**Upper Deschutes Watershed Council**

**Technical Report**

# Middle Deschutes River Instream Flow Restoration and Temperature Responses 2001-2019

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**Executive Summary**

Since 1996, the Deschutes River Conservancy (DRC) has engaged in efforts to restore summer stream flow in the middle Deschutes River and lower Tumalo Creek through a variety of techniques, including conservation, leasing, and acquisition. The DRC has identified stream flow restoration in the Deschutes River between the City of Bend and Lake Billy Chinook (middle Deschutes River) and Tumalo Creek downstream from Tumalo Irrigation District's (TID's) diversion (lower Tumalo Creek) as a priority because very low summer flows in these two reaches consistently result in summer water temperatures that exceed the Oregon Department of Environmental Quality (ODEQ) standard established to protect salmon and trout rearing and migration.

To evaluate the effectiveness and potential of stream flow restoration efforts in reducing temperature in the middle Deschutes River, the DRC, its funders, and other partners have been interested in understanding: 1) how stream flow has changed with cumulative stream flow restoration actions; 2) how stream temperature has changed with cumulative stream flow restoration actions; 3) how stream flow affects stream temperature; and 4) how stream flow restoration in the Deschutes River and Tumalo Creek can achieve the greatest reduction in stream temperature. Since 2008 the DRC has partnered with the Upper Deschutes Watershed Council (UDWC) to conduct temperature monitoring to investigate observed and potential temperature changes associated with stream flow restoration projects. This ongoing monitoring effort incorporates data collected from 2001 to 2017 and builds off analyses developed for the Upper Deschutes Basin Study to address the following key questions:

1) Stream flow status and trend: How have flows in the middle Deschutes River changed with cumulative stream flow restoration actions?

   *Key findings:*

   - July median stream flow in the middle Deschutes at North Canal Dam more than tripled from 2002 to 2012, from 47 cfs to 158 cfs.
   - July median flows in the middle Deschutes from 2013 to 2018 (129-136 cfs) represent a marked decrease from 2010 to 2012 flows (148 to 158 cfs), and were similar to that observed in 2009 (131 cfs).
   - In two of the last three years (2017 and 2019) median July and August flows in the middle Deschutes at North Canal Dam have been lower than any median for these months recorded since 2009
   - July median flow in the middle Deschutes in 2019 (122 cfs) was the lowest observed since 2008.
   - Stream flow restoration in Tumalo Creek has increased July median flow to a new high of 24 cfs (17.3 cfs protected) in 2019.

   July median stream flow in the middle Deschutes at North Canal Dam more than tripled from 2002 to 2012, from 47 cfs to 158 cfs. July median streamflow in the middle Deschutes dropped in 2013 to 129 cfs and from 2013 to 2018 approximated the 2009 July median flow of 131 cfs, fluctuating between 129 and 136 cfs, commensurate with reductions in flow leased instream and less flow left instream by irrigation districts under a voluntary agreement. In 2019 July median flow in the middle Deschutes dropped to 122 cfs, the lowest median observed since 2008. Deschutes River flows closely track flow protected instream, which increased from 107 cfs in 2008 to 158 cfs in 2012, dropped to 124 cfs in 2013, and has since fluctuated between 126 and 134 cfs. July median stream flow and median protected flow in the middle Deschutes from 2013 to 2019 represents a marked decrease from 2010-2012 flows. The median July flow protected instream was 132 cfs in 2018 and 127 cfs in 2019; the median recorded average daily flow in July of each year was 135 cfs and 122 cfs, respectively.

Stream flow in Tumalo Creek exceeds flow protected instream in most years, including in 2018 and 2019, when July median flow was 16.2 cfs and 24 cfs to 14.7 and 17.3 cfs July median protected flow, respectively. July median flow in Tumalo increased from 5 cfs in 2001 to a high of 58 cfs in 2012, in most years hovering between 12 and 15 cfs. Flows protected instream with pre-1961 priority dates range from 7.8 cfs in 2009 to 17.3 cfs in 2019.

2) <u>Temperature status and trend</u>: What was the status of middle Deschutes River and Tumalo Creek Seven-Day Moving Average Maximum (7DADM) stream temperature in 2018 and 2019 relative to the State of Oregon 18°C (64°F) standard protecting salmon and trout rearing and migration, and in relation to previous years?

*Key findings:*

- Stream temperature at Lower Bridge on the middle Deschutes River (DR 133.50) met the state temperature standard for a month or barely over a month between April and September in 2018 and 2019. This is half the number of days during which stream temperatures met the state standard in 2017.
- Stream temperature at four sites spanning 32 miles downstream of Bend exceeded the 18°C state standard for for 31-79% of days between April 30 and September 21 in 2018 and for 38-75% of days between April 30 and September 21 in 2019.
- July stream temperatures downstream of Bend from 2013 to 2019 were far lower and exceeded 24°C far less frequently than from 2001 to 2007 but were on average two degrees warmer than from 2008 to 2012.
- The increase in stream temperature and in days exceeding 24°C from 2013 to 2019 coincides with the 2013 drop in flows protected in the middle Deschutes. However, stream flow explains only 29% of the variation in stream temperature in the middle Deschutes in July and further investigation of variables explaining warmer temperatures from 2013 to 2019 is needed.
- Stream temperatures exceeding 24°C for 2% of days in 2019 represent the second-lowest number of days above the lethal threshold since 2013.

- Stream temperature at the mouth of Tumalo Creek (TC 000.25) met the 18°C state temperature standard for 90% of days in 2019 and exceeded the standard for only 10% of days between April 30 and September 21 in 2019, and stream temperature at this site has met the 18°C standard for 81-100% of days between April 30 and September 21 since 2006. Limited stream temperature data were available from this site from 2018.
- Stream flow restoration actions targeted at reducing stream temperatures specifically during the July 2nd to August 5th period when temperatures most often exceed 24°C, and continuing to invest in stream flow restoration in Tumalo Creek, will attenuate the worst effects of low flows on stream conditions for fish.

Stream temperature in the middle Deschutes River exceeded the 18°C state standard protecting salmon and trout rearing and migration for 31-79% of days between April 30 and September 21 in 2018 and for 38-75% of days between April 30 and September 21 in 2019, at all four Deschutes River monitoring locations downstream of Bend:

- Stream temperatures at the site characterized by the highest temperatures, DR 133.50, exceeded the standard for more days in 2018 (79% or 114 days) and 2019 (75% or 109 days) than in any year except 2001. Stream temperatures met the standard for about one month in each year. This is approximately half the number of days during which temperatures met the 18°C standard in 2017.
- Downstream of the confluence with Tumalo Creek, at DR 160.00, temperatures exceeded the standard for the same number or more days in 2018 and 2019 (41% or 60 days and 43% or 62 days respectively) than in all but one year since 2005.
- Temperatures at DR 160.25 exceeded the standard for fewer days in 2018 (58% or 84 days) than in the previous three years, but for more days than in the ten years from 2004-2014. In 2019 temperatures at this site met the standard for fewer days (47% or 68 days) than in any year except 2003.
- Temperatures at DR 164.75, immediately downstream of North Canal Dam, exceeded the standard for more days in 2018 (31% or 45 days), and met the standard for fewer days (69% or 100 days), than in all but two years. In 2019 temperatures at this site exceeded the standard for more days (38% or 55 days) and met the standard for fewer (62% or 90 days) than in all years but one.
- Stream temperatures at Lower Bridge (DR 133.50) remained below 24°C (the lethal threshold for trout rearing; ODEQ 1995) for more days in 2019 (2% or 3 days) than in all but one year since 2013. Stream temperatures exceeded 24°C for more days in 2018 than in three of the six years from 2013-2018. The increase in the number of days exceeding the 24°C lethal threshold in 2018 is consistent with other years including and since 2013.

Temperatures recorded at Lower Bridge (DR 133.50) in 2018 and 2019 show a return to temperatures above the state standard for the longest duration since the earliest days of stream flow restoration in 2001, with 7DADM temperatures exceeding the 24°C lethal threshold for a limited number of days in both years. From 2013 to 2019 stream temperatures exceeded 24°C as early as July 2nd and as late as August 5th. Stream flow restoration actions targeted at reducing stream temperatures specifically during the period when temperatures most often exceed 24°C will attenuate the worst effects of low flows on stream conditions for fish.

Although stream temperatures continue to exceed 24°C at Lower Bridge, the number and percent of days for which temperatures at Lower Bridge were above 24°C were lower from 2013 to 2019 than prior to 2008, signaling a reduction in the amount time each year during which fish are exposed to potentially lethal stream conditions. This reduction coincides with increases in protected flow and observed stream flow in the Deschutes River at North Canal Dam and in Tumalo Creek compared to 2008 and earlier years. However, the number and percent of days for which temperatures at Lower Bridge were above 24°C were higher from 2013 to 2017 than from 2008 to 2013, again coincident with the 2013 drop in flows protected in the middle Deschutes.

Despite worse stream temperature conditions in 2018 and 2019 than in most years for which data are available, stream flow in the Deschutes downstream of North Canal Dam, in Tumalo Creek downstream of the TID diversion, and in the Deschutes downstream of the confluence with Tumalo Creek was roughly equivalent to or higher than in years with fewer days exceeding 18°C and 24°C, pointing to other factors influencing stream temperature. Increases in stream temperatures observed between North Canal Dam and the confluence of the Deschutes River and Tumalo Creek, and a decreasing $R^2$ value for the relationship between temperature and flow at DR 160.25 upstream of the confluence, also indicate less variation in stream temperature at DR 160.25 is being explained by stream flow and could signal the effects of a warmer climate on Deschutes River flow stored in Wickiup and Crane Prairie reservoirs. Additionally, changes to Wickiup Reservoir operations resulting in lower summer reservoir levels beginning in 2018 could be affecting stream temperature.

3) <u>Restoration effectiveness</u>: Have cumulative increases in stream flow resulted in reduced water temperatures at key locations along the middle Deschutes River?

*Key findings:*

- July and August stream temperatures at Lower Bridge and three other temperature monitoring sites downstream of Bend decreased as July and August median flows increased from 2000-2012
- Stream temperatures in Tumalo Creek were substantially lower at the highest flow than at the lowest flow recorded in Tumalo Creek; temperatures in the middle Deschutes were moderately lower at the highest flow than at the lowest flow recorded in the Deschutes River below North Canal Dam.

- Regressions of stream flow and temperature data show lower stream temperatures at higher stream flows.
- These results suggest higher stream flows in Tumalo Creek and in the middle Deschutes River result in lower stream temperatures.
- Building on the observed success of increased stream flow resulting in lower stream temperatures in Tumalo Creek, there is nothing more important we can do than continuing to invest in stream flow restoration in Tumalo Creek.

Multiple lines of evidence show reduced stream temperatures at the higher stream flows achieved through stream flow restoration in the middle Deschutes River and Tumalo Creek. July and August stream temperatures at DR 133.50 decreased alongside increasing July median flows in the middle Deschutes and in Tumalo Creek from 2001-2012. Comparison of seven-day average daily maximum temperatures (7DADM) at DR 160.25 and TC 000.25 at the lowest and highest July flows recorded from 2002 to 2015 show that moderately (in the Deschutes River) to substantially (in Tumalo Creek) lower stream temperatures occurred at higher flows. Regressions of mean July 7DADM temperatures and corresponding flow values from 2001-2019 at DR 160.25, DR 160.00, and TC 000.25 show temperatures decreasing as flows increase. Stream flow from the Deschutes River or from Tumalo Creek explained 29%, 56%, and 76% of variation in stream temperature in the middle Deschutes at DR 160.25, at DR 160.00, and in Tumalo Creek, respectively, providing statistical support for the role of higher stream flows in reducing stream temperature.

4) <u>Target stream flow</u>: What flow scenarios for the Deschutes River and Tumalo Creek will most efficiently achieve the 18°C temperature standard immediately below the confluence of the Deschutes River and Tumalo Creek?

*Key findings:*

- Restoring as much flow as possible in Tumalo Creek in July will achieve the maximum reduction possible in stream temperature in the middle Deschutes downstream of Tumalo Creek.
- Forty-three cfs in Tumalo Creek and 127 cfs in the Deschutes River below North Canal Dam in July is estimated to achieve, on average, 18°C ± 1.9°C (prediction interval) in the Deschutes River immediately downstream of the confluence
- Because the Deschutes River is 3°C warmer at Lower Bridge Road than immediately below the confluence of Tumalo Creek and the Deschutes River, often resulting in July temperatures that are lethal to redband trout, it is important to achieve the greatest possible reduction in stream temperature below this confluence.

Flow scenarios developed from regression and mass balance equations indicate that allocating the maximum possible Tumalo Creek flow to instream use during July will achieve the greatest reduction in stream temperature in the middle Deschutes. At the 127 cfs protected instream in the Deschutes River at North Canal Dam as of 2019, 43 cfs from Tumalo Creek is estimated to produce an average 7DADM temperature of 18°C ± 1.9°C in the Deschutes immediately downstream of the confluence with Tumalo Creek. While this scenario would significantly improve temperatures in the Deschutes River, the approximately 3°C warming that typically occurs at these flows between the confluence of the Deschutes and Tumalo Creek and DR 133.50 means that some reaches along approximately 26 miles of the middle Deschutes River would continue to exceed the state temperature standard by up to seven degrees (at 43 cfs in Tumalo Creek), with potential peak temperatures of 22.6°C or higher.

**Acknowledgments**

Thanks to Deschutes River Conservancy for ongoing funding support for the monitoring and analyses that form the basis for this report. Water quality monitoring conducted by Upper Deschutes Watershed Council is also funded in large part by the Oregon Watershed Enhancement Board. Monitoring by the City of Bend, ODEQ, Oregon State University (OSU), Oregon Water Resources Department (OWRD), and DRC has contributed invaluable data to UDWC's long-term monitoring effort. Many thanks to members of the founding Water Quality Committee and contributing partners who provided expertise, insight, and time in support of the development of the UDWC Regional Water Quality Monitoring Program from which the data and analyses included here originated. Special thanks to Lesley Jones, who spearheaded and grew the UDWC Regional Water Quality Monitoring Program to produce rigorous statistical analyses of the effects of stream flow restoration on temperature, and to Lisa Ganio at OSU and Mike Cole of Cole Ecological Inc., who have provided excellent insight into and thoughtful review of the analyses presented.

**Abbreviations**

Organizations

| | |
|---|---|
| DRC | Deschutes River Conservancy |
| UDWC | Upper Deschutes Watershed Council |
| ODEQ | Oregon Department of Environmental Quality |
| ODFW | Oregon Department of Fish and Wildlife |
| OWRD | Oregon Water Resources Department |

Terminology

| | |
|---|---|
| °C | Degree Celsius |
| °F | Degree Fahrenheit |
| 7DADM | Seven Day Moving Average Daily Maximum |
| df | Degrees of freedom |
| PI | Prediction interval |
| cfs | Cubic feet per second |
| Ln | Natural logarithm |
| QA/QC | Quality assurance / quality control |
| QD | Average daily flow |
| S | Standard error |

# 1 Introduction

The middle Deschutes River watershed (formally designated as the McKenzie Canyon – Deschutes River watershed) is located in the Deschutes Basin, Oregon, and is bordered by the Metolius River, Whychus Creek, Tumalo Creek, and Upper Deschutes River watersheds (Figure 1). The middle Deschutes River from the North Canal Diversion Dam to Whychus Creek has been listed since 2004 as a temperature impaired waterway under Clean Water Act Section 303(d) for not meeting State of Oregon water temperature standards for salmon and trout rearing and migration (ODEQ 2020).

Since 1996, the Deschutes River Conservancy (DRC) has engaged in efforts to restore summer stream flow in the middle Deschutes River and lower Tumalo Creek. DRC has prioritized stream flow restoration in these two reaches, where irrigation season low flows result in temperatures that exceed the Oregon Department of Environmental Quality standard of 18°C/64°F established to protect salmon and trout rearing and migration, and where stream flow restoration can have the greatest impact on stream temperature in those reaches and in reaches downstream. DRC stream flow restoration efforts aim to meet the State of Oregon instream flow targets of 250 cfs in the Deschutes River from North Canal Dam (RM 165) to Lake Billy Chinook (RM 119), and 32 cfs in Tumalo Creek from the Tumalo Irrrigation District's diversion to the mouth, in order to, among other objectives, improve water temperature to support sustainable anadromous and resident fish populations.

Based on recent analyses of temperature and flow in Tumalo Creek and the Deschutes River suggesting the relative contribution of flow from each stream substantially influences downstream temperature, the DRC increasingly aims to restore streamflow preferentially in Tumalo Creek to maximize temperature reductions in the middle Deschutes River. Because Deschutes River water is consistently at or above 18°C at North Canal Dam in July, restoring stream flow in the Deschutes River at North Canal Dam can only decrease downstream temperatures by decreasing the rate of warming through increasing the amount of flow. Restoring stream flow in Tumalo Creek reduces warming downstream of the TID diversion, delivering cooler flows to the Deschutes River and actively cooling Deschutes River water. Tumalo Creek, approximately five miles downstream of North Canal Dam, is the only tributary and source of additional flow between the dam and Lower Bridge Road approximately 31 miles downstream, where temperatures are historically highest and conditions worst for fish. Increasing flows in Tumalo Creek therefore represents an opportunity to achieve the greatest cooling effect in the Deschutes River between Tumalo Creek and Lower Bridge Road by contributing a greater volume of colder water at the confluence, reducing warming and actively cooling Deschutes River flows.

The DRC has partnered with the Upper Deschutes Watershed Council (UDWC) since 2008 to monitor water temperature in the middle Deschutes River and quantify temperature changes associated with stream flow restoration. Although model results and substantial empirical evidence indicate that reductions in summer stream flow lead to increased water temperatures in central Oregon (ODEQ 2010; ODEQ 2004; UDWC 2006), the DRC and restoration partners are interested in evaluating how increasing flows in the middle Deschutes River and Tumalo Creek through stream flow restoration transactions affects water temperatures in downstream reaches. We evaluated available Deschutes River and

Tumalo Creek stream temperature and flow data from 2001 through 2019 to address the following questions: 1) How have flows in the middle Deschutes River and Tumalo Creek changed with cumulative stream flow restoration actions? 2) What was the status of middle Deschutes River water temperature in 2016 relative to the State of Oregon 18°C (64°F) standard and in relation to previous years?; 3) Have cumulative increases in stream flow resulted in reduced water temperatures at key locations along the middle Deschutes River; and 4) What flow scenarios for the Deschutes River and Tumalo Creek will achieve the 18°C temperature standard in the Deschutes River immediately below the confluence with Tumalo Creek? We present 2018 and 2019 temperature results and discuss implications for stream flow restoration.

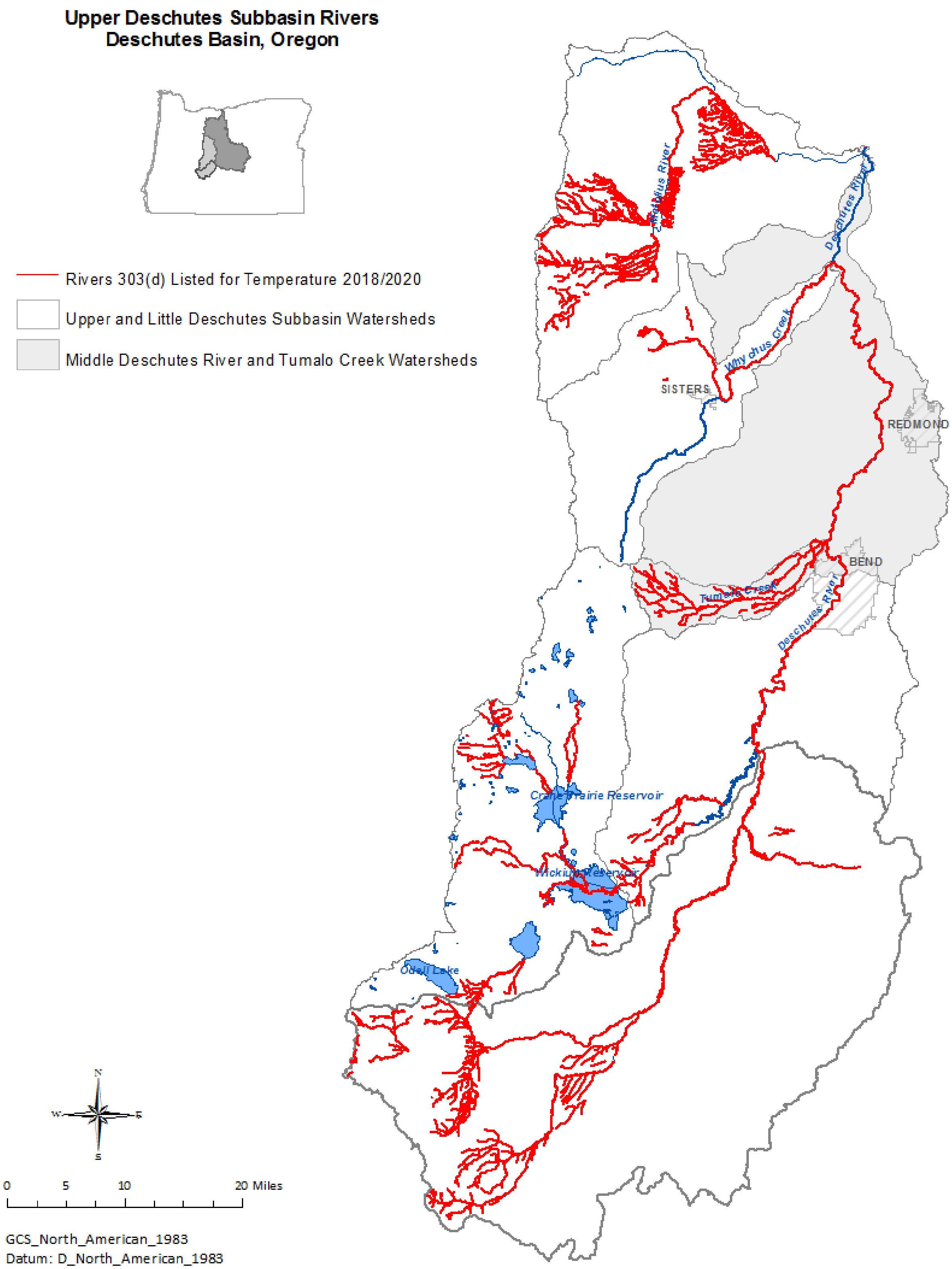



**Figure 1.** The Upper Deschutes and Little Deschutes subbasins, middle Deschutes River and Tumalo Creek watersheds, and river and creek ODEQ assessment units 303(d) listed as exceeding state temperature standards for salmon and trout rearing and migration in DEQ's 2018/2020 Integrated Report (ODEQ 2020).

# 2 Methods

## 2.1 Data Collection

### *2.1.1 Stream Temperature*

UDWC collected and compiled continuous water temperature data for 2001-2019 from six stream temperature monitoring stations on the Deschutes River and one monitoring station on Tumalo Creek (Table 1; Figure 2), using Vemco and HOBO dataloggers rated to an accuracy of 0.5°C and 0.2°C, respectively. With the exception of 2019 data, continuous temperature data for Tumalo Creek were obtained from the City of Bend; UDWC began collecting continuous temperature data at this site in 2019. Data is not available for all years due to equipment failure or no monitoring (Table 2). UDWC operates per its *Water Quality Monitoring Program Standard Operating Procedures* (UDWC 2008a) under a Quality Assurance Project Plan approved by DEQ in 2008 and an addendum to this plan approved in 2015 (UDWC 2008b, UDWC 2015).

### *2.1.2 Stream Flow*

We obtained July median daily instream water rights data for the Deschutes River and for Tumalo Creek from DRC. Reductions in July median daily instream water rights between years reflect a reduction in the amount of flow allocated instream by irrigation districts under a long-standing gentleman's agreement, as well as a decline in the volume of water leased instream through the DRC's Annual Water Leasing Program. We refer to July median daily instream water rights as median protected flow to differentiate from the state instream water right. July median daily instream water right data are available from 2007-2019 for the Deschutes River, and from 2006-2019 for Tumalo Creek. Tumalo Creek July median daily instream water rights exclude water rights with a priority date junior to 1961, which as a result of their late priority date are never delivered.

UDWC obtained average daily stream flow (QD) data for the Deschutes River and Tumalo Creek from the Oregon Water Resources Department (OWRD 2020) (Table 1; Figure 2). All Deschutes River flow data through September 2018 and Tumalo Creek flow data through September 2008 and from October 2009 through September 2011, are considered published; Deschutes River flow data from October 1, 2018 through 2019 and Tumalo Creek flow data from October 2008 through September 2009 and from October 2011 through 2019 included in this report are considered provisional and subject to change.

**Table 1.** Middle Deschutes River and Tumalo Creek flow gages and temperature monitoring stations

| Station ID | Waterway | Description | Latitude | Longitude | Elev. (ft) |
|---|---|---|---|---|---|
| OWRD gage #14073520 | Tumalo Creek | d/s of Tumalo Feed Canal | 44.08944 | -121.36667 | 3550 |
| OWRD gage #14070500 | Deschutes River | d/s of North Canal Dam, Bend | 44.08280 | -121.30690 | 3495 |
| DR 217.25 | Deschutes River | Pringle Falls | 43.74075 | -121.60672 | 4250 |
| DR 181.50 | Deschutes River | Benham Falls | 43.93080 | -121.41107 | 4140 |
| DR 164.75 | Deschutes River | u/s of Riverhouse Hotel | 44.07733 | -121.30592 | 3540 |
| DR 160.25 | Deschutes River | u/s of Tumalo Creek | 44.11501 | -121.33904 | 3240 |
| DR 160.00 | Deschutes River | d/s of Tumalo Creek | 44.11767 | -121.33326 | 3210 |
| DR 133.50 | Deschutes River | Lower Bridge | 44.35970 | -121.29378 | 2520 |
| TC 000.25 | Tumalo Creek | u/s of Tumalo Creek mouth | 44.11567 | -121.34031 | 3250 |

**Table 2.** Summary of available July temperature data 2001-2017

| Station ID | Description | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DR 217.25 | Pringle Falls | | x | x | x | x | x | x | - | x | x | x | x | x | x | x | x | x | x | x |
| DR 181.50 | Benham Falls | | | x | | x | x | x | x | x | x | x | x | x | x | x | - | x | - | - |
| DR 164.75 | u/s Riverhouse Hotel | | | | x | x | | - | x | x | x | x | x | x | x | x | x | x | x | x |
| DR 160.25 | u/s Tumalo Creek | | x | x | x | x | | - | x | x | x | x | x | x | x | x | x | x | x | x |
| DR 160.00 | d/s Tumalo Boulder Field | | | | | x | x | x | x | x | x | x | x | - | x | x | - | x | x | x |
| DR 133.50 | Lower Bridge | x | x | | x | x | x | x | x | - | x | x | x | x | x | - | x | x | - | x |
| TC 000.25 | u/s of Tumalo Creek mouth | | | | x | x | - | x | | x | x | x | x | x | x | x | - | x | - | x |

x *Data available for analysis*

\- *Limited data available for analyses*

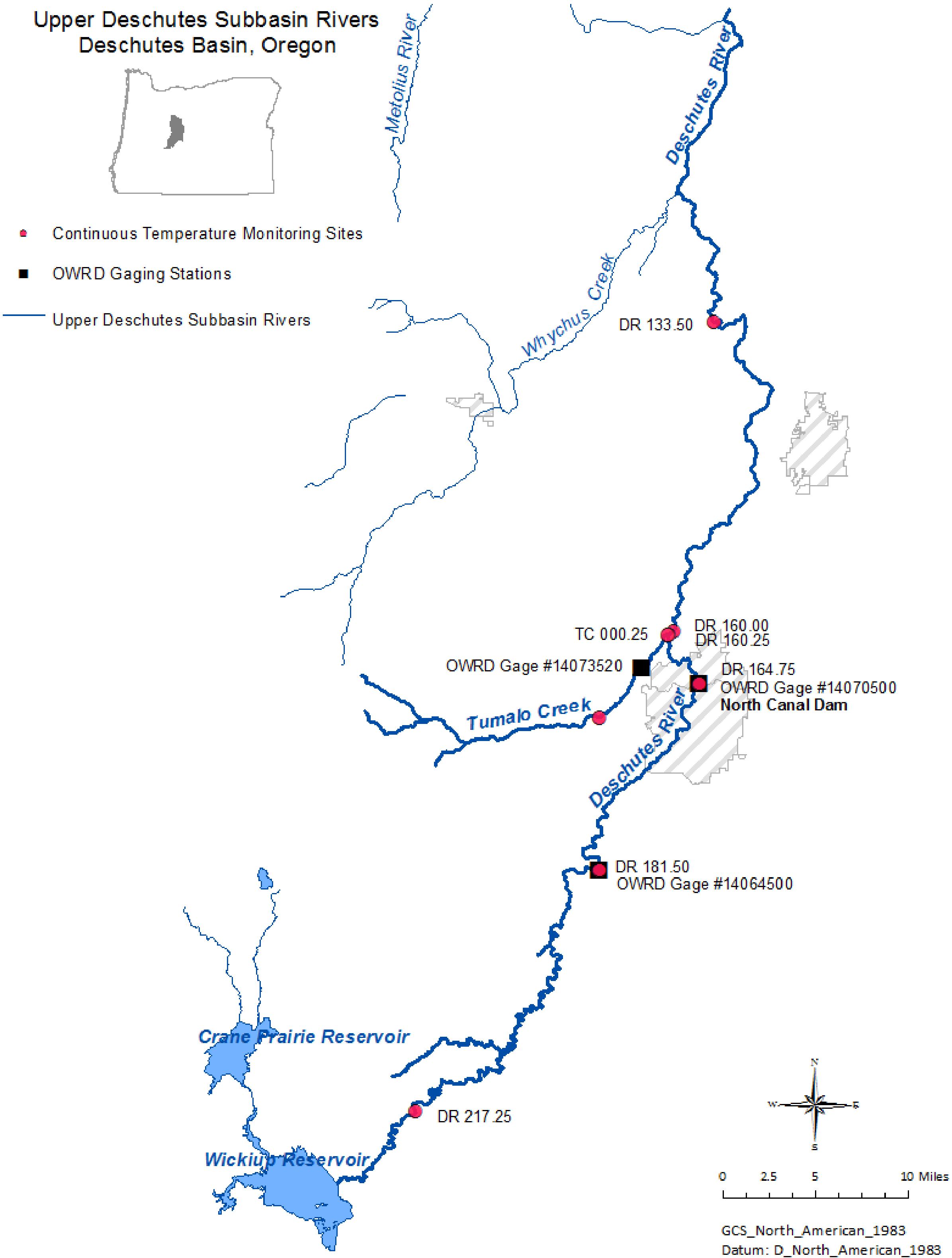



**Figure 2.** UDWC continuous temperature monitoring sites and OWRD stream flow gages on the middle and upper Deschutes River and on Tumalo Creek.

## 2.2 Data Analysis

### *2.2.1 Stream Flow Status and Trend*

We evaluated July and August median daily protected flow and median average daily flow to understand how stream flow has increased in response to stream flow restoration. Both the daily protected stream flow and average daily flow change within and across years. We selected July median flow as an indicator because it represents the central tendency of flow rates during one of the hottest summer months. We included August median flow as a measure of base flow resulting from stream flow restoration.

### *2.2.2 Stream Temperature Status and Trend*

We used the Oregon Department of Environmental Quality (ODEQ) Hydrostat Simple spreadsheet (ODEQ, 2010) to calculate the seven day moving average daily maximum (7DADM) temperature, the statistic used by the State of Oregon to evaluate stream temperatures. 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). We evaluated 7DADM temperatures from 2001-2019 in relation to the state standard of 18°C to describe changes in temperature in the middle Deschutes River since 2001 and to assess progress toward the 18°C state standard for salmonid rearing and migration.

To describe the proportion of the irrigation season when stream temperatures exceeded the 18°C state standard between 2001 and 2019, we calculated the number and percent of days in each year between April 30 and September 21 when the 7DADM stream temperature met the 18°C standard, exceeded the 18°C standard, or exceeded the 24°C lethal threshold. We selected April 30 and September 21 as the earliest and latest calendar dates when stream temperatures have exceeded 18°C. 7DADM datasets for some sites and years are incomplete because of data loss due to datalogger stranding, damage or loss. We reviewed data for years for which fewer than the 145 days between April 30 and September 21 were available. For some data gaps it was possible to extrapolate with high confidence whether 7DADM temperatures met or exceeded 18°C at a given site from temperature trends at upstream or downstream dataloggers. Where possible to do so with high confidence, we extrapolated temperatures to be above or below 18°C. Where temperature data were missing, adjacent data available (dates and sites) did not suggest stream temperatures exceeding 24°C; it is not known whether stream temperatures exceeded 24°C in the years and at the sites for which data were extrapolated. Accordingly, all percentages for days exceeding 24°C represent recorded (not extrapolated) data values.

We evaluated July temperature data from DR 160.00, downstream of the confluence of the Deschutes River and Tumalo Creek, in relation to the July median average daily flow in the Deschutes below North Canal Dam and in Tumalo Creek below the Tumalo Feed Canal. To evaluate temperature status at DR 133.50 (Lower Bridge Road) we present data for August in addition to July because more data are available for August for years of interest. Both July and August data represent summer conditions characterized by high temperatures and low flows.

### 2.2.3 Effect of Stream Flow on Stream Temperature

To evaluate the effectiveness of increasing flows through stream flow restoration in reducing stream temperature in the middle Deschutes River and in Tumalo Creek, we 1) compared 2001-2019 July 7DADM stream temperatures at DR 133.50 to July median stream flow at the Tumalo Creek (OWRD gage #14073520) and Deschutes Below Bend (OWRD gage #14070500) stream gages, and 2) used regressions of 2001-2019 July stream temperature at DR 160.25, DR 160.00, and at TC 000.25, and flow data from the same two gages, to illustrate the relationships between temperature and flow at the three sites. Methods for regressions, which were also used for stream flow target analyses, are described below.

### 2.2.4 Stream Flow Targets

We used regressions of 2001-2019 temperature and stream flow data and a mass balance approach to develop flow scenarios for the middle Deschutes River and Tumalo Creek that will achieve the greatest temperature reduction in the Deschutes below the confluence with Tumalo Creek. Because the objective of these regressions is to develop flow scenarios, we do not incorporate air temperature, which, although known to influence stream temperature, is beyond the scope restoration partners are able to address through stream flow restoration.

We used stream temperature data from the Deschutes River above Tumalo Creek (DR 160.25) and from the mouth of Tumalo Creek (TC 000.25) with corresponding flow data from OWRD gage #14070500, Deschutes River Below Bend, and from OWRD gage #14073520, Tumalo Creek Below Tumalo Feed Canal. The two temperature monitoring sites are short distances downstream of major points of stream flow restoration on each waterway, and temperatures are anticipated to decrease in response to increased flows; due to the respective locations of the two sites immediately upstream of the confluence of Tumalo Creek and the Deschutes River, these sites most accurately represent the temperature-flow relationships that directly affect stream temperature downstream of the confluence. Because no tributaries or springs enter the Deschutes River between Tumalo Creek and Lower Bridge Road, the relative flow contributions of the Deschutes River and Tumalo Creek at the two upstream sites directly influence stream temperature 26.5 miles downstream at DR 133.50.

Because regression analysis has shown stream flow in the Deschutes River below North Canal Dam to explain only a small proportion of the variation in stream temperature at DR 160.25 upstream of the confluence with Tumalo Creek, we include a third regression, of stream temperature data from DR 160.00 on the Deschutes downstream of Tumalo Creek and stream flow from OWRD gage #14073520, Tumalo Creek Below Tumalo Feed Canal, to evaluate the relationship between stream flow in Tumalo Creek downstream of the diversion and in the Deschutes River immediately downstream of the confluence, and as an alternative approach to estimate stream temperature at DR 160.00 below the confluence.

We restricted data included in the analysis to one month of the year to reduce the effect of intra-annual seasonal variation in the analysis (Helsel & Hirsch, 1991) and selected July as the historically hottest month for water temperatures in the Deschutes River, and the month during which stream flow restoration will most improve stream conditions (UDWC unpublished data). For each site, we included all July dates for which stream temperature and stream flow data were available. We used R open source statistical software (R Core Team, 2020) to perform linear, quadratic, and cubic regressions for each site, using the 7DADM stream temperature with each of two flow metrics (average daily flow and the natural logarithm of average daily flow), for a total of six models (Table 3), to evaluate which metrics and models provided the best model fit. In previous years we had also evaluated the daily maximum stream temperature with each flow metric but because regression models using the 7DADM stream temperature consistently performed better than models using the daily maximum stream temperature, we did not evaluate the latter models for this report.

**Table 3.** Twelve regression models evaluated for the Deschutes River at DR 160.25, Tumalo Creek at TC 000.25, and for the Deschutes River at DR 160.00 with flow from Tumalo Creek below the diversion.

| Regression Model |
|---|
| 1. 7DADM ~ Flow |
| 2. 7DADM ~ Flow + $(\text{Flow})^2$ |
| 3. 7DADM ~ Flow + $(\text{Flow})^2$ + $(\text{Flow})^3$ |
| 4. 7DADM ~ LnFlow |
| 5. 7DADM ~ LnFlow + $(\text{LnFlow})^2$ |
| 6. 7DADM ~ LnFlow + $(\text{LnFlow})^2$ + $(\text{LnFlow})^3$ |

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, and plotted regression data with the selected model and prediction intervals for each of the three sites evaluated.

Using the best regression model for each site, we used R to calculate the predicted temperature and 95% prediction interval for all flows within the observed range (**Appendix A**). 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 $1\text{-}\alpha/2^{th}$ percentile of a T distribution with n-2 degrees of freedom.

To calculate Deschutes River temperatures downstream of the confluence with Tumalo Creek under a variety of flow scenarios we used predicted temperatures for each flow for the two sites in a mass balance equation. We used the following mass balance equation solved for $T_{D2}$:

$$(Q_T * T_T) + (Q_D * T_D) = (Q_T + Q_D) * (T_{D2})$$

$$(T_{D2}) = ((Q_T * T_T) + (Q_D * T_D)) / (Q_T + Q_D)$$

Where:

Q = average daily flow
T = 7DADM temperature
$_T$ = Tumulo Creek (TC 000.25)
$_D$ = Deschutes River (DR 160.25)
$_{D2}$ = Deschutes River (DR 160.00)

We calculated stream temperatures for all Tumalo Creek flows between 10 and 100 cfs at Deschutes River flows of 122, 127, 150, 175, and 200. Ten cfs approximates minimum July flows in Tumalo Creek; 100 cfs exceeds average natural July flows and is well above the ODFW instream water right of 32 cfs. One hundred and twenty-seven cfs approximates the median flow protected instream in the middle Deschutes in July 2019, and 127 cfs approximates the median of average daily flows recorded in the middle Deschutes in July 2019.

We compared temperatures calculated from the best regression model and from the mass balance equation to Heat Source model scenarios for the same locations on the Deschutes River and Tumalo Creek (Watershed Sciences 2008). Heat Source results report the peak seven-day average daily maximum temperature; we compared mass balance equation results to the mean seven day average daily maximum temperature, calculated from Heat Source temperature data. Heat Source temperature data for the Deschutes and for Tumalo Creek included daily maximum temperatures from July 19 to August 7, 2001.

# 3 Results

## 3.1 Stream Flow Status and Trend

July and August median average daily flow in Tumalo Creek and the Deschutes River has increased with median protected flow (Figure 3). Stream flow restoration efforts in the middle Deschutes River began in 2001; data documenting flows protected instream are available for the middle Deschutes River for July from 2003 to 2019 and for August from 2002 to 2019, and for Tumalo Creek for July from 2006 to 2019 and for August from 2005 to 2019.

July and August median stream flow in the Deschutes River at North Canal Dam more than tripled from 2002 to 2012, from 47 cfs in both months to 158 cfs in July and 151 cfs in August, alongside increases in protected flow (Figure 3). Protected flow dropped sharply from 2012 to 2013, from 160 cfs to 126 cfs in July and from 163 cfs to 134 cfs in August, with an accompanying decrease in observed flow, reflecting reductions in flow leased instream and less flow left instream by irrigation districts under a voluntary agreement. Since 2013 protected flows have fluctuated between 126 and 134 in July and between 129 and 136 in August; observed flows closely track protected flows. In 2018 132 cfs were protected in July and in August; in 2019 127 cfs were protected in July and in August. Median flows in July and August 2018 were 135 cfs and 133 cfs, respectively, up to ten cfs higher than the 2017 July and August medians of 128 cfs and 123 cfs, and equivalent to the 134-136 cfs July and 130-134 cfs August medians from

2014-2016. In 2019 median flows in July and August fell to 2017 and pre-2009 levels at 122 cfs in July and 123 cfs in August. Whereas from 2013 to 2016 July and August median streamflow in the middle Deschutes approximated 2009 levels, in two of the last three years median July and August flows have been lower than any median for these months recorded since 2009.

July and August median average daily stream flow in Tumalo Creek is equivalent to or exceeds flow rates protected instream in most years. July median average daily flow in the creek increased from 5 cfs in 2001 to a high of 58 cfs in 2012, hovering between 12 and 15 cfs in most years; August median average daily flow increased from 6 cfs in 2001 to a new high of 21 cfs in 2019, exceeding flow protected instream (Figure 3). July and August senior water rights protected instream with pre-1961 priority dates that are reliably served ranged from 7 cfs in 2005 to a new high of 17.3 cfs in 2019. Up to an additional 7.8 cfs in July and 6.3 cfs in August of protected 1961 water rights may be left instream in years when the amount of flow above the TID diversion is greater than the sum of all rights senior to 1961. In 2018 July and August median flows were 16 cfs and 15 cfs, respectively, in both months within one cfs of the flow protected instream; in 2019 July and August median flows were 24 and 21 cfs, in both months several cfs higher than the 17.3 cfs protected instream.

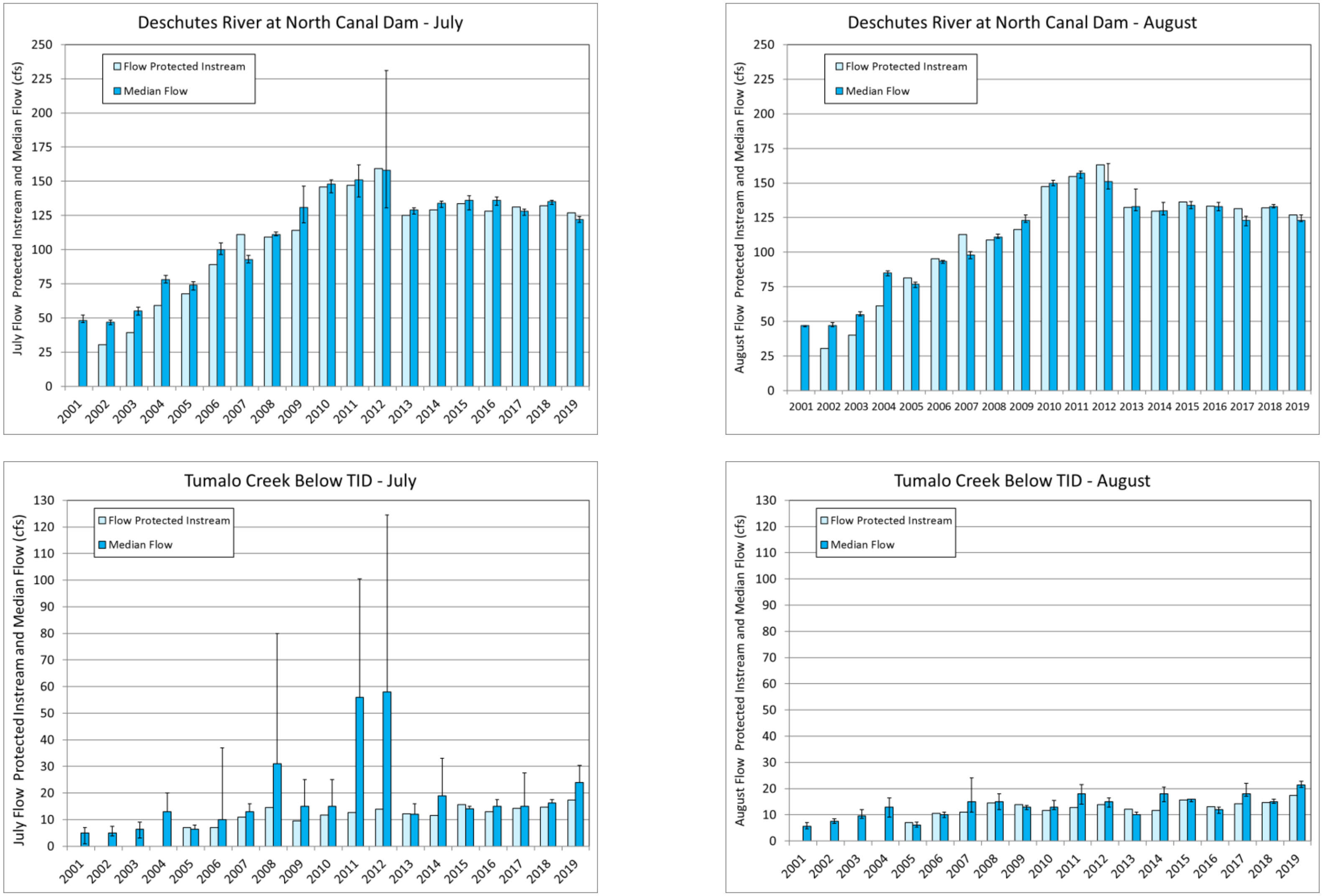



**Figure 3.** Deschutes River and Tumalo Creek July median protected and recorded flow in July and August, 2001-2019.

July and August median Deschutes River flows steadily increased from 2001 to 2012, corresponding to increases in flow protected instream. July and August median Deschutes River flows fell in 2013, reflecting reductions in both flow leased instream and flow left instream by irrigation districts under a voluntary agreement. 2019 marked a new high July and August median protected flow in Tumalo Creek, at 17.3 cfs.

## 3.2 Stream Temperature

### *3.2.1 Data Quality*

Field audits of dataloggers prescribed by UDWC's QAPP and SOP provide quality control data to evaluate the precision of temperatures recorded by dataloggers. UDWC uses a NIST thermometer certified annually by DEQ to measure stream temperature at each datalogger location and records the date and time of the NIST stream temperature measurement. Following download of continuous temperature data from the datalogger, the resulting field audit temperature is compared to the temperature recorded by the datalogger on the same date and at the time closest to the time of the audit. Data for which the field audit measurement is within half a degree (0.5°C) of the datalogger temperature record receives an "A" grade; data for which the field audit measurement is within 2 degrees (2.0°C) of the datalogger temperature record receives a "B" grade; and data for which there is a difference of more than two degrees between the field audit measurement and the datalogger record receives a "C" grade. The "C" grade is applicable to the data from the date of the audit until a subsequent audit provides a "B" or "A" grade.

Audit temperatures resulting in a "C" grade introduce uncertainty regarding the quality of the stream temperature data recorded by the datalogger. Discrepancies between the audit temperature and the datalogger temperature can result from not allowing sufficient time for the datalogger to cool to stream temperature before recording an audit temperature during deployment; from the timing of the audit measurement relative to the hour, on which the datalogger records temperature; from the datalogger being out of the water during the audit (to visually confirm that it is logging) on the hour when it records the temperature; or from incorrectly recording the date and/or time of the audit.

Stream temperatures recorded during multiple field audits of dataloggers deployed at Deschutes River temperature monitoring sites in 2019 resulted in a "C" grade for the audit (Table 4). For DR 133.50 and DR 160.25, where two dataloggers were deployed, we compared stream temperatures recorded by the two dataloggers at, before, and after the time of the audit. For all four sites for which field audits received "C" grades, we reviewed pre- and post-deployment accuracy datalogger audit values and grades. Temperatures recorded by the two dataloggers at DR 133.50 and at DR 160.25 were within 0.3°C of each other over seven days including three days before and three days after audits receiving a "C". All dataloggers for which a field audit resulted in a "C" grade received "A" grades in pre- and post-deployment accuracy audits, with the exception of one datalogger deployed at DR 133.50 which received "B" grades for the post-deployment audit. Based on these data, it seems highly likely that in most or all cases audit measurements resulting in a "C" grade reflect operator error during the audit rather than a true lack of precision in temperatures recorded by dataloggers. Data receiving a "C" grade in 2019 were used to evaluate stream temperature status and trend (Figure 4, Figure 5), but they were not used to evaluate July and August temperatures at Lower Bridge Road (Figure 6) nor in regression analyses (Figure 7).

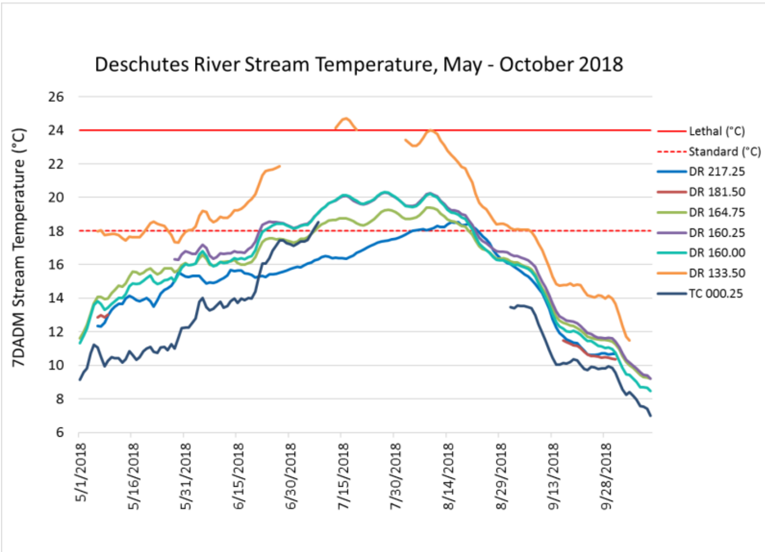
**Table 4.** Deschutes River temperature monitoring sites and dates for which field audit "C" grades are applicable

| Site | Dates for which a field audit "C" grade are applicable |
|---|---|
| DR 133.50 | 5/23/2019 - 6/16/2019 |
| | 9/25/2019 - 10/2/2019 |
| DR 160.25* | 8/26/2019 - 10/14/2019 |
| DR 181.50 | 5/9/2019 - 5/22/2019 |
| DR 217.25 | 5/9/2019 - 5/22/2019 |
| | 7/12/2019 - 8/26/2019 |

* One of two loggers

### *3.2.2 Status and Trend*

Seven-day moving average maximum (7DADM) temperatures exceeded the 18°C state standard for trout and salmon rearing and migration on the middle Deschutes River and Tumalo Creek in 2018 and 2019 at at least one monitoring location on the upper Deschutes River between Wickiup Reservoir and Bend, at the four Deschutes River monitoring locations downstream of North Canal Dam, and on Tumalo Creek at the mouth. Temperatures exceeded the state standard by over 6°C (Figure 4), supporting the existing State of Oregon Section 303(d) listing of the middle and upper Deschutes River for temperature impairment. Temperatures at the four Deschutes River sites downstream of Bend have exceeded the state standard in every year for which data are available for analysis, and exceeded the state standard on Tumalo Creek at the mouth in all but two years for which data are available for analysis. Stream temperature exceeded 18°C in 2018 and 2019 at DR 217.25. Although only very limited temperature data are available from DR 181.50 in 2018 and 2019 (in 2018 due to the datalogger going missing and in 2019 due to the datalogger failing while deployed), given temperatures at DR 217.25 exceeding 18°C in both of these years, it is very likely that temperatures also exceeded 18°C at DR 181.50, almost 36 miles downstream, for an equivalent duration or longer. Prior to 2018 the 7DADM stream temperature had not exceeded 18°C at either DR 217.25 or DR 181.50 since 2009 with the exception of three days in 2015 at DR 181.50.



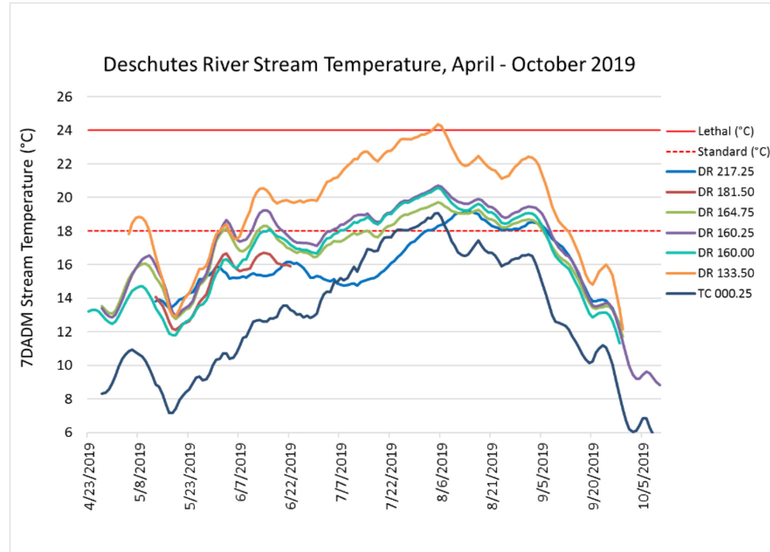




**Figure 4.** Deschutes River and Tumalo Creek temperatures May-October 2018 and April-October 2019

Temperatures exceeded the 18°C State of Oregon temperature standard (dashed red line) at five monitoring sites on the Deschutes River in 2018 and 2019, from DR 133.50 at Lower Bridge to DR 217.25 at Pringle Falls, as well as in Tumalo Creek just upstream of the mouth, at TC 000.25. Data are not available for DR 181.50 at Benham Falls in either year, but temperatures exceeding 18°C at Pringle Falls suggest they were likely also above the standard at DR 181.50. In both years, temperatures exceeded 20°C at three sites downstream of North Canal Dam and exceeded 24°C at DR 133.50.

Percent of data days exceeding 18°C between April 30 and September 21, the dates during which stream temperatures have historically exceeded 18°C in the middle Deschutes River downstream of Bend, represents the amount of time during which stream conditions are likely limiting for rearing trout in this reach; conversely, the percent of days meeting 18°C represents the amount of time during which stream conditions are optimal to support rearing fish. Temperatures downstream of Bend exceeded 18°C for 31-79% of days between April 30 and September 21 in 2018 and for 38-75% of days between April 30 and September 21 in 2019 (Table 5, Figure 5) and conversely met the 18°C standard for 21-69% of those days in 2018 and 25-62% of those days in 2019.

At DR 133.50, temperatures were 18°C or below for only 21% (31 days) and 25% (36 days) of data days in 2018 and 2019, respectively, the lowest number of days meeting the standard in any year except 2001, and half the number of days during which stream temperatures met the state standard in 2017. Despite the high number of days exceeding 18°C in 2018 and 2019, stream temperatures exceeded 24°C (the lethal threshold for trout rearing; ODEQ 1995) for 6% (8) and 2% (3) of those days in 2018 and 2019 respectively, from July 13-19 in 2018 and from August 4-6 in 2019. Six percent of days exceeding 24°C in 2018 represents the third-highest number of days exceeding 24°C in the six years between 2013 and 2018; 2% of days is the second-lowest number exceeding 24°C in the seven years between 2013 and 2019. Stream temperatures exceeding 24°C in almost every year since 2013 are coincident with the 2013 drop in flows protected in the middle Deschutes.[1]

Temperatures at DR 160.00, downstream of the confluence with Tumalo Creek, exceeded 18°C for 41% (60) and 43% (62) of data days in 2018 and 2019 respectively, an equivalent or higher number than in all but one year (2015) since 2005. Temperatures met the temperature standard at this site for 59% (85) and 57% (83) of data days in these two years. Stream temperature at DR 160.00 exceeded 18°C from June 23 to August 21 in 2018, at flows of 143 to 178 cfs (129-157 cfs from the Deschutes and 14-19 cfs from Tumalo Creek). In 2019 stream temperature at DR 160.00 exceeded 18°C from July 7 to September 5, at flows of 138 to 172 cfs (119-150 cfs from the Deschutes and 19-22 cfs from Tumalo Creek).

Temperatures at DR 160.25 met the standard for 58% (84) and 47% (68) of data days in 2018 and 2019 respectively. Fifty-eight percent of days meeting the standard in 2018 represents the highest percent meeting the standard of the four years from 2015-2018, but a lower percent than in the ten years of data from 2004 to 2014 (data for 2006 are not available). Forty-seven percent of days meeting the standard in 2019 represents the lowest percent of days meeting the standard at this site in any year for which data are available except in 2003. Temperatures at DR 164.75, immediately downstream of North Canal Dam, met the standard for 69% (100) of data days in 2018, fewer days than in any other year for

[1] Although no recorded stream temperatures exceeded 24°C in 2015, data for DR 133.50 in 2015 were missing and extrapolated for 48 days between June 20 and August 21. Insufficient data were available to extrapolate with confidence if or for how many days stream temperatures exceeded 24°C during that period, although based on stream temperatures at DR 160.00, temperatures at DR 133.50 almost certainly exceeded the 24°C lethal threshold in 2015.

which data are available except 2004 and 2017, and met the standard for 62% (90) of data days in 2019, fewer than in any year except 2017.

Temperature data from TC 000.25, at the mouth of Tumalo Creek, are available from April 1 to July 8 and from September 1 to October 31, 2018. Data are missing for this site from July 9 to August 31 during the hottest weeks of summer. The 7DADM stream temperature exceeded 18°C on the last two July days (1% of days from April 30-September 21) for which data are available from this site and year. Based on the increasing trend of 7DADM temperatures at TC 000.25 through July 8, and the continued increasing trend of 7DADM temperatures at all four Deschutes River sites downstream of Bend through July 15, we conservatively extrapolated an additional seven days (5% of days April 30 – September 21) to have been above 18°C at TC 000.25 in 2018. Although it's very likely the 7DADM temperature at TC 000.25 exceeded 18°C in 2018 for more days than are represented, given the available data and because temperatures at the mouth of Tumalo Creek are not directly influenced by temperatures at sites on the Deschutes, it's not possible to determine with confidence how many more days exceeded 18°C at this site in 2018.

Stream temperature at the mouth of Tumalo Creek exceeded the 18°C state temperature standard for 10% of days and met the standard for 90% of days between April 30 and September 21 in 2019. Temperatures in Tumalo Creek have exceeded 18°C for between 0 and 19% of days April 30 through September 21 since 2006, meeting the criteria for 81-100% of days April 30 through September 21 during these years[2]; in 2004, the earliest year for which data are available for this site, stream temperatures exceeded 18°C for 27% of days April 30 through September 21 and met the standard for only 73% of days during this date range, and in 2005 temperatures exceeded 18°C for 35% of days April 30 through September 21 and met the standard for only 65% of days.

[2] These data correct the 2017 report, where we stated that temperatures in Tumalo Creek had exceeded 18°C for between 0 and 19% of days April 30 through September 21 since 2005.

**Table 5.** Percent of days between April 21 and September 30 meeting the state temperature standard for salmon and steelhead rearing and migration (≤ 18°C) and exceeding the standard (> 18°C) from 2001 to 2019 at four Deschutes River sites and one Tumalo Creek site downstream of the City of Bend.

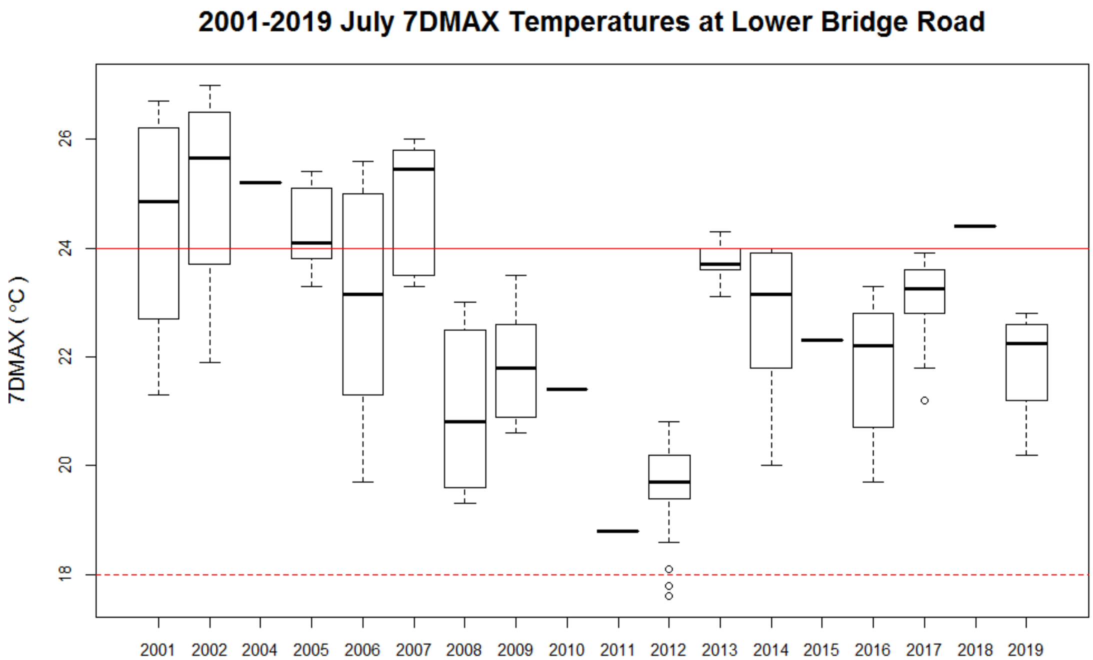
| | DR 164.75 | | DR 160.25 | | DR 160.00 | | DR 133.50 | | TC 000.25 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | % Days ≤ 18°C | % Days > 18°C | % Days ≤ 18°C | % Days > 18°C | % Days ≤ 18°C | % Days > 18°C | % Days ≤ 18°C | % Days > 18°C | % Days ≤ 18°C | % Days > 18°C |
| 2001 | | | | | | | 12% | 88% | | |
| 2002 | | | 55% | 45% | | | 30% | 70% | | |
| 2003 | | | 39% | 61% | | | 0% | 0% | | |
| 2004 | 65% | 35% | 62% | 38% | | | 57% | 43% | 0.73 | 0.27 |
| 2005 | 72% | 28% | 61% | 39% | 60% | 40% | 29% | 71% | 0.65 | 0.35 |
| 2006 | | | | | 68% | 32% | 37% | 63% | 0.86 | 0.14 |
| 2007 | 70% | 30% | 65% | 26% | 62% | 38% | 29% | 71% | 0.81 | 0.19 |
| 2008 | 76% | 24% | 61% | 39% | 76% | 24% | 39% | 61% | | |
| 2009 | 76% | 24% | 64% | 36% | 64% | 36% | 39% | 61% | 0.87 | 0.13 |
| 2010 | 70% | 30% | 65% | 35% | 70% | 30% | 53% | 47% | 0.88 | 0.12 |
| 2011 | 83% | 17% | 69% | 31% | 80% | 20% | 60% | 40% | 1.00 | 0.00 |
| 2012 | 77% | 23% | 62% | 38% | 80% | 20% | 52% | 48% | 1.00 | 0.00 |
| 2013 | 79% | 21% | 66% | 34% | 68% | 32% | 30% | 70% | 0.82 | 0.18 |
| 2014 | 77% | 23% | 65% | 35% | 70% | 30% | 38% | 62% | 0.91 | 0.09 |
| 2015 | 78% | 22% | 50% | 50% | 49% | 51% | 29% | 71% | 0.90 | 0.10 |
| 2016 | 72% | 28% | 54% | 46% | 59% | 41% | 48% | 52% | 0.85 | 0.15 |
| 2017 | 61% | 39% | 55% | 45% | 68% | 32% | 41% | 59% | 0.87 | 0.13 |
| 2018 | 69% | 31% | 58% | 42% | 59% | 41% | 21% | 79% | 0.94 | 0.06 |
| 2019 | 62% | 38% | 47% | 53% | 57% | 43% | 25% | 75% | 0.90 | 0.10 |


**Figure 5.** Percent of data days meeting and exceeding 18°C, 2001-2019.
Stream temperature in the Deschutes River downstream of Bend exceeded 18°C for 31-79% of days between April 30 and September 21 in 2018 and for 38-75% of days between April 30 and September 21 in 2019. The percent of days meeting the stream temperature standard in 2018 and 2019 at all four sites downstream of Bend are among the lowest on record. Stream temperature in Tumalo Creek at the mouth met the 18°C standard for 90% of days in 2019 and for an estimated 6% of days in 2018.

July stream temperatures in the middle Deschutes River downstream of Bend from 2013 to 2019 are far lower and exceed 24°C far less frequently than from 2001 to 2007 (Figure 6). But, median July temperatures from 2013 to 2019 are on average over two degrees warmer than from 2008 to 2012, and in some years since 2013, July and August temperatures have exceeded 24°C, which they did not from 2008 to 2012. Thus, although some sustained progress has been made in reducing stream temperatures, since 2013 stream temperature conditions have deteriorated from the significant gains made between 2008 and 2012.

The 7DADM stream temperature exceeded the lethal 24°C threshold in both July and August 2018, and the median temperature for both months was higher than in any year since 2012. Stream temperature data were incomplete for July 2018. The 7DADM stream temperature exceeded 24°C in July but not in August 2019; the July median 7DADM temperature was lower in 2019 than in any year since 2012 except 2016, while the August median 7DADM temperature was roughly equivalent to the median temperature in 2013, 2016, and 2018, and, interestingly, lower than in 2012. July and August data from DR 133.50 show a consistent decreasing trend in median, maximum and minimum 7DADM stream temperatures from 2001 to 2019.

a




b

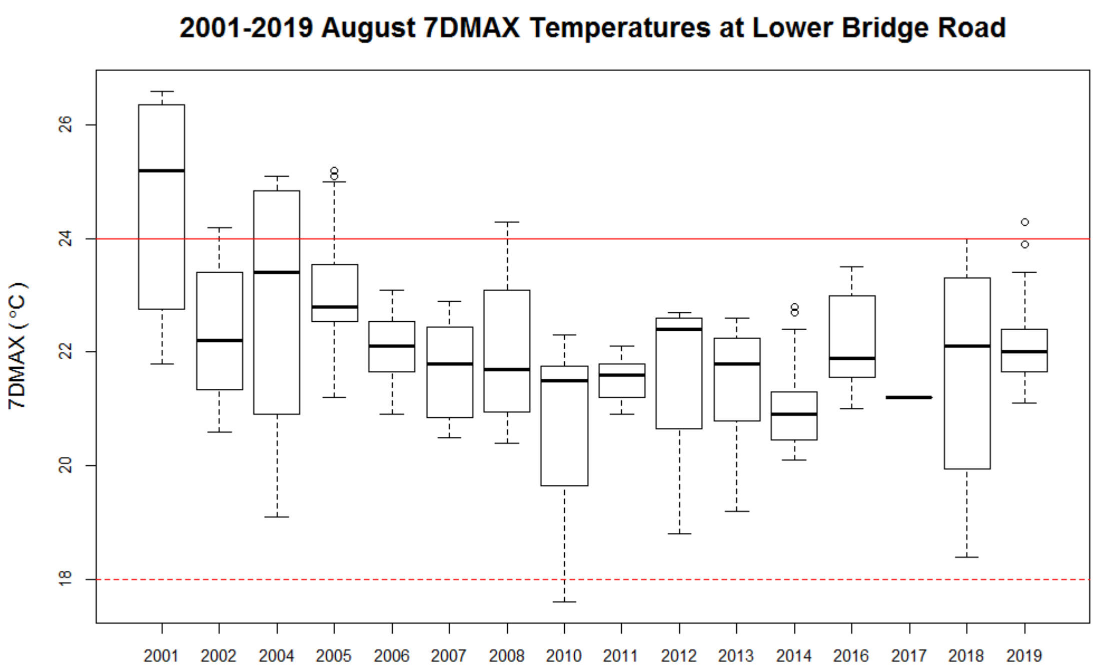



**Figure 6.** 2001-2019 July and August 7DADM temperatures at Lower Bridge
a) July 1-22 and b) August 6-28 7DADM temperatures at Lower Bridge (DR 133.50) chart a declining trend since 2001. Years for which data are not available are not represented; for years for which some data are available, the median of available values is shown. Despite reductions of approximately 2-4°C between 2001 and 2019, temperatures at Lower Bridge remain well above the 18°C standard (dashed red line) throughout July and August.

## 3.3 Effect of Stream Flow on Stream Temperature

Multiple lines of evidence show reduced stream temperatures at higher stream flows achieved through stream flow restoration in the middle Deschutes River and Tumalo Creek. This relationship is strongest in July but is also evident in August. As July median flows in the middle Deschutes and in Tumalo Creek increased from 2001-2012, July and August stream temperatures decreased (Figure 3, Figure 6). July stream temperatures spiked with the 2013 drop in middle Deschutes River stream flow and have come down somewhat as flows have crept up from 2013 levels. August stream temperatures also dropped through 2010 and have fluctuated since. Regressions of mean July 7DADM temperatures and corresponding flow values from 2001-2017 at DR 160.25 and at TC 000.25 show temperatures decreasing as flows increase (Figure 7).

The regression for each site represents a range of flows for each year that reflect July flows resulting in part from stream flow restoration. The range of flows annually for which temperature data are available between 2002 and 2019 increased from a low of 41 cfs and a high of 51 cfs in 2002 to a low of 100 cfs and high of 327 cfs in 2011 in the Deschutes at North Canal Dam; in Tumalo Creek, flows included in regressions increased from a low of 3.3 cfs and high of 37 cfs in 2004 to a low of 11 and high of 177 cfs in 2008.[3] Stream flow explained 29% of the variation in stream temperature at DR 160.25 ($R^2$ = 0.29), 76% of the variation in stream temperature at TC 000.25 ($R^2$ = 0.76), and 56% of the variation in stream temperature at DR 160.00 ($R^2$ = 0.56) in July, providing further support for increases in July stream flow contributing to reduced stream temperatures.

Increasing flows in the Deschutes River versus Tumalo Creek resulted in dramatically different estimated reductions in stream temperature. At DR 160.25, where increased flows reduce warming rather than actively cooling stream temperature, and the distance over which to reduce warming is relatively short (< 5 mi from North Canal Dam), modest reductions in predicted temperature were observed as flows increased. A flow rate of 41 cfs from the Deschutes River at North Canal Dam (the lowest flow included in the analysis) resulted in a predicted 7DADM temperature of 20.7°C ± 1.5°C (upper interval = 22.2°C) at DR 160.25, approximately five miles downstream; flows between 233 and 308 cfs resulted in a mean temperature *only 2.2°C lower*, at 18.4°C ± 1.5°C (upper interval = 19.9°C). In Tumalo Creek, a smaller-volume system which flows directly from its headwaters with no impoundment or associated warming, proportionally greater increases in colder stream flow have a greater effect on temperature: for the purpose of illustration, the lowest flow included in the analysis, 3.3 cfs, resulted in a mean temperature of 20.6°C ± 2.7°C (upper interval = 23.3°C), with flows between 106 and 132 cfs resulting in the lowest mean temperature of 11.4 ± 2.7°C (upper interval=14.1°C), a temperature reduction of more than 9°C. Increasing flows in Tumalo Creek also reduced stream temperature in the Deschutes below the confluence with Tumalo, at DR 160.00, more dramatically than the effect of flow at North Canal Dam observed at DR 160.25 but less so than the effect of flow below the TID diversion in Tumalo Creek on temperatures at the mouth. At 3.3 cfs in Tumalo Creek the 7DADM temperature at DR 160.00 is predicted to be 20.1 ± 1.8°C (upper interval = 21.9°C); flows in Tumalo Creek between 127 and 154 are

[3] Temperature data were not available for the dates on which 177 cfs was recorded on Tumalo Creek below the TID diversion (July 1, 2008) and accordingly this flow value is not included in the regression.

predicted to result in a 7DADM temperature at DR 160.00 almost 4°C lower at 16.2 ± 1.8°C (upper interval = 18°C).

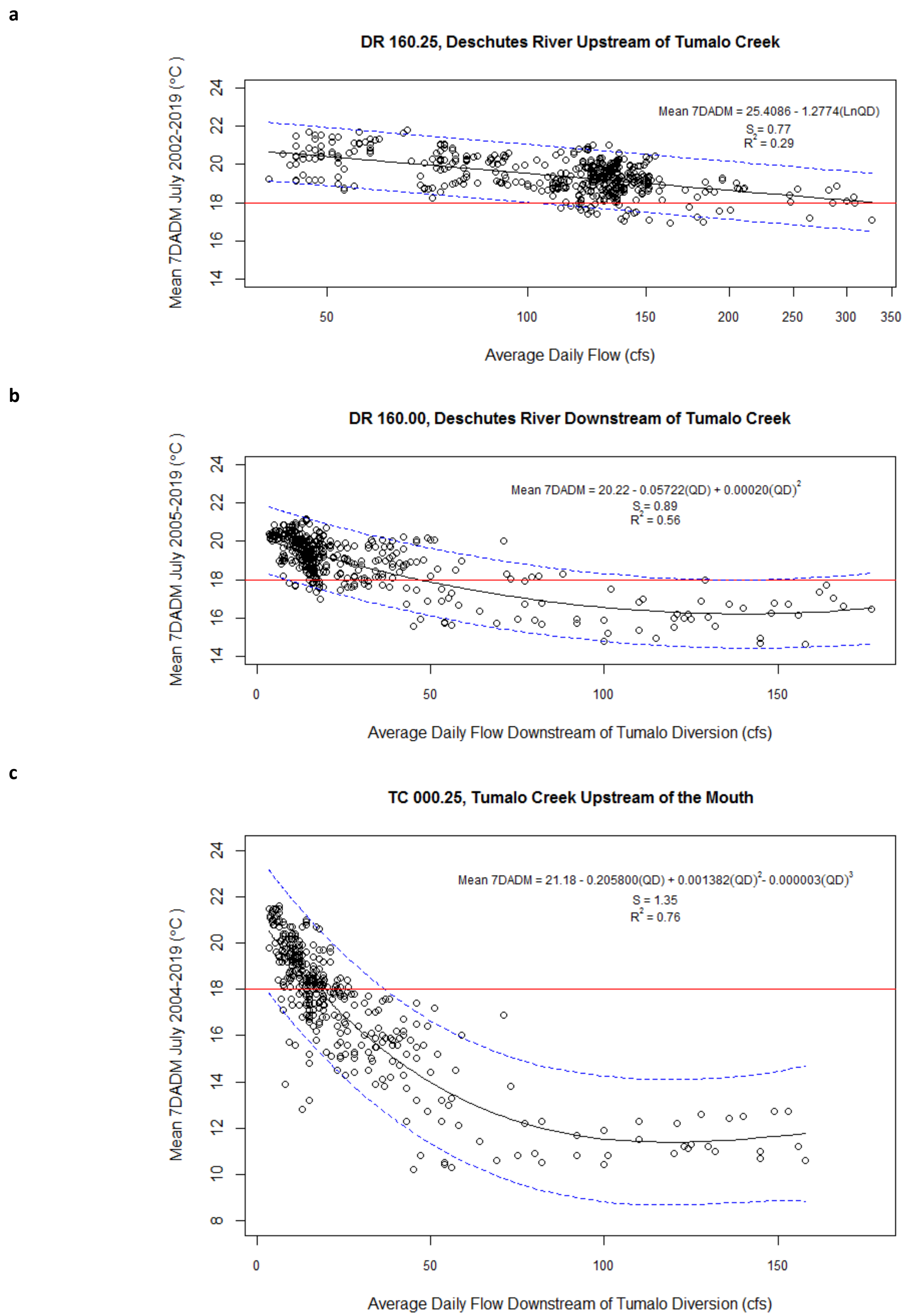



**Figure 7.** Temperature-flow regression models.
Regression models fitted to temperature-flow data demonstrate lower temperatures at higher flows and describe the relationship between temperature at a) DR 160.25 upstream of the confluence with Tumalo Creek and flow at North Canal Dam from July 2002-2019, b) DR 160.00 downstream of the confluence with Tumalo Creek and flow in Tumalo Creek downstream of the diversion from July 2005-2019, and c) TC 000.25, Tumalo Creek upstream of the mouth and flow in Tumalo Creek downstream of the diversion from July 2004-2019.

## 3.4 Target Stream Flow

Temperature records were available from DR 160.25 for July dates from 2002-2019 at Deschutes River flows between 41 and 308 cfs, from TC 000.25 for July dates from 2004-2019 at Tumalo Creek flows between 3.5 and 158 cfs, and from DR 160.00 from 2005-2019 at Tumalo Creek flows between 3.5 and 158 cfs. The linear regression of the 7DADM stream temperature on the natural logarithm of the average daily flow (7DADM ~ LnFlow) performed best of the six regression models for DR 160.25; this model demonstrates the relatively small influence of the amount of Deschutes River flow on stream temperature at this site in July, explaining only 29% of the variation in stream temperature ($R^2 = 0.29$; Table 4). For DR 160.00 July stream temperature and flow from OWRD gage #14073520 on Tumalo Creek below the diversion, the quadratic regression of the 7DADM stream temperature on the average daily flow (7DADM ~ Flow + $(Flow)^2$) performed best of the six models for this site and explained 56% of the variation in stream temperature ($R^2 = 0.56$). For TC 000.25 stream temperature and flow data, the cubic regression of the 7DADM stream temperature on average daily flow (7DADM ~ Flow + $(Flow)^2$ + $(Flow)^3$) performed best of the six models. Stream flow explained 76% of the variation in stream temperature at the mouth of Tumalo Creek in July ($R^2 = 0.76$). Residuals for the best performing model for each site were approximately normally distributed. We used the resulting equations to calculate predicted temperatures for the range of flows on which regressions were trained for the three sites (Appendix A).

**Table 5.** The best three regression models for predicting stream temperature for July at DR 160.25, DR 160.00, and TC 000.25.

| Regression Model | Intercept | Coefficient 1 | Coefficient 2 | Coefficient 3 | n | df | $R^2$ | S | AIC value |
|---|---|---|---|---|---|---|---|---|---|
| DR 160.25 | | | | | | | | | |
| **7DADM ~ LnFlow** | **25.41** | **-1.27740** | **--** | **--** | **500** | **498** | **0.29** | **0.77** | **-259** |
| 7DADM ~ LnFlow + $(\text{LnFlow})^2$ | 22.33348 | 0.07762 | -0.14809 | -- | 500 | 497 | 0.29 | 0.77 | -258 |
| 7DADM ~ Flow + $(\text{Flow})^2$ | 21.2 | -0.01943 | 0.00003 | -- | 500 | 497 | 0.29 | 0.77 | -257 |
| | | | | | | | | | |
| DR 160.00 | | | | | | | | | |
| **7DADM ~ Flow + $(\text{Flow})^2$** | **20.22** | **-0.05722** | **0.00** | **--** | **424** | **421** | **0.56** | **0.89** | **-95** |
| 7DADM ~ Flow + $(\text{Flow})^2$ + $(\text{Flow})^3$ | 20.15 | -0.05043 | 0.00008218 | 0.00 | 424 | 420 | 0.56 | 0.89 | -94 |
| 7DADM ~ LnFlow + $(\text{LnFlow})^2$ | 20.6 | 0.07466 | -0.19249 | -- | 424 | 421 | 0.56 | 0.89 | -94 |
| | | | | | | | | | |
| TC 000.25 | | | | | | | | | |
| **7DADM ~ Flow + $(\text{Flow})^2$ + $(\text{Flow})^3$** | **21.1800** | **-0.2058** | **0.001382** | **-0.00000289** | **376** | **372** | **0.76** | **1.35** | **228** |
| 7DADM ~ Flow + $(\text{Flow})^2$ | 20.89 | -0.1770 | 0.001 | -- | 376 | 373 | 0.76 | 1.35 | 230 |
| 7DADM ~ LnFlow + $(\text{LnFlow})^2$ + $(\text{LnFlow})^3$ | 18.5708 | 3.87834 | -1.94099 | 0.17156 | 376 | 372 | 0.75 | 1.36 | 237 |

Predicted temperatures calculated for six Deschutes River flow scenarios illustrate dramatic temperature reductions in the Deschutes River below the confluence with Tumalo Creek (DR 160.00) as flows in Tumalo increased (Appendix B). At the July 2019 median protected flow of 127 cfs, 43 cfs in Tumalo Creek was estimated to achieve the state temperature standard of 18°C ± 1.9°C on average in the Deschutes River immediately downstream of the confluence with Tumalo Creek (at the observed July 2019 median middle Deschutes River flow of 122 cfs, the same temperature and prediction interval were predicted for 44 cfs in Tumalo Creek). If Tumalo Creek flows were further increased to 50 cfs, the average 7DADM temperature in the Deschutes River below the confluence with Tumalo Creek would be reduced to 17.7°C ± 1.9°C at both the July 2019 median protected and observed Deschutes River flows of 127 and 122 cfs, respectively. Increasing Deschutes River flows from the 2019 protected flow of 127 cfs to the instream flow target of 250 cfs was estimated to achieve an additional 0.8°C reduction in stream temperature at the 2019 protected Tumalo Creek flow of 17 cfs, a 0.4°C reduction in stream temperature at 32 cfs in Tumalo Creek and a 0.2°C reduction in stream temperature at 43 cfs in Tumalo Creek. At 50 cfs in Tumalo Creek stream temperature in the Deschutes downstream of the confluence was estimated to be approximately equivalent (within 0.1°C) at 127 or at 250 cfs in the Deschutes (Table 5), highlighting the significant reductions in stream temperature that can be achieved in the middle Deschutes River by prioritizing stream flow restoration in Tumalo Creek over stream flow restoration at North Canal Dam.

**Table 6.** Estimated Deschutes River stream temperatures at four Tumalo Creek flows and two Deschutes River flows**.** Seventeen (17) and 127 cfs in Tumalo Creek and the Deschutes River, respectively, represent flows protected instream in 2019. Forty-three cfs represents the flow needed in Tumalo to meet 18**°**C downstream of the confluence with the Deschutes at the 127 cfs currently protected in the Deschutes.

| Tumalo Creek Stream Flow (cfs) | Deschutes River Stream Flow (cfs) | Estimated 7DADM Stream Temperature (°C) | Deschutes River Stream Flow (cfs) | Estimated 7DADM Stream Temperature (°C) |
|---|---|---|---|---|
| 17 | 127 | 19.1°C ± 1.7°C | 250 | 18.3°C ± 1.6°C |
| 32 | 127 | 18.5°C ± 1.8°C | 250 | 18.1°C ± 1.7°C |
| 43 | 127 | 18.0°C ± 1.9°C | 250 | 17.8°C ± 1.7°C |
| 50 | 127 | 17.7°C ± 1.9°C | 250 | 17.6°C ± 1.7°C |

Whereas increasing stream flow in Tumalo Creek from the July 2019 protected flow of 17 cfs to 50 cfs was estimated to achieve large reductions in stream temperature, simultaneously increasing Deschutes River stream flow conferred small additional reductions in stream temperature that diminished as Tumalo Creek flows approached 50 cfs. From 55 to 58 cfs in Tumalo Creek, increasing Deschutes River flow from 127 to 250 cfs had no effect on temperature. Above 58 cfs in Tumalo Creek, adding stream flow in the Deschutes River was predicted to result in higher stream temperatures in the Deschutes than at the lower Deschutes River flow.

At benchmark, achievable Tumalo Creek flows, 7DADM stream temperatures calculated using the DR 160.00 ~ Tumalo Creek flow regression model were slightly higher than, and within 0.2°C of, those calculated using the mass balance equation (Table 6, Appendix C). At the lowest flows and at higher flows the difference in 7DADM calculated using the two approaches increases, with a half-degree or greater difference at 10 cfs and at and above 72 cfs.

**Table 7.** Comparison of stream temperatures at DR 160.00 below the confluence of Tumalo Creek and the Deschutes River calculated using a mass balance equation and a regression equation**.**

| Tumalo Creek Stream Flow (cfs) | Deschutes River Stream Flow (cfs) | Mass Balance Estimated Stream Temperature (°C) | DR 160.00 Regression Estimated Stream Temperature (°C) |
|---|---|---|---|
| 17 | 127 | 19.1°C ± 1.7°C | 19.3°C ± 1.8°C |
| 32 | 127 | 18.5°C ± 1.8°C | 18.6°C ± 1.8°C |
| 43 | 127 | 18.0°C ± 1.9°C | 18.1°C ± 1.8°C |
| 50 | 127 | 17.7°C ± 1.9°C | 17.9°C ± 1.8°C |

The Heat Source model developed by Watershed Sciences and MaxDepth Aquatics under contract with ODEQ (Watershed Sciences and MaxDepth Aquatics 2008) simulated stream temperature from historical stream flow and temperature measurements for the Deschutes River and Tumalo Creek, and provides estimated stream temperatures against which we can compare those calculated from our regression equations. Heat Source model estimates are available for state instream water right (ODFW) flows in July for the Deschutes River (250 cfs) and for Tumalo Creek (32 cfs). The Heat Source average seven day average daily maximum (7DADM) temperature estimate for Deschutes flows of 250 cfs and Tumalo flows of 32 cfs at approximately DR 160.00 (Heat Source rkm 72.4) is 17.4°C, over half a degree lower than the mass balance temperature estimate of 18.1°C for the same flow at the same site based on our analysis. The Heat Source average 7DADM for the Deschutes at 250 cfs at approximately DR 160.25 (Heat Source rkm 72.8), above the confluence with Tumalo, was 17.2°C, over a degree lower than the 18.4°C calculated from the regression equation. The Heat Source estimate for Tumalo Creek flows of 32 cfs at approximately TC 000.25 was 15.7°C, 0.2°C lower than the 15.9°C calculated from the regression equation for that flow and site.

# 4 Discussion

## 4.1 Stream Flow Status and Trend

Stream flow in the middle Deschutes River steadily increased alongside protected flows through 2012. Since 2012 protection of additional flow in stream has stalled, returning the amount of flow protected, as well as flow recorded in stream, to pre-2010 levels. Median flow protected and observed in the middle Deschutes River in 2019 was the lowest since 2013 and 2008, respectively. The increase in 2019 to 17.3 cfs protected in Tumalo Creek marked new progress in flow protected in the tributary, up from the previous high of 15.7 in 2015, with the July 2019 median flow, at 24 cfs, even higher than the rate protected.

## 4.2 Temperature Status and Trend

Stream temperature at four locations on the middle Deschutes River downstream of Bend that met the 18°C state standard for 21-69% of days between April 30 and September 21, 2018 and for 25-62% of days between April 30 and September 21, 2019 represent optimal temperature conditions for rearing salmon and trout. Conversely, temperatures exceeding the 18°C standard for 31-79% of days between April 30 and September 21, 2018 and 38-75% of days between April 30 and September 21, 2019 represent temperature conditions that cause physiological stress for salmon and trout at those locations and may create a competitive advantage for non-native brown trout. At Lower Bridge (DR 133.50), stream temperature met the state temperature standard for a month or barely over a month between April and September in 2018 and in 2019, half the number of days during which stream temperatures met the state standard in 2017. These data represent a return to or further deterioration from 2011 to 2015 conditions following a brief recovery from 2015 to 2017.

Given July median flows of 122 cfs in the Deschutes River and 24 cfs in Tumalo Creek, temperatures above 18°C at DR 160.00 for 43% of days in 2019, including every day in July, are consistent with mass balance results which predict 44 cfs required in Tumalo Creek at 122 cfs in the Deschutes to achieve 18°C at this site, and with DR 160.00 regression results which predict 46 cfs required in Tumalo Creek to achieve 18°C at the same site.

From 2008 to 2012 no 7DADM stream temperatures 24°C or higher were recorded at Lower Bridge, coincident with higher flows during these years achieved in part through stream flow restoration. Since 2013 stream temperatures 24°C and above have been recorded at Lower Bridge in every year except 2015, when data were unavailable from June 20th to July 15th. The return to summer stream temperatures exceeding the lethal 24°C threshold corresponds to the 2013 drop in flows protected in the middle Deschutes. The percent of days in 2018 and 2019 exceeding 24°C at Lower Bridge were the highest observed since 2001. Regression analysis of stream flow, stream temperature, and air temperature data for the Deschutes (DR 160.25) and Tumalo Creek (TC 000.25) developed for the Upper Deschutes Basin Study resulted in models that incorporated both stream flow and air temperature explaining the greatest proportion of variation in stream temperature of the models run (UDWC 2016). This result indicates that air temperature, in addition to stream flow, influences stream temperature in the middle Deschutes and in Tumalo Creek. Despite similar July stream flow medians and ranges in 2009 and from 2013-2019, the proportion of days exceeding the 18°C state standard at DR 133.50 has fluctuated by up to 27%, between 52% and 79%, over those years. Differences in air temperature between years, as well as other factors such as variation in flow in earlier months or effects of solar radiation and reservoir level on the temperature of flow released from Wickiup and Crane Prairie reservoirs, could explain the wide variation in number of days exceeding the 18°C state standard at similar July flows.

## 4.3 Restoration Effectiveness

Higher stream flows resulting from stream flow restoration (water rights transferred and delivered instream) have resulted in lower stream temperatures in Tumalo Creek and in the middle Deschutes

River. July and August stream temperatures at DR 133.50 decreased with increases in July median flows in the middle Deschutes and in Tumalo Creek between 2001 and 2012. Comparison of 7DADM temperatures at DR 160.25 and TC 000.25 at the lowest and highest July flows recorded from 2002 to 2015 show lower stream temperatures have historically occurred at higher flows. Regressions of mean July 7DADM temperatures and corresponding flow values from 2001-2019 at DR 160.25, DR 160.00, and TC 000.25 also show lower temperatures occurring at higher flows.

Stream flow explained 76% of the variation in stream temperature in Tumalo Creek ($R^2$ = 0.76) and 56% of the variation in stream temperature in the Deschutes River downstream of the confluence (DR 160.00, $R^2$ = 0.56), providing support for higher protected flows in Tumalo Creek guaranteeing higher baseflows and lower stream temperatures in Tumalo Creek and in the Deschutes downstream of Tumalo Creek. But, for the Deschutes immediately upstream of the confluence with Tumalo Creek, stream flow explained only 29% of the variation in stream temperature ($R^2$ = 0.29), indicating factors other than stream flow contribute substantially to stream temperature at this site; and, whereas observed and calculated stream temperatures at DR 160.25 decrease as flows increase, stream temperature is only estimated to be 2°C lower at 250 cfs than it is at 50 cfs. Additionally, the $R^2$ value for the DR 160.25 regression equation has decreased over time with addition of more recent stream flow and temperature data, suggesting the influence of stream flow at NCD on temperature is decreasing, possibly in relation to hotter air temperatures and a changing climate. While these data suggest stream flow restoration in the middle Deschutes will have a relatively small effect on stream temperature at DR 160.25, increasing flows at North Canal Dam remains important to reduce the rate of warming downstream of Tumalo Creek and for the greater amount of aquatic habitat provided by higher flows.

## 4.4 Target Stream Flow

Mass balance equation results suggest that restoring 43 cfs in Tumalo Creek will achieve the 18°C standard in the Deschutes downstream of the confluence at a Deschutes River flow of 127 cfs below North Canal Dam, the median flow protected as of July 2019; DR 160.00 regression results indicate 46 cfs in Tumalo Creek will result in 18°C. Increasing Tumalo Creek flows to 50 cfs is estimated to reduce stream temperature in the Deschutes below the confluence to 17.7°C ± 1.9°C (or 17.9 ± 1.8°C calculated from the DR 160.00 regression equation) and allow in part for downstream warming between the confluence and Lower Bridge (DR 133.50). Achieving the 18°C standard in the Deschutes downstream of the confluence at the Tumalo Creek state instream water right of 32 cfs would require more than 250 cfs (the pending state instream water right) in the Deschutes. In light of the 2019 status of protected flows, 127 cfs in the Deschutes and 17.3 cfs in Tumalo Creek, these results suggest that achieving the desired reductions in stream temperature in the middle Deschutes River may be significantly accelerated by strategically prioritizing Tumalo Creek water transactions; preferentially increasing flows in Tumalo Creek over restoring stream flow in the Deschutes may achieve the greatest temperature benefits at the lowest cost.

Mass balance results for Tumalo Creek and Deschutes River flows immediately below the confluence of Tumalo Creek and the Deschutes, and results of the regression of DR 160.00 stream temperature and Tumalo Creek stream flow, suggest that even by optimizing Tumalo Creek and Deschutes River flows to achieve the greatest possible temperature reduction, the lowest temperatures achievable at DR 160.00 given total flow potentially available for stream flow restoration in Tumalo Creek will likely still be too high to achieve 18°C at Lower Bridge (DR 133.50) given observed rates of temperature increase between DR 160.00 and DR 133.50 (~ 3°C in July). While direct comparison is difficult because of how river miles/kilometers are measured in the two analyses, the Heat Source model for the Deschutes River suggests that, at instream water right (ODFW) flows for both the river and for Tumalo Creek, temperatures in the Deschutes exceed 18°C in reaches totaling approximately 9 miles between the confluence with Tumalo Creek and the confluence with Whychus Creek at RM 123 (Watershed Sciences 2008). Mass balance results that are higher than Heat Source stream temperatures for the Deschutes likely reflect the influence of air temperature and changing climate conditions on middle Deschutes River stream temperature since 2001, the year for which Heat Source temperatures were calculated.

Higher flows achieved through stream flow restoration scenarios described above will reduce stream temperatures meaningfully. However, mass balance and Heat Source model results suggest that it is not possible to meet the state temperature standard in all reaches of the middle Deschutes River between Tumalo Creek and Whychus Creek given diversion of Tumalo Creek flows for municipal and agricultural use, and while Deschutes River water is subject to heating in Wickiup and Crane Prairie reservoirs prior to being released downstream. Preliminary analysis of stream temperature from Pringle Falls at DR 217.25, approximately ten miles below Wickiup Reservoir, and stream temperature from DR 164.75, immediately below North Canal Dam, suggest stream temperature at North Canal Dam increases as a function of increasing stream temperature at DR 217.25 ($R^2$ = 0.35), which in turn we hypothesize increases as a function of reservoir depth and solar radiation. Further evidence for reservoir storage resulting in increased stream temperature in the Deschutes River is found in historic accounts of abundant bull trout, which require cooler (10°C) stream temperatures than other salmonids, in the Deschutes River at Pringle Falls (DR 217.25; Fies et al 1996). Allocating the maximum amount of streamflow possible from Tumalo Creek and the Deschutes River during the month of July will reduce the frequency and duration of lethal stream temperatures in the middle Deschutes and improve rearing habitat for juvenile redband.

### 4.5 Implications for Native Redband Populations

7DADM stream temperature was not a significant explanatory variable for young of year redband trout or brown trout occupancy probabilities in the middle Deschutes River in a 2015 study (Starcevich and Bailey 2017) despite 7DADM temperatures exceeding 18°C. While the thermal range and temperature tolerance of redband may exceed the state standard, the authors cited the substantial body of literature documenting adverse effects of temperatures above 18°C on redband trout physiology, growth and survival, and identifying optimal temperature preferences of redband trout as below the 18°C state standard. Starcevich and Bailey further note that exceeding the 18°C standard may preferentially benefit nonnative brown trout, which have a higher occurrence probability than redband in warmer stream temperatures.

Whether or not it is possible to meet the state temperature standard along every mile of the middle Deschutes River between North Canal Dam and Lower Bridge Road given current reservoir operations and irrigation infrastructure and management, increases in flow that approach or exceed the instream water right and DRC flow targets in the Deschutes River and Tumalo Creek may nonetheless confer substantial ecological benefits beyond improving temperature conditions. Although elevated stream temperature is an important consequence of modified flows in the Deschutes and in Tumalo Creek, altered flows affect other stream functions and habitat parameters, notably stream width and depth which contribute to habitat availability and diversity. And, while temperature requirements for salmon and trout are well-documented and encoded in state water quality standards, specific requirements for the habitat functions of the hydrograph in the middle Deschutes River are less well understood. Starcevich and Bailey (2017) found channel width between North Canal Dam and Steelhead Falls was on average eight meters narrower during irrigation season than during water storage season, demonstrating the dramatic reduction in the sheer amount of fish habitat that results from irrigation withdrawals at North Canal Dam. Allocating resources to stream flow restoration in Tumalo Creek will optimize reductions in temperature in Tumalo Creek and in the Deschutes River downstream of Tumalo Creek, as well as habitat benefits associated with increased habitat quantity (stream width and depth) in the reach of Tumalo Creek where stream flow is restored. Restoring stream flow in the Deschutes River will provide important habitat benefits associated with increased habitat quantity, while providing an additional cooling effect when Tumalo Creek flows are 54 cfs or below. This report provides information that will allow fisheries managers to identify flow scenarios for Tumalo Creek and the middle Deschutes River that balance the habitat benefits of lower stream temperatures and increased habitat quantity to provide the greatest habitat benefit for resident redband trout.

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## **APPENDIX A** Estimated temperatures at given flows calculated from regression equations

Deschutes River upstream of Tumalo Creek (DR 160.25)

| Flow (cfs) | Mean Temp (7DADM) | PI (±) | Flow (cfs) | Mean Temp (7DADM) | PI (±) | Flow (cfs) | Mean Temp (7DADM) | PI (±) | Flow (cfs) | Mean Temp (7DADM) | PI (±) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **41** | 20.7 | 1.5 | **94** | 19.6 | 1.5 | **147** | 19.0 | 1.5 | **200** | 18.6 | 1.5 |
| **42** | 20.6 | 1.5 | **95** | 19.6 | 1.5 | **148** | 19.0 | 1.5 | **201** | 18.6 | 1.5 |
| **43** | 20.6 | 1.5 | **96** | 19.6 | 1.5 | **149** | 19.0 | 1.5 | **202** | 18.6 | 1.5 |
| **44** | 20.6 | 1.5 | **97** | 19.6 | 1.5 | **150** | 19.0 | 1.5 | **203** | 18.6 | 1.5 |
| **45** | 20.5 | 1.5 | **98** | 19.6 | 1.5 | **151** | 19.0 | 1.5 | **204** | 18.6 | 1.5 |
| **46** | 20.5 | 1.5 | **99** | 19.5 | 1.5 | **152** | 19.0 | 1.5 | **205** | 18.6 | 1.5 |
| **47** | 20.5 | 1.5 | **100** | 19.5 | 1.5 | **153** | 19.0 | 1.5 | **206** | 18.6 | 1.5 |
| **48** | 20.5 | 1.5 | **101** | 19.5 | 1.5 | **154** | 19.0 | 1.5 | **207** | 18.6 | 1.5 |
| **49** | 20.4 | 1.5 | **102** | 19.5 | 1.5 | **155** | 19.0 | 1.5 | **208** | 18.6 | 1.5 |
| **50** | 20.4 | 1.5 | **103** | 19.5 | 1.5 | **156** | 19.0 | 1.5 | **209** | 18.6 | 1.5 |
| **51** | 20.4 | 1.5 | **104** | 19.5 | 1.5 | **157** | 18.9 | 1.5 | **210** | 18.6 | 1.5 |
| **52** | 20.4 | 1.5 | **105** | 19.5 | 1.5 | **158** | 18.9 | 1.5 | **211** | 18.6 | 1.5 |
| **53** | 20.3 | 1.5 | **106** | 19.5 | 1.5 | **159** | 18.9 | 1.5 | **212** | 18.6 | 1.5 |
| **54** | 20.3 | 1.5 | **107** | 19.4 | 1.5 | **160** | 18.9 | 1.5 | **213** | 18.6 | 1.5 |
| **55** | 20.3 | 1.5 | **108** | 19.4 | 1.5 | **161** | 18.9 | 1.5 | **214** | 18.6 | 1.5 |
| **56** | 20.3 | 1.5 | **109** | 19.4 | 1.5 | **162** | 18.9 | 1.5 | **215** | 18.5 | 1.5 |
| **57** | 20.2 | 1.5 | **110** | 19.4 | 1.5 | **163** | 18.9 | 1.5 | **216** | 18.5 | 1.5 |
| **58** | 20.2 | 1.5 | **111** | 19.4 | 1.5 | **164** | 18.9 | 1.5 | **217** | 18.5 | 1.5 |
| **59** | 20.2 | 1.5 | **112** | 19.4 | 1.5 | **165** | 18.9 | 1.5 | **218** | 18.5 | 1.5 |
| **60** | 20.2 | 1.5 | **113** | 19.4 | 1.5 | **166** | 18.9 | 1.5 | **219** | 18.5 | 1.5 |
| **61** | 20.2 | 1.5 | **114** | 19.4 | 1.5 | **167** | 18.9 | 1.5 | **220** | 18.5 | 1.5 |
| **62** | 20.1 | 1.5 | **115** | 19.3 | 1.5 | **168** | 18.9 | 1.5 | **221** | 18.5 | 1.5 |
| **63** | 20.1 | 1.5 | **116** | 19.3 | 1.5 | **169** | 18.9 | 1.5 | **222** | 18.5 | 1.5 |
| **64** | 20.1 | 1.5 | **117** | 19.3 | 1.5 | **170** | 18.8 | 1.5 | **223** | 18.5 | 1.5 |
| **65** | 20.1 | 1.5 | **118** | 19.3 | 1.5 | **171** | 18.8 | 1.5 | **224** | 18.5 | 1.5 |
| **66** | 20.1 | 1.5 | **119** | 19.3 | 1.5 | **172** | 18.8 | 1.5 | **225** | 18.5 | 1.5 |
| **67** | 20.0 | 1.5 | **120** | 19.3 | 1.5 | **173** | 18.8 | 1.5 | **226** | 18.5 | 1.5 |
| **68** | 20.0 | 1.5 | **121** | 19.3 | 1.5 | **174** | 18.8 | 1.5 | **227** | 18.5 | 1.5 |
| **69** | 20.0 | 1.5 | **122** | 19.3 | 1.5 | **175** | 18.8 | 1.5 | **228** | 18.5 | 1.5 |
| **70** | 20.0 | 1.5 | **123** | 19.3 | 1.5 | **176** | 18.8 | 1.5 | **229** | 18.5 | 1.5 |
| **71** | 20.0 | 1.5 | **124** | 19.3 | 1.5 | **177** | 18.8 | 1.5 | **230** | 18.5 | 1.5 |
| **72** | 19.9 | 1.5 | **125** | 19.2 | 1.5 | **178** | 18.8 | 1.5 | **231** | 18.5 | 1.5 |
| **73** | 19.9 | 1.5 | **126** | 19.2 | 1.5 | **179** | 18.8 | 1.5 | **232** | 18.5 | 1.5 |
| **74** | 19.9 | 1.5 | **127** | 19.2 | 1.5 | **180** | 18.8 | 1.5 | **233** | 18.4 | 1.5 |
| **75** | 19.9 | 1.5 | **128** | 19.2 | 1.5 | **181** | 18.8 | 1.5 | **234** | 18.4 | 1.5 |
| **76** | 19.9 | 1.5 | **129** | 19.2 | 1.5 | **182** | 18.8 | 1.5 | **235** | 18.4 | 1.5 |
| **77** | 19.9 | 1.5 | **130** | 19.2 | 1.5 | **183** | 18.8 | 1.5 | **236** | 18.4 | 1.5 |
| **78** | 19.8 | 1.5 | **131** | 19.2 | 1.5 | **184** | 18.7 | 1.5 | **237** | 18.4 | 1.5 |
| **79** | 19.8 | 1.5 | **132** | 19.2 | 1.5 | **185** | 18.7 | 1.5 | **238** | 18.4 | 1.5 |
| **80** | 19.8 | 1.5 | **133** | 19.2 | 1.5 | **186** | 18.7 | 1.5 | **239** | 18.4 | 1.5 |
| **81** | 19.8 | 1.5 | **134** | 19.2 | 1.5 | **187** | 18.7 | 1.5 | **240** | 18.4 | 1.5 |
| **82** | 19.8 | 1.5 | **135** | 19.1 | 1.5 | **188** | 18.7 | 1.5 | **241** | 18.4 | 1.5 |
| **83** | 19.8 | 1.5 | **136** | 19.1 | 1.5 | **189** | 18.7 | 1.5 | **242** | 18.4 | 1.5 |
| **84** | 19.7 | 1.5 | **137** | 19.1 | 1.5 | **190** | 18.7 | 1.5 | **243** | 18.4 | 1.5 |
| **85** | 19.7 | 1.5 | **138** | 19.1 | 1.5 | **191** | 18.7 | 1.5 | **244** | 18.4 | 1.5 |
| **86** | 19.7 | 1.5 | **139** | 19.1 | 1.5 | **192** | 18.7 | 1.5 | **245** | 18.4 | 1.5 |
| **87** | 19.7 | 1.5 | **140** | 19.1 | 1.5 | **193** | 18.7 | 1.5 | **246** | 18.4 | 1.5 |
| **88** | 19.7 | 1.5 | **141** | 19.1 | 1.5 | **194** | 18.7 | 1.5 | **247** | 18.4 | 1.5 |
| **89** | 19.7 | 1.5 | **142** | 19.1 | 1.5 | **195** | 18.7 | 1.5 | **248** | 18.4 | 1.5 |
| **90** | 19.7 | 1.5 | **143** | 19.1 | 1.5 | **196** | 18.7 | 1.5 | **249** | 18.4 | 1.5 |
| **91** | 19.6 | 1.5 | **144** | 19.1 | 1.5 | **197** | 18.7 | 1.5 | **250** | 18.4 | 1.5 |
| **92** | 19.6 | 1.5 | **145** | 19.1 | 1.5 | **198** | 18.7 | 1.5 | | | |
| **93** | 19.6 | 1.5 | **146** | 19.0 | 1.5 | **199** | 18.6 | 1.5 | | | |

Deschutes River downstream of Tumalo Creek (DR160.00) at Tumalo Creek flows

| Flow (cfs) | Mean Temp (7DADM) | PI (±) | Flow (cfs) | Mean Temp (7DADM) | PI (±) | Flow (cfs) | Mean Temp (7DADM) | PI (±) |
|---|---|---|---|---|---|---|---|---|
| **3** | 20.1 | 1.8 | **56** | 17.7 | 1.8 | **109** | 16.4 | 1.8 |
| **4** | 20.0 | 1.8 | **57** | 17.6 | 1.8 | **110** | 16.4 | 1.8 |
| **5** | 19.9 | 1.8 | **58** | 17.6 | 1.8 | **111** | 16.4 | 1.8 |
| **6** | 19.9 | 1.8 | **59** | 17.6 | 1.8 | **112** | 16.4 | 1.8 |
| **7** | 19.8 | 1.8 | **60** | 17.5 | 1.8 | **113** | 16.4 | 1.8 |
| **8** | 19.8 | 1.8 | **61** | 17.5 | 1.8 | **114** | 16.3 | 1.8 |
| **9** | 19.7 | 1.8 | **62** | 17.5 | 1.8 | **115** | 16.3 | 1.8 |
| **10** | 19.7 | 1.8 | **63** | 17.4 | 1.8 | **116** | 16.3 | 1.8 |
| **11** | 19.6 | 1.8 | **64** | 17.4 | 1.8 | **117** | 16.3 | 1.8 |
| **12** | 19.6 | 1.8 | **65** | 17.4 | 1.8 | **118** | 16.3 | 1.8 |
| **13** | 19.5 | 1.8 | **66** | 17.3 | 1.8 | **119** | 16.3 | 1.8 |
| **14** | 19.5 | 1.8 | **67** | 17.3 | 1.8 | **120** | 16.3 | 1.8 |
| **15** | 19.4 | 1.8 | **68** | 17.3 | 1.8 | **121** | 16.3 | 1.8 |
| **16** | 19.4 | 1.8 | **69** | 17.2 | 1.8 | **122** | 16.3 | 1.8 |
| **17** | 19.3 | 1.8 | **70** | 17.2 | 1.8 | **123** | 16.3 | 1.8 |
| **18** | 19.3 | 1.8 | **71** | 17.2 | 1.8 | **124** | 16.3 | 1.8 |
| **19** | 19.2 | 1.8 | **72** | 17.2 | 1.8 | **125** | 16.3 | 1.8 |
| **20** | 19.2 | 1.8 | **73** | 17.1 | 1.8 | **126** | 16.3 | 1.8 |
| **21** | 19.1 | 1.8 | **74** | 17.1 | 1.8 | **127** | 16.2 | 1.8 |
| **22** | 19.1 | 1.8 | **75** | 17.1 | 1.8 | **128** | 16.2 | 1.8 |
| **23** | 19.0 | 1.8 | **76** | 17.1 | 1.8 | **129** | 16.2 | 1.8 |
| **24** | 19.0 | 1.8 | **77** | 17.0 | 1.8 | **130** | 16.2 | 1.8 |
| **25** | 18.9 | 1.8 | **78** | 17.0 | 1.8 | **131** | 16.2 | 1.8 |
| **26** | 18.9 | 1.8 | **79** | 17.0 | 1.8 | **132** | 16.2 | 1.8 |
| **27** | 18.8 | 1.8 | **80** | 16.9 | 1.8 | **133** | 16.2 | 1.8 |
| **28** | 18.8 | 1.8 | **81** | 16.9 | 1.8 | **134** | 16.2 | 1.8 |
| **29** | 18.7 | 1.8 | **82** | 16.9 | 1.8 | **135** | 16.2 | 1.8 |
| **30** | 18.7 | 1.8 | **83** | 16.9 | 1.8 | **136** | 16.2 | 1.8 |
| **31** | 18.6 | 1.8 | **84** | 16.9 | 1.8 | **137** | 16.2 | 1.8 |
| **32** | 18.6 | 1.8 | **85** | 16.8 | 1.8 | **138** | 16.2 | 1.8 |
| **33** | 18.6 | 1.8 | **86** | 16.8 | 1.8 | **139** | 16.2 | 1.8 |
| **34** | 18.5 | 1.8 | **87** | 16.8 | 1.8 | **140** | 16.2 | 1.8 |
| **35** | 18.5 | 1.8 | **88** | 16.8 | 1.8 | **141** | 16.2 | 1.8 |
| **36** | 18.4 | 1.8 | **89** | 16.7 | 1.8 | **142** | 16.2 | 1.8 |
| **37** | 18.4 | 1.8 | **90** | 16.7 | 1.8 | **143** | 16.2 | 1.8 |
| **38** | 18.3 | 1.8 | **91** | 16.7 | 1.8 | **144** | 16.2 | 1.8 |
| **39** | 18.3 | 1.8 | **92** | 16.7 | 1.8 | **145** | 16.2 | 1.8 |
| **40** | 18.3 | 1.8 | **93** | 16.7 | 1.8 | **146** | 16.2 | 1.8 |
| **41** | 18.2 | 1.8 | **94** | 16.6 | 1.8 | **147** | 16.2 | 1.8 |
| **42** | 18.2 | 1.8 | **95** | 16.6 | 1.8 | **148** | 16.2 | 1.8 |
| **43** | 18.1 | 1.8 | **96** | 16.6 | 1.8 | **149** | 16.2 | 1.8 |
| **44** | 18.1 | 1.8 | **97** | 16.6 | 1.8 | **150** | 16.2 | 1.8 |
| **45** | 18.1 | 1.8 | **98** | 16.6 | 1.8 | **151** | 16.2 | 1.8 |
| **46** | 18.0 | 1.8 | **99** | 16.6 | 1.8 | **152** | 16.2 | 1.8 |
| **47** | 18.0 | 1.8 | **100** | 16.5 | 1.8 | **153** | 16.2 | 1.8 |
| **48** | 17.9 | 1.8 | **101** | 16.5 | 1.8 | **154** | 16.2 | 1.8 |
| **49** | 17.9 | 1.8 | **102** | 16.5 | 1.8 | **155** | 16.3 | 1.8 |
| **50** | 17.9 | 1.8 | **103** | 16.5 | 1.8 | **156** | 16.3 | 1.8 |
| **51** | 17.8 | 1.8 | **104** | 16.5 | 1.8 | **157** | 16.3 | 1.8 |
| **52** | 17.8 | 1.8 | **105** | 16.5 | 1.8 | **158** | 16.3 | 1.8 |
| **53** | 17.8 | 1.8 | **106** | 16.4 | 1.8 | | | |
| **54** | 17.7 | 1.8 | **107** | 16.4 | 1.8 | | | |
| **55** | 17.7 | 1.8 | **108** | 16.4 | 1.8 | | | |

Tumalo Creek upstream of the mouth (TC 000.25)

| Flow (cfs) | Mean Temp (7DMAX) | PI (±) | Flow (cfs) | Mean Temp (7DMAX) | PI (±) | Flow (cfs) | Mean Temp (7DMAX) | PI (±) |
|---|---|---|---|---|---|---|---|---|
| **3** | 20.6 | 2.7 | **56** | 13.5 | 2.7 | **109** | 11.4 | 2.7 |
| **4** | 20.4 | 2.7 | **57** | 13.4 | 2.7 | **110** | 11.4 | 2.7 |
| **5** | 20.2 | 2.7 | **58** | 13.3 | 2.7 | **111** | 11.4 | 2.7 |
| **6** | 20.0 | 2.7 | **59** | 13.2 | 2.7 | **112** | 11.4 | 2.7 |
| **7** | 19.8 | 2.7 | **60** | 13.2 | 2.7 | **113** | 11.4 | 2.7 |
| **8** | 19.6 | 2.7 | **61** | 13.1 | 2.7 | **114** | 11.4 | 2.7 |
| **9** | 19.4 | 2.7 | **62** | 13.0 | 2.7 | **115** | 11.4 | 2.7 |
| **10** | 19.3 | 2.7 | **63** | 13.0 | 2.7 | **116** | 11.4 | 2.7 |
| **11** | 19.1 | 2.7 | **64** | 12.9 | 2.7 | **117** | 11.4 | 2.7 |
| **12** | 18.9 | 2.7 | **65** | 12.8 | 2.7 | **118** | 11.4 | 2.7 |
| **13** | 18.7 | 2.7 | **66** | 12.8 | 2.7 | **119** | 11.4 | 2.7 |
| **14** | 18.6 | 2.7 | **67** | 12.7 | 2.7 | **120** | 11.4 | 2.7 |
| **15** | 18.4 | 2.7 | **68** | 12.7 | 2.7 | **121** | 11.4 | 2.7 |
| **16** | 18.2 | 2.7 | **69** | 12.6 | 2.7 | **122** | 11.4 | 2.7 |
| **17** | 18.1 | 2.7 | **70** | 12.5 | 2.7 | **123** | 11.4 | 2.7 |
| **18** | 17.9 | 2.7 | **71** | 12.5 | 2.7 | **124** | 11.4 | 2.7 |
| **19** | 17.7 | 2.7 | **72** | 12.4 | 2.7 | **125** | 11.4 | 2.7 |
| **20** | 17.6 | 2.7 | **73** | 12.4 | 2.7 | **126** | 11.4 | 2.7 |
| **21** | 17.4 | 2.7 | **74** | 12.3 | 2.7 | **127** | 11.4 | 2.7 |
| **22** | 17.3 | 2.7 | **75** | 12.3 | 2.7 | **128** | 11.4 | 2.7 |
| **23** | 17.1 | 2.7 | **76** | 12.2 | 2.7 | **129** | 11.4 | 2.7 |
| **24** | 17.0 | 2.7 | **77** | 12.2 | 2.7 | **130** | 11.4 | 2.7 |
| **25** | 16.8 | 2.7 | **78** | 12.2 | 2.7 | **131** | 11.4 | 2.7 |
| **26** | 16.7 | 2.7 | **79** | 12.1 | 2.7 | **132** | 11.4 | 2.7 |
| **27** | 16.6 | 2.7 | **80** | 12.1 | 2.7 | **133** | 11.5 | 2.7 |
| **28** | 16.4 | 2.7 | **81** | 12.0 | 2.7 | **134** | 11.5 | 2.7 |
| **29** | 16.3 | 2.7 | **82** | 12.0 | 2.7 | **135** | 11.5 | 2.7 |
| **30** | 16.2 | 2.7 | **83** | 12.0 | 2.7 | **136** | 11.5 | 2.7 |
| **31** | 16.0 | 2.7 | **84** | 11.9 | 2.7 | **137** | 11.5 | 2.7 |
| **32** | 15.9 | 2.7 | **85** | 11.9 | 2.7 | **138** | 11.5 | 2.7 |
| **33** | 15.8 | 2.7 | **86** | 11.9 | 2.7 | **139** | 11.5 | 2.7 |
| **34** | 15.7 | 2.7 | **87** | 11.8 | 2.7 | **140** | 11.5 | 2.7 |
| **35** | 15.5 | 2.7 | **88** | 11.8 | 2.7 | **141** | 11.5 | 2.7 |
| **36** | 15.4 | 2.7 | **89** | 11.8 | 2.7 | **142** | 11.5 | 2.7 |
| **37** | 15.3 | 2.7 | **90** | 11.7 | 2.7 | **143** | 11.6 | 2.7 |
| **38** | 15.2 | 2.7 | **91** | 11.7 | 2.7 | **144** | 11.6 | 2.7 |
| **39** | 15.1 | 2.7 | **92** | 11.7 | 2.7 | **145** | 11.6 | 2.8 |
| **40** | 15.0 | 2.7 | **93** | 11.7 | 2.7 | **146** | 11.6 | 2.8 |
| **41** | 14.9 | 2.7 | **94** | 11.6 | 2.7 | **147** | 11.6 | 2.8 |
| **42** | 14.8 | 2.7 | **95** | 11.6 | 2.7 | **148** | 11.6 | 2.8 |
| **43** | 14.7 | 2.7 | **96** | 11.6 | 2.7 | **149** | 11.6 | 2.8 |
| **44** | 14.5 | 2.7 | **97** | 11.6 | 2.7 | **150** | 11.6 | 2.8 |
| **45** | 14.4 | 2.7 | **98** | 11.6 | 2.7 | **151** | 11.7 | 2.8 |
| **46** | 14.4 | 2.7 | **99** | 11.5 | 2.7 | **152** | 11.7 | 2.8 |
| **47** | 14.3 | 2.7 | **100** | 11.5 | 2.7 | **153** | 11.7 | 2.8 |
| **48** | 14.2 | 2.7 | **101** | 11.5 | 2.7 | **154** | 11.7 | 2.9 |
| **49** | 14.1 | 2.7 | **102** | 11.5 | 2.7 | **155** | 11.7 | 2.9 |
| **50** | 14.0 | 2.7 | **103** | 11.5 | 2.7 | **156** | 11.7 | 2.9 |
| **51** | 13.9 | 2.7 | **104** | 11.5 | 2.7 | **157** | 11.7 | 2.9 |
| **52** | 13.8 | 2.7 | **105** | 11.5 | 2.7 | **158** | 11.8 | 2.9 |
| **53** | 13.7 | 2.7 | **106** | 11.4 | 2.7 | | | |
| **54** | 13.6 | 2.7 | **107** | 11.4 | 2.7 | | | |
| **55** | 13.6 | 2.7 | **108** | 11.4 | 2.7 | | | |

## **APPENDIX B** Estimated temperatures at six Deschutes River flow scenarios

| | Estimated temperature at TC+DR flow | | | | | | | Estimated temperature at TC+DR flow | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TC 000.25 | DR QD (cfs) | | | | | | TC 000.25 | DR QD (cfs) | | | | | |
| Flow (cfs) | 122 | 127 | 150 | 175 | 200 | 250 | Flow (cfs) | 122 | 127 | 150 | 175 | 200 | 250 |
| 10 | 19.3 | 19.2 | 19.0 | 18.8 | 18.7 | 18.4 | 56 | 17.5 | 17.4 | 17.5 | 17.5 | 17.5 | 17.5 |
| 11 | 19.3 | 19.2 | 19.0 | 18.8 | 18.7 | 18.4 | 57 | 17.4 | 17.4 | 17.5 | 17.5 | 17.5 | 17.4 |
| 12 | 19.3 | 19.2 | 19.0 | 18.8 | 18.7 | 18.4 | 58 | 17.4 | 17.4 | 17.4 | 17.4 | 17.4 | 17.4 |
| 13 | 19.2 | 19.1 | 19.0 | 18.8 | 18.6 | 18.4 | 59 | 17.3 | 17.3 | 17.4 | 17.4 | 17.4 | 17.4 |
| 14 | 19.2 | 19.1 | 19.0 | 18.8 | 18.6 | 18.4 | 60 | 17.3 | 17.3 | 17.3 | 17.4 | 17.4 | 17.4 |
| 15 | 19.2 | 19.1 | 19.0 | 18.8 | 18.6 | 18.4 | 61 | 17.2 | 17.2 | 17.3 | 17.3 | 17.3 | 17.3 |
| 16 | 19.2 | 19.1 | 18.9 | 18.8 | 18.6 | 18.3 | 62 | 17.2 | 17.2 | 17.3 | 17.3 | 17.3 | 17.3 |
| 17 | 19.1 | 19.1 | 18.9 | 18.7 | 18.6 | 18.3 | 63 | 17.1 | 17.1 | 17.2 | 17.3 | 17.3 | 17.3 |
| 18 | 19.1 | 19.0 | 18.9 | 18.7 | 18.6 | 18.3 | 64 | 17.1 | 17.1 | 17.2 | 17.2 | 17.3 | 17.2 |
| 19 | 19.1 | 19.0 | 18.9 | 18.7 | 18.6 | 18.3 | 65 | 17.1 | 17.0 | 17.1 | 17.2 | 17.2 | 17.2 |
| 20 | 19.1 | 19.0 | 18.8 | 18.7 | 18.5 | 18.3 | 66 | 17.0 | 17.0 | 17.1 | 17.2 | 17.2 | 17.2 |
| 21 | 19.0 | 18.9 | 18.8 | 18.7 | 18.5 | 18.3 | 67 | 17.0 | 17.0 | 17.1 | 17.1 | 17.2 | 17.2 |
| 22 | 19.0 | 18.9 | 18.8 | 18.6 | 18.5 | 18.3 | 68 | 16.9 | 16.9 | 17.0 | 17.1 | 17.1 | 17.1 |
| 23 | 19.0 | 18.9 | 18.8 | 18.6 | 18.5 | 18.3 | 69 | 16.9 | 16.9 | 17.0 | 17.1 | 17.1 | 17.1 |
| 24 | 18.9 | 18.8 | 18.7 | 18.6 | 18.5 | 18.2 | 70 | 16.8 | 16.8 | 17.0 | 17.0 | 17.1 | 17.1 |
| 25 | 18.9 | 18.8 | 18.7 | 18.6 | 18.4 | 18.2 | 71 | 16.8 | 16.8 | 16.9 | 17.0 | 17.0 | 17.1 |
| 26 | 18.8 | 18.8 | 18.7 | 18.5 | 18.4 | 18.2 | 72 | 16.8 | 16.7 | 16.9 | 17.0 | 17.0 | 17.0 |
| 27 | 18.8 | 18.7 | 18.6 | 18.5 | 18.4 | 18.2 | 73 | 16.7 | 16.7 | 16.8 | 16.9 | 17.0 | 17.0 |
| 28 | 18.8 | 18.7 | 18.6 | 18.5 | 18.4 | 18.2 | 74 | 16.7 | 16.7 | 16.8 | 16.9 | 16.9 | 17.0 |
| 29 | 18.7 | 18.7 | 18.6 | 18.5 | 18.3 | 18.1 | 75 | 16.6 | 16.6 | 16.8 | 16.9 | 16.9 | 17.0 |
| 30 | 18.7 | 18.6 | 18.5 | 18.4 | 18.3 | 18.1 | 76 | 16.6 | 16.6 | 16.7 | 16.8 | 16.9 | 16.9 |
| 31 | 18.6 | 18.6 | 18.5 | 18.4 | 18.3 | 18.1 | 77 | 16.5 | 16.6 | 16.7 | 16.8 | 16.9 | 16.9 |
| 32 | 18.6 | 18.5 | 18.5 | 18.4 | 18.3 | 18.1 | 78 | 16.5 | 16.5 | 16.7 | 16.8 | 16.8 | 16.9 |
| 33 | 18.5 | 18.5 | 18.4 | 18.3 | 18.2 | 18.1 | 79 | 16.5 | 16.5 | 16.6 | 16.7 | 16.8 | 16.9 |
| 34 | 18.5 | 18.4 | 18.4 | 18.3 | 18.2 | 18.0 | 80 | 16.4 | 16.4 | 16.6 | 16.7 | 16.8 | 16.8 |
| 35 | 18.5 | 18.4 | 18.4 | 18.3 | 18.2 | 18.0 | 81 | 16.4 | 16.4 | 16.6 | 16.7 | 16.7 | 16.8 |
| 36 | 18.4 | 18.4 | 18.3 | 18.2 | 18.1 | 18.0 | 82 | 16.4 | 16.4 | 16.5 | 16.6 | 16.7 | 16.8 |
| 37 | 18.4 | 18.3 | 18.3 | 18.2 | 18.1 | 18.0 | 83 | 16.3 | 16.3 | 16.5 | 16.6 | 16.7 | 16.8 |
| 38 | 18.3 | 18.3 | 18.2 | 18.2 | 18.1 | 17.9 | 84 | 16.3 | 16.3 | 16.5 | 16.6 | 16.7 | 16.7 |
| 39 | 18.3 | 18.2 | 18.2 | 18.1 | 18.1 | 17.9 | 85 | 16.3 | 16.3 | 16.4 | 16.5 | 16.6 | 16.7 |
| 40 | 18.2 | 18.2 | 18.2 | 18.1 | 18.0 | 17.9 | 86 | 16.2 | 16.2 | 16.4 | 16.5 | 16.6 | 16.7 |
| 41 | 18.2 | 18.1 | 18.1 | 18.1 | 18.0 | 17.9 | 87 | 16.2 | 16.2 | 16.4 | 16.5 | 16.6 | 16.7 |
| 42 | 18.1 | 18.1 | 18.1 | 18.0 | 18.0 | 17.8 | 88 | 16.2 | 16.2 | 16.3 | 16.5 | 16.5 | 16.6 |
| 43 | 18.1 | 18.0 | 18.0 | 18.0 | 17.9 | 17.8 | 89 | 16.1 | 16.1 | 16.3 | 16.4 | 16.5 | 16.6 |
| 44 | 18.0 | 18.0 | 18.0 | 18.0 | 17.9 | 17.8 | 90 | 16.1 | 16.1 | 16.3 | 16.4 | 16.5 | 16.6 |
| 45 | 18.0 | 18.0 | 18.0 | 17.9 | 17.9 | 17.8 | 91 | 16.1 | 16.1 | 16.3 | 16.4 | 16.5 | 16.6 |
| 46 | 17.9 | 17.9 | 17.9 | 17.9 | 17.8 | 17.7 | 92 | 16.0 | 16.0 | 16.2 | 16.4 | 16.4 | 16.6 |
| 47 | 17.9 | 17.9 | 17.9 | 17.8 | 17.8 | 17.7 | 93 | 16.0 | 16.0 | 16.2 | 16.3 | 16.4 | 16.5 |
| 48 | 17.8 | 17.8 | 17.8 | 17.8 | 17.8 | 17.7 | 94 | 16.0 | 16.0 | 16.2 | 16.3 | 16.4 | 16.5 |
| 49 | 17.8 | 17.8 | 17.8 | 17.8 | 17.7 | 17.7 | 95 | 15.9 | 16.0 | 16.1 | 16.3 | 16.4 | 16.5 |
| 50 | 17.7 | 17.7 | 17.8 | 17.7 | 17.7 | 17.6 | 96 | 15.9 | 15.9 | 16.1 | 16.3 | 16.4 | 16.5 |
| 51 | 17.7 | 17.7 | 17.7 | 17.7 | 17.7 | 17.6 | 97 | 15.9 | 15.9 | 16.1 | 16.2 | 16.3 | 16.5 |
| 52 | 17.7 | 17.6 | 17.7 | 17.7 | 17.6 | 17.6 | 98 | 15.8 | 15.9 | 16.1 | 16.2 | 16.3 | 16.4 |
| 53 | 17.6 | 17.6 | 17.6 | 17.6 | 17.6 | 17.5 | 99 | 15.8 | 15.8 | 15.9 | 16.0 | 16.2 | 11.5 |
| 54 | 17.6 | 17.5 | 17.6 | 17.6 | 17.6 | 17.5 | 100 | 15.8 | 15.8 | 15.9 | 16.0 | 16.2 | 11.5 |
| 55 | 17.5 | 17.5 | 17.5 | 17.6 | 17.5 | 17.5 | | | | | | | |

**APPENDIX C** 7DADM temperatures and prediction intervals estimated for DR 160.00 from regression and mass balance equations

| Tumalo Creek Flow (cfs) | Regression Mean Temp (7DADM) | Regression PI (±) | Mass Balance Mean Temp (7DADM) | Mass Balance PI (±) | Flow (cfs) | Regression Mean Temp (7DADM) | Regression PI (±) | Mass Balance Mean Temp (7DADM) | Mass Balance PI (±) |
|---|---|---|---|---|---|---|---|---|---|
| **10** | 19.7 | 1.8 | 19.2 | 1.6 | **56** | 17.7 | 1.8 | 17.4 | 1.9 |
| **11** | 19.6 | 1.8 | 19.2 | 1.6 | **57** | 17.6 | 1.8 | 17.4 | 1.9 |
| **12** | 19.6 | 1.8 | 19.2 | 1.6 | **58** | 17.6 | 1.8 | 17.4 | 1.9 |
| **13** | 19.5 | 1.8 | 19.1 | 1.7 | **59** | 17.6 | 1.8 | 17.3 | 1.9 |
| **14** | 19.5 | 1.8 | 19.1 | 1.7 | **60** | 17.5 | 1.8 | 17.3 | 1.9 |
| **15** | 19.4 | 1.8 | 19.1 | 1.7 | **61** | 17.5 | 1.8 | 17.2 | 2.0 |
| **16** | 19.4 | 1.8 | 19.1 | 1.7 | **62** | 17.5 | 1.8 | 17.2 | 2.0 |
| **17** | 19.3 | 1.8 | 19.1 | 1.7 | **63** | 17.4 | 1.8 | 17.1 | 2.0 |
| **18** | 19.3 | 1.8 | 19.0 | 1.7 | **64** | 17.4 | 1.8 | 17.1 | 2.0 |
| **19** | 19.2 | 1.8 | 19.0 | 1.7 | **65** | 17.4 | 1.8 | 17.0 | 2.0 |
| **20** | 19.2 | 1.8 | 19.0 | 1.7 | **66** | 17.3 | 1.8 | 17.0 | 2.0 |
| **21** | 19.1 | 1.8 | 18.9 | 1.7 | **67** | 17.3 | 1.8 | 17.0 | 2.0 |
| **22** | 19.1 | 1.8 | 18.9 | 1.7 | **68** | 17.3 | 1.8 | 16.9 | 2.0 |
| **23** | 19.0 | 1.8 | 18.9 | 1.7 | **69** | 17.2 | 1.8 | 16.9 | 2.0 |
| **24** | 19.0 | 1.8 | 18.8 | 1.7 | **70** | 17.2 | 1.8 | 16.8 | 2.0 |
| **25** | 18.9 | 1.8 | 18.8 | 1.8 | **71** | 17.2 | 1.8 | 16.8 | 2.0 |
| **26** | 18.9 | 1.8 | 18.8 | 1.8 | **72** | 17.2 | 1.8 | 16.7 | 2.0 |
| **27** | 18.8 | 1.8 | 18.7 | 1.8 | **73** | 17.1 | 1.8 | 16.7 | 2.0 |
| **28** | 18.8 | 1.8 | 18.7 | 1.8 | **74** | 17.1 | 1.8 | 16.7 | 2.0 |
| **29** | 18.7 | 1.8 | 18.7 | 1.8 | **75** | 17.1 | 1.8 | 16.6 | 2.0 |
| **30** | 18.7 | 1.8 | 18.6 | 1.8 | **76** | 17.1 | 1.8 | 16.6 | 2.0 |
| **31** | 18.6 | 1.8 | 18.6 | 1.8 | **77** | 17.0 | 1.8 | 16.6 | 2.0 |
| **32** | 18.6 | 1.8 | 18.5 | 1.8 | **78** | 17.0 | 1.8 | 16.5 | 2.0 |
| **33** | 18.6 | 1.8 | 18.5 | 1.8 | **79** | 17.0 | 1.8 | 16.5 | 2.0 |
| **34** | 18.5 | 1.8 | 18.4 | 1.8 | **80** | 16.9 | 1.8 | 16.4 | 2.0 |
| **35** | 18.5 | 1.8 | 18.4 | 1.8 | **81** | 16.9 | 1.8 | 16.4 | 2.0 |
| **36** | 18.4 | 1.8 | 18.4 | 1.8 | **82** | 16.9 | 1.8 | 16.4 | 2.0 |
| **37** | 18.4 | 1.8 | 18.3 | 1.8 | **83** | 16.9 | 1.8 | 16.3 | 2.0 |
| **38** | 18.3 | 1.8 | 18.3 | 1.8 | **84** | 16.9 | 1.8 | 16.3 | 2.0 |
| **39** | 18.3 | 1.8 | 18.2 | 1.8 | **85** | 16.8 | 1.8 | 16.3 | 2.0 |
| **40** | 18.3 | 1.8 | 18.2 | 1.8 | **86** | 16.8 | 1.8 | 16.2 | 2.0 |
| **41** | 18.2 | 1.8 | 18.1 | 1.9 | **87** | 16.8 | 1.8 | 16.2 | 2.0 |
| **42** | 18.2 | 1.8 | 18.1 | 1.9 | **88** | 16.8 | 1.8 | 16.2 | 2.0 |
| **43** | 18.1 | 1.8 | 18.0 | 1.9 | **89** | 16.7 | 1.8 | 16.1 | 2.0 |
| **44** | 18.1 | 1.8 | 18.0 | 1.9 | **90** | 16.7 | 1.8 | 16.1 | 2.1 |
| **45** | 18.1 | 1.8 | 18.0 | 1.9 | **91** | 16.7 | 1.8 | 16.1 | 2.1 |
| **46** | 18.0 | 1.8 | 17.9 | 1.9 | **92** | 16.7 | 1.8 | 16.0 | 2.1 |
| **47** | 18.0 | 1.8 | 17.9 | 1.9 | **93** | 16.7 | 1.8 | 16.0 | 2.1 |
| **48** | 17.9 | 1.8 | 17.8 | 1.9 | **94** | 16.6 | 1.8 | 16.0 | 2.1 |
| **49** | 17.9 | 1.8 | 17.8 | 1.9 | **95** | 16.6 | 1.8 | 16.0 | 2.1 |
| **50** | 17.9 | 1.8 | 17.7 | 1.9 | **96** | 16.6 | 1.8 | 15.9 | 2.1 |
| **51** | 17.8 | 1.8 | 17.7 | 1.9 | **97** | 16.6 | 1.8 | 15.9 | 2.1 |
| **52** | 17.8 | 1.8 | 17.6 | 1.9 | **98** | 16.6 | 1.8 | 15.9 | 2.1 |
| **53** | 17.8 | 1.8 | 17.6 | 1.9 | **99** | 16.6 | 1.8 | 15.8 | 2.1 |
| **54** | 17.7 | 1.8 | 17.5 | 1.9 | **100** | 16.5 | 1.8 | 15.8 | 2.1 |
| **55** | 17.7 | 1.8 | 17.5 | 1.9 | | | | | |