  

Columbia Riverkeeper White Paper

Computer modeling shows that Lower Snake River dams caused dangerously hot water for salmon in 2015.

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Abstract

Computer simulations show that, if the lower four Snake River dams did not exist, the Lower Snake River in eastern Washington would have been cool enough for salmon migration during the summer of 2015.

Dead sockeye salmon, White Salmon River, summer 2015.

Executive Summary

In summer 2015, 96 percent of the returning Snake River sockeye salmon run died prematurely in the Columbia and Lower Snake rivers because the reservoirs, coupled with record air temperature and low flows, caused the water to become too warm.[1] Most Snake River sockeye failed to even reach the Snake River in 2015, turning back and dying in the Columbia.[2] Snake River sockeye are an endangered species,[3] and experts warn that warm water conditions similar to 2015 could become more frequent as climate change intensifies.[4]

The Lower Snake River in eastern Washington is impounded by four dams—Ice Harbor, Lower Monumental, Little Goose, and Lower Granite—that create a series of reservoirs. When the sun shines on these relatively shallow, stagnant reservoirs, the water warms.[5] The Lower Snake River often becomes too warm for salmon in the summer and fall.[6]

In 2001, the U.S. Environmental Protection Agency ("EPA") created a computer model, called "RBM-10," to study the temperature of the Columbia and Lower Snake rivers.[7] EPA's model considers water surface area, flow rate, air temperature, and other factors to predict accurately the rivers' temperatures under different conditions.[8]

Columbia Riverkeeper used RBM-10 to evaluate what the temperature of the Lower Snake would have been throughout the summer of 2015 if the four dams on the Lower Snake River in eastern Washington did not exist. The model revealed that a free-flowing Lower Snake River would have remained cool enough for salmon to migrate successfully in 2015, despite that summer's record-breaking air temperatures and low flows. By comparison, most parts of the dammed-up Lower Snake River were too warm for salmon and steelhead during July and August of 2015.

Introduction and Background

When Lewis and Clark traversed the Northwest Territory, between 5 and 11 million adult salmon returned each year to the portion of the Columbia basin above Bonneville Dam.[9] Today, dams, habitat degradation, water quality problems, and other factors have caused steep declines.[10] Modern salmon runs are typically less than ten percent of the historic runs,[11] and thirteen populations of Columbia and Snake river salmon and steelhead are listed under the Endangered Species Act.[12] Many populations of Columbia basin salmon are already extinct.[13]

Snake River sockeye salmon are in particular danger of extinction, their numbers sustained largely by captive breeding.[14] Roughly 30,000 wild adult sockeye salmon once spawned in the Snake River basin each year.[15] By the 1990s, the Snake River sockeye population had collapsed, with just a few sockeye returning to Redfish Lake in central Idaho's Sawtooth Valley.[16]

Sockeye salmon need cool water to survive.[17] Among other negative impacts, warm water encourages the growth of disease-causing bacteria and fungi, delays migration, and depletes the energy reserves of migrating fish.[18] How warm is too warm? Adult salmon have difficulty migrating upstream when water temperatures approach 68 °F.[19] Migration stops altogether when water temperatures reach 72 to 73 °F.[20] Salmon that have stopped or slowed their migration, and languish for days or weeks in warm water, begin dying from stress and disease.[21] Warm, main-stem rivers that are dominated by reservoirs—like the Columbia and Lower Snake—are especially harmful to adult sockeye salmon, which migrate during the hottest part of the year.[22]

Map showing the locations of the four Lower Snake River dams. There are also eleven dams on the main-stem Columbia River in Oregon and Washington.

In the summer of 2015, which brought severe heat and drought,[23] parts of the Lower Snake River stayed warmer than 68 °F for two straight months.[24] All told, roughly 250,000 adult sockeye salmon—fish returning either to the Snake or to upper Columbia tributaries—died in the Columbia and Snake because of warm water in 2015.[25] For the Snake River's endangered sockeye, the result was catastrophic: most died in the Columbia, and just four percent of the Snake River sockeye that returned to the Columbia basin in 2015 made it past the four Lower Snake dams.[26]

What do the Lower Snake River reservoirs have to do with climate change and water temperature? Reservoirs' effects on water temperature have been studied extensively.[27] Reservoirs that have large surface areas but are comparatively shallow—like the four Lower Snake reservoirs—warm up during the summer because they collect a lot of solar energy (heat) relative to the volume of water they contain. Water also moves more slowly through these reservoirs than it would through a free-flowing river, giving the water more time to accumulate heat.[28] When air and upstream water temperatures drop, a free-flowing river also cools down more quickly than a reservoir.[29]

The temperatures of rivers and reservoirs can be studied and modeled using computer simulations. Models use physics equations to predict river temperatures based on data about climate, the shape of the river, upstream water temperature, and other factors.[30] Computer modeling by the EPA in 2002 showed that the four Lower Snake River reservoirs significantly increase the river's temperature during the summer and fall.[31]

While some dismissed 2015's record air and water temperatures as outliers, climate scientists predict that such temperatures could become commonplace.[32] 2015 was disastrous for Snake River sockeye, but it provided a glimpse of how climate change may impact the Snake River—and what could be done to protect salmon and steelhead.[i]

Methods

We explored the effects of the four Lower Snake River dams on river temperature in 2015 using the computer simulation model RBM-10. This river temperature model was developed by John Yearsley and other EPA employees, and EPA used RBM-10 to generate a draft Temperature Maximum Daily Load Analysis for the Columbia and Lower Snake rivers in 2003.[33] RBM-10 has been peer reviewed and used to assess the effects of dams on temperatures in the Klamath River.[34] A conceptually similar model has been used to study, and even forecast, water temperatures in the Sacramento River.[35]

Using RBM-10, we modeled the cross-sectional daily average temperatures of the (existing) dammed and (hypothetical) free-flowing Lower Snake River during summer 2015. We parameterized the existing RBM-10 model using publicly available data from the Columbia River Data Access in Real Time ("DART") database, the United States Geological Survey, and the National Weather Service. We calibrated the model as described by John Yearsley,[36] using publicly available real-time temperature data collected between 2005 and 2015 at Columbia and Snake river dams.[37] Model input data are listed in Appendix A: "Sources of Data."

We investigated the impacts of the four Lower Snake River dams on river temperature by running the RBM-10 model with, and without, the four reservoirs. Predicted and observed temperatures for the dammed Lower Snake River for 2015 were quite similar, generally less than .7 °F different. Hence, we used the observed 2015 temperatures as a basis for discussion. We then created graphs to compare the predicted daily average temperatures of a free-flowing Lower Snake River to the temperatures observed at each Lower Snake River dam tailrace during the summer of 2015.

[i] While sockeye mortality captured the headlines in 2015, sockeye are by no means the only salmonids threatened by high summer water temperatures in the main-stem Columbia and Snake. The Fish Passage Center reported that the "survival of adult migrating summer Chinook salmon was also a historical low in 2015[,] coincident with high water temperatures." Fish Passage Center, *Review of April 2016 Draft of NOAA Fisheries report* 2015 Sockeye Salmon Passage Report, p.2 (2016). And the EPA explained that "maintaining [68 °F] or below temperatures in the Lower Columbia and Snake Rivers during the late June and July timeframe would be beneficial for adult summer Chinook and steelhead survival as well and would also be beneficial to juvenile salmon and steelhead out migrating during this period." U.S. Environmental Protection Agency, *Comments on NOAA fisheries 2015 Adult Sockeye Salmon Passage April 2016 draft Report*, p.2 (2016).

Results & Conclusions

Figure 1, below, compares the actual average daily temperature in the Lower Snake River in the summer of 2015 (left) to what the RBM-10 model predicted the river's temperature would have been without the four Lower Snake River reservoirs during the same time period (right). Each colored line on the graphs shows the river's temperature at a different dam throughout the summer. The blue horizontal lines across each graph show 68 °F—the water temperature that seriously impairs salmon migration.[38]

Figure 1 shows that a free-flowing Lower Snake River would have remained cooler than 68 °F during most of the summer of 2015. By comparison, water temperatures in most of the dammed Lower Snake—specifically, the three downstream reservoirs—reached 68 °F in mid to late June and remained near or above 68 °F until September. The Snake River at Ice Harbor Dam reached 70 °F by the beginning of July and stayed at least that warm until late August.

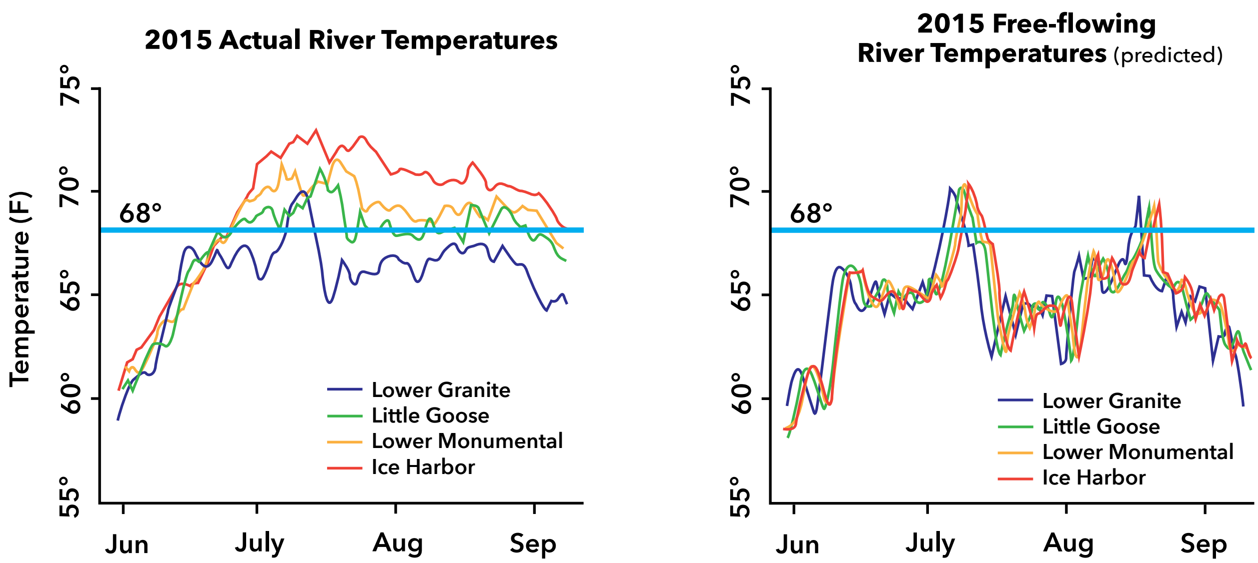

Figure 1. Comparison of 2015 summer water temperatures between the actual, dammed Lower Snake River (left) and a modeled, free-flowing Lower Snake River (right).

Our modeling and graphs confirm scientists' general understanding of how the reservoirs affect temperature in the Lower Snake.[39] Figure 1 shows an additive effect on river temperature as the water moves slowly downstream through the four Lower Snake reservoirs, with each reservoir increasing the river temperature by about 2 °F. This effect is notably absent from the simulated free-flowing Lower Snake River. Without the dams, water in the Lower Snake River would not warm up significantly as it flowed across eastern Washington. These results corroborate EPA's previous finding that each Lower Snake River reservoir can raise the water temperature by roughly 2 to 4 °F.[40]

The graphs also illustrate that the reservoirs retain heat, while the free-flowing river would flush warm water downstream and cool quickly. In both scenarios, "fronts" or "pulses" of hot water can be seen moving past each dam location over time, likely caused by hot weather or low flows upstream. A pulse of hot water took roughly two weeks to pass through the dammed Lower Snake, whereas that same hot water would pass through the free-flowing river in just a few days, as cooler water from upstream replaced the pulse of hot water.

Discussion, Implications, and Limitations

Graphing the outputs of the RBM-10 model provided a clear, and troubling, picture of how the four Lower Snake River reservoirs increased the river's average temperature in 2015. From a conservation and restoration perspective, however, our results contain a kernel of hope: despite the unprecedented air temperatures and low flows in 2015, the Lower Snake would have remained cool enough for salmon to migrate if the four Lower Snake River dams did not exist. In other words, a free-flowing Lower Snake River could remain viable salmon habitat—at least from a water temperature perspective—despite some degree of climate change.

Critics of efforts to regulate or reduce water temperature in the Lower Snake routinely point out that, without the lower four dams, the river would still exceed 68 °F.[41] Indeed, our modeling showed that a free-flowing Lower Snake River would have briefly exceeded 68 °F on two occasions in 2015. But our modeling also showed that the free-flowing Lower Snake would have returned to temperatures consistent with salmon migration within a few days; whereas the dammed Lower Snake downstream of Lower Monumental Dam remained above 68 °F from late June to early September. This sustained, cumulative exposure to water above 68 °F triggers the migration delays, and the associated mortality, observed in 2015.[42] Discussions focused exclusively on historical maximum river temperatures are of dubious conservation value.[43]

Our modeling effort only examined what the average temperature in the Lower Snake River would have been in 2015 if the four Lower Snake River dams did not exist; we did not attempt to remove the temperature impacts of all dams, or all human influences, in the Snake River basin. For instance, Dworshak Dam on the North Fork Clearwater River generally has a cooling effect, while the Hells Canyon dam complex may warm the Snake River in the fall. During the summer of 2015, and some previous years, dam operators attempted to decrease water temperatures in the Lower Snake by releasing cold water from Dworshak Dam. We simply incorporated the actual flow volumes and temperatures observed in the Snake and Clearwater rivers in 2015—including water releases from Dworshak Dam—into our modeling of average temperature in a free-flowing Lower Snake River.

RMB-10 is a "one-dimensional" model; it assumes that all of the water at any given point in the river is the same temperature.[44] The Snake and Columbia are generally well mixed, so this assumption is realistic enough for RBM-10 to predict accurately average river temperatures.[45] But certain areas of the rivers are consistently warmer or colder than average, and these local temperature differences can have important impacts on salmon migration. Fish ladders, for instance, frequently contain water that is warmer than the average river temperature.[46] Such conditions can create or exacerbate migration blockages and mortality.[47] On the other hand, cool water may collect in the deep parts of some reservoirs, especially behind Lower Granite Dam. After 2015, the U.S. Army Corps of Engineers implemented a system to pump this cool water into the Lower Granite Dam fish ladder to improve fish migration. However, it is not clear whether the three downstream Snake reservoirs contain enough cool water to meaningfully improve fish passage in those fish ladders.

Warm water harms salmon not just in the Lower Snake River, but throughout the entire river system—from the Columbia River estuary[48] to Snake River tributaries in central Idaho. Most of the 2015 Snake River sockeye run succumbed to warm water before even reaching the Lower Snake River.[49] And, of the few sockeye that passed Lower Granite Dam in 2015, only a small percentage survived the rest of their migration to Idaho's Sawtooth Valley.[50] Nevertheless, a cooler, free-flowing Lower Snake River could provide refuge for endangered sockeye and other salmon that survive the first part of their difficult journey—rather than forcing these fish to migrate through another 140 miles of hot, stagnant reservoirs and fish ladders. Without significant changes in the operation or configuration of the dams,[51] the Columbia and Snake rivers will only continue to get warmer as climate change intensifies.[52] A free-flowing Lower Snake River would create opportunities and flexibility, both for migrating salmon and for the state, federal, and tribal governments working to recover these iconic fish.

About the Authors:

Miles Johnson is Columbia Riverkeeper's Clean Water Attorney. Miles earned a JD from Lewis and Clark Law School, a BA in Biology and Environmental Studies from Whitman College, and spent several years doing fisheries research before joining Columbia Riverkeeper. Columbia Riverkeeper is a non-profit organization that works to protect the water quality of the Columbia River basin and all life connected to it.

Matthew Shultz was Columbia Riverkeeper's Salmon Conservation Intern in 2016. Matthew is a former software engineer with a Master's Degree in Environmental Science from Yale University, where his research involved computer modeling of carbon transport in the Connecticut River. Matthew is currently earning his PhD at Stanford University, focusing on predictive water quality modeling.

Citations

[1] Fish Passage Center, *Requested Data Summaries and Actions Regarding Sockeye Adult Fish Passage and Water Temperature Issues in the Columbia and Snake Rivers*, pp.2–3 (2015); *see also* Northwest Fisheries Science Center, *Status Review Update for Pacific Salmon and Steelhead Listed Under the Endangered Species Act: Pacific Northwest,* pp.319–320 (2015).

[2] Fish Passage Center, *Requested Data Summaries and Actions Regarding Sockeye Adult Fish Passage and Water Temperature Issues in the Columbia and Snake Rivers*, p.15 (2015).

[3] *Final Listing Determinations for 16 ESUs of West Coast Salmon and Final 4(d) Protective Regulations for Threatened Salmonid ESUs*, 70 Fed. Reg. 123 (2005).

[4] *E.g.* Fish Passage Center, *Review of April 2016 Draft of NOAA Fisheries Report* 2015 Sockeye Salmon Passage Report, p.1 (2016) (explaining that "under a climate change scenario, the long-recognized and largely unaddressed problem of high water temperatures in the present FCRPS configuration becomes an ever-increasing threat to the survival of salmon in the Columbia River Basin."); *see also* Northwest Fisheries Science Center, *Status Review Update for Pacific Salmon and Steelhead Listed Under the Endangered Species Act: Pacific Northwest*, p.330 (2015).

[5] U.S. Environmental Protection Agency, *Columbia River Preliminary Draft Temperature TMDL*, Appendix A, p.11 (2003).

[6] *Id*. at p.viii.

[7] *See* U.S. Environmental Protection Agency, *Application of a 1-D Heat Budget Model to the Columbia River System* (001).

[8] *Id*.

[9] U.S. Environmental Protection Agency, *Columbia River Preliminary Draft Temperature TMDL*, Appendix A, p.4 (2003).

[10] *See* Northwest Power and Conservation Council, *Return to the River,* Ch.1, pp.2, 11 (2000); *see also*, *e.g.*, National Marine Fisheries Service, *2015 Adult Sockeye Salmon Passage Report*, pp.7–8 (2016) (explaining that "hydropower development, water withdrawal and diversions, water storage, harvest, predation, and inadequate regulatory mechanisms [are] factors contributing to the decline of Snake River sockeye salmon").

[11] Northwest Power and Conservation Council, *Return to the River,* Ch.1, p.5 (2000).

[12] Northwest Fisheries Science Center, *Status Review Update for Pacific Salmon and Steelhead Listed Under the Endangered Species Act: Pacific Northwest* (2015).

[13] Northwest Power and Conservation Council, *Return to the River,* Ch.1, pp.7–8 (2000).

[14] Lisa Crozier, *et al., Passage and Survival of Adult Snake River Sockeye Salmon Within and Upstream from the Federal Columbia River Power System*, pp.iii, 2 (2014) ("Snake River sockeye salmon *Oncorhynchus nerka* is among the most endangered of all evolutionarily significant units (ESUs) of Pacific salmon, with production sourced primarily from captive broodstock since 1990.").

[15] Idaho Department of Fish and Game, *"Sockeye Salmon" webpage* (https://idfg.idaho.gov/conservation/sockeye).

[16] National Marine Fisheries Service, *2015 Adult Sockeye Salmon Passage Report,* p.7 (2016).

[17] Northwest Fisheries Science Center, *Status Review Update for Pacific Salmon and Steelhead Listed Under the Endangered Species Act: Pacific Northwest*, p.326 (2015). ("Pacific salmon are a cold water species: they flourish in cold streams and cold and productive marine ecosystems . . . .").

[18] U.S. Environmental Protection Agency, *Summary of Technical Literature Examining the Physiological Effects of Temperature on Salmonids*, p.9 (2001).

[19] National Marine Fisheries Service, *Biological Opinion on the EPA's Proposed Approval of Certain Oregon Water Quality Standards for Temperature and Intergravel Dissolved Oxygen*, p.130 (2015) citing U.S. Environmental Protection Agency, *Summary of Technical Literature Examining the Physiological Effects of Temperature on Salmonids*, p.9 (2001).

[20] *Id*.

[21] National Marine Fisheries Service, 2015 *Adult Sockeye Salmon Passage Report*, pp.20–22 (2016).

[22] U.S. Environmental Protection Agency, *Summary of Technical Literature Examining the Physiological Effects of Temperature on Salmonids*, p.9 (2001) ("Elevated temperatures in mainstem rivers that provide migration corridors (especially those dominated by reservoirs) are harmful for survival and reproduction of bull trout, chinook, steelhead, and sockeye (especially, because of their adult migration timing)."); *see also* U.S. Environmental Protection Agency, *Salmonid Behavior and Water Temperature*, p.15 (2011).

[23] National Marine Fisheries Service, *2015 Adult Sockeye Salmon Passage Report*, p.7 (2016).

[24] Data obtained through the "Columbia River DART (Data Access in Real Time)" website (http://www.cbr.washington.edu/dart), represented in Figure 1.

[25] U.S. Environmental Protection Agency, *Defendant's Answer to Complaint in Columbia Riverkeeper et al. v. Scott Pruitt et al.*, Case No. 2:17-cv-00289-RSM, p.2 (May 15, 2017) (admitting that "the death of roughly 250,000 adult sockeye salmon [in 2015] was attributable primarily to warm water").

[26] Fish Passage Center, *Requested Data Summaries and Actions Regarding Sockeye Adult Fish Passage and Water Temperature Issues in the Columbia and Snake Rivers*, p.3 (2015) ("In 2015, Snake River sockeye adult survival (BON-LGR) was 0.04 . . . .").

[27] *See review of literature in* John Bartholow *et al*., *Predicting the Thermal Effects of Dam Removal on the Klamath River,* 34 Environmental Management 856–874 (2004); *see also* U.S. Environmental Protection Agency, *Columbia River Preliminary Draft Temperature TMDL*, Appendix A, pp.29–35 (2003).

[28] U.S. Environmental Protection Agency, *Application of a 1-D Heat Budget Model to the Columbia River System*, p.1 (2001) ("Construction of impoundments for hydroelectric facilities and navigational locks . . . increase the time waters of the Columbia and Snake are exposed to high summer temperatures . . . .").

[29] U.S. Environmental Protection Agency, *Columbia River Preliminary Draft Temperature TMDL*, p.26 (2003).

[30] *See, e.g.,* U.S. Environmental Protection Agency, *Application of a 1-D Heat Budget Model to the Columbia River System*, pp.11–14 (2001).

[31] U.S. Environmental Protection Agency, *Columbia River Preliminary Draft Temperature TMDL*, Appendix F, p.4 (2003).

[32] *See discussion in* John Yearsley, *A Semi-Lagrangian Water Temperature Model for Advection-Dominated River Systems*, 45 Water Resources Research, 12 (2009).

[33] *See generally* U.S. Environmental Protection Agency, *Columbia River Preliminary Draft Temperature TMDL* (2003).

[34] *See* R.W. Perry *et al.*, *Simulating Daily Water Temperatures of the Klamath River Under Dam Removal and Climate Change Scenarios*, U.S. Geological Survey Open-File Report 2011-1243 (2011).

[35] Andrew Pike *et al., Forecasting River Temperatures in Real Time Using a Stochastic Dynamics Approach*, 49 Water Resources Research 9 (2013).

[36] *See* U.S. Environmental Protection Agency, *Application of a 1-D Heat Budget Model to the Columbia River System*, p.36 (2001).

[37] See University of Washington State, "Columbia River DART (Data Access in Real Time)" website (http://www.cbr.washington.edu/dart).

[38] National Marine Fisheries Service, *Biological Opinion on the EPA's Proposed Approval of Certain Oregon Water Quality Standards for Temperature and Intergravel Dissolved Oxygen*, p.130 (2015); *see also* U.S. Environmental Protection Agency, *Summary of Technical Literature Examining the Physiological Effects of Temperature on Salmonids,* p.9 (2001).

[39] U.S. Environmental Protection Agency, *Columbia River Preliminary Draft Temperature TMDL*, p.26 (2003) ("The dams appear to be a major cause of warming of the temperature regimes of the [Columbia and Snake] rivers.").

[40] *See* U.S. Environmental Protection Agency, *Columbia River Preliminary Draft Temperature TMDL*, Appendix F, p.4 (July, 2003) (depicting the thermal impact of the lower four Snake dams).

[41] *E.g.* John McKern, *The Case Against Breaching the Four Lower Snake River Dams to Recover Wild Snake River Salmon,* p.5 (2016) ("The Lower Snake River dams have not increased water temperatures over historic levels . . . . In 1953, the water reached 83°F at the mouth of the Snake River. In a mid-1950s study, it reached up to 77°F.").

[42] National Marine Fisheries Service, *2015 Adult Sockeye Salmon Passage Report*, pp.20–22 (2016); *see also* Northwest Fisheries Science Center, *Status Review Update for Pacific Salmon and Steelhead Listed Under the Endangered Species Act: Pacific Northwest*, p.333 (2015) ("After prolonged exposure to temperatures over 20°C, salmon are especially likely to succumb to diseases that they might otherwise have survived").

[43] *See* Fish Passage Center, *Review of April 2016 Draft of NOAA Fisheries report* 2015 Sockeye Salmon Passage Report, pp.5–6 (2016).

[44] U.S. Environmental Protection Agency, *Application of a 1-D Heat Budget Model to the Columbia River System*, pp.8–10 (2001).

[45] *Id*. at p.8.

[46] *See* National Marine Fisheries Service, *Endangered Species Act Section 7(a)(2) Consultation Regarding 1994–1998 Operation of the Federal Columbia River Power System and Juvenile Transportation Program in 1994–1998*, p.76 (1994) (directing action agencies to address high water temperatures in fish ladders).

[47] *See, e.g.*, Fish Passage Center, *Requested Data Summaries and Actions Regarding Sockeye Adult Fish Passage and Water Temperature Issues in the Columbia and Snake Rivers*, p.12 (2015).

[48] Northwest Fisheries Science Center, *Estuarine Habitat and Juvenile Salmon: Current and Historical Linkages in the Lower Columbia River and Estuary*, pp.23, 41–42 (2011).

[49] Fish Passage Center, *Requested Data Summaries and Actions Regarding Sockeye Adult Fish Passage and Water Temperature Issues in the Columbia and Snake Rivers*, p.15 (2015) ("In 2015, BON-MCN survival was 0.15 . . . .").

[50] *Id*. ("In 2015, adult survival above LGR was 0.26 . . . .").

[51] *See* U.S. Environmental Protection Agency, *Comments on NOAA fisheries 2015 Adult Sockeye Salmon Passage April 2016 Draft Report,* p.1 (2016) (describing the need for additional measures to "reducing the overall river temperatures during the latter part of June and July to improve adult sockeye survival through the Lower Columbia and Lower Snake Rivers.").

[52] U.S. Environmental Protection Agency, *EPA Region 10 Climate Change and TMDL Pilot Research Plan*, p.1 (2013) ("[S]tream temperature is projected to increase in most rivers under climate change scenarios due in part to increases in air temperature, which, in turn, could adversely affect coldwater fish species such as salmon.") citing Levi Brekke *et al., Climate Change and Water Resources Management: A Federal Perspective*, USGS Circular 1331 (2009).

Appendix A – Sources of Data

Data for this report were generally derived from Yearsley *et al.* (2001), with some modifications and improvement reflecting changes in available data. First-order weather stations at Lewiston (WBAN24149) and Yakima (WBAN24343) both provided most of the required meteorological variables, through downloadable Quality Controlled Local Climatological Data sets. Only maximum and minimum air temperature were available for the Wenatchee (USC00459074) and Richland (USC00457015) weather stations, through Global Historical Climatology Network daily data sets, so additional meteorological variables were synthesized from the closest first-order weather station. Net shortwave radiation, net longwave radiation, and percentage cloud cover were extracted from North American Regional Reanalysis gridded data products using the point coordinates of each weather station. Temperatures for calibration at all dams were downloaded from Columbia River Data Access in Real Time.

Sources of River Discharge Data

Station Identification	Station Name	Start Date	End Date
13340000 (USGS)	Clearwater River at Orofino, ID	1930-10-01	2016-08-29
DWR (DART)	Dworshak Tailwater (Used for USGS13341000 before period of record begins)	2005-01-01	2015-12-31
13334300 (USGS)	Snake River near Anatone, WA	1958-07-22	2016-08-29
13344500 (USGS)	Tucannon River near Starbuck, WA	1958-07-22	2016-08-29
13351000 (USGS)	Palouse River at Hooper, WA	1897-10-01	2016-08-29
GCGW (DART)	Grand Coulee Downstream	2005-01-01	2015-12-31
12447200 (USGS)	Okanogan	1965-12-18	2016-08-29
12449950 (USGS)	Methow	1959-04-01	2016-08-29
12452500 (USGS)	Chelan Spillway	1903-11-01	2015-09-30
12462500 (USGS)	Wenatchee	1959-02-12	2016-05-31
12472600 (USGS)	Crab Creek near Beveraly	1959-02-12	2016-05-31
12510500 (USGS)	Yakima	1905-10-01	2016-08-29
14018500 (USGS)	Walla Walla	1951-10-01	2016-08-29
14048000 (USGS)	John Day	1904-12-01	2016-08-29
14103000 (USGS)	Deschutes	1897-10-01	2016-08-29

Sources of River Temperature Data

Station Identification	Station Name	Start Date	End Date
13340000 (USGS)	Clearwater River at Orofino, ID	1930-10-01	2016-08-29
13341000 (USGS)	North Fork Clearwater at Ahsahka	2010-01-01	2016-08-30
DWR (DART)	Dworshak Tailwater (Used for USGS13341000 before period of record begins)	2005-01-01	2015-12-31
13334300 (USGS)	Snake River near Anatone, WA	1959-10-01	2016-08-29
13344500 (USGS)	Tucannon River near Starbuck, WA	Estimated*	
13351000 (USGS)	Palouse River at Hooper, WA	Estimated*	
GCGW (DART)	Grand Coulee Downstream	2005-01-01	2015-12-31
12447200 (USGS)	Okanogan	1969-11-12	2016-08-29
12449950 (USGS)	Methow	Estimated*	
12462500 (USGS)	Wenatchee	Estimated*	
12472600 (USGS)	Crab Creek near Beveraly	Estimated*	
12510500 (USGS)	Yakima	Estimated*	
14018500 (USGS)	Walla Walla	Estimated*	
14048000 (USGS)	John Day	Estimated*	
14103000 (USGS)	Deschutes	1897-10-01	2016-08-29

* Stations marked 'Estimated' were estimated from air temperatures as described by Mohseni *et al.* (1998), following Yearsley *et al.* (2001).

Resources

Mohseni, O., H.G. Stefan, and T.R. Erickson. A nonlinear regression model for weekly stream temperatures. Water Resources Research 34(10): 2685–2692. 1998.

Yearsley, J, D. Karna, S. Peene and B. Watson. Application of a 1-D heat budget model to the Columbia River system. EPA 910-R-01-004. EPA Region 10, Seattle, Washington. 2001.