Upper Deschutes Watershed Council

Technical Report

Middle Deschutes River Instream Flow Restoration and Temperature Responses 2001-2016

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Table of Contents

List of Figures

List of Tables

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 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 2016 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?

   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. Flows dropped in 2013 to 129 cfs and have fluctuated between 129 and 136 cfs since. 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 2016 represents a marked decrease from 2010-2012 flows, approximating 2009 levels.

   Stream flow in Tumalo Creek exceeds flow protected instream in most years, including in 2016, when July median flow was 15 cfs to 13 cfs July median protected flow. 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 15.6 cfs in 2015.

2) Temperature status and trend: What was the status of middle Deschutes River stream temperature in 2016 relative to the State of Oregon 18°C (64°F) standard and in relation to previous years?

Stream temperature in the middle Deschutes River exceeded the 18°C state standard protecting salmon and trout rearing and migration for 28-52% of days in between April 30 and September 21, 2016, 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 fewer days (52% or 76 days) than in all but four of fifteen years for which temperature data are available (2001-2016);
- Downstream of the confluence with Tumalo Creek, at DR 160.00, temperatures exceeded 18°C for 41% of days, lower than in 2015 but higher than in any other year for which data are available;
- Temperatures at DR 160.25 exceeded the standard for exceeded the standard for fewer days (46%) than in all but two years, but temperatures at DR 164.75, immediately downstream of North Canal Dam, exceeded the standard for more days than in all but three years and for the same percent of days as in 2005;
- Stream temperatures exceeded 24°C (the lethal threshold for trout rearing; ODEQ 1995) for 3% of days (5 days) in 2016, consistent with other years including and since 2013, coincident with the 2013 drop in flows protected in the middle Deschutes.

Conversely, stream temperature was 18°C or lower, representing suitable rearing conditions for trout, for 48-72% of data days in 2016 at sites downstream of points of stream flow restoration. These data represent an improvement over 2015 conditions, but fail to attain even 2014 temperatures much less reverse the continued decline from 2011 conditions.

Although stream temperatures continue to exceed 24°C at Lower Bridge, the number and percent of days for which temperatures are above 24°C have been far lower since 2013 than prior to 2008, reducing 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.

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

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 2001-2015 at DR 160.25 and at TC 000.25 show temperatures decreasing as flows increase. Stream flow explained 33% and 78% of variation in stream temperature in the middle Deschutes and in Tumalo Creek, respectively, providing statistical support for the role of higher stream flows in reducing stream temperature.

4) Target stream flow: 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?

   Flow scenarios developed from regression and mass balance equations indicate that allocating the maximum possible Tumalo Creek flow to instream use during July while holding constant Deschutes River flow downstream of North Canal Dam at the 127 cfs July median protected instream as of 2016 will achieve the greatest reduction in stream temperature in the middle Deschutes. At the 2016 July median protected flow of 127 cfs, 43 cfs from Tumalo Creek will produce an average 7DADM temperature of 18°C ± 1.8°C in the Deschutes River immediately downstream of the confluence. Increasing Tumalo Creek flows to 54 cfs (*i.e.*, approximately the 80% exceedence surface water availability during July, less an 18 cfs City of Bend diversion) is predicted to reduce the average 7DADM temperature in the Deschutes River below the confluence to 17.5°C ± 1.9°C. While these scenarios 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 of the Deschutes River would continue to exceed the state temperature standard by up to five degrees (at 43 cfs in Tumalo Creek), with potential peak temperatures of 22.5°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 and the Oregon Department of Environmental Quality (ODEQ) 319 Grant Program. 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 is listed 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 2012).

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 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 both 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, 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, both 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 2016 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 2016 temperature results and discuss implications for stream flow restoration.

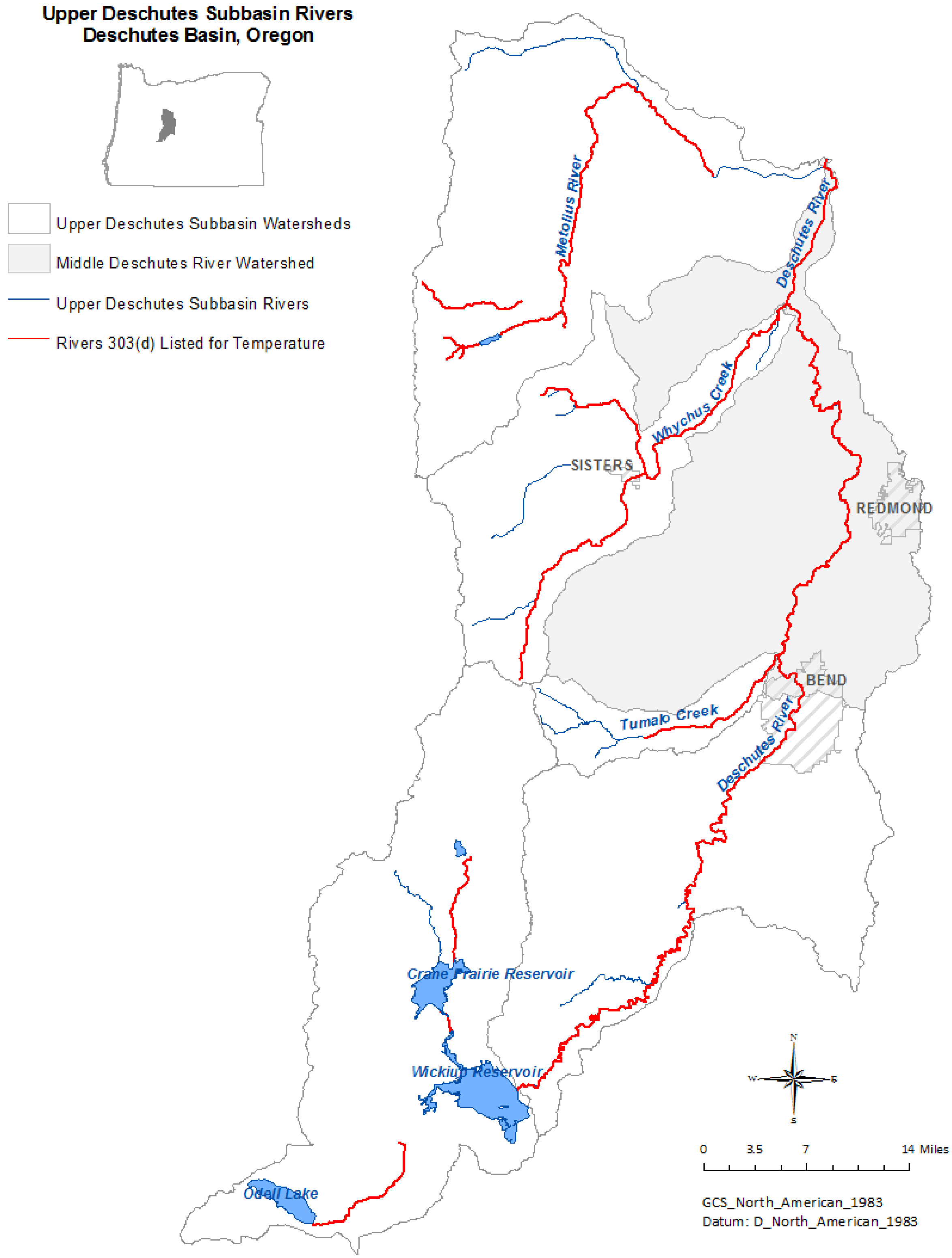


Figure 1. The Upper Deschutes subbasin and middle Deschutes River watershed**.**
Extensive reaches of most Upper Deschutes Subbasin rivers are 303(d) listed as exceeding state temperature standards for salmon and trout rearing and migration (ODEQ 2012).

2 Methods

2.1 Data Collection

2.1.1 Stream Temperature

UDWC collected and compiled continuous water temperature data for 2001-2016 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. Data for Tumalo Creek since 2009 were obtained from the City of Bend. 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 State of Oregon approved Quality Assurance Project Plan (UDWC 2008b).

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 2007-2016 for the Deschutes River, and from 2006-2016 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 2016) (Table 1; Figure 2). All Deschutes River flow data through September 2012 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, 2012 to the present and Tumalo Creek flow data from October 2008 through September 2009 and from October 2011 to the present are considered provisional and subject to change.

Table 1. Middle Deschutes River 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 2001-2015

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

X *Data available for analysis*

\- *Limited data available for analyses*

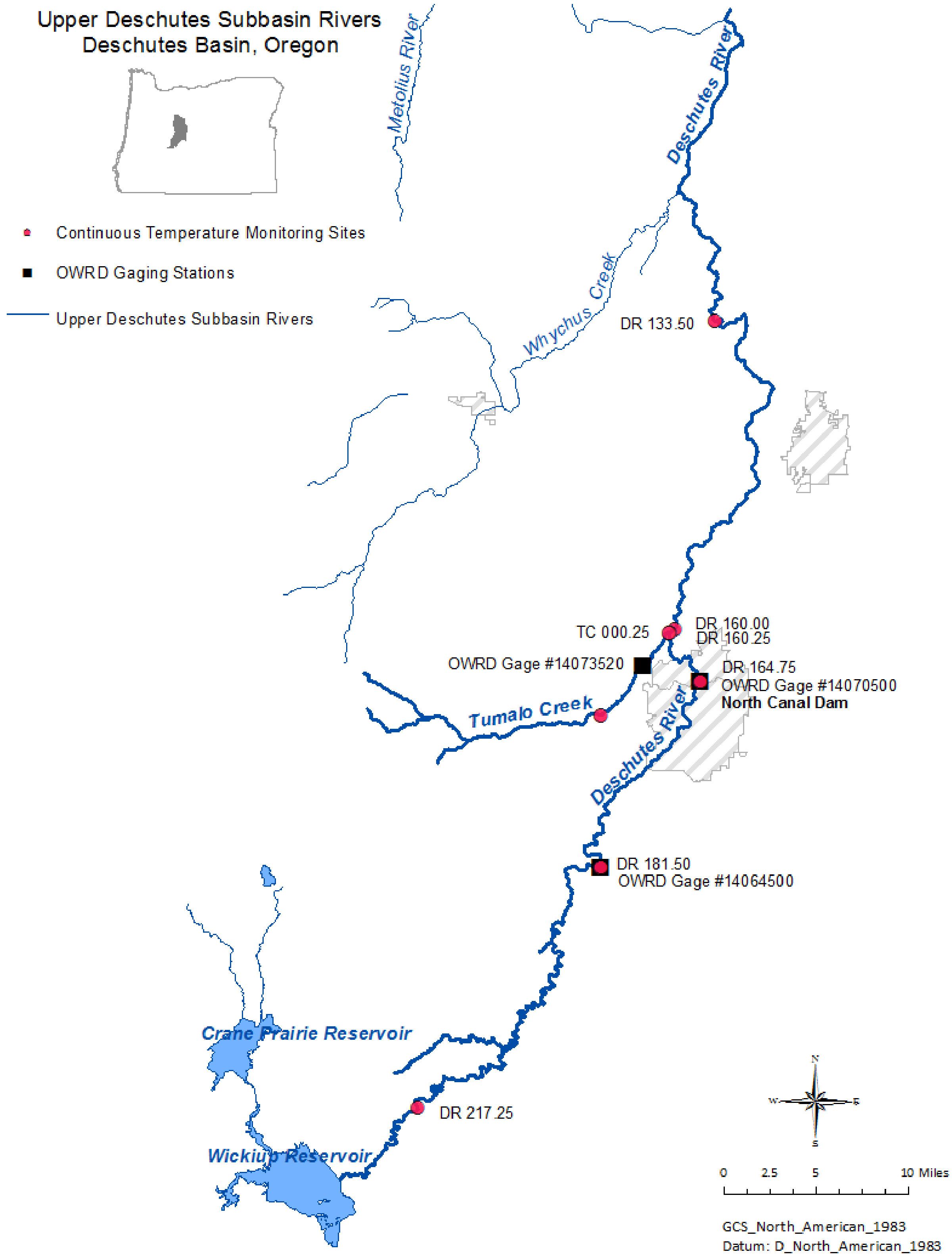


Figure 2. UDWC continuous temperature monitoring sites and OWRD stream flow gages on the middle and upper Deschutes River.

2.2 Data Analysis

2.2.1 Stream Flow Status and Trend

We evaluated July median daily protected flow and July 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. July median flow was selected as an indicator as it represents the central tendency of flow rates during one of the hottest summer months.

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 2001-2016 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 2016, 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 2001-2016 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 gauges, and 2) and used regressions of 2001-2015 July stream temperature and flow data at DR 160.25 and at TC 000.25 to illustrate the relationship between temperature and flow. 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 2001-2015 temperature and stream flow data with a mass balance approach to develop flow scenarios for the middle Deschutes River and Tumalo 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. No additional flow was protected in stream in either Tumalo Creek or in the middle Deschutes River from 2015 to 2016, July median stream flow was nearly identical in 2015 and 2016, and the range of flows was within the range already represented by the 2001-2015 regression equations; thus we did not run new regressions with 2016 data, but instead used 2016 protected and observed flows with 2001-2015 regression and mass balance results to discuss flow scenarios for meeting 18°C at DR 160.00, below the confluence of the Deschutes and Tumalo Creek.

We used 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.

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, 2015) to perform linear, quadratic, and cubic regressions for each site: 1) with each of two stream temperature metrics (7DADM and daily maximum); and 2) with each of two flow metrics (average daily flow and the natural logarithm of average daily flow), for a total of twelve models (Table 3), to evaluate which metrics and models provided the best model fit.

Table 3. Twelve regression models evaluated for the Deschutes River at DR 160.25 and for Tumalo Creek at TC 000.25.

Regression Model	
1.	7DADM ~ Flow
2.	7DADM ~ Flow + $(Flow)^2$
3.	7DADM ~ Flow + $(Flow)^2$ + $(Flow)^3$
4.	7DADM ~ LnFlow
5.	7DADM ~ LnFlow + $(LnFlow)^2$
6.	7DADM ~ LnFlow + $(LnFlow)^2$ + $(LnFlow)^3$
7.	Daily Max ~ Flow
8.	Daily Max ~ Flow + $(Flow)^2$
9.	Daily Max ~ Flow + $(Flow)^2$ + $(Flow)^3$
10.	Daily Max ~ LnFlow
11.	Daily Max ~ LnFlow + $(LnFlow)^2$
12.	Daily Max ~ LnFlow + $(LnFlow)^2$ + $(LnFlow)^3$

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 predicted v. observed values for the top three models.

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 127, 136, 160, 180, 200, and 250. 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 twenty-seven cfs represents the July median flow protected instream in the middle Deschutes in 2016.

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.

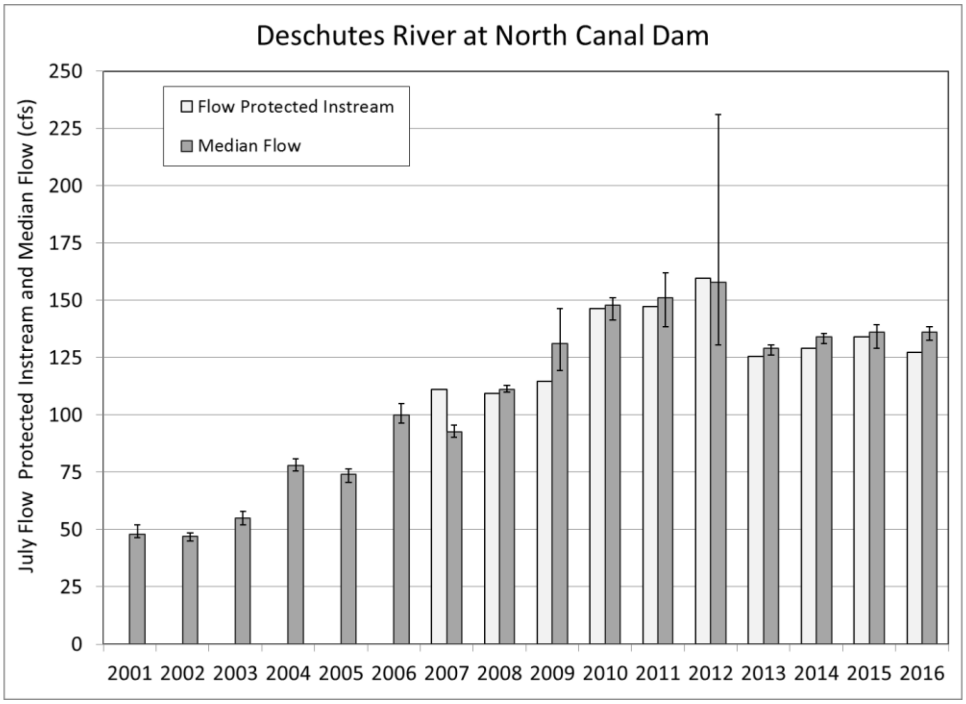
3 Results

3.1 Stream Flow Status and Trend

July median daily flow in Tumalo Creek and the Deschutes River has increased with median daily 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 from 2007 to 2016 and for Tumalo Creek from 2006 to 2016.

July median stream flow in the Deschutes River at North Canal Dam more than tripled from 2002 to 2012, from 47 cfs to 158 cfs, alongside increases in protected flow (Figure 3). Protected flow dropped sharply from 2012 to 2013, from 160 cfs to 126 cfs, 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, closely tracked by observed flows. In 2016 127 cfs were protected; July median flow was 136 cfs, maintaining the increasing trend observed since 2013. July median stream flow in the middle Deschutes from 2013 to 2016 approximated 2009 levels.

July median average daily stream flow in Tumalo Creek exceeds flow rates protected instream in most years, although the 2015 July median flow (14 cfs) fell short of the 2015 July median protected flow (15 cfs). 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 (Figure 3). Flows protected instream with pre-1961 priority dates range from 7.8 cfs in 2009 to 15.6 cfs in 2015. In 2016 the July median flow was 15 cfs, slightly higher than the 13 cfs protected in stream.



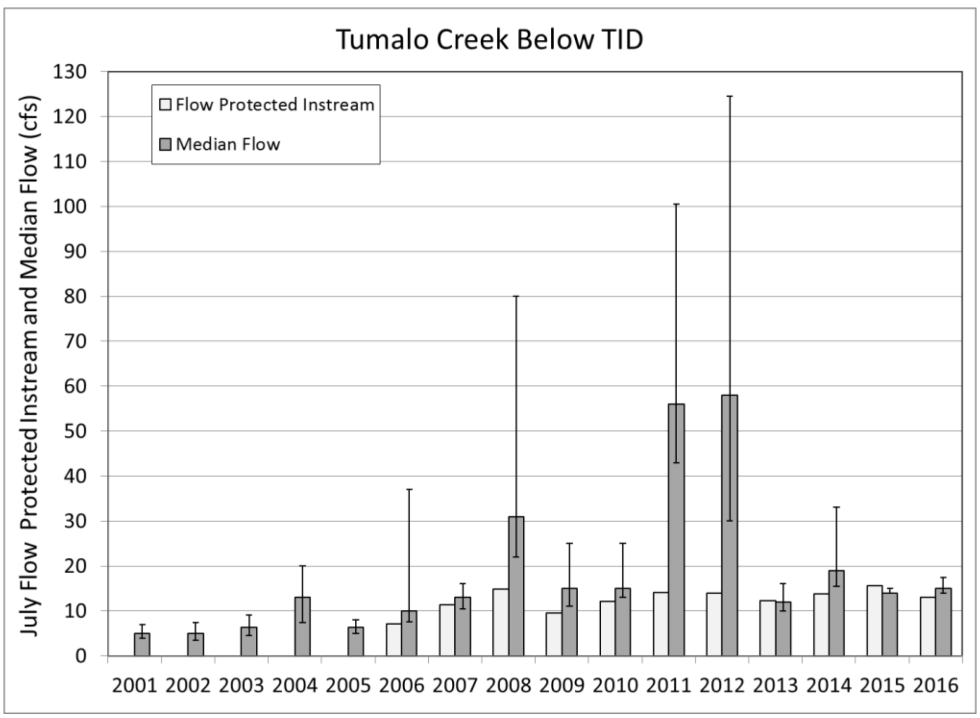


Figure 3. Deschutes River and Tumalo Creek July median protected and recorded flow, 2001-2016.

July median Deschutes River flows steadily increased from 2001 to 2012, corresponding to increases in flow protected instream. July median Deschutes River flows fell in 2013, reflecting reductions in flow leased instream and flow left instream by irrigation districts under a voluntary agreement. July median flows protected in Tumalo Creek have fluctuated between 10 and 15 cfs since 2007, with flows recorded instream varying widely.

3.2 Stream Temperature Status and Trend

Seven-day moving average maximum (7DADM) temperatures exceeded the 18°C state standard for steelhead and salmon rearing and migration at the four monitoring locations downstream of North Canal Dam in 2016, by up to 6.6°C (Figure 4), supporting the existing State of Oregon Section 303(d) listing of the middle for temperature impairment. 2016 data are not available prior to July 24 for DR 181.50, upstream of North Canal Dam, a site where temperatures have exceeded 18°C in some years (2002, 2004, 2005, 2009, 2015) but in most years remain below 18°C; temperatures at this site did not exceed 18°C after July 24. Temperatures at all four monitoring sites downstream of North Canal Dam (and below major irrigation diversions) exceeded the state standard in 2016 and in every other year for which data are available for analysis.

Percent of data days exceeding 18°C between April 30 and September 21, the dates during which stream temperatures have historically exceeded 18°C, represents the amount of time during which stream conditions may be limiting for rearing trout in the middle Deschutes River; 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 28-52% of days between April 30 and September 21, 2016 (Figure 5). At DR 133.50, temperatures exceeded 18°C for 52% of data days (76 days), the lowest percentage for all but four of fifteen years of data, exceeding 24°C (the lethal threshold for trout rearing; ODEQ 1995) for 3% (5) of those days, consistent with other years including and since 2013, 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% of data days in 2016 (74 days), lower than in 2015 but higher than in any other year for which data are available, from June 24 to July 5 and July 14 to August 29, at flows of 130 to 182 cfs (121-160 cfs from the Deschutes and 7.6-37 cfs from Tumalo Creek). Temperatures at DR 160.25 exceeded the standard for fewer data days (46%) than in all but two years; temperatures at DR 164.75, immediately downstream of North Canal Dam, exceeded the standard for more days than in all but three years, and for the same percent of days as in 2005.

Although stream temperature data available for DR 133.50 in 2015 were limited and do not provide a useful comparison to temperatures observed in other years, 2016 data for July show a decreasing trend from high 2013 and 2014 temperatures and a return to the lower, sub-24°C temperatures observed from 2008-2012 (Figure 6). August 2016 stream temperatures increased from 2014; although the August median was lower than in 2012 and similar to most years since 2006, minimum and maximum August 2017 temperatures were higher than in most years since 2006. July and August data from DR 133.50

[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.

show a consistent decreasing trend in medians and ranges of 7DADM stream temperatures from 2001 to 2016.

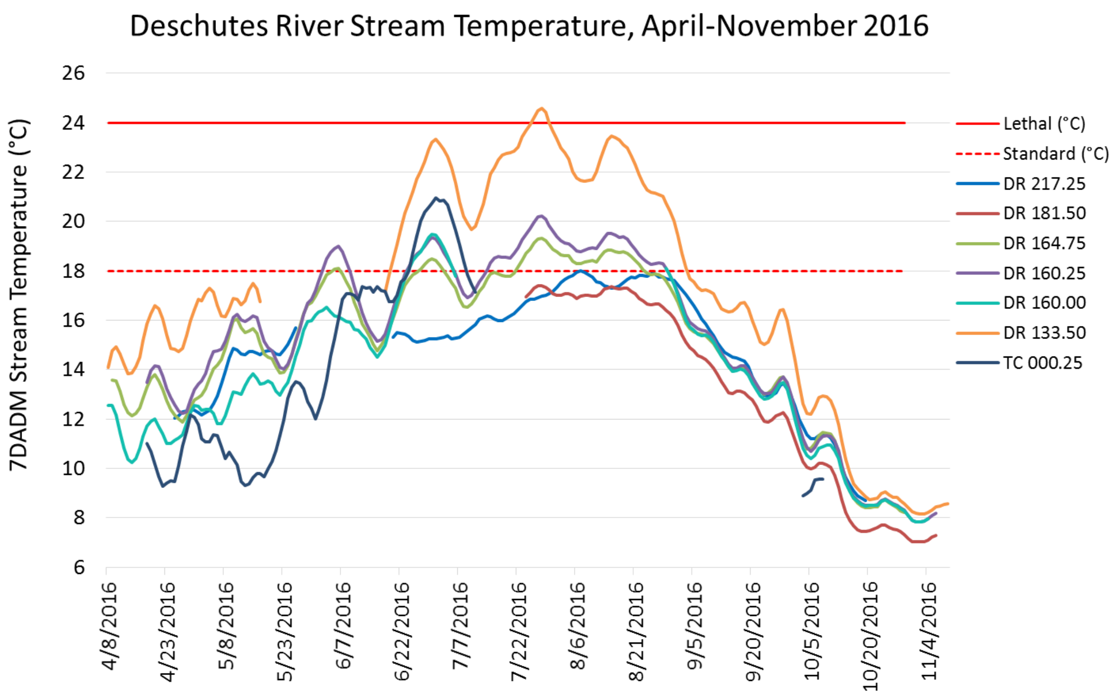


Figure 4. Deschutes River temperature April-November 2016

Temperatures exceeded the 18°C State of Oregon temperature standard (dashed red line) at four of six monitoring sites on the Deschutes River in 2016, from DR 133.50 to DR 164.75, and in Tumalo Creek just upstream of the mouth, at TC 000.25.

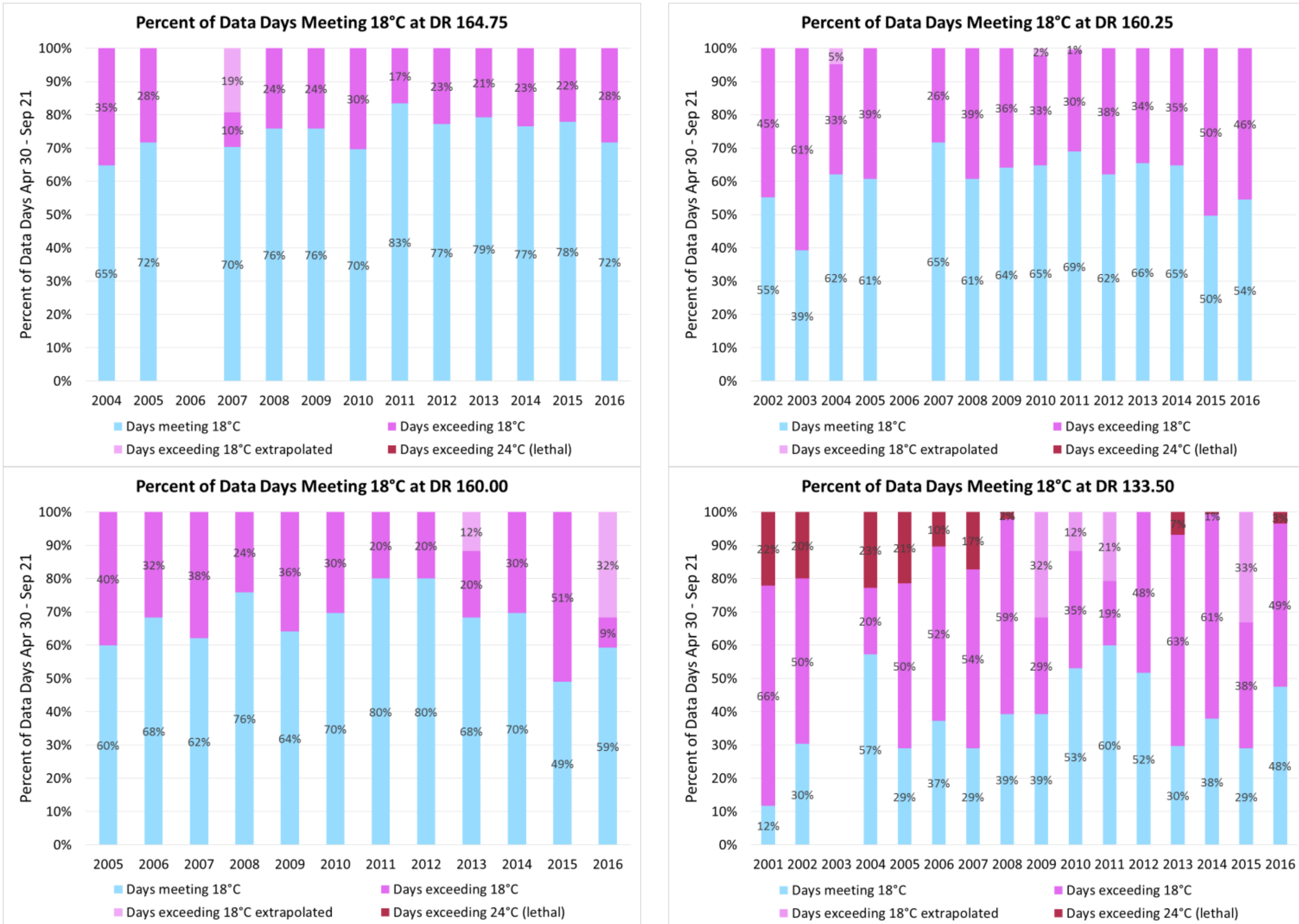
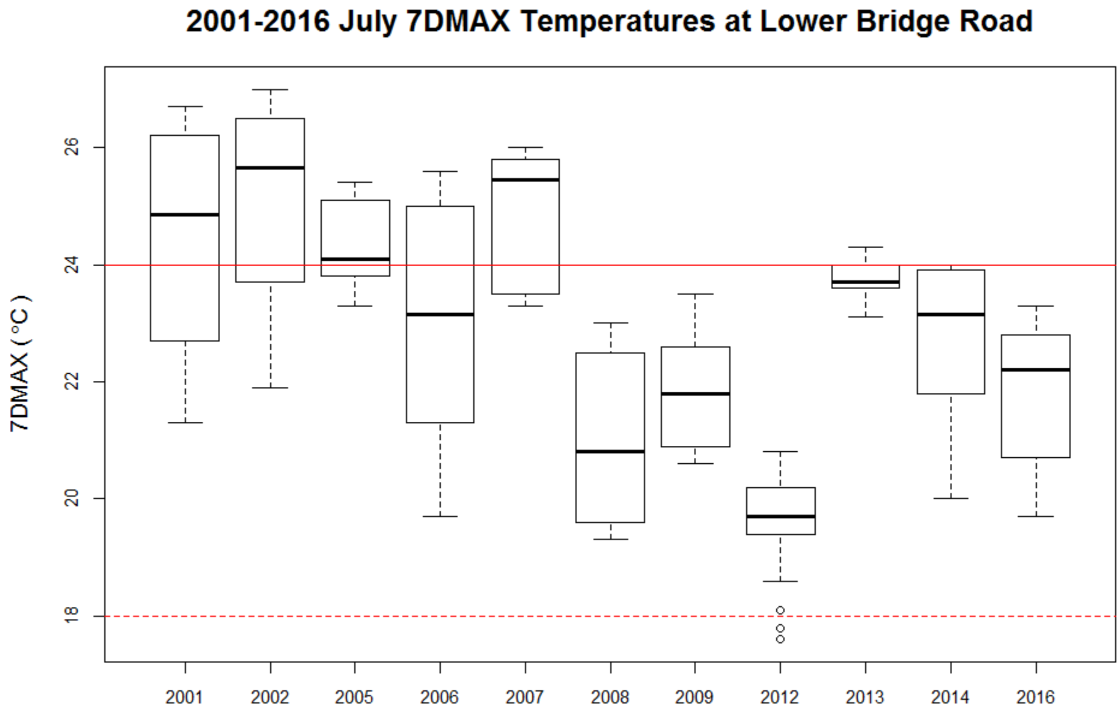


Figure 5. Percent of data days meeting and exceeding 18°C, 2001-2016.
Stream temperature downstream of Bend exceeded 18°C for 28-52% of days between April 30 and September 21, 2016. The most dramatic improvements in the percent of days meeting stream temperature have occurred at Lower Bridge, DR 133.50.

a



b

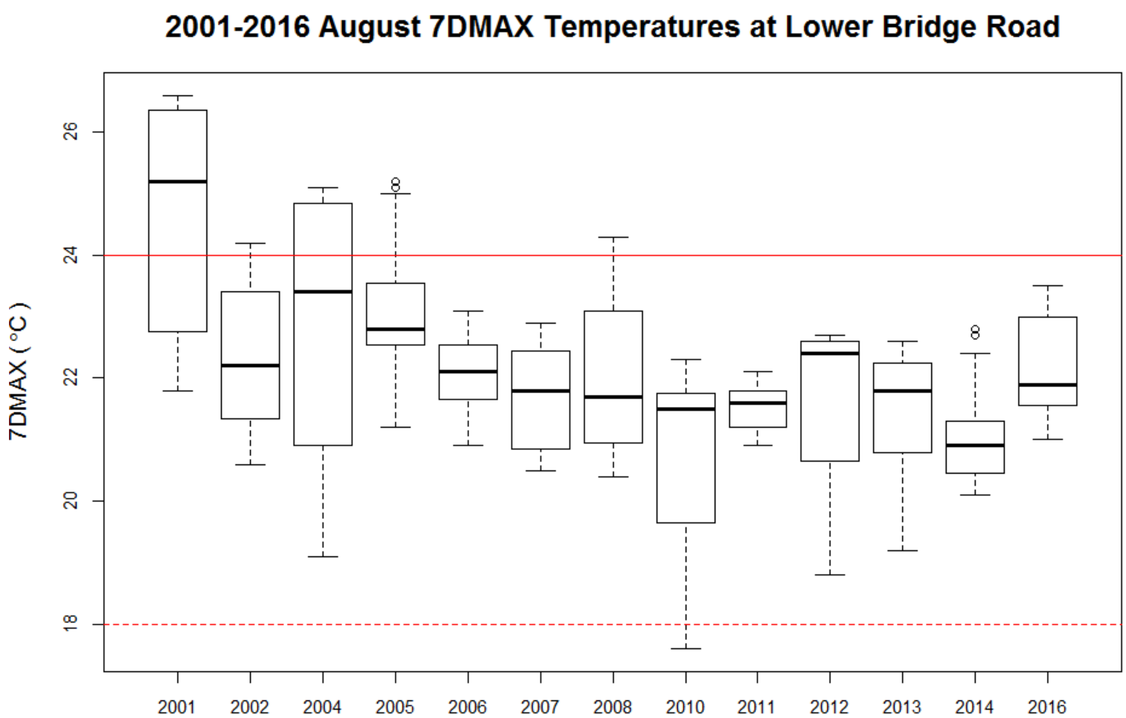


Figure 6. 2001-2016 July and August 7DADM temperatures at Lower Bridge
a) July 1-22 and b) August 6-28 7DADM temperatures at Lower Bridge (DR 133.50) chart a declining trend since 2001. Years for which data are not available or are incomplete are not represented. Despite reductions of approximately 2-4°C between 2001 and 2016, temperatures at Lower Bridge remain well above the 18°C standard (dashed red line) throughout July and August.

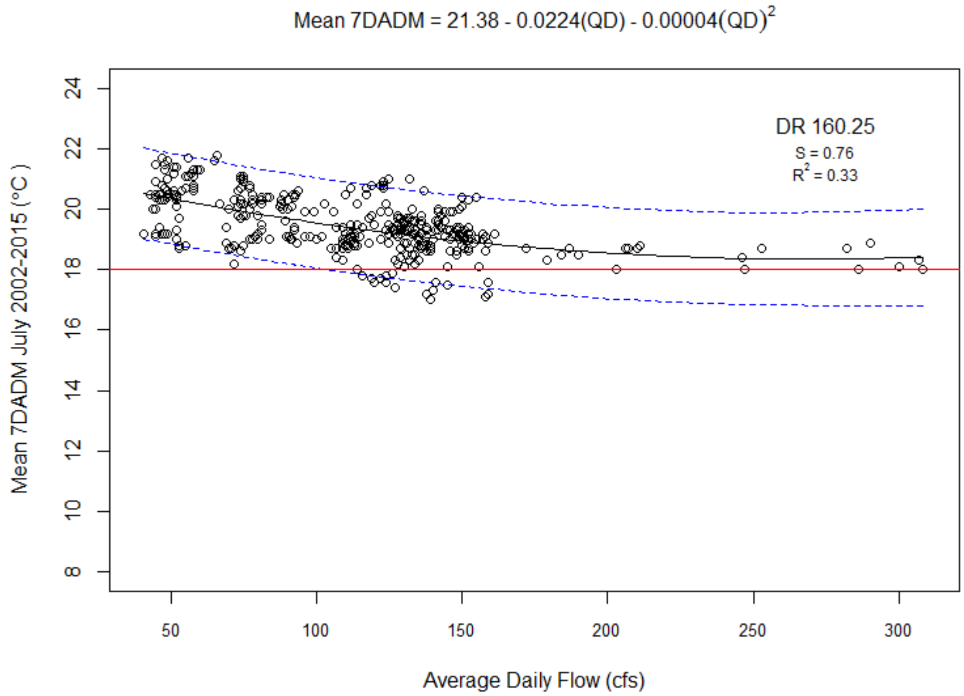
3.3 Effect of Stream Flow on Stream Temperature

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 slightly 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 2001-2015 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 increased July flows resulting in part from stream flow restoration. The range of flows annually for which temperature data are available between 2001 and 2015, included in regressions, 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. Stream flow explained 33% of the variation in stream temperature at DR 160.25 (R^2 = 0.33), and 78% of the variation in stream temperature at TC 000.25 (R^2 = 0.78) 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 20.5°C ± 1.5°C (upper interval = 22.0°C) at DR 160.25, approximately five miles downstream; flows between 222 and 308 cfs resulted in a mean temperature *only 2°C lower*, at 18.4°C ± 1.5-1.6°C (upper interval = 19.9-20°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: the lowest flow included in the analysis, 3.3 cfs, resulted in a mean temperature of 20.7°C ± 2.8°C (upper interval = 23.5°C), with flows between 106 and 129 cfs resulting in the lowest mean temperature of 11.4 ± 2.9°C (upper interval=14.3°C), a temperature reduction of more than 9°C.

a



b

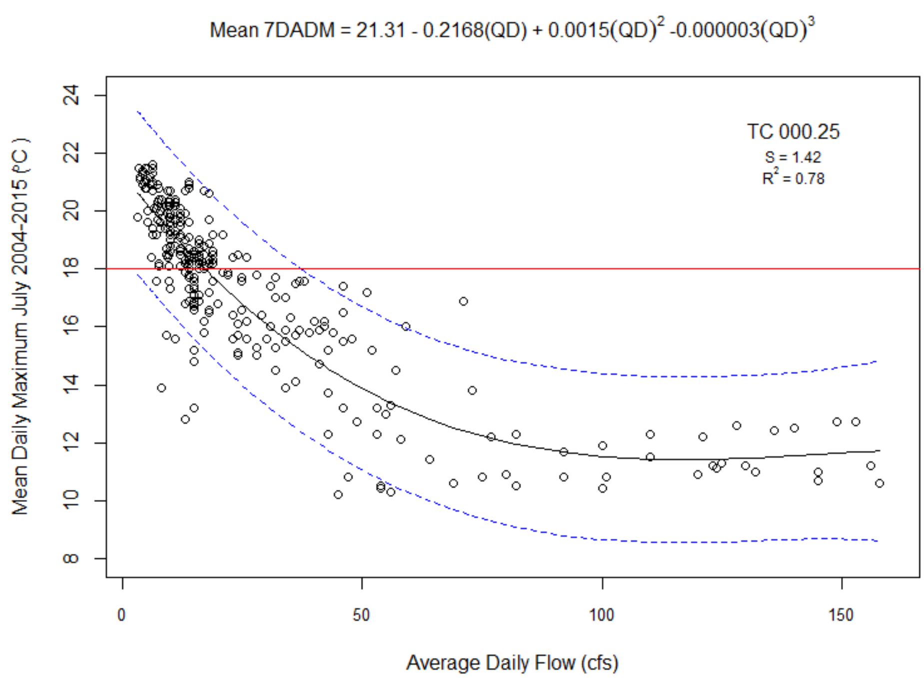


Figure 7. Temperature-flow regression models.
Regression models fitted to temperature-flow data demonstrate lower temperatures at higher flows and describe the relationship between temperature and flow observed a) during July 2002-2015 at DR 160.25, the Deschutes River upstream of the confluence with Tumalo Creek, and b) during July 2004-2015 at TC 000.25, Tumalo Creek upstream of the mouth.

3.4 Target Stream Flow

Temperature records were available from TC 000.25 for July dates from 2004 through 2015 at Tumalo Creek flows between 3.5 and 158 cfs, and for DR 160.25 for July dates from 2002-2015 at Deschutes River flows between 41 and 308 cfs. The quadratic regression of the 7DADM stream temperature on average daily flow (7DADM ~ Flow + $(\text{Flow})^2$) performed best of the twelve regression models for DR 160.25; this model demonstrates the relatively small influence of Deschutes River flow on stream temperature in July, explaining only 33% of the variation in stream temperature ($R^2 = 0.33$). For TC 000.25 stream temperature and flow data, the cubic regression of the 7DADM stream temperature on average daily flow (7DADM ~ Flow + $(\text{Flow})^2$ + $(\text{Flow})^3$) performed best of the twelve models (Table 4). Stream flow explained 75% of the variation in stream temperature at the mouth of Tumalo Creek in July ($R^2 = 0.78$). 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 both sites (Appendix A).

Table 4. The top three regression models for predicting stream temperature for July at DR 160.25 and at TC 000.25.

Regression Model	Intercept	Coefficient 1	Coefficient 2	Coefficient 3	n	df	R^2	S	AIC value
DR 160.25									
7DADM ~ Flow + $(\text{Flow})^2$	**21.38**	**-0.02243**	**0.00004**	**--**	**376**	**373**	**0.33**	**0.76**	**-204**
7DADM ~ Flow + $(\text{Flow})^2$ + $(\text{Flow})^3$	21.7	-0.03115	0.00011	-0.0000001	376	372	0.33	0.76	-203
7DADM ~ LnFlow	25.3153	-1.2608	--	--	376	374	0.32	0.76	-200
TC 000.25									
7DADM ~ Flow + $(\text{Flow})^2$ + $(\text{Flow})^3$	21.31	-0.2168	0.00153	-0.000003	**282**	**278**	**0.78**	**1.42**	**203**
7DADM ~ Flow + $(\text{Flow})^2$	20.97	-0.1806	0.001	--	282	279	0.78	1.43	206
7DADM ~ LnFlow + $(\text{LnFlow})^2$ + $(\text{LnFlow})^3$	18.4222	4.14709	-2.05195	0.18421	282	278	0.76	1.48	227

Predicted temperatures calculated for six Deschutes River flow scenarios illustrated dramatic temperature reductions in the Deschutes River below the confluence with Tumalo Creek (DR 160.00) as flows in Tumalo increased (Appendix B).

At both the July 2016 median protected flow of 127 cfs and the observed median Deschutes River flow of 136 cfs, 43 cfs in Tumalo Creek was estimated to result in an average 7DADM temperature of 18°C ± 1.8°C in the Deschutes River immediately downstream of the confluence with Tumalo Creek. If Tumalo Creek flows were further increased to 54 cfs (*i.e.*, approximately the 80% exceedance surface water availability during July, less an 18 cfs City of Bend diversion[2]) at the same Deschutes River flow, the average 7DADM temperature in the Deschutes River below the confluence with Tumalo Creek would be reduced to 17.5°C ± 1.9°C at both the July 2016 median protected and observed Deschutes River flows of 127 and 136 cfs, respectively. Increasing Deschutes River flows from the 2016 protected flow of 127 cfs to the instream flow target of 250 cfs was estimated to achieve an additional 0.7°C reduction in stream temperature at the current protected Tumalo Creek flow of 13 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 54 cfs in Tumalo Creek stream temperature in the Deschutes downstream of the confluence was estimated to be equivalent at 127 or 250 cfs in the Deschutes (Table 5).

Table 5. Estimated Deschutes River stream temperatures at four Tumalo Creek flows and two Deschutes River flows.

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)
13	127	19.1°C ± 1.6°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 ± 1.8°C	250	17.8°C ± 1.7°C
54	127	17.5°C ± 1.9°C	250	17.5°C ± 1.8°C

Increasing stream flow in Tumalo Creek from the July 2016 protected flow of 13 cfs to 54 cfs was estimated to achieve substantial 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. Between 50 and 55 cfs in Tumalo Creek, increasing Deschutes River flow from 127 to 250 cfs had no effect on temperature. Above 55 cfs in Tumalo Creek, adding stream flow in the Deschutes River required commensurate increases in Tumalo Creek flow to achieve the same temperature met at lower flows in both Tumalo Creek and in the Deschutes. For example, flows of 65 cfs in Tumalo Creek and 127 cfs in the Deschutes, or 72 cfs in Tumalo Creek and 250 cfs in the Deschutes, both resulted in an estimated stream temperature of 17°C in the Deschutes downstream of the confluence.

Heat Source model estimates are available for 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

[2] calculated as the 80% exceedence surface water availability during July (72 cfs) minus the average City of Bend net water withdrawal (18 cfs; DRC, unpublished data)

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. 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, a tenth of a degree lower than the 15.8°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. Stream flow protected in Tumalo Creek has fluctuated but increased in 2015 to the highest flow protected since restoration began, falling slightly in 2016. Actual Tumalo Creek July median instream flow in 2016 was slightly higher than the July 2016 median protected flow.

4.2 Temperature Status and Trend

Stream temperature in the middle Deschutes River exceeded the 18°C state standard protecting salmon and trout rearing and migration for 28-52% of days April 30 to September 21 in 2016, at all four Deschutes River monitoring locations downstream of North Canal Dam. Conversely, stream temperature was 18°C or lower, representing optimal rearing conditions for trout, for 48-72% of days in 2016, and for 48-59% of data days downstream of points of stream flow restoration at North Canal Dam and the Tumalo Irrigation District diversion. These data represent an improvement over 2015 conditions, but fail to attain even 2014 temperatures much less reverse the continued decline from 2011 conditions.

Given July median flows of 136 cfs in the Deschutes River and 15 cfs in Tumalo Creek, temperatures above 18°C at DR 160.00 for 41% of days in 2016, including every day in July, are consistent with mass balance results which predict 42 cfs required in Tumalo Creek at 136 cfs in the Deschutes to achieve 18°C at this site.

Although stream temperatures continue to exceed 24°C at Lower Bridge, the number and percent of days for which temperatures are above 24°C have been far lower since 2013 than prior to 2008, reducing the amount time each year during which fish are exposed to potentially lethal stream conditions. This reduction coincides with increases in stream flow, both protected and observed, in the Deschutes River at North Canal Dam and in Tumalo Creek.

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 2013-2016, the proportion of days exceeding the 18°C state standard at DR 133.50 has fluctuated by 20%, between 29% and 29%, over those years. This trend might result from variation in flow in other months, but it could also signal a response to warmer air temperatures associated with global climate change; 2016, at 49% of days exceeding 18°C at Lower Bridge on the Deschutes, ranked as the hottest year on record (NASA 2017). Stream temperature at DR 164.75, which we assume to be strongly influenced by stream temperature in the Deschutes above North Canal Dam, also exceeded 18°C for more days in 2016 than in most other years, potentially in response to warmer air temperatures.

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 2001-2015 at DR 160.25 and at TC 000.25 also show lower temperatures occurring at higher flows. Stream flow explained 33% and 78% of variation in stream temperature in the middle Deschutes and in Tumalo Creek, respectively ($R^2 = 0.33$; $R^2 = 0.78$), providing statistical support for the role of higher stream flows in reducing stream temperature. Together, these data provide support for higher protected flows guaranteeing higher baseflows and lower stream temperatures.

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 136 cfs below North Canal Dam, the median flow observed in July 2016. Increasing Tumalo Creek flows to 54 cfs, the 80% exceedance surface water availability during July assuming a City of Bend diversion of 18 cfs, is estimated to reduce stream temperature in the Deschutes below the confluence to 17.5°C ±1.8°C 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 the 250 cfs pending instream water right in the Deschutes. In light of the 2016 status of protected flows, 127 cfs in the Deschutes and 13 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 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.

Although higher flows will have some effect in reducing the rate of warming, mass balance and Heat Source model results suggest that current instream water right flows for the middle Deschutes River and for Tumalo Creek may be insufficient to meet the state temperature standard in some reaches of the middle Deschutes River between Tumalo Creek and Whychus Creek while Deschutes River water continues to be subject to heating in Wickiup and Crane Prairie reservoirs prior to being released downstream. Preliminary analysis of stream temperature from 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).

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, 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 7.9 m narrower during irrigation season than during water storage season, demonstrating the large reduction in habitat quantity that results from irrigation withdrawals at North Canal Dam. Increasing Tumalo Creek flows at the expense of further flow restoration in the Deschutes River at North Canal Dam will achieve temperature reductions in Tumalo Creek and in the Deschutes 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. However, this approach should take into account potential long-term trade-offs of deferring greater gains in stream flow volume, and corresponding habitat benefits, in the Deschutes downstream of North Canal Dam, in favor of achieving lower temperatures at lower flows.

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

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 (±)	Flow (cfs)	Mean Temp (7DMAX)	PI (±)
3	20.7	2.8	**56**	13.4	2.8	**109**	11.4	2.9			
4	20.5	2.8	**57**	13.3	2.8	**110**	11.4	2.9			
5	20.3	2.8	**58**	13.2	2.8	**111**	11.4	2.9			
6	20.1	2.8	**59**	13.2	2.8	**112**	11.4	2.9			
7	19.9	2.8	**60**	13.1	2.8	**113**	11.4	2.9			
8	19.7	2.8	**61**	13.0	2.8	**114**	11.4	2.9			
9	19.5	2.8	**62**	12.9	2.8	**115**	11.4	2.9			
10	19.3	2.8	**63**	12.9	2.8	**116**	11.4	2.9			
11	19.1	2.8	**64**	12.8	2.8	**117**	11.4	2.9			
12	18.9	2.8	**65**	12.8	2.8	**118**	11.4	2.9			
13	18.7	2.8	**66**	12.7	2.8	**119**	11.4	2.9			
14	18.6	2.8	**67**	12.6	2.8	**120**	11.4	2.9			
15	18.4	2.8	**68**	12.6	2.8	**121**	11.4	2.9			
16	18.2	2.8	**69**	12.5	2.8	**122**	11.4	2.9			
17	18.1	2.8	**70**	12.5	2.8	**123**	11.4	2.9			
18	17.9	2.8	**71**	12.4	2.8	**124**	11.4	2.9			
19	17.7	2.8	**72**	12.4	2.8	**125**	11.4	2.9			
20	17.6	2.8	**73**	12.3	2.8	**126**	11.4	2.9			
21	17.4	2.8	**74**	12.3	2.8	**127**	11.4	2.9			
22	17.2	2.8	**75**	12.2	2.8	**128**	11.4	2.9			
23	17.1	2.8	**76**	12.2	2.8	**129**	11.4	2.9			
24	16.9	2.8	**77**	12.1	2.8	**130**	11.5	2.9			
25	16.8	2.8	**78**	12.1	2.8	**131**	11.5	2.9			
26	16.7	2.8	**79**	12.1	2.8	**132**	11.5	2.9			
27	16.5	2.8	**80**	12.0	2.8	**133**	11.5	2.9			
28	16.4	2.8	**81**	12.0	2.8	**134**	11.5	2.9			
29	16.2	2.8	**82**	11.9	2.9	**135**	11.5	2.9			
30	16.1	2.8	**83**	11.9	2.9	**136**	11.5	2.9			
31	16.0	2.8	**84**	11.9	2.9	**137**	11.5	2.9			
32	15.8	2.8	**85**	11.8	2.9	**138**	11.5	2.9			
33	15.7	2.8	**86**	11.8	2.9	**139**	11.5	2.9			
34	15.6	2.8	**87**	11.8	2.9	**140**	11.5	2.9			
35	15.5	2.8	**88**	11.8	2.9	**141**	11.5	2.9			
36	15.3	2.8	**89**	11.7	2.9	**142**	11.6	2.9			
37	15.2	2.8	**90**	11.7	2.9	**143**	11.6	2.9			
38	15.1	2.8	**91**	11.7	2.9	**144**	11.6	2.9			
39	15.0	2.8	**92**	11.7	2.9	**145**	11.6	2.9			
40	14.9	2.8	**93**	11.6	2.9	**146**	11.6	2.9			
41	14.8	2.8	**94**	11.6	2.9	**147**	11.6	2.9			
42	14.7	2.8	**95**	11.6	2.9	**148**	11.6	2.9			
43	14.6	2.8	**96**	11.6	2.9	**149**	11.6	3.0			
44	14.4	2.8	**97**	11.6	2.9	**150**	11.6	3.0			
45	14.3	2.8	**98**	11.5	2.9	**151**	11.6	3.0			
46	14.2	2.8	**99**	11.5	2.9	**152**	11.7	3.0			
47	14.2	2.8	**100**	11.5	2.9	**153**	11.7	3.0			
48	14.1	2.8	**101**	11.5	2.9	**154**	11.7	3.0			
49	14.0	2.8	**102**	11.5	2.9	**155**	11.7	3.0			
50	13.9	2.8	**103**	11.5	2.9	**156**	11.7	3.1			
51	13.8	2.8	**104**	11.5	2.9	**157**	11.7	3.1			
52	13.7	2.8	**105**	11.5	2.9	**158**	11.7	3.1			
53	13.6	2.8	**106**	11.4	2.9						
54	13.5	2.8	**107**	11.4	2.9						
55	13.5	2.8	**108**	11.4	2.9						

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)	127	136	160	180	200	250	Flow (cfs)	127	136	160	180	200	250
10	19.2	19.1	18.9	18.7	18.6	18.4	**56**	17.4	17.4	17.4	17.4	17.4	17.5
11	19.2	19.1	18.9	18.7	18.6	18.4	**57**	17.4	17.4	17.4	17.4	17.4	17.4
12	19.2	19.1	18.9	18.7	18.6	18.4	**58**	17.3	17.3	17.4	17.4	17.4	17.4
13	19.1	19.0	18.8	18.7	18.6	18.4	**59**	17.3	17.3	17.3	17.3	17.3	17.4
14	19.1	19.0	18.8	18.7	18.6	18.4	**60**	17.2	17.2	17.3	17.3	17.3	17.3
15	19.1	19.0	18.8	18.7	18.5	18.4	**61**	17.2	17.2	17.2	17.3	17.3	17.3
16	19.1	19.0	18.8	18.6	18.5	18.4	**62**	17.1	17.2	17.2	17.2	17.2	17.3
17	19.1	19.0	18.8	18.6	18.5	18.3	**63**	17.1	17.1	17.2	17.2	17.2	17.3
18	19.0	18.9	18.8	18.6	18.5	18.3	**64**	17.1	17.1	17.1	17.1	17.2	17.2
19	19.0	18.9	18.7	18.6	18.5	18.3	**65**	17.0	17.0	17.1	17.1	17.1	17.2
20	19.0	18.9	18.7	18.6	18.5	18.3	**66**	17.0	17.0	17.1	17.1	17.1	17.2
21	18.9	18.9	18.7	18.6	18.4	18.3	**67**	16.9	16.9	17.0	17.0	17.1	17.2
22	18.9	18.8	18.7	18.5	18.4	18.3	**68**	16.9	16.9	17.0	17.0	17.0	17.1
23	18.9	18.8	18.6	18.5	18.4	18.3	**69**	16.8	16.9	16.9	17.0	17.0	17.1
24	18.8	18.8	18.6	18.5	18.4	18.2	**70**	16.8	16.8	16.9	16.9	17.0	17.1
25	18.8	18.7	18.6	18.5	18.4	18.2	**71**	16.8	16.8	16.9	16.9	16.9	17.1
26	18.8	18.7	18.5	18.4	18.3	18.2	**72**	16.7	16.8	16.8	16.9	16.9	17.0
27	18.7	18.7	18.5	18.4	18.3	18.2	**73**	16.7	16.7	16.8	16.8	16.9	17.0
28	18.7	18.6	18.5	18.4	18.3	18.2	**74**	16.6	16.7	16.8	16.8	16.9	17.0
29	18.6	18.6	18.5	18.3	18.3	18.1	**75**	16.6	16.6	16.7	16.8	16.8	16.9
30	18.6	18.5	18.4	18.3	18.2	18.1	**76**	16.6	16.6	16.7	16.8	16.8	16.9
31	18.6	18.5	18.4	18.3	18.2	18.1	**77**	16.5	16.6	16.7	16.7	16.8	16.9
32	18.5	18.5	18.3	18.3	18.2	18.1	**78**	16.5	16.5	16.6	16.7	16.7	16.9
33	18.5	18.4	18.3	18.2	18.2	18.1	**79**	16.5	16.5	16.6	16.7	16.7	16.9
34	18.4	18.4	18.3	18.2	18.1	18.0	**80**	16.4	16.5	16.6	16.6	16.7	16.8
35	18.4	18.3	18.2	18.2	18.1	18.0	**81**	16.4	16.4	16.5	16.6	16.7	16.8
36	18.3	18.3	18.2	18.1	18.1	18.0	**82**	16.3	16.4	16.5	16.6	16.6	16.8
37	18.3	18.2	18.2	18.1	18.0	18.0	**83**	16.3	16.4	16.5	16.5	16.6	16.8
38	18.2	18.2	18.1	18.1	18.0	17.9	**84**	16.3	16.3	16.5	16.5	16.6	16.7
39	18.2	18.2	18.1	18.0	18.0	17.9	**85**	16.2	16.3	16.4	16.5	16.6	16.7
40	18.2	18.1	18.1	18.0	17.9	17.9	**86**	16.2	16.3	16.4	16.5	16.5	16.7
41	18.1	18.1	18.0	18.0	17.9	17.9	**87**	16.2	16.2	16.4	16.4	16.5	16.7
42	18.1	18.0	18.0	17.9	17.9	17.8	**88**	16.1	16.2	16.3	16.4	16.5	16.6
43	18.0	18.0	17.9	17.9	17.8	17.8	**89**	16.1	16.2	16.3	16.4	16.5	16.6
44	18.0	17.9	17.9	17.9	17.8	17.8	**90**	16.1	16.1	16.3	16.4	16.4	16.6
45	17.9	17.9	17.9	17.8	17.8	17.8	**91**	16.1	16.1	16.3	16.3	16.4	16.6
46	17.9	17.9	17.8	17.8	17.7	17.7	**92**	16.0	16.1	16.2	16.3	16.4	16.6
47	17.8	17.8	17.8	17.7	17.7	17.7	**93**	16.0	16.1	16.2	16.3	16.4	16.5
48	17.8	17.8	17.7	17.7	17.7	17.7	**94**	16.0	16.0	16.2	16.3	16.3	16.5
49	17.7	17.7	17.7	17.7	17.7	17.6	**95**	15.9	16.0	16.1	16.2	16.3	16.5
50	17.7	17.7	17.7	17.6	17.6	17.6	**96**	15.9	16.0	16.1	16.2	16.3	16.5
51	17.6	17.6	17.6	17.6	17.6	17.6	**97**	15.9	15.9	16.1	16.2	16.3	16.5
52	17.6	17.6	17.6	17.6	17.6	17.6	**98**	15.9	15.9	16.1	16.2	16.2	16.4
53	17.5	17.5	17.5	17.5	17.5	17.5	**99**	15.8	15.8	15.9	16.1	16.1	16.4
54	17.5	17.5	17.5	17.5	17.5	17.5	**100**	15.8	15.8	15.9	16.0	16.1	16.3
55	17.5	17.5	17.5	17.5	17.5	17.5							