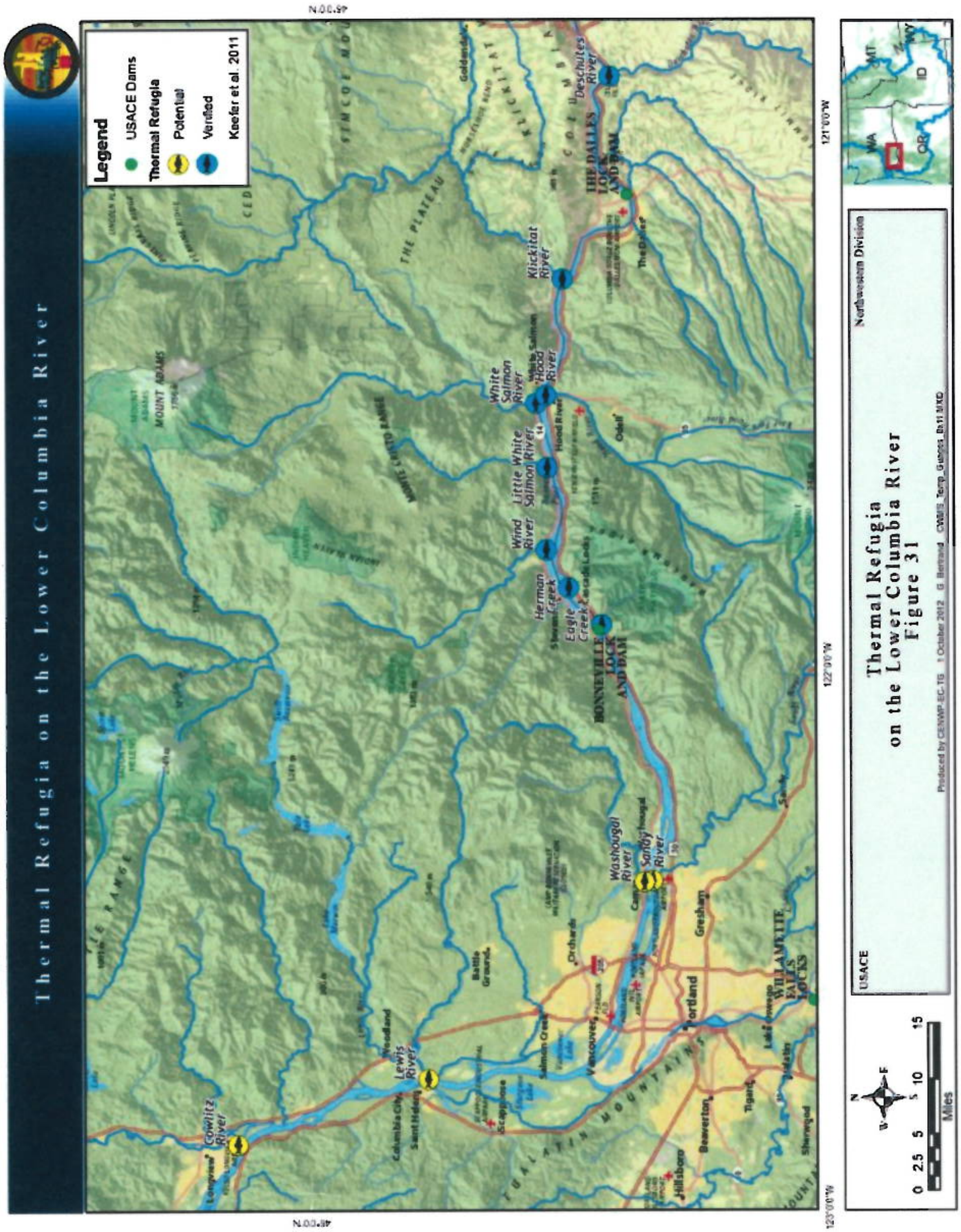
• ***Delayed effects*** – The effects of refugia use on fecundity and fitness have not been quantified, though these are among the most important uncertainties associated with the behavior. Experimental or field testing of the effects of thermal exposure (including simulated or actual refugia use) would help clarify the role that refugia have on Columbia River salmon and steelhead populations. Example studies include Mann and Peery (2005) and Crossin et al. (2008). Discussions on development of effective methods to identify and quantify delayed effects are needed because it remains largely unknown how refugia use relates to reproductive success.

• ***Harvest management*** – As shown in Keefer et al. (2009), the concentration of steelhead in lower Columbia River refugia sites (e.g., at Drano Lake at the Little White Salmon confluence and the Deschutes River mouth) can result in high exploitation rates. Harvest impacts on upriver populations are also possible for Chinook salmon (especially summer and fall runs) and at sites other than those studied by the UI and NMFS. Harvest management at these sites may become increasingly important, particularly if impacts on threatened populations are deemed significant. The population-specific migration timing data, combined with the temperature threshold-refugia use data in this report should be useful for developing criteria for managing fisheries inside refugia sites.

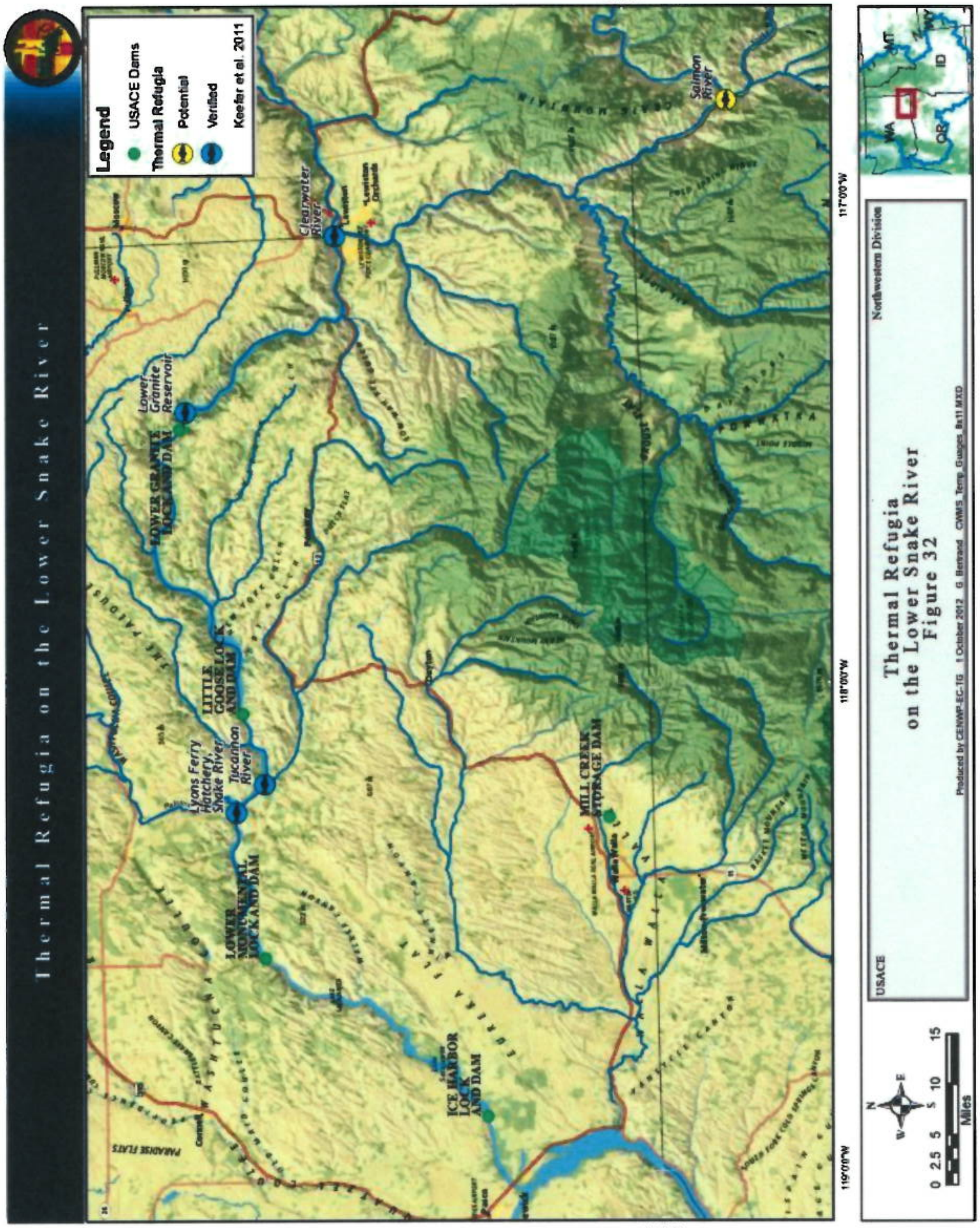
Section 4: Conclusion

This report uses existing information on adult migration, temperature monitoring data, and modeling efforts to document what is currently known regarding the use and location of adult salmon thermal refugia in the lower Columbia and lower Snake rivers. Figure 31, shows verified and potential thermal refugia sites on the lower Columbia River including the Cowlitz, Lewis, Washougal, Sandy, Wind, Little White Salmon, White Salmon, Hood, Klickitat and Deschutes rivers and Herman and Eagle creeks. Figure 32, shows known and potential thermal refugia sites on the lower Snake River including Lyons Ferry Hatchery – Snake River, Tucannon, Clearwater and Salmon River and Lower Granite Reservoir.

A full understanding of the effects of thermoregulation and thermal refugia use during upstream migration will require a better understanding of several inter-related factors: 1) the behavioral flexibility of adults to find and use refugia; 2) species- and population-specific responses to and use of refugia; 3) the spatial and temporal extent and distribution of refugia; 4) the interaction of refugia use with impacts such as fisheries; 5) the delayed effects of thermal stress and the degree to which these effects are ameliorated by refugia use; 6) the interactions among main stem temperature exposure, pathogen exposure, refugia use, and the conditions adults experience in tributaries during spawning; and, 7) the effects of predicted climate change. Identification and protection of thermal refugia areas may become relatively more important for salmon under warmer climate conditions.



Thermal Refugia
on the Lower Columbia River
Figure 31


Thermal Refugia on the Lower Snake River
Legend
USACE Dams
Thermal Refugia
Potential
Verified
Keefer et al. 2011
Lower Granite Reservoir
LOWER GRANITE LOCK AND DAM
LITTLE GOOSE LOCK AND DAM
Lyons Ferry Hatchery, Snake River
Tucannon River
LOWER MONUMENTAL LOCK AND DAM
ICE HARBOR LOCK AND DAM
MILL CREEK STORAGE DAM
Clearwater River
Lewiston Orchards
Salmon River
46°30'N
46°0'N
119°0'W
118°0'W
117°0'W
0 2.5 5 10 15
Miles
USACE
Northwestern Division
Thermal Refugia on the Lower Snake River
Figure 32
MT
WA
ID
OR
WY

References for Comparison of Existing Tributary and Lower Snake and Lower Columbia River Temperature Data and Lower Snake River Temperature Conditions

Dominguez, L.G., S.P. Cramer and S. Duery, December 2010. Temperature Characteristics of Herman Creek Cove and its Function as a Cool-Water Refuge for Adult Salmon and Steelhead in the Columbia River. Cramer Fish Sciences, Gresham, OR.

Haskell, C.A., K.T. Tiffan, R.C. Koch, J.A. Heinz, M.G. Mesa, and D.W. Rondorf. 2002. Water Temperature Effects on Fall Chinook Salmon in the Snake and Columbia Rivers. U.S. Geological Survey report to the U.S. Army Corps of Engineers, Contract W68SBV11591407, Walla Walla, Washington.

Huntington, C., T. Hardin, R. Raymond. April 1999. Water Temperatures in the Lower Deschutes River, Oregon. Prepared for Portland General Electric.

National Marine Fisheries Service (NMFS) 2000. Endangered Species Act Section 7 Biological Opinion on the Reinitiation of Consultation on Operation of the Federal Columbia River Power System, Including the Juvenile Fish Transportation Program, and 19 Bureau of Reclamation Projects in the Columbia Basin. NMFS, Portland, Oregon.

National Marine Fisheries Service (NMFS) 2010. Endangered Species Act - Section 7(a)(2) Consultation Supplemental Biological Opinion. Supplemental consultation on remand for operation of the Federal Columbia River Power System, 11 Bureau of Reclamation Projects in the Columbia Basin, and ESA Section 10(a)(I)(A) permit for Juvenile fish transportation program. May 20, 2010. NMFS, Portland, Oregon.

Peery, C. A., T. C. Bjornn, and L. C. Stuehrenberg. 2003. Water temperatures and passage of adult salmon and steelhead in the lower Snake River. Technical Report 2003-2, Idaho Cooperative Fish and Wildlife Research Unit, University of Idaho, Moscow, Idaho.

USACE, 2004. Water Temperatures in Adult Fishways at Mainstem Dams on the Snake and Columbia Rivers: Phase 1- Physical Characterization. Prepared for NOAA Fisheries (2000 FCRPS Biological Opinion, RPA Action 114), U.S. Army Corps of Engineers Walla Walla District, Walla Walla, Washington, January 2004.

Weber, L.J., M. Politano, G.S. Constantinescue, and Md. M. Hague, 2006. McNary Dam Forebay Temperature Improvements Computational Fluid Dynamics (CFD) Model. IIHR – Hydroscience and Engineering, College of Engineering, University of Iowa, Iowa City, Iowa.

White, J, R. Plumb Underwood Conservation District, June 2005. Assess Current and Potential Salmonid Production in Rattlesnake Creek Associated with Restoration Efforts. Project Number 200102500, 2003-2004 Annual Report prepared for Bonneville Power Administration, Portland, Oregon.

Literature Cited for University of Idaho Study

Berman, C.H., and T. P. Quinn. 1991. Behavioural thermoregulation and homing by spring chinook salmon, *Oncorhynchus tshawytscha* (Walbaum), in the Yakima River. Journal of Fish Biology 39:301-312.

Caudill, C. C., T. S. Clabough, G. P. Naughton, C. A. Peery, and B. J. Burke. 2006. Water temperatures in adult fishways at mainstem dams on the Snake and Columbia rivers: Phase 2 – biological effects. Technical Report 2006-3, Idaho Cooperative Fish and Wildlife Research Unit, University of Idaho, Moscow.

Clabough, T.S., C.C. Caudill, C.A. Peery, T.C. Bjornn, and B.J. Burke. 2007a. Associations between adult salmon and steelhead body temperature during upstream migration and estimated water temperatures in Lower Granite reservoir during cold water releases from Dworshak Reservoir, 2001-2002. Technical Report 2006-4 of Idaho Cooperative Fish and Wildlife Research Unit to U.S. Army Corps of Engineers.

Clabough, T.S., C.C. Caudill, C.A. Peery, T.C. Bjornn, and B.J. Burke. 2007b. Associations between adult salmon and steelhead body temperature during upstream migration and estimated water temperatures in Lower Granite reservoir during cold water releases from Dworshak Reservoir, 2004. Technical Report 2007-3 of Idaho Cooperative Fish and Wildlife Research Unit to U.S. Army Corps of Engineers.

Clabough, T.S., C.C. Caudill, M.L. Keefer, M.A. Jepson, C.A. Peery, T.C. Bjornn, and L.C. Stuehrenberg. 2008. Body temperature during migration in adult Chinook salmon and steelhead through the lower Columbia and Snake rivers, 2000 and 2002. Technical Report 2008-3 of Idaho Cooperative Fish and Wildlife Research Unit, University of Idaho, Moscow.

Crossin, G. T., S. G. Hinch, S. J. Cooke, D. W. Welch, D. A. Patterson, S. R. M. Jones, A. G. Lotto, R. A. Leggatt, M. T. Mathes, J. M. Shrimpton, G. V. D. Kraak, and A. P. Farrell. 2008. Exposure to high temperature influences the behaviour, physiology, and survival of sockeye salmon during spawning migration. Canadian Journal of Zoology 86:127-140.

Crozier, L. G., M. D. Scheuerell, and R. W. Zabel. 2011. Using time series analysis to characterize evolutionary and plastic responses to environmental change: a case study of a shift toward earlier migration date in sockeye salmon. American Naturalist 178:755-773.

Ebersole, J. L., W. J. Liss, and C. A. Frissell. 2003. Thermal heterogeneity, stream channel morphology, and salmonid abundance in northeastern Oregon streams. Canadian Journal of Fisheries and Aquatic Sciences 60:1266-1280.

Eliason, E. J., T. D. Clark, M. J. Hague, L. M. Hanson, Z. S. Gallagher, K. M. Jeffries, M. K. Gale, D. A. Patterson, S. G. Hinch, and A. P. Farrell. 2011. Differences in thermal tolerance among sockeye salmon populations. Science 332:109-112.

Farrell, A. P. S. G. Hinch, S. J. Cooke, D. A. Patterson, G. T. Crossin, M. Lapointe, and M. T. Mathes. 2008. Pacific salmon in hot water: applying metabolic scope models and biotelemetry to predict the success of spawning migrations. Physiological and Biochemical Zoology 81:697-708.

Flett, P. A., G. V. D. Kraak, and J. F. Leatherland. 1996. Overripening as the cause of low survival to hatch in Lake Erie coho salmon (*Oncorhynchus kisutch*) embryos. Canadian Journal of Zoology 74:851-857.

Fryer, J. K. 2009. Use of PIT tags to determine upstream migratory timing and survival of Columbia Basin sockeye salmon in 2008. Technical Report 09-03, Columbia River Intertribal fish Commission, Portland, OR.

Goniea, T. M., M. L. Keefer, T. C. Bjornn, C. A. Peery, D. H. Bennett, and L. C. Stuehrenberg. 2006. Behavioral thermoregulation and slowed migration by adult fall Chinook salmon in response to high Columbia River water temperatures. Transactions of the American Fisheries Society 135:408-419.

High, B., C. A. Peery, and D. H. Bennett. 2006. Temporary staging of Columbia River summer steelhead in coolwater areas and its effect on migration rates. Transactions of the American Fisheries Society 135:519-528.

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

Hyatt, K. D., M. M. Stockwell, and D. P. Rankin. 2003. Impact and adaptation responses of Okanagan River sockeye salmon (*Oncorhynchus nerka*) to climate variation and chane effects during freshwater migration: stock restoration and fisheries management implications. Canadian Water Resources Journal 28:689-713.

Jepson, M. A., M. L. Keefer, G. P. Naughton, C. A. Peery, and B. J. Burke. 2010. Population composition, migration timing, and harvest of Columbia River Chinook salmon in late summer and fall. North American Journal of Fisheries Management 30:72-88.

Johnson, E. L., T. S. Clabough, D. H. Bennett, T. C. Bjornn, C. A. Peery, C. C. Caudill, and L. C. Stuehrenberg. 2005. Migration depths of adult spring and summer Chinook salmon in the lower Columbia and Snake rivers in relation to dissolved gas supersaturation. Transactions of the American Fisheries Society 134:1213-1227.

Johnson, E. L., T. S. Clabough, C. C. Caudill, M. L. Keefer, C. A. Peery, and M. C. Richmond. 2010. Migration depths of adult steelhead *Oncorhynchus mykiss* in relation to dissolved gas supersaturation in a regulated river system. Journal of Fish Biology 76:1520-1528.

Keefer, M. L., C. A. Peery, C.C. Caudill. 2011. Temperature regimes during upstream migration and the use of thermal refugia by adult salmon steelhead in Columbia River Basin. Technical memo to David Clugston, USACE Portland District. December 15, 2011, from Idaho Cooperative Fish and Wildlife Research Unit, University of Idaho, Moscow.

Keefer, M. L., C. A. Peery, R. Stansell, M. Jonas, and B. Burke. 2003. Passage of radio-tagged adult salmon and steelhead at John Day Dam with emphasis on fishway temperatures: 1997-1998. Technical Report 2003-1, Idaho Cooperative Fish and Wildlife Research Unit, University of Idaho, Moscow.

Keefer, M. L., C. A. Peery, M. A. Jepson, K. R. Tolotti, and L. C. Stuehrenberg. 2004. Stock-specific migration timing of adult spring-summer Chinook salmon in the Columbia River basin. North American Journal of Fisheries Management 24:1145-1162.

Keefer, M. L., C. A. Peery, and M. J. Heinrich. 2008a. Temperature-mediated en route migration mortality and travel rates of endangered Snake River sockeye salmon. Ecology of Freshwater Fish 17:136-145.

Keefer, M. L., C. C. Caudill, C. A. Peery, and C. T. Boggs. 2008. Non-direct homing behaviours by adult Chinook salmon in a large, multi-stock river system. Journal of Fish Biology 72:27-44.

Keefer, M. L., C. A. Peery, and B. High. 2009. Behavioral thermoregulation and associated mortality trade-offs in migrating adult steelhead (*Oncorhynchus mykiss*): variability among sympatric populations. Canadian Journal of Fisheries and Aquatic Sciences 66:1734-1747.

Keefer, M. L., G. A. Taylor, D. F. Garletts, G. A. Gauthier, T. M. Pierce, and C. C. Caudill. 2010. Prespawn mortality in adult spring Chinook salmon outplanted above barrier dams. Ecology of Freshwater Fish 19:361-372.

King, H. R., N. W. Pankhurst, and M. Watts. 2007. Reproductive sensitivity to elevated water temperatures in female Atlantic salmon is heightened at certain stages of vitellogenesis. Journal of Fish Biology 70:190-205.

Lee, C. G., A. P. Farrell, A. Lotto, M. J. MacNutt, S. G. Hinch, and M. C. Healey. 2003. The effect of temperature on swimming performance and oxygen consumption in adult sockeye (*Oncorhynchus nerka*) and coho (*O. kisutch*) salmon stocks. The Journal of Experimental Biology 206:3239-3251.

Major, R. L., and J. L. Mighell. 1967. Influence of Rocky Reach Dam and the temperature of the Okanogan River on the upstream migration of sockeye salmon. Fisheries Bulletin 66:131-147.

Mann, R.D. 2007. The effects of high temperature exposures on migration success and embryo quality of Snake River adult Chinook salmon and steelhead. M.S. Thesis, University of Idaho, Moscow.

Mann, R.D., and C.A. Peery. 2005. Effects of water temperature exposure on spawning success and developing gametes of migrating anadromous fish – 2004. Progress Report, University of Idaho, Moscow.

Mann, R.D., C.A. Peery, A.M. Pinson, and C.R. Anderson. 2008. Energy use, migration times, and spawning success of adult spring–summer Chinook salmon returning to spawning areas in the South Fork Salmon Rifer in central Idaho: 2002-2007. Technical Report 2008-4, Idaho Cooperative Fish and Wildlife Research Unit, University of Idaho, Moscow.

Mann, R.D., C.C. Caudill, M.L. Keefer, and C.A. Peery. 2010. Migration behavior and spawning success of spring Chinook salmon in Fall Creek and the North Fork Middle Fork Willamette River: Relationships among fate, fish condition, and environmental factors. UI FERL Report 2010-7-DRAFT for the US Army Corps of Engineers, Portland District.

Naughton, G. P., C. C. Caudill, M. L. Keefer, T. C. Bjornn, L. C. Stuehrenberg, and C. A. Peery. 2005. Late-season mortality during migration of radio-tagged sockeye salmon (*Oncorhynchus nerka*) in the Columbia River. Canadian Journal of Fisheries and Aquatic Sciences 62:30-47.

Newell, J. C., and T. P. Quinn. 2005. Behavioral thermoregulation by maturing adult sockeye salmon (*Oncorhynchus nerka*) in a stratified lake prior to spawning. Canadian Journal of Zoology 83:1232-1239.

Peery, C. A., T. C. Bjornn, and L. C. Stuehrenberg. 2003. Water temperatures and passage of adult salmon and steelhead in the lower Snake River. Technical Report 2003-2, Idaho Cooperative Fish and Wildlife Research Unit, University of Idaho, Moscow.

Pinson, A. 2005. Energy use, migration time, and spawning success of adult Chinook salmon returning to the South Fork Salmon River in central Idaho. M.S. Thesis, University of Idaho, Moscow.

Quinn, T. P., S. Hodgson, and C. Peven. 1997. Temperature, flow, and the migration of adult sockeye salmon (*Oncorhynchus nerka*) in the Columbia River. Canadian Journal of Fisheries and Aquatic Sciences 54(6):1349-1360.

Reid, I. S. 2007. Influence of motorboat use on thermal refuges and implications to salmonid physiology in the lower Rogue River, Oregon. North American Journal of Fisheries Management 27:1162-1173.

Richter, A., and S. A. Kolmes. 2005. Maximum temperature limits for Chinook, coho, and chum salmon, and steelhead trout in the Pacific Northwest. Reviews in Fisheries Science 13:23-49.

Roscoe, D. W., S. G. Hinch, S. J. Cooke, and D. A. Patterson. 2009. Behaviour and thermal experience of adult sockeye salmon migrating through stratified lakes near spawning grounds: the roles of reproductive and energetic states. Ecology of Freshwater Fish 19:51-62.

Stuehrenberg, L.C., K.L. Liscom, and G.E. Monan. 1978. A study of apparent losses of Chinook salmon and steelhead based on count discrepancies between dams on the Columbia and Snake rivers, 1967-1968. U.S. Army Corps of Engineers, Final Report, Portland, OR.

Tiffan, K. F., T. J. Kock, W. P. Connor, R. K. Steinhorst, and D. W. Rondorf. 2009. Behavioural thermoregulation by subyearling fall (autumn) Chinook salmon *Oncorhynchus tshawytscha* in a reservoir. Journal of Fish Biology 74:1562-1579.

Wagner, G. N., S. G. Hinch, L. J. Kuchel, A. Lotto, S. R. M. Jones, D. A. Patterson, J. S. Macdonald, G. V. D. Kraak, M. Shrimpton, K. K. English, S. Larsson, S. J. Cooke, M. C. Healey, and A. P. Farrell. 2005. Metabolic rates and swimming performance of adult Fraser River sockeye salmon (*Oncorhynchus nerka*) after a controlled infection with *Parvicapsula minibicornis*. Canadian Journal of Fisheries and Aquatic Sciences 62:2124-2133.

Response to the December 2012 USFWS Comments on the *Location and Use of Adult Salmon Thermal Refugia in the Lower Columbia and Lower Snake Rivers Draft Final Report*.

USFWS Comment 1: *"One question...concerns Table 1 at the top of page 8,...which identifies tributary and Mainstem gauges for temperature comparisons. The lead in sentence and the table title both refer to a tributary gauge and the closest upstream gauge. The problem is that the first four pairs of gauges do not fit that definition. In all of these pairings the tributary gauge is upstream of the Mainstem gauge."*

Corps response to Comment 1: Originally the Corps intended to compare tributary gauges and the closest upstream gauge. However due to the limited temperature data for tributaries, gauges were selected for comparison that did not fit the original criteria but still proved to be informative, e.g. ORFI vs. LGNW. The language describing Figures 1-5 has been modified to reflect this change.

USFWS Comment 2: *"In Figure 3 the listed pair of gauges is not LEWI vs. ANQW, but LEWI vs. ANAW, not the gauge ANQW listed in Table 1."*

Corps response to Comment 2: Figure 3 has been update to correctly represent LEWI vs. ANQW as listed in Table 1.