Whychus Creek Water Quality Status, Temperature Trends, and Stream Flow Restoration Targets 2020-2021

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Abstract

Diversion of almost 90% of summer stream flow and channelization of 50% of the length of Whychus Creek have degraded water quality, resulting in an ODEQ listing of water quality limited (Category 5) since 1998. Deschutes River Conservancy (DRC), Three Sisters Irrigation District, and other partners have been implementing stream flow restoration actions to ameliorate low flows and high stream temperatures in Whychus Creek since 1997. To evaluate how stream temperature is changing with higher flows, Upper Deschutes Watershed Council has monitored temperature annually since 2000 at eleven sites representing diverse flow conditions in Whychus Creek. This report incorporates 2020 and 2021 data to 1) evaluate the 2020 and 2021 status of stream temperature in Whychus Creek relative to the 2020 Deschutes Basin Habitat Conservation Plan (DBHCP) temperature threshold and state standards for salmonid spawning, rearing and migration; 2) quantify 2000-2021 temperature trends in relation to stream flow; 3) describe the effects of stream flow and air temperature on stream temperature in Whychus Creek, and 4) update temperatures predicted to occur at the observed range of Whychus Creek stream flows. Stream temperatures at River Mile 6 (RM 6) exceeding applicable thresholds and standards for 2-3 months, and for 50%-100% of data days for steelhead and Chinook salmon spawning respectively, demonstrate an ongoing and significant stream temperature problem resulting in poor to unsuitable temperature conditions for reintroduced salmon and steelhead and resident native trout over a prolonged period during the irrigation season. Data from 2000-2021 show modestly lower July stream temperatures at July flows that have more than doubled since early years of restoration but remain well below the 33 cfs state instream water right. Regression models indicate 41 cfs will on average support the 20°C DBHCP temperature threshold at RM 6 in July, with 67 cfs needed to meet the 18°C salmon and trout rearing and migration state standard; from April 1-May 15 when steelhead spawn, 18 cfs is estimated to on average support the 13°C state spawning standard but the influence of air temperature is equal to that of stream flow. During September when Chinook spawn, air temperature has a larger influence on stream temperature than stream flow, with as much as 67 cfs failing to lower temperatures to the 13°C spawning standard, flagging the September Chinook salmon spawning period as requiring special attention for creative water management solutions. Our results emphasize the critical and urgent need for continued development of creative and responsive stream flow restoration and management solutions, such as pulse flows during key periods, as well as habitat restoration solutions, that meaningfully reduce irrigation season stream temperatures in the downstream reaches of Whychus Creek to support the recovery of native fish populations.

Introduction

Restoration partners have identified the Whychus Creek watershed as a priority watershed for conservation and restoration within the upper Deschutes Basin (NWPPC 2004, UDWC 2006). Diversion of almost 90% of average summer flows creates conditions that contribute to elevated stream temperatures with likely commensurate adverse impacts to dissolved oxygen and other water quality parameters. Whychus Creek has been listed by ODEQ under Clean Water Act Section 303(d) as water quality limited for flow modification (Category 4C) since 2002 and water quality limited with TMDLs needed for temperature (Category 5) since 2004 (Table 1, Figure 1). Development of a TMDL for the Deschutes Basin has been suspended since 2012 as a result of litigation of DEQ's natural condition temperature criterion and is pending resolution of the litigation.

UDWC began monitoring temperature on Whychus Creek in 1995. In 1999 DRC stream flow restoration efforts first returned continuous summer flows to Whychus Creek, and the volume of flows protected instream has incrementally increased since. Restoration partners expect that increasing stream flow will reduce temperatures in Whychus Creek to more frequently and consistently meet spawning and rearing and migration habitat requirements for native fish including anadromous steelhead trout and Chinook salmon re-introduced to the creek in 2007 and 2009, respectively.

Water temperature affects the growth and survival of aquatic organisms. Temperature naturally fluctuates on a daily and seasonal basis, with daily fluctuations resulting from continuous changes in solar radiation and air temperature, and seasonal fluctuations in response to changes in climate, solar aspect, and variable amounts of stream flow from snowmelt and precipitation. Water temperature naturally increases as water flows downstream, and temperature can decrease as a result of groundwater inflows (springs) or the inflow of cooler tributaries. Anthropogenic changes that alter the natural hydrograph, such as diversions for irrigation, groundwater pumping, and climate change, also influence temperature.

ODEQ state temperature standards were developed to protect fish and other aquatic life in Oregon waterways (ODEQ 2009). The year-round temperature standard applied to Whychus Creek for salmon and trout rearing and migration specifies that seven-day moving average maximum (7DADM) temperatures are not to exceed 18°C (Appendix A). The 2002 303(d) list also identified Whychus Creek as not meeting the 13°C state temperature standard for salmon and steelhead spawning. No subsequent 303(d) list has applied this criterion to Whychus Creek because spawning was no longer considered a designated fish use in Whychus Creek prior to reintroduction of salmon and steelhead. Adult steelhead and salmon first returned to Whychus Creek in 2011. As of the writing of this report in December 2022, Chinook salmon spawning has been documented in Whychus Creek, in Deschutes Land Trust's Willow Springs Preserve, on August 24th, 2022, demonstrating the spawning standard is applicable to Whychus Creek and that spawning can be expected to occur in Whychus as early as August.

In 2022, NOAA issued an incidental take permit to the Deschutes Basin Board of Control (DBBC), comprised of the seven Upper Deschutes subbasin irrigation districts, and the City of Prineville, for incidental take of endangered steelhead and sockeye resulting from irrigation district and City operations. The permit is predicated on permittees meeting conditions specified in the Deschutes Basin Habitat Conservation Plan (HCP) signed into effect in December, 2022. For Whychus Creek, the HCP as it pertains to steelhead and sockeye requires stream temperature at River Mile 6 not to exceed 20°C for more than one week of the year by year 9 (2031) of implementation of the HCP. Specifically, the year 2023 represents year 1 of DBHCP implementation. Under the HCP, the 7DADM from Whychus Creek RM 6 (WC 006.00) will be reviewed annually by the Services and TSID, beginning in year 1 of HCP implementation, to track progress toward reducing the 7DADM at this site. Seven-day average daily maximum stream temperature from RM 6 from Years 9 and 10 (2031 and 2032) will be evaluated in Year 10 to determine whether the 7DADM in these two years does not exceed 20°C for more than one week (7 consecutive days). Seven-day average daily maximum stream temperatures from RM 6 exceeding 20°C for more than one week in either summer will trigger consideration of a suite of additional factors identified in the HCP that will contribute to a determination of whether the presumption of decreasing peak water temperatures in Whychus Creek is to be considered correct. If this presumption is not considered correct, TSID and NOAA will identify additional measures TSID can implement to reduce or mitigate for high peak water temperatures (Biota Pacific, 2020).

The State of Oregon 1992-1994 Water Quality Standards Review (ODEQ 1995) identified 24°C as the lethal temperature threshold for salmon and trout. Multiple studies (Richter and Kolmes 2005) have shown stream temperatures between 19°C to 23.9°C to block adult salmon and steelhead migration; a review of field studies of chinook salmon, steelhead, and rainbow trout identified a mean daily water temperature of 20°C and a maximum daily water temperature of 22°C to 24°C as the distributional temperature limits for these species (McCullough 1999 cf Richter and Kolmes 2005). Twenty-two degrees Celsius (22°C) is generally agreed to have severe consequences for trout, including decreased foraging and increased aggressive behavior (Nielsen 1994), elimination of salmonids from a location (Nielsen 1994, US EPA 1999), and broad mortality (US EPA 2003). Higher water temperatures and longer exposure to warm water have also been shown to increase the feeding rate of predatory species consuming juvenile salmonids (Sauter et al 2001), such as the predatory brown trout that are abundant in Whychus Creek. For steelhead and Chinook salmon spawning conditions, egg mortality is high at 15°C compared to lower temperatures (Myrick and Cech 2001).

In addition to temperature, dissolved oxygen and pH levels also directly affect aquatic organisms. Waterways naturally produce oxygen through photosynthesis and aeration. Dissolved oxygen is consumed through respiration and degradation of organic plant compounds. The amount of dissolved oxygen available (percent saturation) is also affected by altitude and temperature: water at higher altitudes holds less dissolved oxygen than water at lower altitudes (because the degree of atmospheric pressure is less at higher altitudes), and cold water holds more dissolved oxygen than warm water. When oxygen is consumed at a faster rate than it is produced, dissolved oxygen concentrations fall, negatively affecting aquatic organisms. Salmon and trout, especially in their early life stages, are very susceptible to low dissolved oxygen concentrations.

Water pH levels (alkalinity) are primarily affected by plant photosynthesis but can also be influenced by the chemistry of the local substrate. The volcanic soils of the Upper Deschutes Basin may increase the acidity (and decrease pH) of basin waterways. Water pH directly influences aquatic insect populations as well as salmon and trout egg development, egg hatching, and embryo development. Extreme pH levels can negatively impact fish by increasing the availability and toxicity of pollutants such as heavy metals and ammonia.

ODEQ assessed dissolved oxygen and pH in Whychus Creek in 2022 (ODEQ 2022). Two DEQ Assessment Units, Whychus Creek from Indian Ford Creek to the confluence with the Deschutes River and Upper Whychus Creek from Indian Ford Creek upstream to 0.5 mi below USFS Road 1514 (RM 33.6) were designated as Category 2, Attaining, for dissolved oxygen; the Headwaters Whychus Creek Assessment Unit was designated as Category 3, Insufficient data, for dissolved oxygen.

Dissolved oxygen attained the state water quality standard in two DEQ Assessment Units, Whychus Creek from Indian Ford Creek to the confluence with the Deschutes River, and Upper Whychus Creek from Indian Ford Creek upstream to 0.5 mi below USFS Road 1514 (RM 33.6); in the Headwaters Whychus Creek Assessment Unit from RM 33.6 upstream, insufficient data was available to assess dissolved oxygen for spawning or year-round use. UDWC analyses of dissolved oxygen data collected from 2006 to 2008 indicated that Whychus Creek met state dissolved oxygen standards for salmon and trout rearing and migration, although dissolved oxygen levels did not consistently meet state criteria for salmon and trout spawning (Jones 2010). Because dissolved oxygen saturation is directly affected by temperature, we expect dissolved oxygen levels to track temperature trends. While observed trends in stream temperature continue to demonstrate cooling, and in the absence of other novel environmental conditions, we expect dissolved oxygen levels to improve or remain constant. Under these circumstances, temperature data are a suitable proxy for dissolved oxygen data, and indicate dissolved oxygen levels that will continue to meet the state standard for salmon and trout rearing and migration. UDWC discontinued monitoring dissolved oxygen on Whychus Creek in 2009 on this premise. A consistent warming trend in temperature would flag potentially deteriorating dissolved oxygen conditions and warrant resuming monitoring of dissolved oxygen.

PH attained the state standard from Indian Ford Creek to the confluence with the Deschutes River but was 303(d) listed as impaired (not attaining the state standard) and needing a TMDL from the headwaters of Whychus Creek to the confluence with Indian Ford Creek. Low pH values in Whychus Creek have been attributed to the influence of volcanic soils and are not expected either to limit ecological function or to be affected by increases in summer stream flow associated with stream flow restoration. Accordingly, UDWC also discontinued monitoring pH after 2009. While this report does not present dissolved oxygen or pH data, we consider the observed trends in temperature to provide a surrogate measure of water quality in Whychus Creek. For further discussion of temperature, dissolved oxygen, pH, and state standards for each parameter, refer to *Whychus Creek Water Quality Status, Temperature Trends, and Stream flow Restoration Targets* (Jones 2010).

The stream flow and habitat restoration efforts of Deschutes River Conservancy (DRC), UDWC, and restoration partners aim to improve water temperatures to meet the 20°C HCP threshold and the 18°C state standard, and to support sustainable anadromous and resident native fish populations by reducing warming rates, improving water quality, and reconnecting the creek to floodplains and groundwater. DRC and restoration partners adopted a stream flow target for Whychus Creek consistent with state instream water rights. State of Oregon March, April and May instream water rights protect 20 cfs upstream and 50 cfs downstream of Indian Ford Creek (RM 18); state water rights for June, July, August and September when flows are historically low, specify 20 cfs upstream and 33 cfs downstream of Indian Ford Creek. However, these rights are the most junior rights on the creek and because Whychus Creek is overallocated not enough water is available at most times during the irrigation season to leave the state water right in the creek. State instream water rights correspond to recommended minimum flows identified through the Oregon Method, which relates stream flow to fish habitat availability (Thompson 1972). UDWC analyses and the HeatSource model (Watershed Sciences and MaxDepth Aquatics 2008) have shown these flows to be insufficient to create suitable conditions for fish or meet state temperature standards. The DRC stream flow restoration target aims to protect 33 cfs of consistent and measurable water instream at Sisters City Park. Because no substantial flows enter Whychus Creek between this location and Alder Springs just below WC 001.50, the DRC target will effectively also protect 33 cfs downstream of Indian Ford Creek.

This report presents analyses of 2000-2021 temperature and flow data that: 1) evaluate the 2020 and 2021 status of stream temperature in Whychus Creek relative to the HCP threshold, state standards, and anticipated and observed timing for salmonid spawning, rearing and migration and 2) quantify temperature trends in relation to stream flow. We also present 2000-2021 regression analyses to describe the effects of stream flow and air temperature on stream temperature in Whychus Creek, as well as temperatures predicted to occur at the observed range of Whychus Creek stream flows.

Table 1. 2022 Oregon Clean Water Act Section 303(d) status of Whychus Creek.

	Parameter	**Temperature**			**Dissolved Oxygen**		**pH**
	Designated or Beneficial Use	Salmon & Trout Rearing & Migration	Steelhead Spawning	Chinook Salmon Spawning	Salmon & Trout Non-Spawning	Salmon & Trout Spawning	Fish and Aquatic Life
	Season	Year Round	January 1 - May 15*	August 15 – October 7*	Year Round	January 1 - May 15	Year Round
	Standard	18° C	13° C	13° C	8.0 mg / L @ 90% Sat	11.0 mg / L @ 90% Sat	6.5-8.5 SU
ODEQ Assessment Unit (River Mile)	Indian Ford Creek to confluence with Deschutes RM 0 – 19.55	Category 5: Impaired, TMDL needed	Use not designated for Deschutes Basin	Use not designated for Deschutes Basin	Category 2: Attaining standard	Category 2: Attaining standard	Category 2: Attaining standard
	HUC 12: Upper Whychus Creek	Category 5: Impaired, TMDL needed	Use not designated for Deschutes Basin	Use not designated for Deschutes Basin	Category 2: Attaining standard	Category 2: Attaining standard	Category 5: Impaired, TMDL needed
	HUC 12: Headwaters Whychus	Category 2: Attaining standard	Use not designated for Deschutes Basin	Use not designated for Deschutes Basin	Category 3: Insufficient data	Category 3: Insufficient data	Category 5: Impaired, TMDL needed

Source: ODEQ 2022

* Anticipated steelhead and Chinook salmon spawning timing for Whychus Creek provided by B. Spateholts, personal communication, Feb 15 2015 and supported by PGE redd survey data, November 2022.

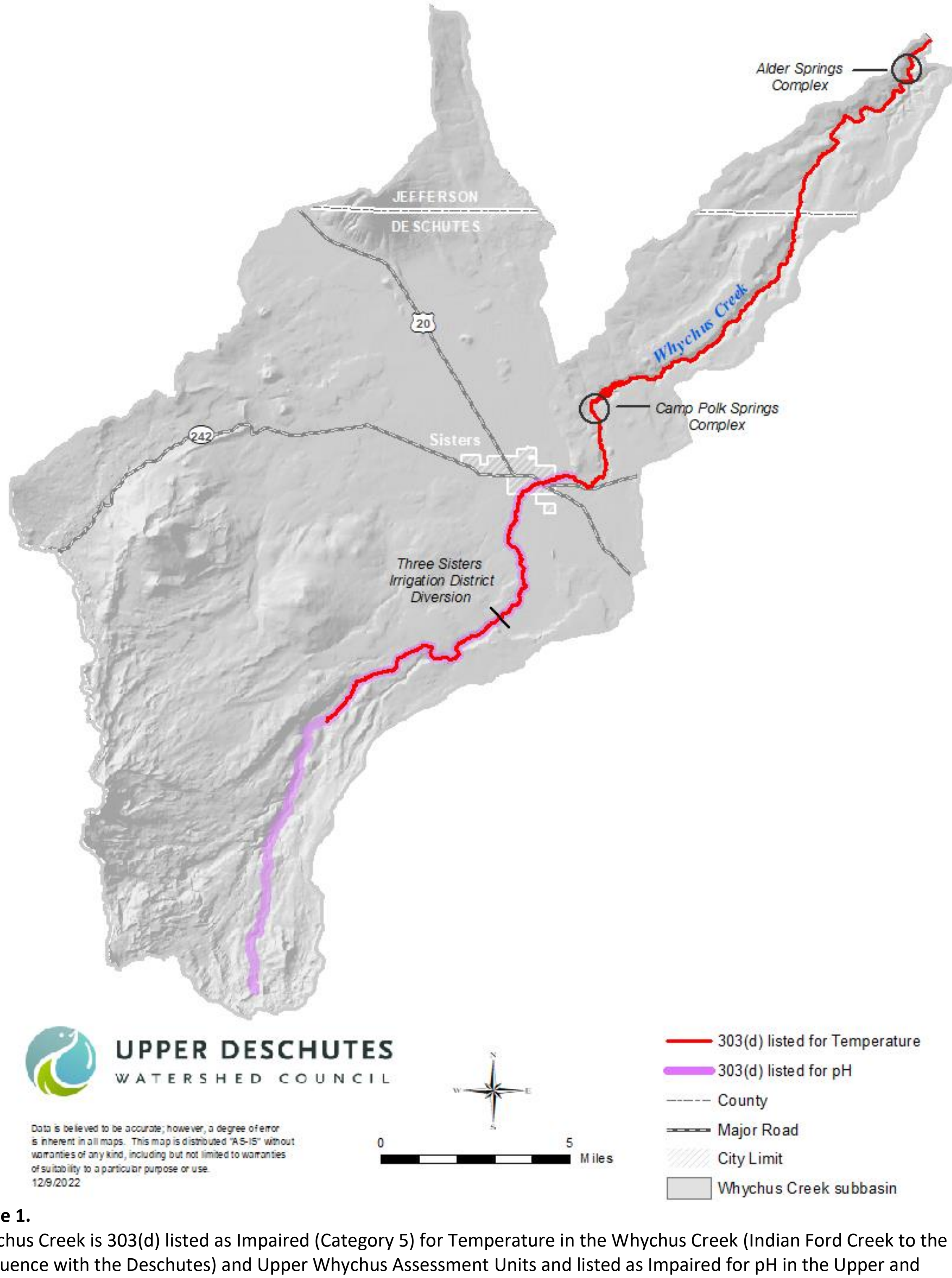


Figure 1.
Whychus Creek is 303(d) listed as Impaired (Category 5) for Temperature in the Whychus Creek (Indian Ford Creek to the confluence with the Deschutes) and Upper Whychus Assessment Units and listed as Impaired for pH in the Upper and Headwaters Whychus Creek Assessment Units under ODEQ's 2022 303(d) list. (ODEQ 2022)

Methods

Data collection

Stream Temperature Data

Beginning in 1995, UDWC and partners collected continuous temperature data annually at a subset of thirteen locations on Whychus Creek between River Mile (RM) 38 and RM 0.25 (Figure 2). All temperature data used in analyses were collected by USFS, BLM, ODEQ, and UDWC. Coordinated monitoring efforts were conducted according to standard methods and protocols outlined in the ODEQ-approved UDWC Quality Assurance Project Plan with Addendum (UDWC 2015a) and summarized in UDWC Water Quality Monitoring Program Standard Operating Procedures (UDWC 2015b).

In 2009 UDWC, Deschutes Land Trust (DLT), private landowners and other restoration partners reached an agreement to restore stream habitat in Whychus Creek along 1.9 valley miles within Rimrock Ranch. The restoration design included diverting the creek from the confined channel along the toe slope into the meadow; as a result, the UDWC monitoring station historically located on the pre-restoration channel would no longer be on the stream. To replace this monitoring location and generate pre-restoration data above and below the restoration project reach UDWC established two new temperature monitoring stations, one upstream (WC 010.25) and one downstream (WC 008.50) of the planned restoration. As of 2009 UDWC discontinued temperature monitoring at the old Rimrock temperature monitoring station at WC 009.00 and began monitoring temperatures at the two new locations. Site names assigned to the two new sites were based on distance from the original WC 009.00 site. Although the downstream site is 0.7 mi from WC 009.00, another site had already been designated as WC 008.25. We accordingly designated the downstream Rimrock site as WC 008.50, the next closest quarter-mile increment.

In 2021 UDWC and Deschutes Land Trust implemented Phase IIa of restoration at Whychus Canyon Preserve along the upper half-mile of Rimrock Ranch. This project included filling the confined, incised channel and diverting the stream onto a constructed floodplain surface to promote channel and floodplain connectivity and evolution. Site WC 010.25, the upstream site established in 2009, was relocated in July 2021, within a quarter mile of the WC 010.25 station coordinates, to immediately downstream of the restoration reach where streamflow remains consolidated in a single channel.

Stream Flow Data

We obtained average daily stream flow (QD) data for Whychus Creek from Oregon Water Resources Department (OWRD) gage 14076050 at the City of Sisters (OWRD 2022). This gage is located downstream from the Three Sisters Irrigation District diversion and other major irrigation diversions. We use data collected at this gage from 2000 to 2021 in this report, including some data considered by OWRD to be provisional and subject to change.

Air Temperature Data

We obtained daily maximum air temperature data from the Colgate, Oregon Western Regional Climate Center (WRCC 2022) RAWS station (44° 18’ 57”, 121° 36’ 20”), the closest RAWS station to Whychus Creek.

Data analysis

Stream Temperature Status

We used the Oregon Department of Environmental Quality (ODEQ) Hydrostat Simple spreadsheet (ODEQ, 2010) to calculate the seven day average daily maximum (7DADM) temperature, the statistic used by the State of Oregon to evaluate stream temperature. The State of Oregon water temperature standard for salmon and trout rearing and migration identifies a 7DADM threshold of 18°C/64°F (OAR 340-041-0028). Because steelhead spawning season has yet to be identified for Whychus Creek, we reference the January 1 – May 15 spawning season identified for the Lower Deschutes sub-basin for evaluation of temperature relative to the 13°C state standard for steelhead and salmon spawning. Chinook salmon spawning in Whychus Creek has been documented in late August, and is anticipated to occur from late August through early October with incubation occurring through March or April (personal communication, B. Spateholts, February 15, 2015), earlier than the October 15 – May 15 spawning and October 15 – June 15 incubation dates designated for the lower Deschutes.

We evaluated 7DADM stream temperatures from 2001-2021 in relation to the 20°C HCP threshold and 18°C and 13°C state standards (for salmon and trout rearing and migration and steelhead and salmon spawning, respectively) to describe changes in temperature in Whychus Creek since 2001 and to assess progress toward the HCP threshold and state standard temperatures. To determine the percent of days when 7DADM stream temperatures exceeded the 20°C HCP threshold and 18°C rearing and migration standard on Whychus Creek, we identified the earliest and latest dates on which stream temperatures have exceeded 18°C and used the number of days between and including these dates as our total number of data days. For six years (2000, 2002, 2006, 2009, 2020, and 2021) data were missing between the earliest and latest dates exceeding 18°C. For these years, we were able to extrapolate 7DADM stream temperatures to be greater or less than 20°C and 18°C based on temperatures at upstream and downstream sites, allowing percent of days exceeding 20°C and 18°C to be calculated from the same dates and number of days for each year.

UDWC stream temperature monitoring in Whychus Creek has been focused on summer stream temperatures, when instantaneous flows in Whychus Creek drop as low as ten cfs and stream temperatures exceed the lethal threshold for native redband trout and steelhead. As a result, datasets between April 1 and May 15, when steelhead are anticipated to spawn in Whychus Creek and diversions for irrigation have resumed but it is not yet warm enough for snow to melt and contribute additional flow, are incomplete. To evaluate stream temperature conditions for spawning steelhead in Whychus Creek between April 1 and May 15, we report the number of days for which data are available at WC 006.00 from April 1 to May 15, the earliest of those dates when stream temperature exceeded 13°C, and the number and percent of days exceeding 13°C. For Chinook, we report the number of days in September when stream temperature at WC 006.00 exceeded the 13°C spawning criteria.

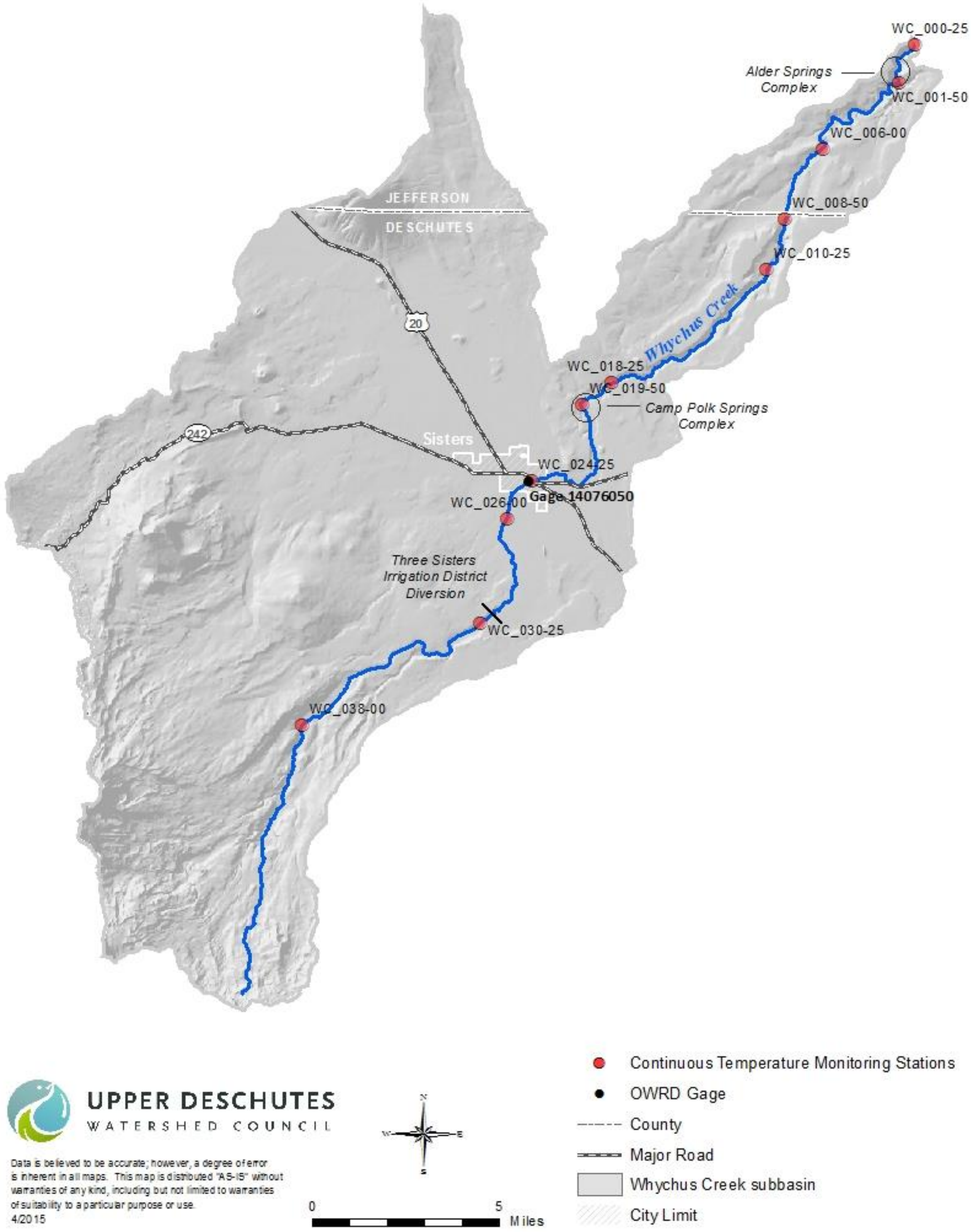


Figure 2.

Continuous temperature monitoring stations monitored in 2020 and 2021, and OWRD Gage 14076050 at Sisters City Park, on Whychus Creek.

Target Stream Flow

We used regressions of stream temperature, stream flow, and air temperature data to 1) quantify the effects of stream flow and air temperature on stream temperature, and 2) to calculate stream flows estimated to produce the 20°C HCP threshold, 18°C rearing temperature standard, and 13°C steelhead spawning temperature standard at Whychus Creek RM 6, monitoring station WC 006.00, located upstream of USFS Road 6360 on Whychus Creek. Temperature data from WC 006.00 represent the historically worst temperature conditions on the creek, and thus the location that is both most critically in need of and also stands to benefit the most from stream flow restoration. In previous reports we have also calculated stream flows required to produce state temperature standards at RM 24.25, monitoring station WC 024.25, at Sisters City Park. Because flows required to meet state standard stream temperatures at Sisters City Park do not provide information about flows required to meet temperature thresholds and standards in downstream reaches, we did not update analysis of stream flow and temperature at Sisters City Park for this report. This analysis is available for data from 2000-2019 in Whychus Creek Water Quality Status, Temperature Trends, and Stream Flow Restoration Targets 2018-2019 (Mork 2020).

While the use of air temperature to predict stream temperature has been the subject of debate within the scientific community, we included air temperature in regressions based on an extensive body of scientific literature supporting its application for this purpose. Air temperature has been shown to be a useful proxy for heat energy transfer from the atmosphere to water by long-wave radiation and sensible heat transfer (Webb and Zhang 1997; Mohseni and Stefan 1999), and multiple studies have used air temperature to accurately predict stream temperature variation (e.g. Webb et al. 2003; Mohseni et al. 2003; Morrill et al. 2005; Carlson et al. 2015).

We used 7DADM temperature data from WC 006.00 for each year included in the analysis with corresponding stream flow data from the OWRD gage at Sisters City Park and air temperature data from the Colgate, OR Western Regional Climate Center RAWS station (WRCC 2020). We restricted data included in each regression to a one-month (30-day) interval to reduce the effect of intra-annual seasonal variation in the analysis (Helsel and Hirsch 2002). To calculate stream flows required to produce 20°C and 18°C we evaluated July stream temperature data from WC 006.00. We selected July as the historically hottest month for stream temperature in Whychus Creek (UDWC unpublished data). To calculate stream flows required to produce 13°C during the January 1 – May 15 spawning season we evaluated April stream temperature data from WC 006.00. We selected April as the month during which stream temperature most often begins to exceed the 13°C steelhead spawning standard and evaluated the relationship between stream temperature and stream flow at WC 006.00 as the site which typically represents the highest stream temperatures. To calculate stream flows required to produce 13°C during the late August to early October period during which Chinook salmon spawning is anticipated to occur in Whychus Creek we evaluated September stream temperature data from WC 006.00. We selected September as the month encompassing the most dates during which Chinook salmon are anticipated to spawn. For data for each month we evaluated the effect of air temperature on stream temperature to account for variation in stream temperature not explained by stream flow.

For each month we included all dates for which stream temperature, stream flow, and air temperature data were available. We used R open source statistical software (R Core Team 2022) to perform linear, quadratic, and cubic regressions for each site: 1) with each of two flow metrics (average daily flow and the natural logarithm of average daily flow); and 2) with each of two air temperature metrics (daily maximum and three-day moving average maximum; 3DAir) for a total of twelve models (Table 2), to evaluate which metrics and models best described the data. Based on regressions of 2000-2015 September data resulting in poor fits between the models and the data as indicated by low R^2 values (Mork 2016), we included two multiple regression models for September: regression of 7DADM stream temperature on the natural log of average daily flow and the three-day moving average maximum daily air temperature (7DADM ~ LnQD + 3DAir), and regression of 7DADM stream temperature on the average daily flow and the three-day moving average maximum daily air temperature (7DADM ~ QD + 3DAir). The resulting equations represent the relationship between flow and temperature and can be used to estimate stream temperature values for WC 006.00 within the evaluated time period, and within the range of flows observed. We used the 2010-2021 September median maximum daily temperature in combination with selected flows to estimate stream temperature in September.

Table 2. Fourteen regression models evaluated for Whychus Creek at WC 006.00.

	Regression Model
1.	7DADM ~ QD
2.	7DADM ~ QD + $(QD)^2$
3.	7DADM ~ QD + $(QD)^2$ + $(QD)^3$
4.	7DADM ~ Ln QD
5.	7DADM ~ Ln QD + $(\text{Ln QD})^2$
6.	7DADM ~ Ln QD + $(\text{Ln QD})^2$ + $(\text{Ln QD})^3$
7.	7DADM ~ Air
8.	7DADM ~ Air + $(\text{Air})^2$
9.	7DADM ~ Air + $(\text{Air})^2$ + $(\text{Air})^3$
10.	7DADM ~ 3DAir
11.	7DADM ~ 3DAir + $(\text{3DAir})^2$
12.	7DADM ~ 3DAir + $(\text{3DAir})^2$ + $(\text{3DAir})^3$
13.	7DADM ~ LnQD + 3DAir *(September only)*
14.	7DADM ~ QD + 3DAir *(September only)*

We used the extractAIC function in R to generate Akaike Information Criterion (AIC) values for each regression model. AIC values rank models relative to each other on the basis of goodness of fit and number of parameters, with values decreasing as models improve; the lowest value indicates the best model. A difference of two or more between AIC values for two models denotes a statistically better model. For each site we evaluated R-squared (R^2), residual standard error (S), and AIC values to select the model that resulted in the best fit to the observed data; we evaluated residuals plots and normal probability plots for normality of residuals for the best model.

Using the best regression model for each site for July, April, and September, we used R to calculate the predicted temperature and 95% prediction interval for all flows within the observed range (Appendix B). The 95% prediction interval (PI) is calculated as:

$$\hat{y}^*_i \pm T_{df=n-2,\alpha/2} * SE(\hat{y}^*_i \mid x_o)$$

where T is the $1-\alpha/2^{th}$ percentile of a T distribution with n-2 degrees of freedom.

For July data, we compared the resulting 2000-2020 temperature-flow regressions and predicted temperatures at given flows to Heat Source model scenarios for WC 006.00 on Whychus Creek (Watershed Sciences and MaxDepth Aquatics 2008). Because available Heat Source scenarios assume

62 cfs at WC 006.00, we compared 2000-2020 predicted temperatures to Heat Source estimates for this flow.

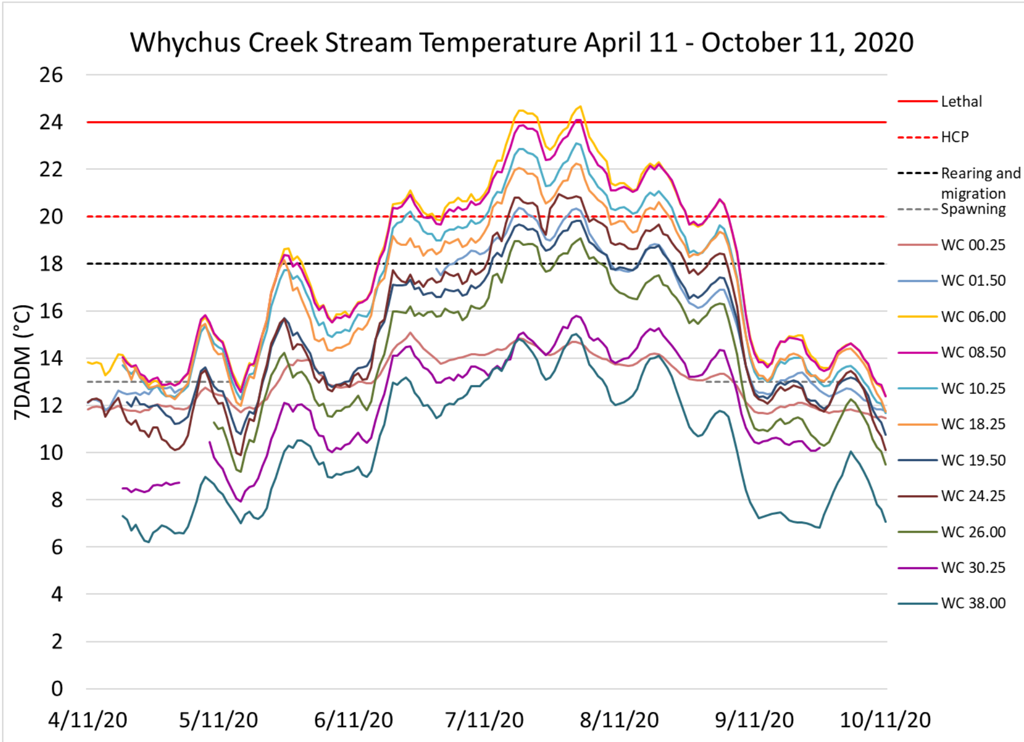
Results

Temperature status

Stream temperatures in 2020 and 2021 substantiate the need for restoration actions to reduce stream temperature, and support the existing State of Oregon Section 303(d) listing of Whychus Creek as water quality limited (Figure 3). In 2020, 7DADM temperatures exceeded the 20°C HCP threshold at six sites between RM 1.5 (WC 01.50) and RM 24.25 (WC 024.25), exceeded the 18°C state standard for trout and salmon rearing and migration at eight sites below the TSID diversion from RM 1.5 (WC 001.50) to RM 26 (WC 026.00), and exceeded the 24°C lethal threshold at two sites from RM 6 to RM 8.5 (WC 008.50). Temperatures exceeded the 13°C spawning standard during the April 1-May 15 steelhead spawning season at six sites between RM 6 and RM 24.25 and exceeded the 13°C spawning standard in September 2020 during the spring Chinook salmon spawning season at all nine sites below the TSID diversion, from RM 0.25 (WC 000.25) to RM 26. In 2021, September 7DADM stream temperatures did not exceed 13°C at RM 0.25 but did exceed this standard at RM 30.25 (WC 030.25) and all other sites between RM 30.25 and RM 1.5.

Seven-day moving average maximum (7DADM) temperatures from RM 6 (WC 006.00) are available from April 6 to May 11 and from August 8 to October 15, 2021. Data from May 12 to August 7 are not available due to loss of one datalogger and cable deployment assembly and failure of the temperature sensor in a second datalogger. In 2021, 7DADM temperatures exceeded the 20°C HCP threshold at six sites from RM 1.5 (WC 001.50) to RM 24.25 (WC 024.25) and exceeded the 18°C rearing standard at eight sites from RM 1.5 to RM 26 (WC 026.00). Temperatures exceeded the 24°C lethal threshold at RM 8.5 (WC 008.50) and, although data are not available from RM 6, it is highly likely that temperatures also exceeded this threshold at RM 6. Temperatures in 2021 exceeded the 13°C spawning standard during the April 1-May 15 steelhead spawning season at eight sites between RM 0.25 and RM 24.25 and exceeded the 13°C spawning standard in September during the spring Chinook salmon spawning season at eight sites from below to above the TSID diversion, from RM 1.5 to RM 30.25.

Seven-day moving average maximum (7DADM) temperatures exceeded the 20°C HCP threshold at RM 6 for 72 days in 2020, between June 20 and September 5. In 2021, 7DADM temperatures at RM 6 exceeded the 20°C HCP threshold for eleven consecutive days for which data were available between August 8 and 18. The 7DADM at RM 8.5 (WC 008.50), 2.5 miles upstream, where stream temperature is historically the same as or slightly cooler than at RM 6, exceeded the 20°C HCP threshold for 58 days in 2021, between June 22 and August 18. Given the observed relationship between stream temperature at RM 8.5 and RM 6, it is highly unlikely the 7DADM at RM 6 exceeded 20°C for fewer than 58 days in 2021.



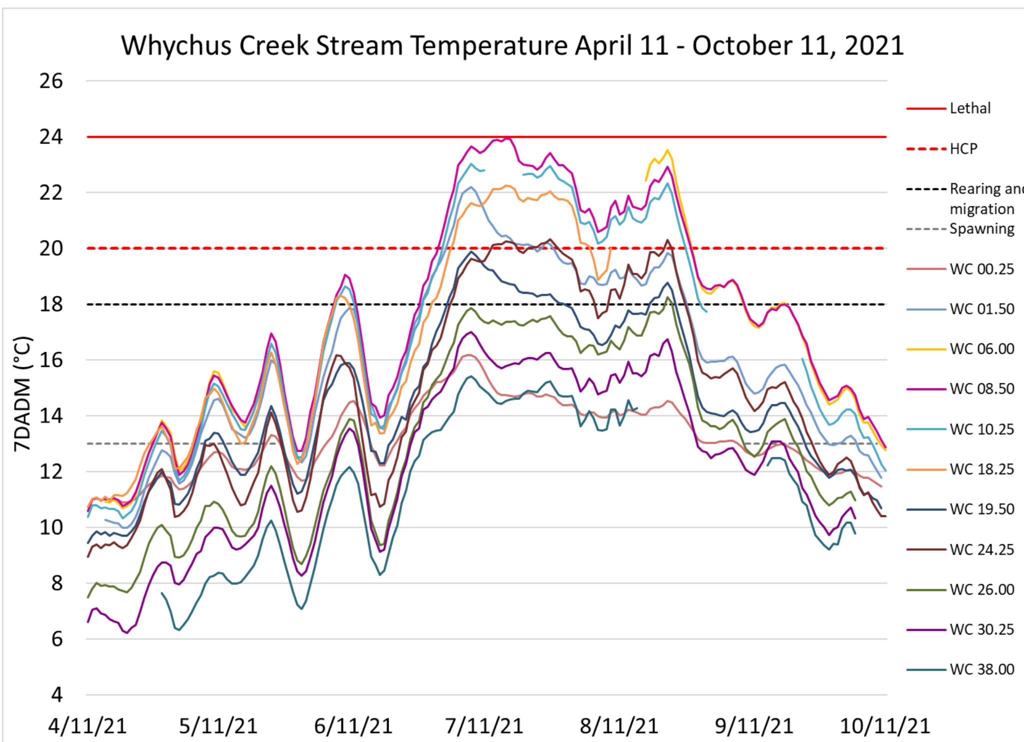


Figure 3. 7DADM temperatures April 11 – October 11, 2020 and 2021, at eleven Whychus Creek monitoring sites.

Percent of data days exceeding 18°C between May 6 and September 21 at RM 6 (WC 006.00) represent the maximum amount of time annually during which stream conditions are unsuitable for rearing trout and salmon at this location on Whychus Creek; conversely, the percent of days meeting 18°C represents the amount of time during which stream conditions are suitable to support rearing trout and salmon at this site. Similarly, the percent of data days exceeding or meeting 13°C between April 1 and May 15, and during the month of September, represent the amount of time during which stream conditions are unsuitable or suitable at RM 6 for spawning summer steelhead and Chinook salmon, respectively.

Stream temperature at WC 006.00 exceeded 18°C for 55% and 57% of days (77 and 79 days) between May 6 and September 21 in 2020 and 2021, respectively (Figure 4), more days than in nine of the 17 years for which data are available and fewer than or the same number of days as in the remaining eight years for which data are available (data for 2003, 2004, and 2008 are unavailable). Temperatures at this site met the applicable standard, providing suitable conditions for rearing trout, for 45% and 43% of days (62 and 60 days) May 6 - September 21 in 2020 and 2021, respectively. Temperatures exceeded 24°C at WC 006.00 for 7% of days May 6 – September 21 (10 days) in 2020. Based on 2021 7DADM temperatures at RM 8.5 (WC 008.50), stream temperature at WC 006.00 likely exceeded 24°C for at least 1% of days (2 days) in 2021. Temperatures at RM 6 exceeded 18°C from May 25-30 and June 17-September 7, 2020, at Sisters City Park minimum daily flows of 7.39-57 cfs. Based on 7DADM data from RM 8.5, stream temperature at RM 6 likely exceeded 18°C from May 29 - June 2 and June 18 - August 30, 2021, when minimum daily flows were between 8.7 and 53.5 cfs.

Data were available for 35 and 36 days between April 1 and May 15 at WC 006.00 in 2020 and 2021, respectively: from April 11 to May 15, 2020, and from April 6 to May 11, 2021. Stream temperature at WC 006.00 exceeded 13°C for 54% (19) of those days in 2020, higher than in nine of the 16 years from 2001-2020 for which data are available, and exceeded 13°C for 56% (20) of those days in 2021, higher than in 10 of the 17 years for which data are available (Table 3). Because temperature data are available for different numbers of days and different dates from April 1 – May 15 between years, direct comparison of trends in the number and percent of days exceeding the spawning standard will not be accurate. However, temperatures exceeding the spawning standard for 13% to 71% of data days from April 1 to May 15 since adult steelhead first returned to Whychus Creek in October 2011 flag a consistent temperature problem at this site for spawning steelhead. In 2020, stream temperatures at RM 6 exceeded 13°C from April 11 – 24, from April 26 – 27, and from May 3 – 14 at Sisters City Park daily minimum flows of 11.3 to 58.5 cfs. In 2021 stream temperatures at RM 6 exceeded 13°C from April 17 – 21 and from April 27 – May 11, 2021 at Sisters City Park daily minimum flows of 13.5 to 49.4 cfs.

Stream temperature at WC 006.00 exceeded 13°C for all 30 days (100% of days) in September 2020 and 2021. Temperatures have exceeded 13°C for 70-100% of September data days since September 2011, the first September when adult Chinook had been passed upstream of the Pelton Round Butte hydroelectric facility. September average daily stream flow at Sisters City Park from 2011-2021 ranged from 9.6 to 65 cfs, with a median average daily flow of 21 cfs.

Because data from WC 006.00 were not available for July 2021, we used the WC 008.50 dataset to illustrate the range and median of July temperatures in 2021 (Figure 5a). July 7DADM temperatures have decreased since the earliest years of flow restoration (e.g. 2000-2007), corresponding to consistently higher flows since these years (Figure 5b). But, in all but the years with the highest flows, most July temperatures remain above the 18°C state standard, and 7DADM temperatures consistently exceed the 20°C HCP threshold in July.

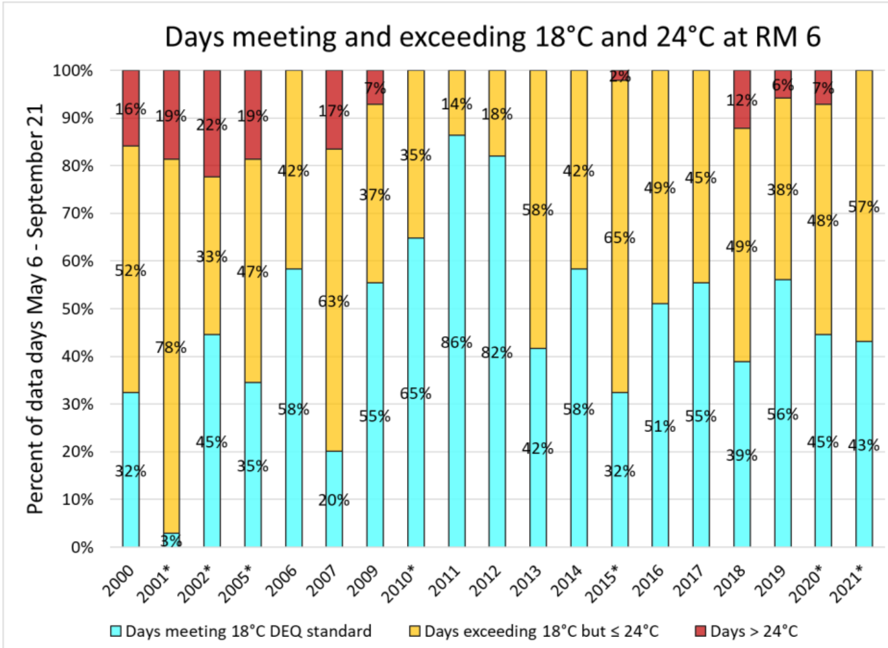


Figure 4. Percent of data days meeting and exceeding the 18°C state temperature standard and the 24°C lethal threshold for rearing native trout and salmon at RM 6 (WC 006.00). Asterisks indicate Governor-declared drought years in Deschutes County (Figure 5b).

Table 3. Number of data days and earliest date, number, and percent of days exceeding 13°C between April 8 and May 15 at RM 6.

	Data days 4/1 - 5/15	Earliest date exceeding 13°C	Number of days exceeding 13°C	Percent of days exceeding 13°C
2001	30	4/22	16	53%
2002	20	4/26	15	75%
2005	37	4/19	24	65%
2007	13	5/3	9	69%
2009	25	4/21	8	32%
2010	36	4/30	15	42%
2011	14	5/7	9	64%
2012	19	5/8	8	42%
2013	38	4/24	19	50%
2014	31	4/30	12	39%
2015	35	4/17	25	71%
2016	38	4/8	20	53%
2017	8	5/8	1	13%
2018	38	4/22	22	58%
2019	25	5/3	13	52%
2020	35	4/21	19	54%
2021	36	4/17	20	56%

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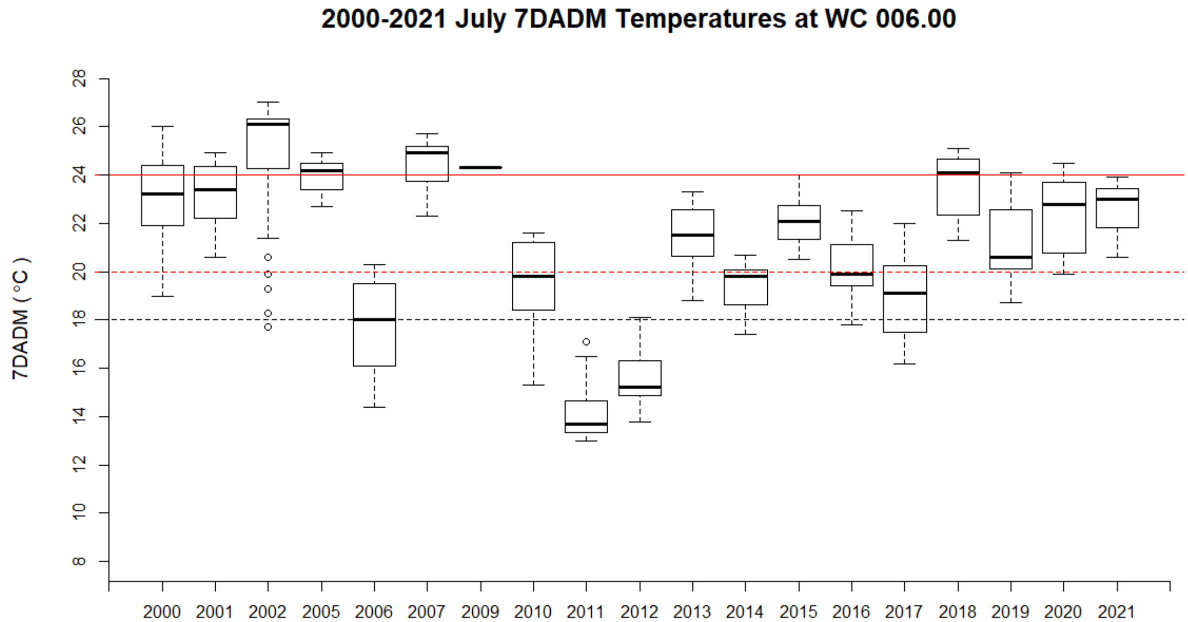

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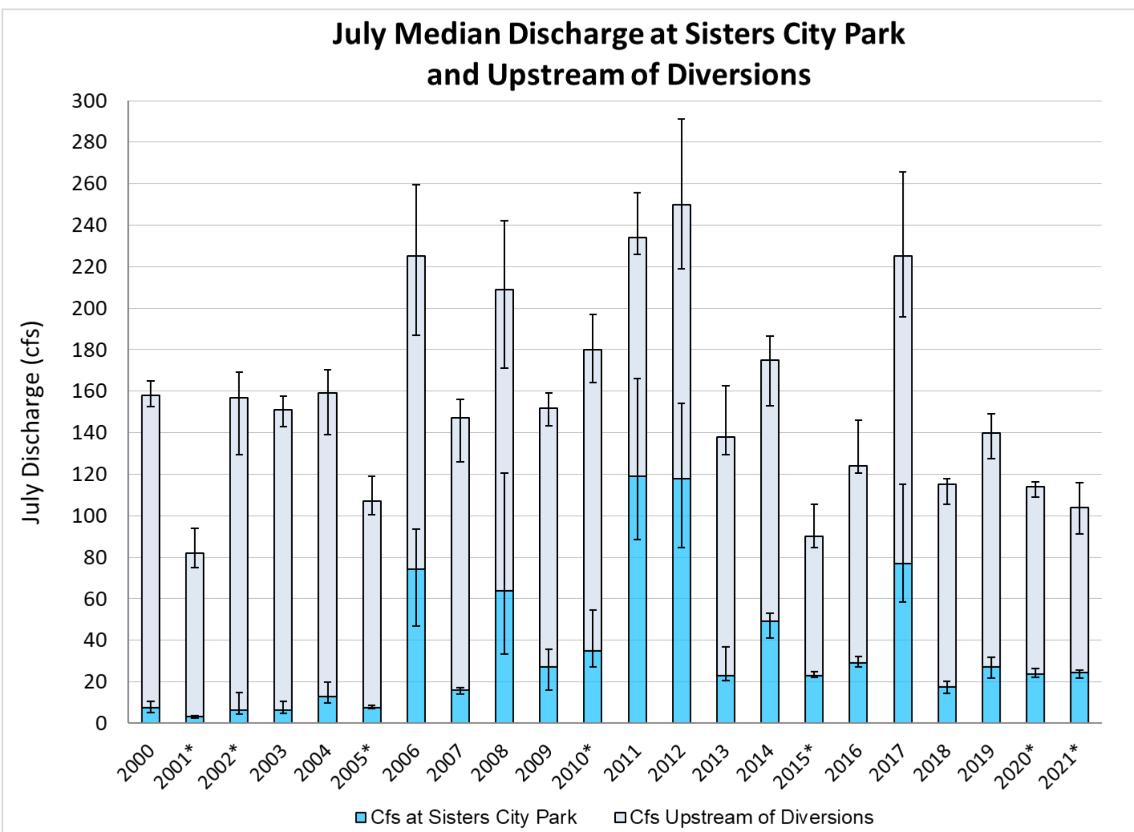

Figure 5. 2001-2021 July Median 7DADM Stream Temperature and Stream Flow

a) July stream temperatures at WC 006.00 (RM 6; Road 6360) correspond closely to b) stream flow at Sisters City Park. Pale grey bars show July median stream flow upstream of all mainstem diversions on Whychus Creek, blue bars show July median stream flow downstream of the TSID diversion, and asterisks indicate Governor-declared drought years in Deschutes County. July stream temperature data were incomplete in 2009 thus the median of available data is shown. No July data were available for RM 6 in 2021; July 2021 data shown are from RM 8.5 (WC 008.50).

Target stream flow

HCP threshold and rearing and migration state standard

Temperature records were available from RM 6 (WC 006.00) for July dates from 2000 through 2020 (Table 4), at Sisters City Park average daily flows from 2 to 201 cfs. July 2021 7DADM data were not available from RM 6. The cubic regression of 7DADM stream temperature on the natural log of average daily flow (7DADM ~ LnQD + $(\text{LnQD})^2$ + $(\text{LnQD})^3$) performed best of the twelve regression models for July (Table 5). Using this model, stream flow explained 79% of the variation in stream temperature in July at WC 006.00 (R^2 = 0.79). Of the six air temperature models for WC 006.00, the quadratic regression of stream temperature on the three day moving average maximum daily air temperature (7DADM ~ 3DAir + $(\text{3DAir})^2$ performed best, explaining 19% of the variation in stream temperature (R^2 = 0.19).

Using the equation for the cubic regression of 2000-2020 7DADM stream temperature on the natural logarithm of flow at RM 6 (WC 006.00) results in 41 cfs estimated to be the minimum average daily stream flow that will achieve a mean 7DADM temperature of 20.0°C ± 3.0°C to meet the HCP threshold in July. This equation results in an estimated 67 cfs as the minimum stream flow that will achieve a mean 7DADM temperature of 18.0°C ± 3.0°C in July. According to this model the state instream water right of 33 cfs below Indian Ford Creek is projected to produce a mean 7DADM temperature of 20.8°C ± 3.0°C at RM 6, exceeding the HCP threshold of 20°C. The estimate of 18.3°C ± 3.0°C at 62 cfs resulting from the 2000-2020 cubic regression model shows strong agreement with the Heat Source model estimate of 18.5°C ± 1°C at 62 cfs at WC 006.00.

Steelhead and salmon spawning standard

Temperature records were available from WC 006.00 for April dates from 2001 through 2016 and from 2018 through 2021 corresponding to Sisters City Park flows from 2 to 128 cfs (Table 4); April data from 2017 are not available. The quadratic regression of 7DADM stream temperature on the natural log of average daily flow (7DADM ~ LnQD + $(\text{LnQD})^2$ performed slightly better than the cubic and linear regressions (7DADM ~ LnQD + $(\text{LnQD})^2$ + $(\text{LnQD})^3$; 7DADM ~ LnQD), explaining slightly more of the variation in stream temperature with a slightly higher R^2 value and a slightly lower standard error (Table 5). Stream flow explained only 33% of the variation in stream temperature in April (R^2 = 0.328). The quadratic regression of stream temperature on three-day moving average air temperature performed best of the six air temperature models and almost as well as the natural log of average daily flow models, explaining 30% of the variation in stream temperature (R^2 = 0.297).

Because the April regression models explained relatively little of the variation in stream temperature, in 2016 we used the same methods to evaluate the same relationships for May stream temperature, stream flow, and air temperature data from 2000-2015. May regressions explained less of the variation in stream temperature than April regressions. The cubic regression of 7DADM stream temperature on average daily flow (7DADM ~ QD + $(\text{QD})^2$ + $(\text{QD})^3$) performed best of the twelve models for May and explained 26% (R^2 = 0.26) of the variation in stream temperature; the best model for air temperature, the quadratic regression of stream temperature on three day moving average air temperature (7DADM ~ 3DAir + $(\text{3DAir})^2$), explained 20% of the variation in stream temperature (R^2 = 0.26). Because the April regression provides better information about the relationship between stream flow and stream temperature during the April 1- May 15 anticipated steelhead spawning season, we have not updated the May analysis since 2016.

We used the April quadratic regression of 7DADM stream temperature on the natural log of average daily flow (7DADM ~ LnQD + $(\text{LnQD})^2$), which explained the greatest proportion of variation in stream temperature of the April regression model, to calculate temperatures at the range of April flows. This model predicts a mean 7DADM stream temperature of 13°C ± 3.2°C (a range encompassing 9.8°C – 16.2°C) at 18 cfs at Sisters City Park. The state instream water right and DRC stream flow target of 33 cfs resulted in 12.2°C ± 3.2°C (8.8°C – 15.4°C). Even at 128 cfs, the highest flow included in the regression, the estimated temperature was 10.4°C, more than half a degree higher than the mean 7DADM 9.8°C required to produce 13°C as the upper limit of the prediction interval at WC 006.00 in April. Given that air temperature explains almost as much of the variation in stream temperature as stream flow does, we can expect April stream temperatures at RM 6 to be strongly influenced by annual April air temperature.

Temperature records were available from WC 006.00 for September dates from 2000 through 2021 at Sisters City Park flows from 1 to 400 cfs. The multiple linear regression of 7DADM stream temperature on the natural logarithm of average daily flow and the three-day moving average maximum daily air temperature (7DADM~LnQD + 3DAir) performed best of the fourteen models, explaining 51% ($R^2 = 0.51$) of the variation in stream temperature. This model predicted a mean 7DADM temperature of 15.4°C ± 3.2°C (12.2°C–18.6°C) at the natural log of 33 cfs (3.4965 LnQD) and the 2010-2021 September median maximum daily air temperature of 26.1°C (79.0°F). At the natural log of the 41 cfs estimated to meet the 20°C HCP threshold in July, and the 2010-2021 September median maximum daily air temperature of 26.1, the September model predicted a mean 7DADM temperature of 15.1°C ± 3.2°C (12.0°C–18.3°C); at the natural log of the 67 cfs estimated to meet the 18 state temperature standard in July and the 2010-2021 September median maximum daily air temperature, the same model predicted a mean 7DADM temperature of 14.6°C ± 3.2°C (11.4°C–17.8°C), still well above the 13°C spawning standard for salmon and steelhead. The best-performing stream flow and air temperature models explained 16% and 39% of the variation in stream temperature, respectively, indicating that air temperature alone, which explained only 12% less of the variation in stream temperature than air temperature and stream flow together in September models, influences stream temperature more than stream flow does in September.

Table 4. Years for which data are available and represented in regression analyses. The number of days for which data are available for any given month and year varies.

Site and Month	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
WC 006.00																						
Apr		x	x			x				x	x		x	x	x	x	x		x	x	x	x
Jul	x	x	x			x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	
Sep	x	x				x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x

Table 5. A cubic regression model provided the best fit to July 2000-2020 temperature-flow data for WC 006.00; the quadratic regression model provided the best fit to April 2000-2021 data for this site. A multiple regression model provided the best fit to September 2000-2021 air temperature, flow, and WC 006.00 stream temperature data. Temperatures calculated using the corresponding regression equations are expected to be the most accurate of the regression models evaluated. The top three best-performing models and associated regression equations are provided for each month.

Regression Model	Intercept	Coefficient 1	Coefficient 2	Coefficient 3	n	df	R^2	S	AIC value
July - WC 006.00									
7DADM ~ LnQD + $(LnQD)^2$ + $(LnQD)^3$	**17.68020**	**8.58980**	**-3.05740**	**0.24560**	**523**	**519**	**0.7909**	**1.525**	**445**
7DADM ~ QD + $(QD)^2$ + $(QD)^3$	25.19	-0.1499	0.000729	-0.000001264	523	519	0.7816	1.558	468
7DADM ~ LnQD + $Ln(QD)^2$	22.88242	2.15777	-0.76762	--	523	520	0.7806	1.562	469
April - WC 006.00									
7DADM ~ LnQD + $(LnQD)^2$	**19.5821**	**-2.8700**	**0.2138**	--	**237**	**234**	**0.328**	**1.599**	**225**
7DADM ~ LnQD + $(LnQD)^2$ + $(LnQD)^3$	20.73489	-4.21429	0.6837	-0.05084	237	233	0.325	1.602	227
7DADM ~ LnQD	17.415	-1.468	--	--	237	235	0.322	1.606	227
September - WC 006.00									
7DADM ~ LnQD + 3DAir	**12.62443**	**-1.2111**	**0.26952**	--	**481**	**478**	**0.511**	**1.613**	**463**
7DADM ~ QD + 3DAir	9.87591	-0.02460	0.26496	--	481	478	0.434	1.736	533
7DADM ~ 3DAir + $(3DAir)^2$ + $(3DAir)^3$	2.457146	1.187796	-0.03962	0.000551	481	477	0.387	1.806	572

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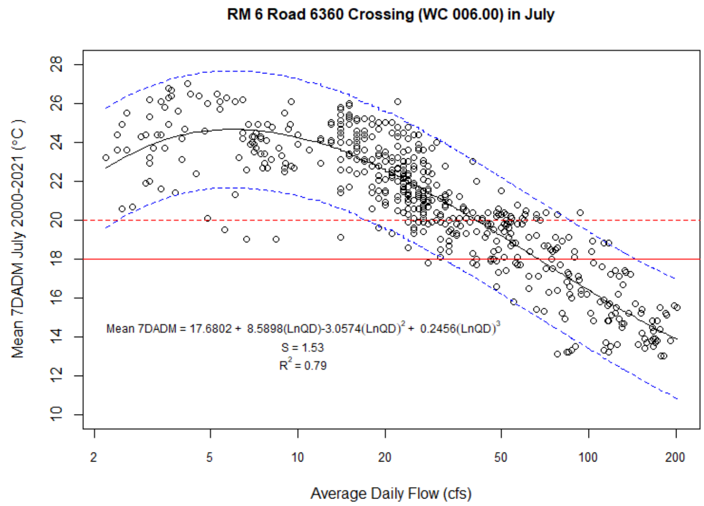

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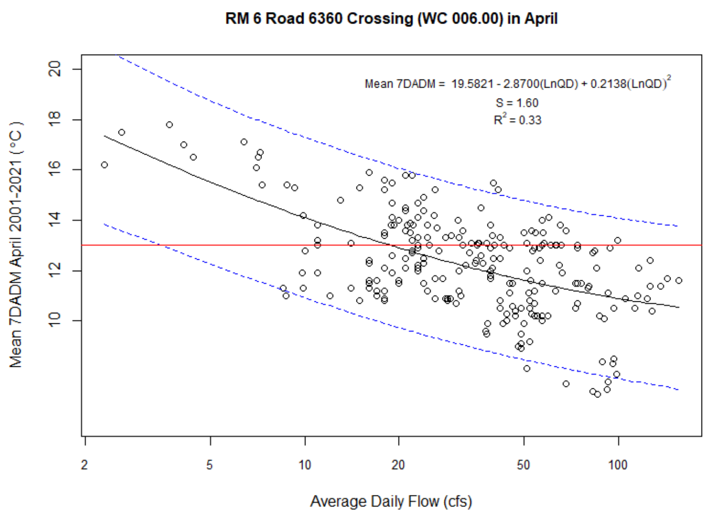

Figure 8. Temperature-Flow Regression Models

Regression models fitted to temperature-flow data demonstrate reduced temperatures at higher flows and describe the relationship between temperature and flow observed a) during July 2000-2020 at WC 006.00 and b) during April 2001-2021 at WC 006.00. The HCP 20°C threshold, 18°C state rearing and migration temperature standard, and 13°C salmon and steelhead spawning standard are indicated for relevant months.

Discussion

Temperature status and trend

7DADM stream temperatures exceeding the state standard for trout rearing and migration in 2020 and 2021 support the ODEQ 2022 303(d) Category 5 listing of Whychus Creek as water quality limited for temperature (ODEQ 2022). Stream temperatures exceeding the 18°C standard in 2020 and 2021 at every monitoring station downstream of the TSID diversion, from RM 1.5 (WC 001.50) to Road 4606 (WC 026.00) over a prolonged duration suggest temperature conditions compromised habitat suitability for rearing and migrating redband and steelhead trout and spring Chinook salmon in Whychus Creek in these years. Seven day average daily maximum (7DADM) temperatures above 13°C for over half of data days April 1-May 15 at WC 006.00 in 2020 and 2021, as well as for most September data days at sites downstream of Camp Polk (WC 018.25), also demonstrate largely unsuitable spawning temperatures for steelhead and Chinook salmon. For April and September, when air temperature strongly influences stream temperature, employing all mechanisms to reduce stream temperature, including stream habitat restoration and possibly pulse flows during periods of high air temperatures when spawning steelhead or salmon are known to be in Whychus, will be an important strategy to reduce stream temperature to meet spawning standards. Stream temperatures at RM 6 and RM 8.5 continued to exceed the 24°C lethal threshold in 2020 and 2021, potentially creating a thermal barrier in the downstream reaches of Whychus Creek for spring Chinook salmon returning to Whychus Creek in July and August. Stream temperatures at RM 6 (WC 006.00) meeting the state standard for less than 50% of data days in 2020 and 2021, and exceeding the 20°C HCP threshold for 72 days in 2020 and at least 11 days in 2021, demonstrate an ongoing need for creative and responsive stream flow restoration and management as well as habitat restoration solutions that reduce summer stream temperatures from the TSID diversion to RM 1.5 at Alder Springs. Simultaneously, July median temperatures a half-degree lower from 2018-2021 than from 2000-2009, and stream temperatures meeting the state standard at RM 6 in 2020 for more than or the same number of days as in eight years (2000-2001, 2005, 2007, 2013, 2015, and 2018), and meeting that standard in 2021 for more than in seven previous years, show sustained improvement over early years of stream flow restoration (data from WC 006.00 are not available for 2003 and 2004).

Regression of temperature and flow data as well as comparison of median monthly temperature and stream flow data and mean 7DADM temperatures for given flow levels show stream temperatures decreasing in Whychus Creek as flows increase. Stream flow restoration has increased flow protected and delivered instream, and use of SCADA (Supervisory Control and Data Acquisition) software to automate irrigation diversion operations beginning in 2021 has increased daily minimum flows, together resulting in higher daily minimum and daily average flows which in turn correspond to lower observed temperatures.

Target stream flow

Deschutes River Conservancy's 33 cfs target for Whychus Creek matches the state instream water right for Whychus Creek downstream of Indian Ford Creek and accounts for the need to provide this flow in the reach between the TSID diversion and Indian Ford Creek where the state instream water right is 20 cfs. The Deschutes Basin Habitat Conservation Plan established a 7DADM stream temperature threshold of 20°C at RM 6 in lieu of a minimum stream flow requirement for Whychus Creek, to be met beginning in Year 9 of HCP implementation (2031), with an allowance for 7DADM temperature to exceed 20°C for one week during the year.

July regression results from Road 6360 (WC 006.00) 2000-2021 temperature and flow data indicate a minimum average daily flow of 67 cfs is necessary to achieve 7DADM stream temperatures of 18°C ± 3.0°C, and a minimum average daily flow of 41 cfs is necessary to achieve 7DADM stream temperatures of 20.0°C ± 3.0°C at this site in July. Importantly, achieving these temperature standards and thresholds at this location will support equivalent or better temperature conditions in reaches upstream to the TSID diversion. According to this model the DRC target stream flow and state instream water right of 33 cfs below Indian Ford Creek is projected to produce a mean 7DADM temperature of 20.8°C ± 3.0°C at Road 6360, above the 18°C state standard and the 20°C HCP threshold; the highest temperature predicted at this flow, 23.8°C, just misses the lethal temperature threshold of 24°C. Although this report presents neither July regression models that incorporate both flow and air temperature nor any regression models for August, further examination of the effect of air temperature on stream temperature in these critical months will assist in refining flows needed to meet applicable temperature thresholds and standards.

Creative management of available water resources that increase flow instream during peak July and August air and stream temperatures will contribute to meaningfully lowering stream temperatures for adult Chinook salmon which return to Whychus Creek between May and September, and for rearing Chinook salmon and redband and steelhead trout. One example of such an approach is the FAST (Fifteenmile Action to Stabilize Temperature) model developed for Fifteenmile Creek on the eastern flank of Mt Hood, where irrigators are compensated to voluntarily reduce diversions and leave more water instream when stream temperatures are predicted to be 22.2°C, the EPA lethal threshold for adult steelhead, or higher at two or more sites for two or more days (The Freshwater Trust, accessed online 12/8/2022). With 20 cfs of senior water already protected instream, adding up to 21 cfs of flow on an as-needed basis through implementation of the FAST model could bring stream temperature along Whychus Creek between the TSID diversion and RM 6 down to the 20°C HCP threshold.

Stream habitat restoration that reconnects Whychus Creek to its floodplain might provide another mechanism to cool stream temperature. In collaboration with OSU-Cascades and USGS, UDWC will implement a study in 2023 that will monitor floodplain recharge and stream discharge upstream and downstream of floodplain reconnection habitat restoration projects. Results from this study will provide information about whether reconnected floodplains release water into the stream during late summer low flows, with potential to strategically inundate reconnected floodplains during early summer peak flows to increase cold groundwater inputs and cool stream temperature in July and August.

Regression of April stream temperature and flow data suggests the 33 cfs DRC stream flow restoration target will result in stream temperatures between 8.8 and 15.4°C at RM 6, spanning and exceeding the 13°C spawning threshold (predicted mean 7DADM = 12.2°C ± 3.2°C). This result suggests 33 cfs will support suitable steelhead spawning temperatures some of the time; the influence of air temperature on stream temperature in April, explaining 30% of the variability in stream temperature during this month, suggests air temperature will determine whether stream temperature meets or exceeds the spawning criteria at 33 cfs. Although 13 cfs is predicted to result in a mean 7DADM 13°C ± 3.2 stream temperature, observed temperatures exceeding that criteria at flows of 20 cfs and higher support the need for 33 cfs or higher in April and May.

Regression of September stream temperature, stream flow, and air temperature data suggests 33 cfs will result in stream temperatures between 12.1°C and 18.5°C (predicted mean 7DADM = 15.3°C ± 3.2°C) at the September median maximum daily air temperature of 25.6°C (78.1°F), also spanning, and exceeding by a greater amount than in April, the 13°C spawning threshold during anticipated Chinook salmon spawning. This result suggests 33 cfs will inconsistently support suitable Chinook salmon spawning temperatures, depending in large part on air temperature. Although only a few September flow records correspond with 7DADM temperatures less than 13°C, the lowest of these is 46 cfs. Given the critical importance of providing suitable spawning temperatures for reintroduced spring Chinook salmon, the large influence of air temperature on September stream temperature, and the high flows (> 67 cfs) indicated by the September regression model to be needed to lower stream temperatures to 13°C, creative water management solutions to increase flows such as the FAST model are also warranted in September during Chinook salmon spawning.

These results clearly demonstrate the current state water right of 33 cfs is well below the stream flow necessary to meet applicable temperature thresholds and state standards and provide suitable conditions for rearing and migrating native trout and salmon, and support the conclusion of previous regression models and Heat Source model results (Watershed Sciences and MaxDepth Aquatics 2008). In addition, minimum flows that on average have resulted in 18°C may not be sufficient to meet that threshold in hotter years given the influence of air temperature on stream temperature. July flows above 52 cfs are predicted to maintain July temperatures below the 22°C threshold at which trout have been shown to suffer severe effects of chronic sub-lethal temperatures; April flows above 44 cfs are predicted to maintain April temperatures below the 15°C threshold at which egg mortality increases.

This report evaluates stream temperature status and trends relative to the HCP temperature thresholds, state temperature standards and stream flow. Given competing needs for a limited amount of stream flow, further analyses by stream flow and habitat restoration partners and fish biologists that prioritize when and where it is most important to meet the applicable state standard will be useful to inform restoration planning. Questions to be addressed might include: Are there critical reaches in which to prioritize meeting the state temperature standard and at what times during the irrigation season, based on life cycle and movement of native fish species? Could strategic pulse flows or use of the FAST model during specific periods help fish migrate into areas that represent better habitat quality, e.g. reaches where springs cool stream flows or cooler upstream reaches?

Conclusions

Stream flow restoration and TSID management practices have achieved some sustained improvements in reducing the magnitude and duration of high stream temperatures in Whychus Creek since the early years of stream flow restoration, suggesting some improvement in the suitability of stream conditions in Whychus Creek for rearing trout, steelhead and salmon, and for migrating adult spring Chinook salmon, during the irrigation season. But, despite these hard-won gains, stream temperatures still continue to exceed biologically-based temperature thresholds and state temperature standards at most monitoring stations and river miles downstream of the TSID diversion for spawning summer steelhead and spring Chinook salmon, for migrating adult Chinook salmon, and for rearing and migrating juvenile redband and steelhead trout and Chinook salmon for extended periods during the irrigation season, reducing the suitability of Whychus Creek habitat for these life stages and at times approaching and exceeding lethal thresholds for all life stages.

Regression analyses of empirical stream temperature and stream flow data substantiate Heat Source model results showing more than 60 cfs is required to meet 18°C on average in lower reaches of Whychus Creek in July; a maximum stream temperatures of 21°C is predicted to occur at RM 6 at 67 cfs in July, emphasizing the need for both stream habitat restoration and creative stream flow restoration and management solutions that will increase stream flow and lower stream temperature from July into

September when stream flow is low and stream temperatures approach lethal thresholds for juvenile and adult trout and salmon (July and August) and for incubating Chinook salmon eggs (September).

Although 60 cfs may not be a feasible restoration target given current land and water use in the Three Sisters Irrigation District, these data provide a benchmark for stream flow restoration and, importantly, show the 33 cfs state water right to be far short of the flows needed to meet the state temperature standard or provide suitable conditions for fish. Small gains in stream flow restoration that result in similarly small reductions in temperature are nonetheless likely to improve habitat conditions for some fish in some locations, for example by providing adequate flow for summer steelhead outmigration and adult spring Chinook salmon in-migration, increasing channel margin habitat by increasing channel width and, in restored reaches, activating side channels, and creating pools and cover.

Our results show that higher stream flow achieved in part through stream flow restoration results in lower temperatures and better stream conditions for all life stages of reintroduced salmon and steelhead trout and resident redband trout, highlight the urgent need for higher flows and creative stream flow and habitat restoration and management solutions to achieve suitable conditions for salmon and trout in Whychus Creek, and contribute to an improved understanding of temperature and flow that that we hope will support restoration partners in planning more ambitious stream flow restoration and management efforts on Whychus Creek.

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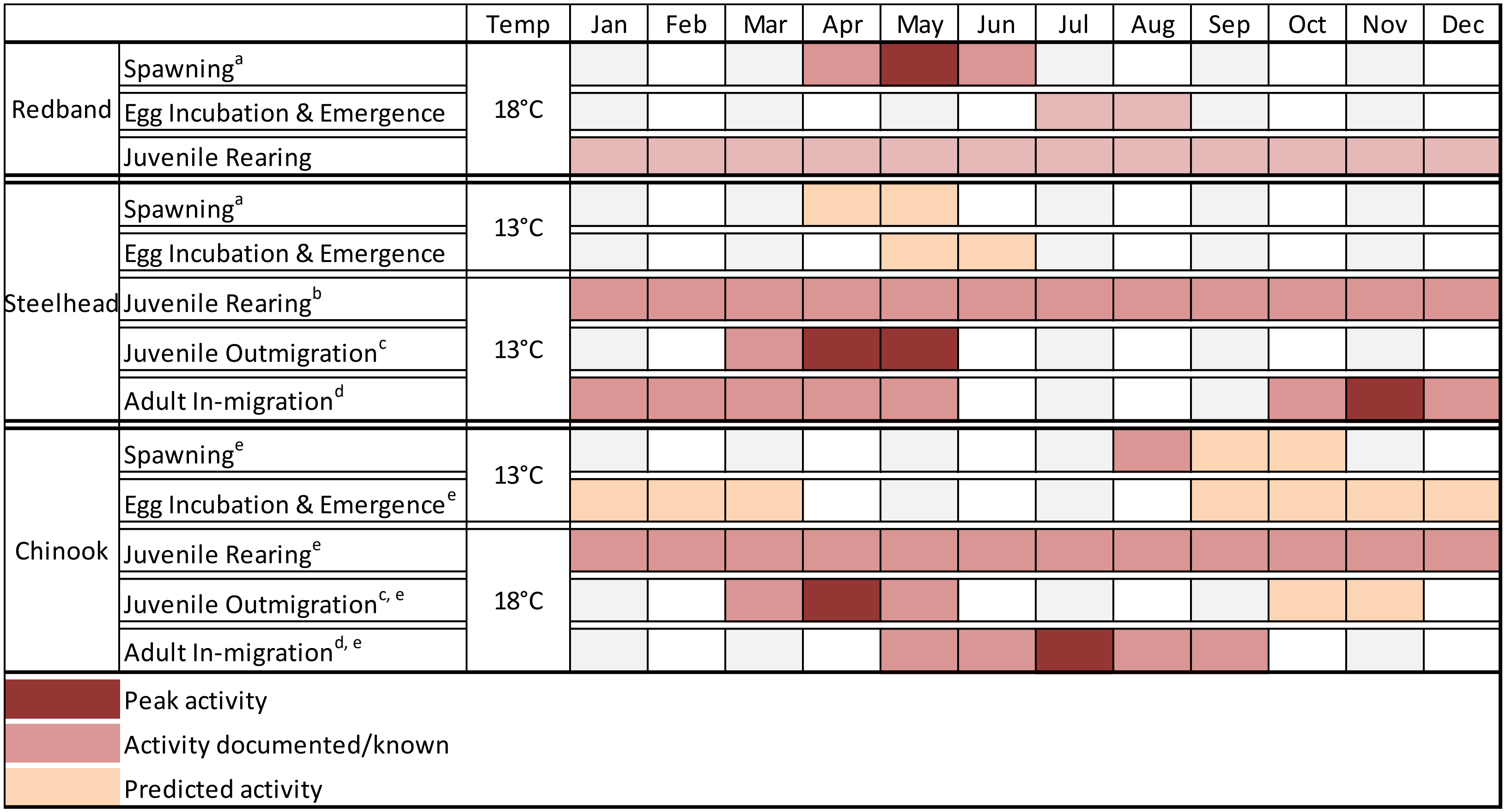
APPENDIX A. Preliminary life history timing and temperature requirements of redband, and steelhead trout and Chinook salmon in Whychus Creek.



[a] Source: PGE redd count data, 2007-2013
[b] Quinn 2005
[c] Hill & Quesada 2014b
[d] Hill *et al* 2014
[e] B. Spateholts, personal communication, January 15,2015

APPENDIX B Temperatures at given flows.

Whychus Creek at RM 6 (WC 006.00) predicted temperatures for July at flows from 2 to 200 cfs

Flow (cfs)	Mean Temp (7DMAX)	PI (±)	Flow (cfs)	Mean Temp (7DMAX)	PI (±)	Flow (cfs)	Mean Temp (7DMAX)	PI (±)	Flow (cfs)	Mean Temp (7DMAX)	PI (±)
2	22.2	3.1	57	18.7	3.0	112	15.9	3.0	167	14.5	3.0
3	23.8	3.0	58	18.6	3.0	113	15.9	3.0	168	14.5	3.0
4	24.4	3.0	59	18.5	3.0	114	15.9	3.0	169	14.4	3.0
5	24.6	3.0	60	18.5	3.0	115	15.8	3.0	170	14.4	3.0
6	24.7	3.0	61	18.4	3.0	116	15.8	3.0	171	14.4	3.0
7	24.6	3.0	62	18.3	3.0	117	15.8	3.0	172	14.4	3.0
8	24.5	3.0	63	18.3	3.0	118	15.7	3.0	173	14.4	3.0
9	24.4	3.0	64	18.2	3.0	119	15.7	3.0	174	14.3	3.0
10	24.2	3.0	65	18.1	3.0	120	15.7	3.0	175	14.3	3.0
11	24.1	3.0	66	18.1	3.0	121	15.6	3.0	176	14.3	3.0
12	23.9	3.0	67	18.0	3.0	122	15.6	3.0	177	14.3	3.0
13	23.7	3.0	68	17.9	3.0	123	15.6	3.0	178	14.3	3.0
14	23.6	3.0	69	17.9	3.0	124	15.6	3.0	179	14.2	3.0
15	23.4	3.0	70	17.8	3.0	125	15.5	3.0	180	14.2	3.0
16	23.2	3.0	71	17.8	3.0	126	15.5	3.0	181	14.2	3.0
17	23.1	3.0	72	17.7	3.0	127	15.5	3.0	182	14.2	3.0
18	22.9	3.0	73	17.6	3.0	128	15.4	3.0	183	14.2	3.0
19	22.7	3.0	74	17.6	3.0	129	15.4	3.0	184	14.2	3.0
20	22.6	3.0	75	17.5	3.0	130	15.4	3.0	185	14.1	3.0
21	22.4	3.0	76	17.5	3.0	131	15.3	3.0	186	14.1	3.0
22	22.3	3.0	77	17.4	3.0	132	15.3	3.0	187	14.1	3.0
23	22.1	3.0	78	17.4	3.0	133	15.3	3.0	188	14.1	3.0
24	22.0	3.0	79	17.3	3.0	134	15.3	3.0	189	14.1	3.0
25	21.8	3.0	80	17.3	3.0	135	15.2	3.0	190	14.1	3.0
26	21.7	3.0	81	17.2	3.0	136	15.2	3.0	191	14.0	3.1
27	21.6	3.0	82	17.2	3.0	137	15.2	3.0	192	14.0	3.1
28	21.4	3.0	83	17.1	3.0	138	15.2	3.0	193	14.0	3.1
29	21.3	3.0	84	17.1	3.0	139	15.1	3.0	194	14.0	3.1
30	21.2	3.0	85	17.0	3.0	140	15.1	3.0	195	14.0	3.1
31	21.1	3.0	86	17.0	3.0	141	15.1	3.0	196	14.0	3.1
32	21.0	3.0	87	16.9	3.0	142	15.1	3.0	197	13.9	3.1
33	20.8	3.0	88	16.9	3.0	143	15.0	3.0	198	13.9	3.1
34	20.7	3.0	89	16.8	3.0	144	15.0	3.0	199	13.9	3.1
35	20.6	3.0	90	16.8	3.0	145	15.0	3.0	200	13.9	3.1
36	20.5	3.0	91	16.8	3.0	146	15.0	3.0			
37	20.4	3.0	92	16.7	3.0	147	14.9	3.0			
38	20.3	3.0	93	16.7	3.0	148	14.9	3.0			
39	20.2	3.0	94	16.6	3.0	149	14.9	3.0			
40	20.1	3.0	95	16.6	3.0	150	14.9	3.0			
41	20.0	3.0	96	16.5	3.0	151	14.8	3.0			
42	19.9	3.0	97	16.5	3.0	152	14.8	3.0			
43	19.8	3.0	98	16.5	3.0	153	14.8	3.0			
44	19.7	3.0	99	16.4	3.0	154	14.8	3.0			
45	19.6	3.0	100	16.4	3.0	155	14.7	3.0			
46	19.5	3.0	101	16.3	3.0	156	14.7	3.0			
47	19.4	3.0	102	16.3	3.0	157	14.7	3.0			
48	19.4	3.0	103	16.3	3.0	158	14.7	3.0			
49	19.3	3.0	104	16.2	3.0	159	14.7	3.0			
50	19.2	3.0	105	16.2	3.0	160	14.6	3.0			
51	19.1	3.0	106	16.2	3.0	161	14.6	3.0			
52	19.0	3.0	107	16.1	3.0	162	14.6	3.0			
53	19.0	3.0	108	16.1	3.0	163	14.6	3.0			
54	18.9	3.0	109	16.0	3.0	164	14.5	3.0			
55	18.8	3.0	110	16.0	3.0	165	14.5	3.0			
56	18.7	3.0	111	16.0	3.0	166	14.5	3.0			

Whychus Creek at RM 6 (WC 006.00) predicted temperatures for April at flows from 2 to 128 cfs

Flow (cfs)	Mean Temp (7DMAX)	PI (±)	Flow (cfs)	Mean Temp (7DMAX)	PI (±)	Flow (cfs)	Mean Temp (7DMAX)	PI (±)
2	18.1	4.0	57	11.5	3.2	112	10.7	3.2
3	16.9	3.4	58	11.5	3.2	113	10.7	3.2
4	16.1	3.3	59	11.5	3.2	114	10.7	3.2
5	15.5	3.2	60	11.5	3.2	115	10.7	3.2
6	15.1	3.2	61	11.4	3.2	116	10.7	3.2
7	14.7	3.2	62	11.4	3.2	117	10.7	3.2
8	14.5	3.2	63	11.4	3.2	118	10.7	3.2
9	14.2	3.2	64	11.4	3.2	119	10.7	3.2
10	14.0	3.2	65	11.4	3.2	120	10.7	3.2
11	13.9	3.2	66	11.3	3.2	121	10.6	3.2
12	13.7	3.2	67	11.3	3.2	122	10.6	3.2
13	13.6	3.2	68	11.3	3.2	123	10.6	3.2
14	13.4	3.2	69	11.3	3.2	124	10.6	3.2
15	13.3	3.2	70	11.3	3.2	125	10.6	3.2
16	13.2	3.2	71	11.3	3.2	126	10.6	3.2
17	13.1	3.2	72	11.2	3.2	127	10.6	3.2
18	13.0	3.2	73	11.2	3.2	128	10.6	3.2
19	13.0	3.2	74	11.2	3.2	129		
20	12.9	3.2	75	11.2	3.2	130		
21	12.8	3.2	76	11.2	3.2	131		
22	12.7	3.2	77	11.2	3.2	132		
23	12.7	3.2	78	11.1	3.2	133		
24	12.6	3.2	79	11.1	3.2	134		
25	12.6	3.2	80	11.1	3.2	135		
26	12.5	3.2	81	11.1	3.2	136		
27	12.5	3.2	82	11.1	3.2	137		
28	12.4	3.2	83	11.1	3.2	138		
29	12.4	3.2	84	11.1	3.2	139		
30	12.3	3.2	85	11.0	3.2	140		
31	12.3	3.2	86	11.0	3.2	141		
32	12.2	3.2	87	11.0	3.2	142		
33	12.2	3.2	88	11.0	3.2	143		
34	12.1	3.2	89	11.0	3.2	144		
35	12.1	3.2	90	11.0	3.2	145		
36	12.1	3.2	91	11.0	3.2	146		
37	12.0	3.2	92	11.0	3.2	147		
38	12.0	3.2	93	10.9	3.2	148		
39	12.0	3.2	94	10.9	3.2	149		
40	11.9	3.2	95	10.9	3.2	150		
41	11.9	3.2	96	10.9	3.2	151		
42	11.9	3.2	97	10.9	3.2	152		
43	11.9	3.2	98	10.9	3.2	153		
44	11.8	3.2	99	10.9	3.2	154		
45	11.8	3.2	100	10.9	3.2	155		
46	11.8	3.2	101	10.9	3.2	156		
47	11.7	3.2	102	10.8	3.2	157		
48	11.7	3.2	103	10.8	3.2	158		
49	11.7	3.2	104	10.8	3.2	159		
50	11.7	3.2	105	10.8	3.2	160		
51	11.6	3.2	106	10.8	3.2	161		
52	11.6	3.2	107	10.8	3.2	162		
53	11.6	3.2	108	10.8	3.2	163		
54	11.6	3.2	109	10.8	3.2	164		
55	11.6	3.2	110	10.8	3.2	165		
56	11.5	3.2	111	10.7	3.2	166		