Upper Deschutes Watershed Council

Water Quality Monitoring Program

2012 Technical Report

Instream Flow Restoration and Temperature Responses

Middle Deschutes River, Deschutes Basin, Oregon

Prepared by

Lauren Mork

Ryan Houston

Upper Deschutes Watershed Council

www.RestoreTheDeschutes.org

Prepared for

Deschutes River Conservancy

www.deschutesriver.org

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Since 1996, the Deschutes River Conservancy (DRC) has engaged in efforts to restore summer streamflow in the Middle Deschutes River and lower Tumalo Creek through a variety of techniques, including conservation, leasing, and acquisition. The DRC has identified streamflow restoration in the Middle Deschutes and Tumalo Creek as a priority because very low summer flows 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 of streamflow restoration efforts in reducing temperature in the Middle Deschutes, the DRC, its funders, and other partners have been interested in tracking 1) whether cumulative streamflow restoration actions have reduced water temperatures in downstream reaches of the river, 2) whether reductions in temperature, if observed, can be attributed to streamflow restoration projects, and 3) how streamflow restoration in the Middle Deschutes and in Tumalo Creek may differentially affect stream temperature. Since 2008 the DRC has partnered with the Upper Deschutes Watershed Council (UDWC) to conduct temperature monitoring to investigate potential temperature changes associated with streamflow restoration projects. This ongoing monitoring effort incorporates data collected from 2001 to 2012 to address the following key questions:

1) Temperature status: What was the status of Middle Deschutes River water temperatures relative to the State of Oregon 18°C/64°F standard as of 2012?

   Temperatures downstream of Bend exceeded the 18°C/64°F state standard set to protect salmon and trout rearing and migration in every year for which data are available for analysis, consistent with the existing Clean Water Act Section 303(d) listing for temperature impairment along the Deschutes River. However, temperatures in the Deschutes downstream of Tumalo Creek remained below 18°C during July for the second year in a row, at combined Deschutes River and Tumalo Creek flows between 223 and 362 cfs, including Tumalo Creek flows of 32 and 153 cfs. And, although summer temperatures continue to exceed the state standard, with August 2012 median 7DMAX temperature at Lower Bridge Road higher than in previous years, temperatures at this site demonstrate a declining trend since 2001.These data suggest that higher flows resulting from streamflow restoration are resulting in temperatures that meet or are very close to the state standard at some sites, but that still higher flows achieved through additional streamflow restoration will be required to meet the 18°C standard at the most impaired sites. Until these flows are achieved, temperature data suggest that the middle Deschutes River will continue to exceed the state temperature standard during the summer months.

2) Restoration effectiveness: Have cumulative increases in streamflow reduced water temperatures at key locations along the Middle Deschutes?

Restoration effectiveness analysis indicated that temperatures immediately downstream of the confluence with Tumalo Creek cooled in response to cumulative increases in combined streamflow from North Canal Dam and from Tumalo Creek from 2005 to 2012. The temperature response observed in the Tumalo reach suggests a strong cooling effect as a result of the increased contribution of cool Tumalo Creek flows in combination with the increase in flows from the Deschutes. Streamflow restoration projects that strategically increase flows in Tumalo Creek in proportion to the flow contribution of the upper Deschutes at North Canal Dam may therefore be an effective approach to maximize reductions in temperature in the middle Deschutes downstream of Tumalo Creek.

Cumulative increases in streamflow from North Canal Dam alone had no effect on stream temperature in the Deschutes reach immediately downstream of the dam. The lack of a temperature response in this reach suggests the approximately five miles between the dam and the downstream end of the reach is too short a distance to realize any temperature benefit of a reduced rate of warming associated with higher flows. Increased flows in the Deschutes at North Canal Dam are nonetheless anticipated to contribute to cooler downstream temperatures as a result of a reduced rate of warming.

3) Target streamflow: What flow scenarios for the Deschutes River and Tumalo Creek will achieve the 18°C temperature standard between North Canal Dam and Lower Bridge Road?

We used temperature estimates calculated from regression of temperature-flow data in a mass balance equation to develop flow scenarios for the Deschutes River and Tumalo Creek that would achieve the 18°C state standard temperature in the Deschutes below the confluence with Tumalo Creek. Mass balance equation results suggest that the Deschutes River flow target of 250 cfs will achieve the 18°C standard immediately downstream of the confluence with Tumalo Creek at 26 cfs in Tumalo Creek. Alternative flow scenarios that will result in 18°C at this location include the 32 cfs instream water right flow in Tumalo Creek and Deschutes flows of 220 cfs, or the current protected Deschutes flow of 160 cfs and 38 cfs in Tumalo Creek.

As flows in Tumalo Creek increase, temperature benefits of higher flows in the Deschutes diminish and ultimately are lost altogether, such that increasing flows in the Deschutes requires commensurate increases in Tumalo flows to achieve the same temperature benefits obtained at lower Deschutes and Tumalo flows. These results provide support for the conclusion that achieving temperature reductions in the Deschutes may be accelerated by strategically prioritizing Tumalo Creek water transactions; preferentially increasing flows in Tumalo Creek over restoring streamflow in the Deschutes may achieve greater temperature benefits at an equivalent cost.

Temperatures thus remain elevated in the middle Deschutes River, exceeding the state standard and likely compromising rearing and migration habitat for salmon and trout, but showed substantial improvement with higher combined flows from the Deschutes and from Tumalo in July 2011 and 2012.

This trend supports both the cooling effect observed in the Tumalo restoration reach from 2005 to 2012 in response to cumulative increases in combined streamflow as well as the temperature estimates from the mass balance equation that illustrate the temperature gains of higher Tumalo flows. BACI analysis, mass balance results, and descriptive exploration of temperature and flow data all point to strategically increasing flows in Tumalo as a means to maximize temperature reductions in the Deschutes downstream of the confluence with Tumalo Creek. Additionally, particularly at the low flow currently protected in Tumalo Creek, increasing flows in the Deschutes is also predicted to result in some temperature benefits.

Whether or not it is possible to meet the state temperature standard along every mile of the Middle Deschutes between North Canal Dam and Lower Bridge Road, increases in flow that approach the instream water right and DRC flow targets in both the Deschutes and in Tumalo Creek will nonetheless result in substantial ecological benefits. Altered flows affect stream width and depth, which in turn determine 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 are less well understood. Data on fish response to increased flows and use of habitat including cold-water refugia, to be collected by ODFW in the Middle Deschutes and in Tumalo Creek between 2012 and 2016, will contribute to the ability of restoration partners to discern how flow and temperature affect habitat availability and use and in which locations, and refine streamflow targets accordingly to maximize ecological benefits. Approaches that prioritize increasing Tumalo Creek flows to advance temperature gains should take into account potential strategic long-term trade-offs of deferring greater gains in streamflow volume, and corresponding habitat benefits, in favor of achieving lower temperatures at lower flows.

Acknowledgments

Deschutes River Conservancy provided funding in support of research and analyses that form the basis for this report. Water quality monitoring conducted by Upper Deschutes Watershed Council is funded in large part by the Oregon Watershed Enhancement Board and the Oregon Department of Environmental Quality (ODEQ) 319 Grant Program; their generous support has been instrumental in the data collection and analysis informing this report. Monitoring by the City of Bend, ODEQ, Oregon State University (OSU), Oregon Water Resources Department (OWRD), and DRC has contributed invaluable data to this long-term effort. Many thanks to members of the Water Quality Committee and contributing partners who provided expertise, insight, and time in support of the development of the UDWC Water Quality Monitoring Program from which the data and analyses included here emerged. Special thanks to Lesley Jones, who spearheaded and grew the UDWC Water Quality Monitoring Program to produce rigorous statistical analyses of the effects of streamflow restoration on temperature, and to Mike Cole of Cole Ecological Inc., who provided excellent insight into and thoughtful review of the analyses presented.

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
7DMAX	Seven Day Moving Average Maximum
BACI	Before After Control Impact
df	Degrees of freedom
CI	Confidence interval
cfs	Cubic feet per second
Ln	Natural logarithm
OAR	Oregon Administrative Rules
QA/QC	Quality assurance / quality control
QD	Average daily flow
S	Standard distance from regression line
StDev	Standard deviation from mean
TMDL	Total Maximum Daily Load

1. Introduction

The Middle 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 (Map 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 (Map 2).

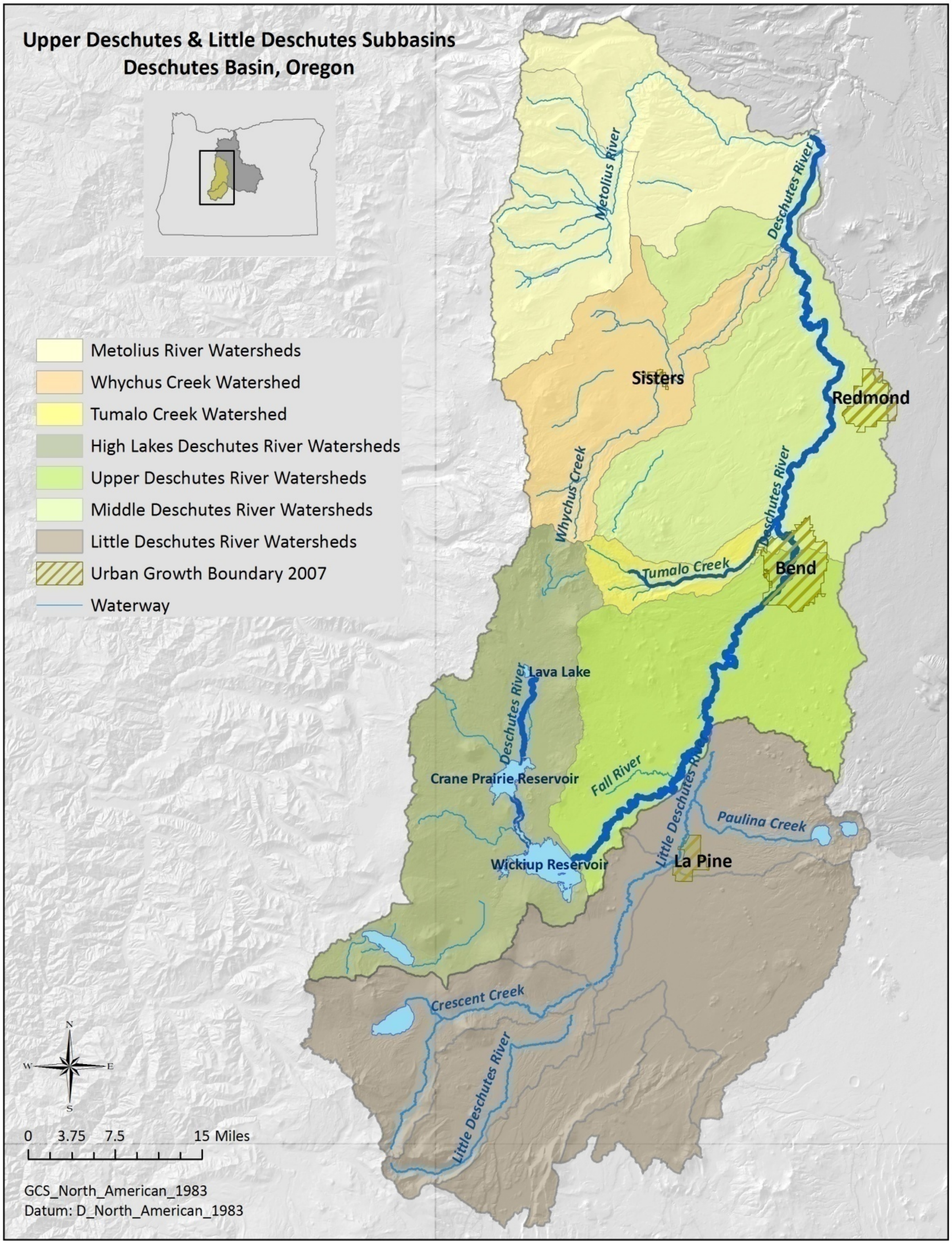
Since 1996, the Deschutes River Conservancy (DRC) has engaged in efforts to restore summer streamflow in the Middle Deschutes River and lower Tumalo Creek. Through a variety of techniques, including conservation, leasing, and acquisition, the DRC has successfully protected approximately 160 cubic feet per second (cfs) of streamflow in-stream in the Middle Deschutes River and more than 10 cfs in Tumalo Creek. As a result, July median average daily streamflow entering the Deschutes River from Tumalo Creek has increased from 5 cfs in 2001 to 58 cfs in 2012, and July median average daily flow in the Deschutes River at North Canal Dam has increased from 48 cfs in 2001 to 158 cfs in 2012. Combined, streamflow restoration efforts at each of these locations have contributed to a 206 cfs increase in middle Deschutes River July median average daily flows, from 53 cfs in 2001 to 259 cfs in 2012. Because flows downstream of these locations have historically resulted 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 because downstream temperatures are driven by streamflow and temperature in these two reaches, DRC has prioritized streamflow restoration in these reaches. DRC streamflow restoration efforts aim to meet the State of Oregon instream flow targets of 250 cfs in the Middle Deschutes from North Canal Dam (RM 165) to Round Butte Reservoir (RM 119), and 32 cfs in Tumalo Creek from the South Fork of Tumalo Creek to the mouth, in order to, among other objectives, improve water temperature to support sustainable anadromous and resident fish populations.

Prior analyses of water temperature in the Middle Deschutes and Tumalo Creek (UDWC, 2012) have suggested that the relative contribution of flows from the two waterways substantially influences the effects of increased flow on temperature downstream of the confluence. Middle Deschutes water flowing over North Canal Dam is consistently at or above 18°C in July (UDWC, 2006) (ODEQ, 2004) (UDWC, unpublished data). Tumalo Creek, approximately five miles downstream of the dam, is the only tributary and source of additional flow between North Canal Dam and Lower Bridge Road, approximately 32 miles downstream, where temperatures are historically highest and conditions worst for fish. Increasing the total volume of flow between North Canal Dam and Lower Bridge Road is anticipated to lower the rate of warming in this reach, making some contribution to reducing temperatures downstream. Increases in flows that are already at or around 18°C at North Canal Dam will nonetheless be minimally effective in achieving the necessary temperature reductions to result in that same temperature 32 miles downstream. While the temperature of flows entering the Deschutes from Tumalo Creek varies with volume, Tumalo Creek flows are typically substantially cooler than flows in the Deschutes above the confluence (UDWC, 2006). Increasing flows in Tumalo Creek may therefore represent an opportunity to achieve the greatest cooling effect in the Middle Deschutes between

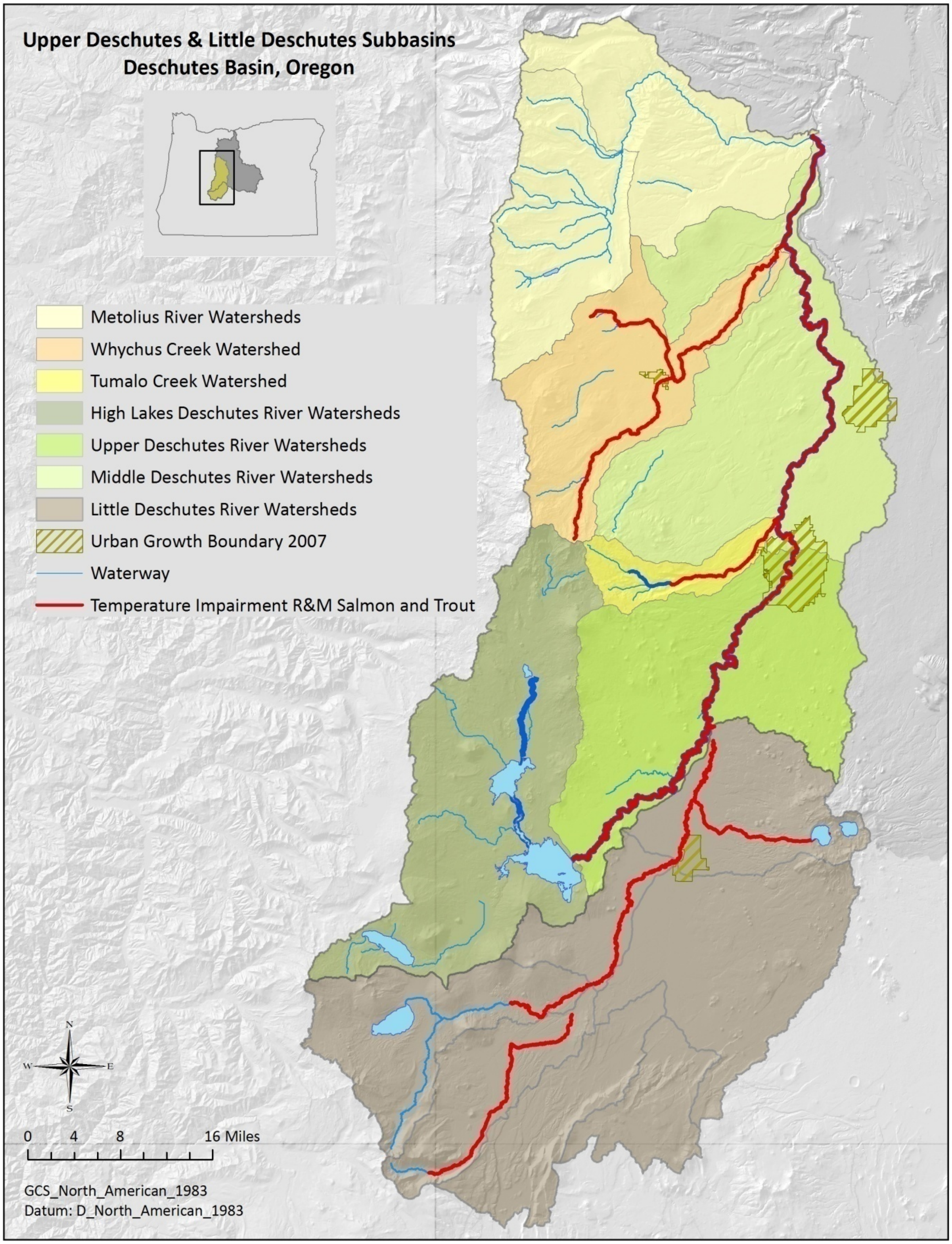
Tumalo Creek and Lower Bridge Road by contributing a greater volume of colder water at the confluence.

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 streamflow restoration projects. Although model predictions and substantial empirical evidence indicate that reductions in summer streamflow lead to increased water temperatures in central Oregon (ODEQ, 2004) (ODEQ, 2007) (UDWC, 2003) (UDWC, 2006), the DRC and restoration partners are interested in evaluating how increasing flows in the Middle Deschutes River and Tumalo Creek through streamflow restoration transactions affects water temperatures in downstream reaches. We evaluated available Deschutes River and Tumalo Creek temperature and flow data from 2001 through 2012 to address the following questions: 1) What was the status of Middle Deschutes River water temperatures relative to the State of Oregon 18°C/64°F standard as of 2012; 2) Have increases in streamflow reduced water temperatures at key locations along the Middle Deschutes; and 3) What flow scenarios for the Deschutes River and Tumalo Creek will achieve the 18°C temperature standard between North Canal Dam and Lower Bridge Road? We present 2012 temperature results and discuss implications for streamflow restoration.

Map 1 Middle Deschutes River Study Area



Map 2 Salmon and Trout Rearing and Migration Section 303(d) Impaired Waterways



2. Methods

2.1. Data Collection

2.1.1. Water Temperature

UDWC compiled continuous water temperature data from six water temperature monitoring stations on the Deschutes River and one monitoring station on Tumalo Creek (Table 1; Map 3). Data for 2001 through 2012 were obtained from the UDWC's online water quality database (UDWC, 2012). 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). All temperature data used in analyses were collected by ODEQ, the City of Bend, and UDWC. UDWC operates per the *Water Quality Monitoring Program Standard Operating Procedures* (UDWC, 2008) under a State of Oregon approved Quality Assurance Project Plan (UDWC, 2008).

2.1.2. Average Daily Flow

UDWC obtained average daily streamflow (QD) data for the Deschutes River and Tumalo Creek from the Oregon Water Resources Department (OWRD) (OWRD, 2012) (Table 1; Map 4). In the absence of an active gage station on the Deschutes River downstream of Tumalo Creek, streamflows recorded at OWRD gage #14070500, Deschutes River below Bend, and at OWRD gage #14073520, Tumalo Irrigation District Feed Canal, are combined to approximate the streamflow below the confluence of the Deschutes River and Tumalo Creek. All 2008-2012 Tumalo Creek and Deschutes River data with the exception of 2009, 2011 and 2012 Tumalo Creek data, and 2012 Deschutes River data, is considered published; data for these years and waterways are considered provisional and subject to change.

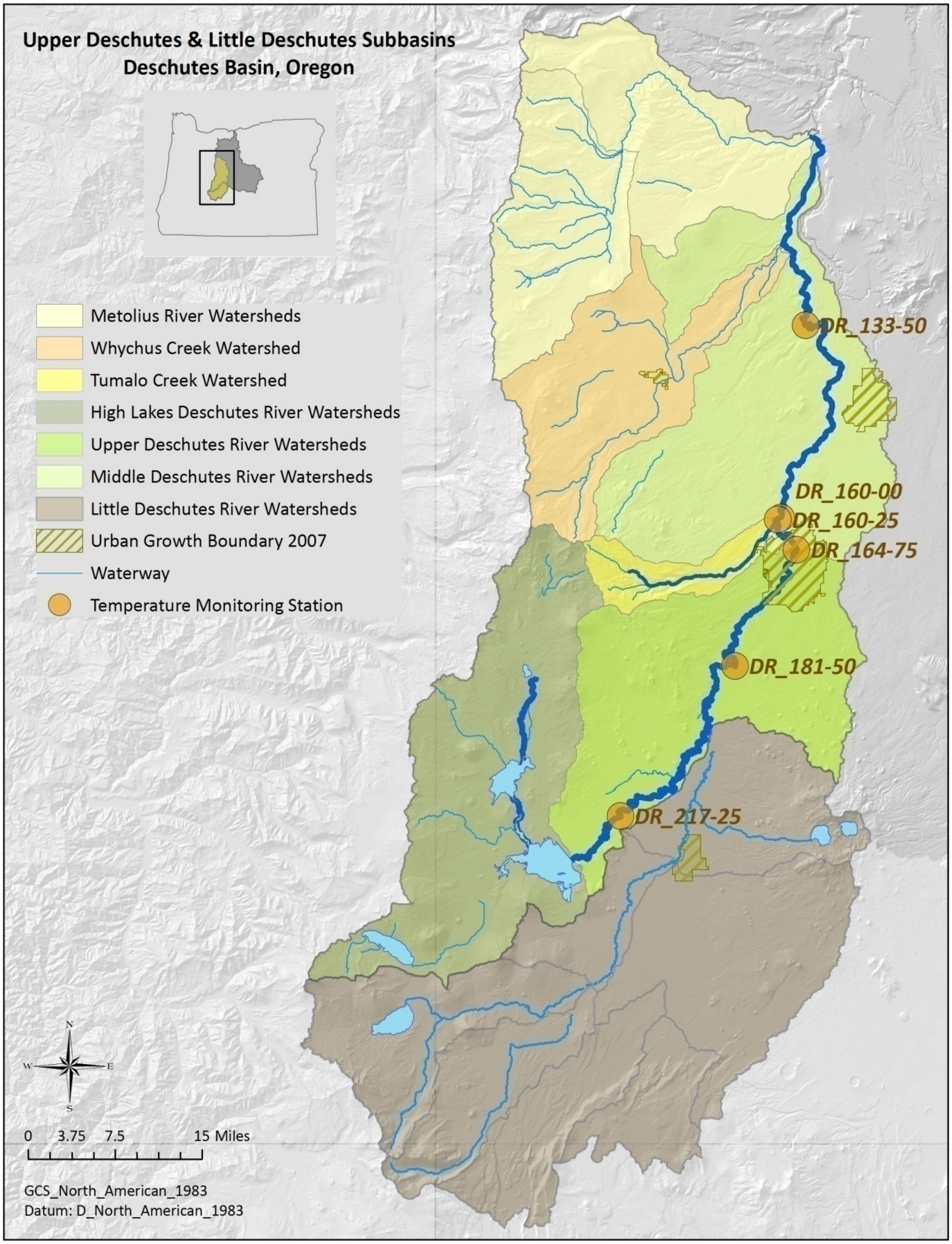
Table 1. Middle Deschutes River Flow and Temperature Monitoring Stations

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

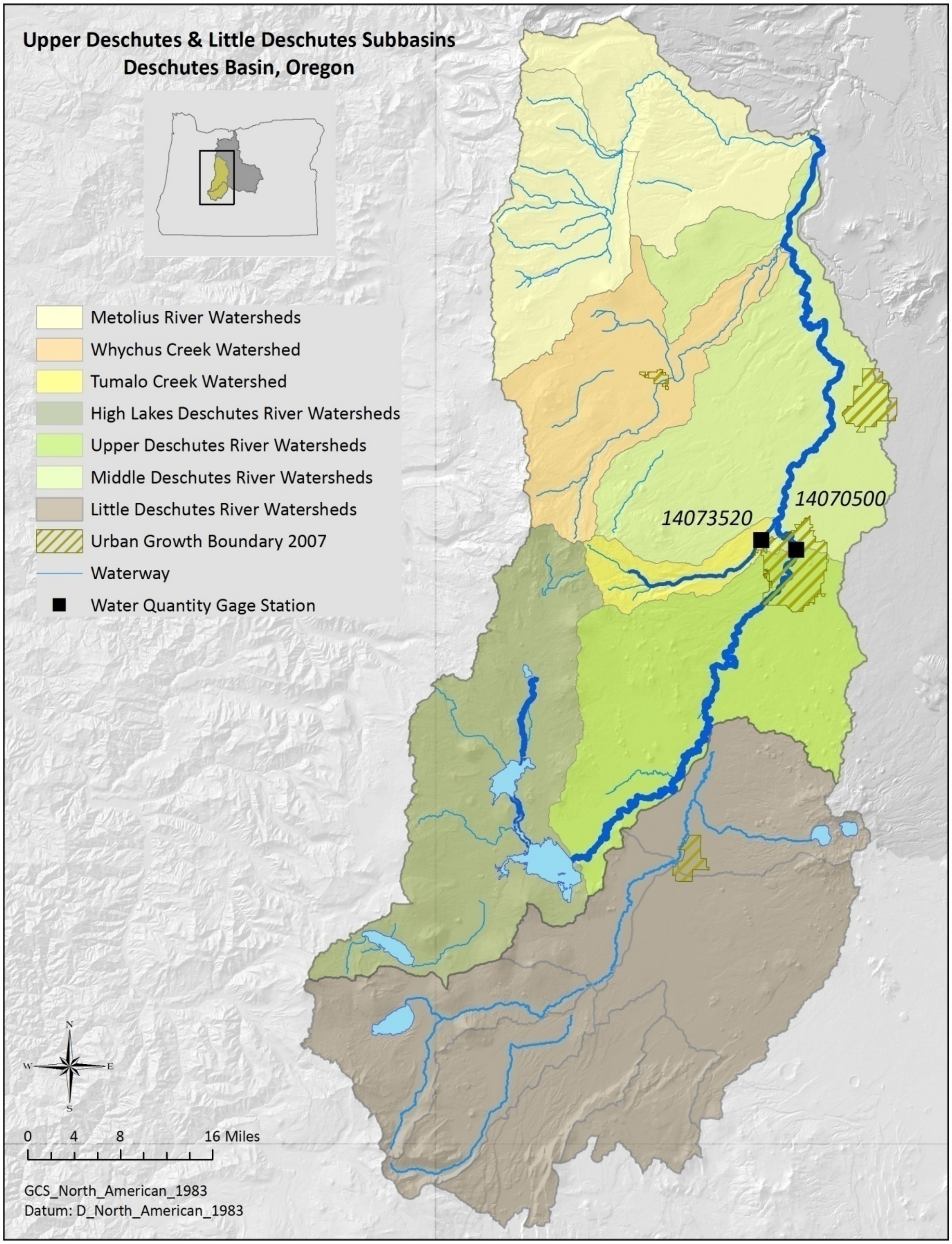
Table 2. Summary of Available July Temperature Data

Station ID	Waterway	Description	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
DR 217.25	Deschutes River	Pringle Falls		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
DR 164.75	Deschutes River	u/s Riverhouse Hotel				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
DR 160.00	Deschutes River	d/s Tumalo Boulder Field					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
TC 000.25	Tumalo Creek	u/s of Tumalo Creek mouth				X	X	-	X		X	X	X	X
X	Data available for analysis													
-	Limited data available for analyses													

Map 3 Temperature Monitoring Stations used in Analyses



Map 4 Streamflow Gaging Stations used in Analyses



2.2. Data Analysis

2.2.1.Temperature Status

We used the Oregon Department of Environmental Quality (ODEQ) Hydrostat Simple spreadsheet (ODEQ, 2010) to calculate the seven day moving average maximum (7DMAX) temperature, the same statistic used by the State of Oregon to evaluate stream temperatures. The current State of Oregon water temperature standard for salmon and trout rearing and migration identifies a 7DMAX threshold of 18°C/64°F (OAR 340-041-0028) (ODEQ, 2012). We evaluated July 7DMAX temperatures from 2001-2012 in relation to the state standard of 18°C to describe changes in temperature in the Middle Deschutes since 2001 and to assess progress toward the 18°C state standard for salmonid rearing and migration. We evaluated July temperature data at DR 160.00, downstream of the confluence of the Deschutes and Tumalo Creek, in relation to the July median average daily flow in the Deschutes below North Canal Dam, Tumalo Creek below the Tumalo Feed Canal, and the July median of combined flows from these two sources. To illustrate temperature status at Lower Bridge Road (DR 133.50) we present data for August instead of July because more data are available for August for the years of interest, however August data equivalently represent summer conditions characterized by high temperatures and low flows.

2.2.2.Restoration Effectiveness

We used a Before-After Control-Impact (BACI) analysis to evaluate the effectiveness of streamflow restoration in reducing stream temperature. BACI analysis allows significant differences between reference (Control) and restoration (Impact) reaches to be attributed to increases in flow by accounting for inter-annual environmental variability. In previous analyses we have compared temperature data from a subsequent year to temperature data from the preceding year to evaluate temperature response to increases in streamflow. This comparison illustrates the temperature response between years to incremental increases in streamflow from one year to the next, but does not demonstrate the cumulative effect of streamflow restoration in reducing stream temperature. To quantify a temperature response to cumulative increased flows resulting from streamflow restoration and to attribute any response observed to increases in flow we used the BACI approach to compare 2012 temperature data to baseline temperature data from 2005 in two reaches where streamflow restoration is expected to have the greatest effect.

We used temperature data from five Deschutes River temperature monitoring stations defining reach boundaries for a reference reach and two restoration reaches (Map 5). The reference reach (DR 217.25 to DR 181.50) provides an experimental control where no streamflow restoration has occurred. Temperature in the Deschutes restoration reach (DR 164.75 to DR 160.25), from downstream of North Canal Dam to upstream of Tumalo Creek, is affected by flow volume at North Canal Dam (Map 6). This reach is upstream of the confluence of the Deschutes and Tumalo Creek and is not influenced by flow levels in Tumalo Creek. Temperature in the quarter-mile Tumalo restoration reach, which spans the confluence of Tumalo Creek and the Deschutes (DR 160.25 to DR 160.00), is affected by flows in the Middle Deschutes at North Canal Dam as well as by flows in Tumalo Creek.

The BACI study design accounts for natural variability in streamflow, climate (e.g. precipitation, solar radiation, air temperature, etc.) and other environmental factors that influence inter-annual differences in temperature by comparing pre- (Before) and post- (After) streamflow restoration temperature differences within a reference (Control) reach to Before-After temperature differences within a restoration (Impact) reach (Smith, 2002; NIST, 2010). We selected 2005 as the baseline year for streamflow restoration and the “Before” year for BACI analysis; although streamflow restoration efforts had resulted in some gains in protected flows prior to 2005, this is the first year for which temperature data are available for the three reaches. Temperature data for 2012 represented the “After” year.

We restricted data included in the analysis to one month of the year, July, to reduce the effect of inter-annual seasonal variation in the analysis (Helsel & Hirsch, 1991). We selected July as the month characterized by the historically hottest temperatures in the Deschutes River (UDWC, 2003) (UDWC, 2006). To calculate BACI differences we subtracted 2012 July daily median temperatures from 2005 July daily median temperatures for each station ($DR\ 217.25_{2005}$ - $DR\ 217.25_{2012}$), then subtracted the downstream difference from the upstream difference for each reach (e.g. $\Delta\ DR\ 217.25_{2005\text{-}2012} - \Delta\ DR\ 181.50_{2005\text{-}2012}$). We used the daily median temperature to reflect small changes in temperature more precisely than if we were to use the daily mean or daily maximum temperature, and at a finer temporal scale than if we used the seven day moving average maximum (7DMAX) temperature.

We used paired t-tests for normally distributed data and permutation tests for non-parametric data to identify 1) whether temperature changes between years in restoration reaches were significantly different than changes between years in reference reaches, and 2) in which direction restoration reach temperature changes occurred, warming or cooling, relative to the reference reach (Helsel & Hirsch, 1991). Analyses were conducted using R open source statistical software (R Core Development Team 2007). We used normality plots and the Shapiro-Wilks test to establish normal distribution of data. For reaches where data were non-normal we used an exact permutation test (Hothorn and Hornik 2006) to evaluate statistically significant differences between restoration reach and reference reach means. An exact permutation test for paired samples compares the observed statistic, the difference of means from two experimental groups, to the expected statistic under a permutation distribution created by randomly resampling from all possible permutations of the data from treatment and control groups. Here the observed statistic is the difference of the restoration and reference reach means. For each restoration reach- reference reach pair we evaluated the following four hypotheses:

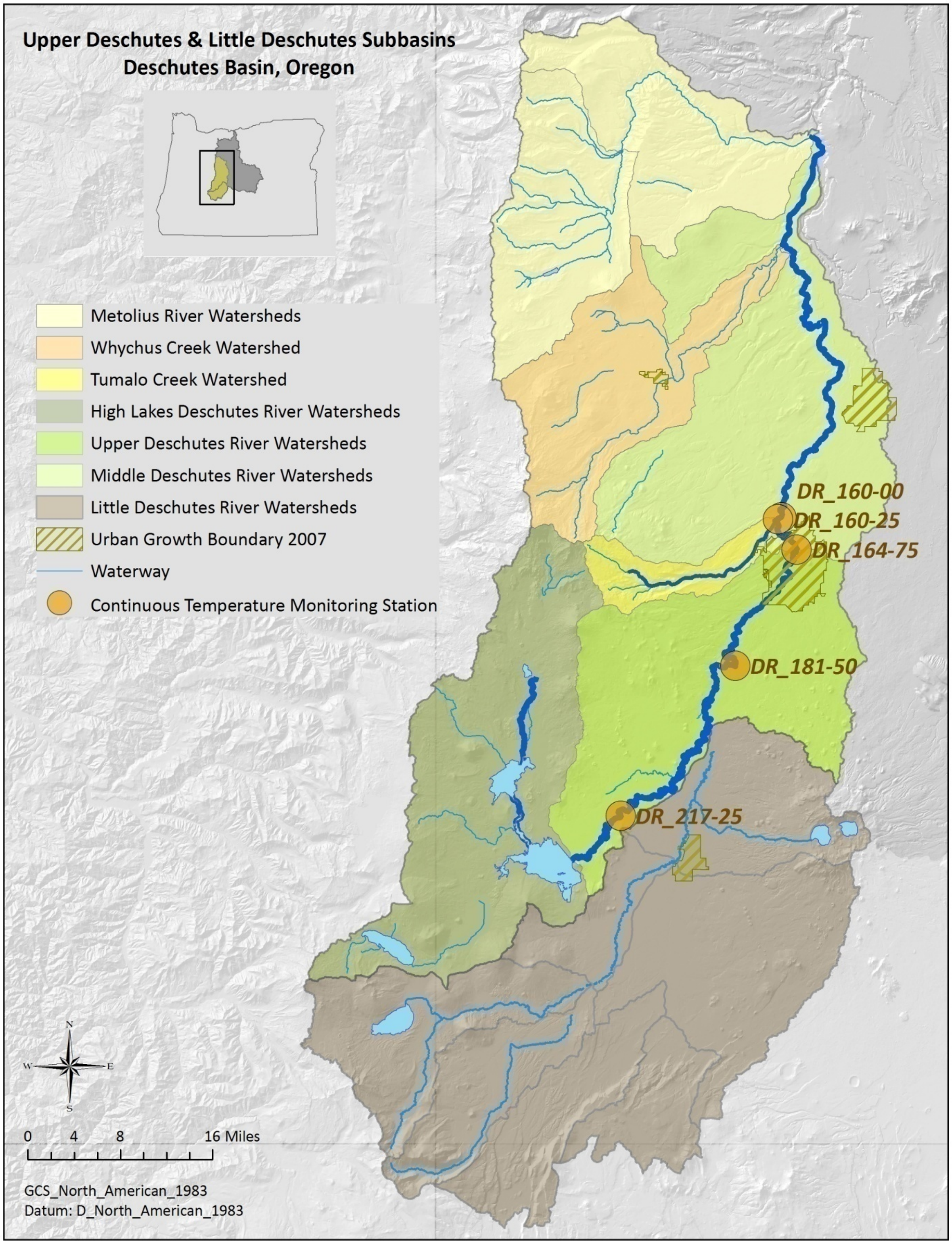
1) H_0: There is no difference between the mean for the restoration reach and the mean for the reference reach.

2) H_1: The mean for the restoration reach and the mean for the reference reach are significantly different.

3) H_2: The mean for the restoration reach is significantly less than the mean for the reference reach; the restoration reach has cooled relative to the reference reach

4) H_3: The mean for the restoration reach is significantly greater than the mean for the reference reach; the restoration reach has warmed relative to the reference reach.

Map 5 Continuous Temperature Monitoring Stations used in Restoration Effectiveness Analysis



Map 6 Deschutes and Tumalo Restoration Reaches used in Restoration Effectiveness Analysis

2.2.3. Target Streamflow

We used regression models and a mass balance equation to develop flow scenarios for the Deschutes River and Tumalo Creek that would achieve the 18°C state standard temperature in the Deschutes below the confluence with Tumalo Creek. We used temperature and flow data from the Deschutes River above Tumalo Creek (DR 160.25) and from the mouth of Tumalo Creek (TC 000.25) to estimate corresponding temperature and flow values for both sites. The two sites are short distances downstream of major sites of streamflow restoration on each waterway and therefore are anticipated to reflect gains in temperature related to increased flows; due to their respective locations immediately upstream of the confluence they also most accurately represent the temperature-flow relationships that directly affect stream temperature downstream of the confluence. Because no tributaries or known springs enter the Deschutes between Tumalo Creek and Lower Bridge Road, the relative flow contributions of the Deschutes and Tumalo Creek at these two sites also directly influence stream temperature 26.5 miles downstream at Lower Bridge Road (DR 133.50), where temperature conditions are historically the worst on the Middle Deschutes.

As in our restoration effectiveness analysis, we restricted data included in the analysis to one month of the year to reduce the effect of inter-annual seasonal variation in the analysis (Helsel & Hirsch, 1991) and identified July as the historically hottest month for water temperatures in the Deschutes River (UDWC, 2003) (UDWC, 2006). We used the seven day moving average maximum temperature (7DMAX) because this is the statistic used by DEQ to determine the status of a waterway in relation to the state water quality standard. For DR 160.25 upstream of Tumalo Creek, we analyzed July 7DMAX temperature and average daily flow data from 2002-2012 with the exception of 2006 for which temperature data were unavailable; for TC 000.25 at the mouth of Tumalo Creek we analyzed July temperature and flow data for 2004-2012 with the exception of 2008, for which temperature data were also not available.

To estimate temperatures at corresponding flows for the two locations we performed a regression of temperature and flow data. The resulting equations accurately represent the relationship between flow and temperature, and can be used to calculate temperature values for the specified locations, within the evaluated time period, and within the range of flows observed. We paired 7DMAX temperature records with the natural log of the corresponding average daily flow (LnQD) for each July day included in the analysis, then ranked flow values and assigned all July temperature records to their corresponding flow value. The seven day moving average maximum temperature for a given day is the average of the maximum temperature for that day, the three days prior, and the three days following; we paired the 7DMAX for a given day with the flow for the same day to best match the 7DMAX temperature to flow conditions on both the first and seventh days represented by the 7DMAX temperature. Although this approach does not reflect the flow corresponding to maximum daily temperatures on the fifth, sixth, or seventh days included in the 7DMAX, the flow corresponding to the 7DMAX for the same date is related to the flow three days before and three days after. On this premise we selected the flow for the same date as the 7DMAX to represent flow conditions corresponding to that temperature statistic.

We plotted flow versus temperature and fitted the linear and polynomial regression trendlines for six permutations of the data to evaluate which approach best represented the observed temperature and flow data and would result in estimated temperatures that would as closely as possible approximate those we might anticipate occurring. We plotted the following permutations of temperature data: 1) all temperature-flow pairs; 2) all temperature-flow pairs excluding flows for which there were fewer than two temperature records; 3) all temperature-flow pairs excluding flows for which there were fewer than five temperature records; 4) all mean temperature-flow pairs representing the average of all temperatures observed at a given flow for all flows for which there was at least one temperature record; 5) mean temperature-flow pairs excluding flows for which there were fewer than two temperature records; and 6) mean temperature-flow pairs excluding flows for which there were fewer than five temperature records. We evaluated the resulting regression trendlines visually, and evaluated regression equations for a given regression model quantitatively by comparing adjusted R^2 values. The R^2 value represents the proportion of the variation in mean 7DMAX temperatures that is explained by streamflow (Ln QD). As the fit of the regression to the data improves, the R^2 value increases toward a maximum 100%.

We selected the regression of all mean temperature-flow pairs as the most representative of conditions observed and accordingly as the most useful for predicting temperature at a given flow. Using all temperature-flow pairs, even excluding flows at which two or fewer or five or fewer temperature records were available, resulted in a regression equation with an extremely low R^2 value, indicating that the equation represented a very low proportion of the variation in 7DMAX temperature-flow pairs and did not effectively describe a relationship between flow and temperature. Although excluding mean temperature-flow pairs with fewer than two or five temperature records in some cases resulted in a regression equation with a higher R^2 value than including all mean temperature-flow pairs, particularly for Deschutes data, we concluded that retaining these pairs resulted in a regression trendline, and therefore equation, that better reflected the data observed than if we were to exclude some pairs, while still maintaining an R^2 value that indicated the equation explained a high proportion of the variation.

For the resulting datasets including all mean temperature-flow pairs for both the Deschutes and for Tumalo Creek, we used an ANOVA in R open source statistical software to determine the highest polynomial term that statistically improved the model on the basis of the R^2 value associated with each model. For Deschutes data, the quadratic model was not statistically better than the linear model. For Tumalo data, the quadratic, cubic, and quartic models were each statistically better than the lower-order model. We elected to use the quartic model to predict Tumalo temperatures because the equation resulted in slightly more conservative (higher) temperature estimates in the 10-32 cfs range within which streamflow restoration is presently occurring.

Using the resulting regression equation for each location, we calculated the estimated temperature and 95% confidence interval for all flows within the observed range (Appendix A). We calculated the 95% confidence interval (CI) as:

$$Y \pm Y^{(Z_{1-\alpha/2}\ S(x) / \surd N)}$$

where $Z_{1-\alpha/2} = Z_{1-0.05/2} = Z_{0.475} = 1.9$ (NIST 2011)

To calculate Deschutes River temperatures downstream of the confluence with Tumalo Creek under a variety of flow scenarios we used the temperatures and given flows from the Deschutes River and Tumalo Creek temperature-flow regression equations in a mass balance equation. We used the following mass balance equation solved for T_{D2}:

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

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

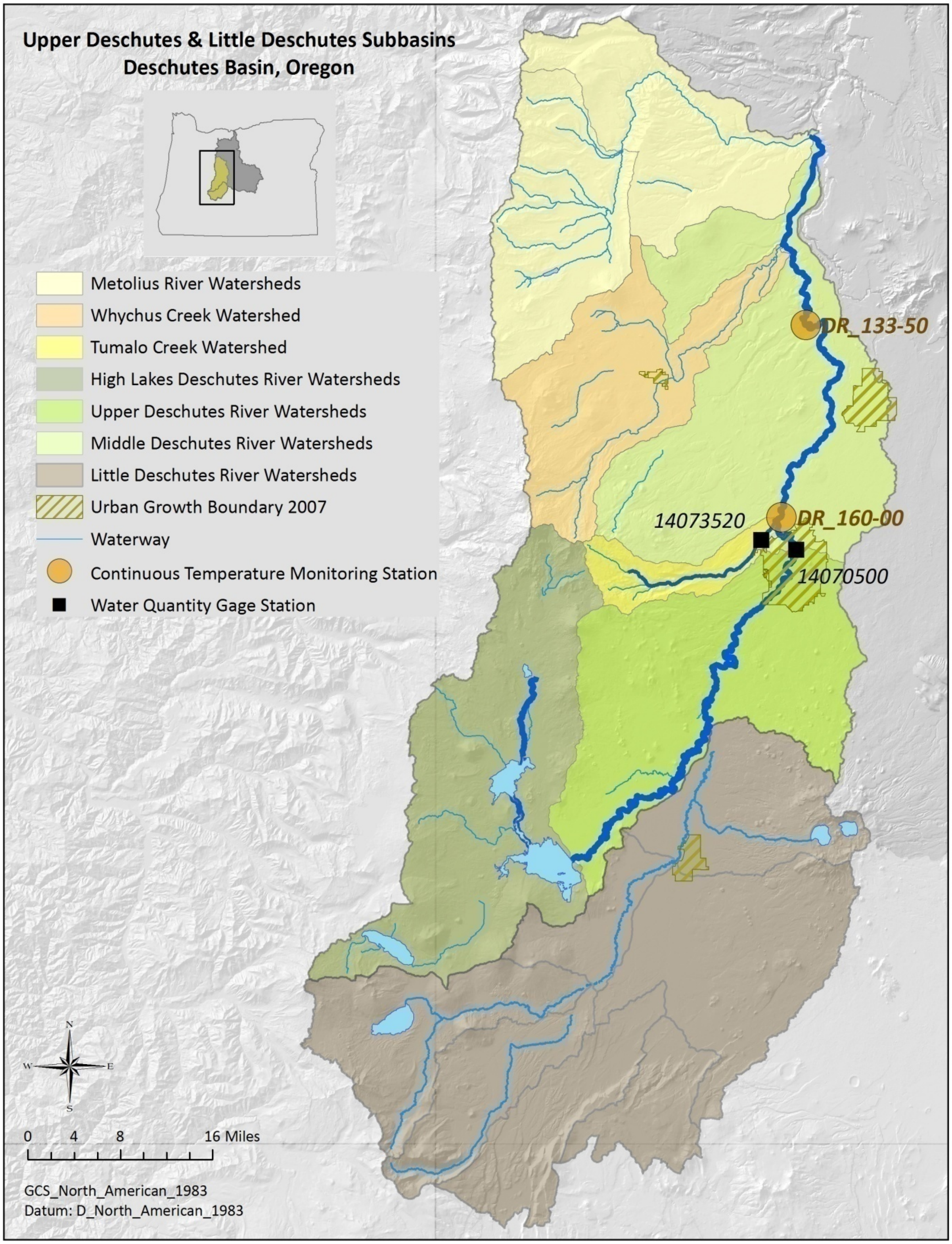
Where:

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

We calculated temperatures for all Tumalo flows between 10 and 100 cfs at Deschutes River flows of 160, 180, 200, 220, and 250. Ten cfs approximates the median flow currently protected instream in Tumalo Creek during July; 100 cfs exceeds average natural July flows and is well above the ODFW instream water right of 32 cfs. 160 cfs is the median flow protected instream in the Deschutes River during July; 250 is the instream water right and DRC streamflow restoration target.

We compared temperatures calculated from temperature-flow regressions and from the mass balance equation to Heat Source model scenarios for the same locations on the Deschutes River and Tumalo Creek (ODEQ, 2007). Heat Source results report the peak seven day average daily maximum temperature; we compared mass balance equation results to the average 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.

Map 7 Temperature Monitoring and Streamflow Gaging Stations used in Target Streamflow Analysis



3. Results

3.1. Temperature Status

Seven-day moving average maximum (7DMAX) temperatures exceeded the 18˚C state standard for steelhead and salmon rearing and migration at four monitoring locations in 2012 (Figure 1), supporting the existing State of Oregon Section 303(d) listing of the middle Deschutes River for temperature impairment. Temperatures in the reference reach (DR 217.25 to DR 181.50), above all major irrigation diversions, have remained below 18°C during July, the month during which the hottest water temperatures have historically been observed, since 2010. Temperatures downstream in the Deschutes restoration reach (DR 164.65 to DR 160.25), the Tumalo restoration reach (DR 160.25 – DR 160.00), and at Lower Bridge Road (DR 133.50) exceeded the state standard in every year for which data is available for analysis.

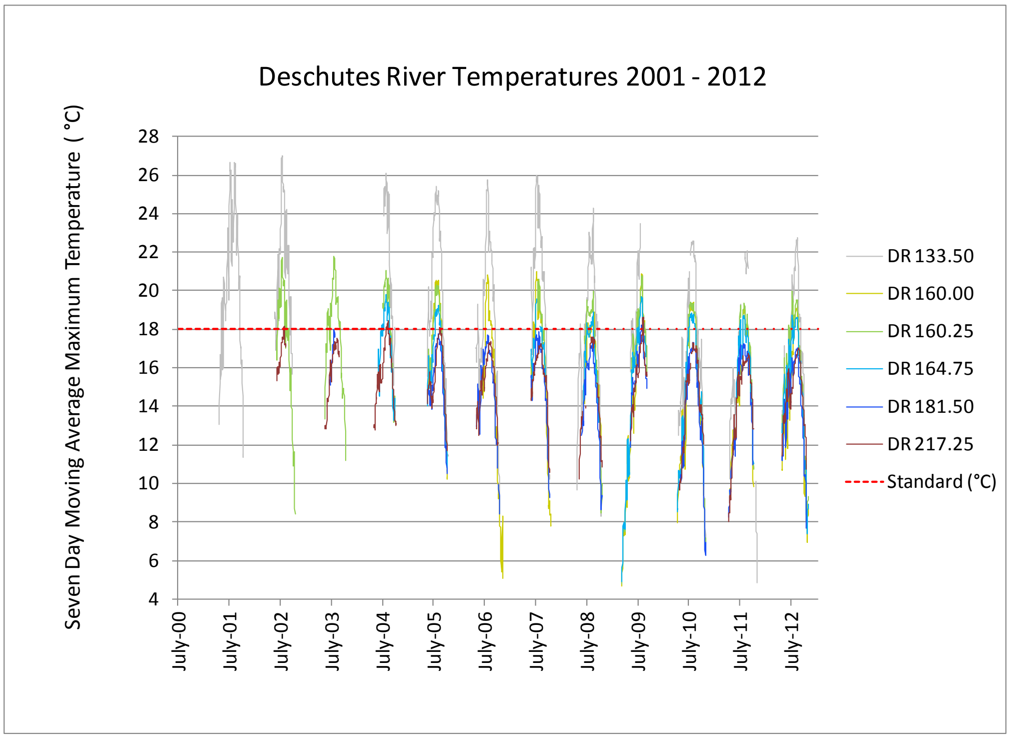


Figure 1. Deschutes River Temperatures 2001-2012
Temperatures at 6 stations along the Deschutes River between 2001 and 2012 exceeded the State of Oregon temperature standard established to protect salmon and trout rearing and migration (dashed red line) at all sites and in most years.

Temperatures at DR 160.00, downstream of the confluence with Tumalo Creek, remained below 18°C during July for the second year in a row. In July 2012 temperatures at DR 160.00 were consistently below 18°C at combined Deschutes River and Tumalo Creek flows between 223 and 362 cfs, with Tumalo Creek flows contributing between 32 and 153 cfs of the total (Figure 2). This pattern paralleled temperature and flow trends for July 2011, when DR 160.00 temperatures remained below 18°C at combined flows between 198 and 447 cfs and Tumalo Creek flows accounting for 45 to 156 cfs. Temperatures exceeded 18°C for a total of 29 days at DR 160.00 in 2012, between July 24 and August

21, at total flows of 156 to 297 cfs and Tumalo Creek flows between 13 and 28 cfs. Temperatures also exceeded 18°C at DR 160.00 for 29 days in 2011, between July 23 and August 12 and between August 20 and 27, at total flows of 134 to 227 cfs and Tumalo Creek flows between 8 and 52 cfs. Despite substantial reductions in temperature observed since 2001, mean 7DMAX temperatures at Lower Bridge Road (DR 133.50) remained well above the 18°C standard in 2012 (Figure 3). However, temperatures at this location continue to remain below the 24°C lethal threshold for fish.

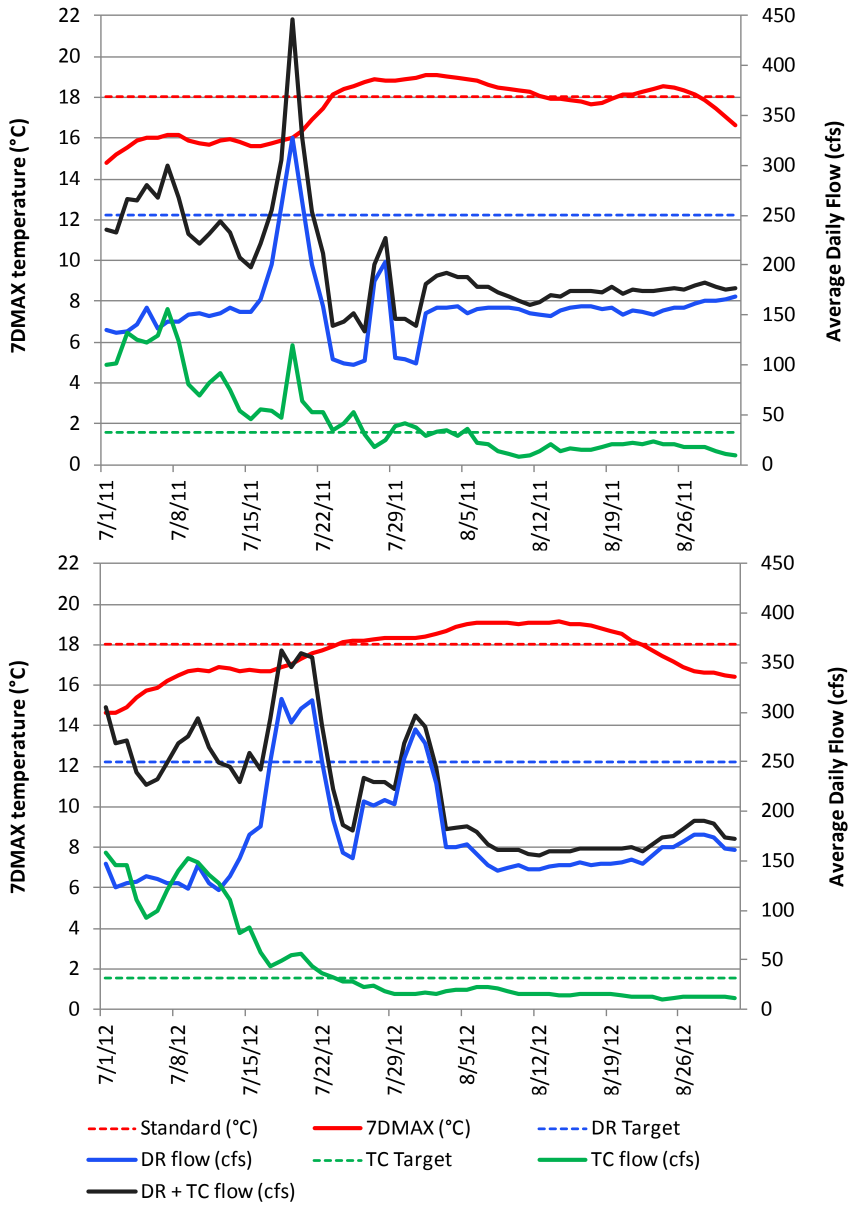


Figure 2. July 2011 and 2012 Temperature and Flow at DR 160.00
Seven-day maximum (7DMAX) temperatures at DR 160.00 remained below the 18°C standard into July in 2011 and 2012 when combined Deschutes River and Tumalo Creek flows were above 198 cfs (2011) and 223 cfs (2012), including minimum Tumalo flows of 32 (2011) and 45 (2012) cfs.

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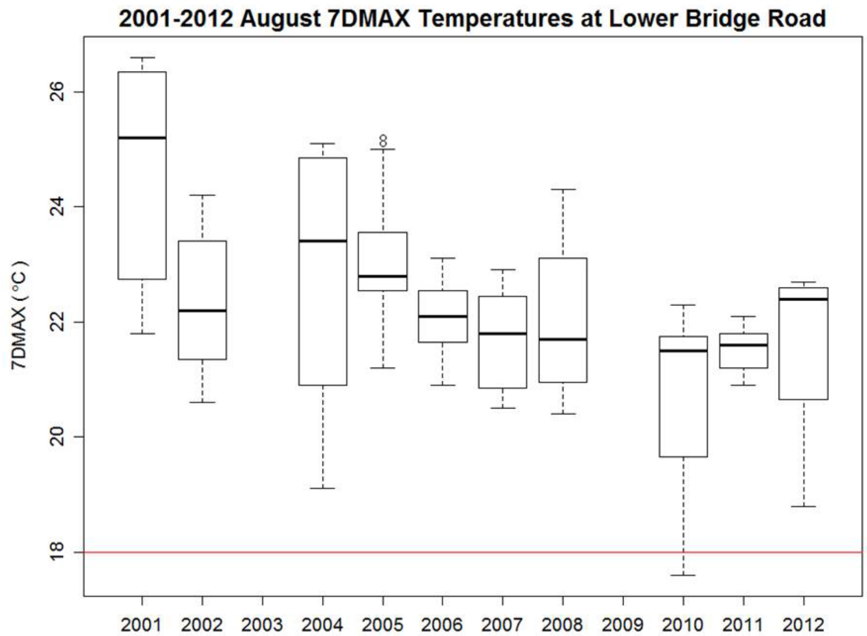


Figure 3. 2001-2012 August 7DMAX Temperatures at Lower Bridge Road
August mean 7DMAX temperatures at Lower Bridge Rd (DR 133.50), the most impaired site for which temperature data are available, chart a declining trend since 2001.

3.2. Streamflow Restoration Effectiveness

Deschutes River temperatures between North Canal Dam and the confluence of the Deschutes and Tumalo Creek are directly affected by the volume of streamflow released at North Canal Dam. This reach includes the Deschutes restoration reach between DR 164.75 and DR 160.25 used in BACI analysis. Temperatures below the confluence with Tumalo Creek, reflected in the Tumalo restoration reach between DR 160.25 and DR 160.00, are influenced by the total volume of combined flows from the Deschutes at North Canal Dam and from Tumalo Creek as well as by the volume of flow from each of those two sources separately.

July median streamflow from North Canal Dam increased in all but three years between 2001 and 2012 (Figure 4). July median streamflow from North Canal Dam more than doubled from 2005 to 2012, from just below 75 cfs to over 150 cfs. July median flow in Tumalo Creek below the Tumalo Irrigation Diversion increased nine-fold between 2005 and 2012, from 6.3 to 58 cfs. The July median of combined flows from the Deschutes and from Tumalo Creek more than tripled from 2005 to 2012, increasing from 81 to 259 cfs.

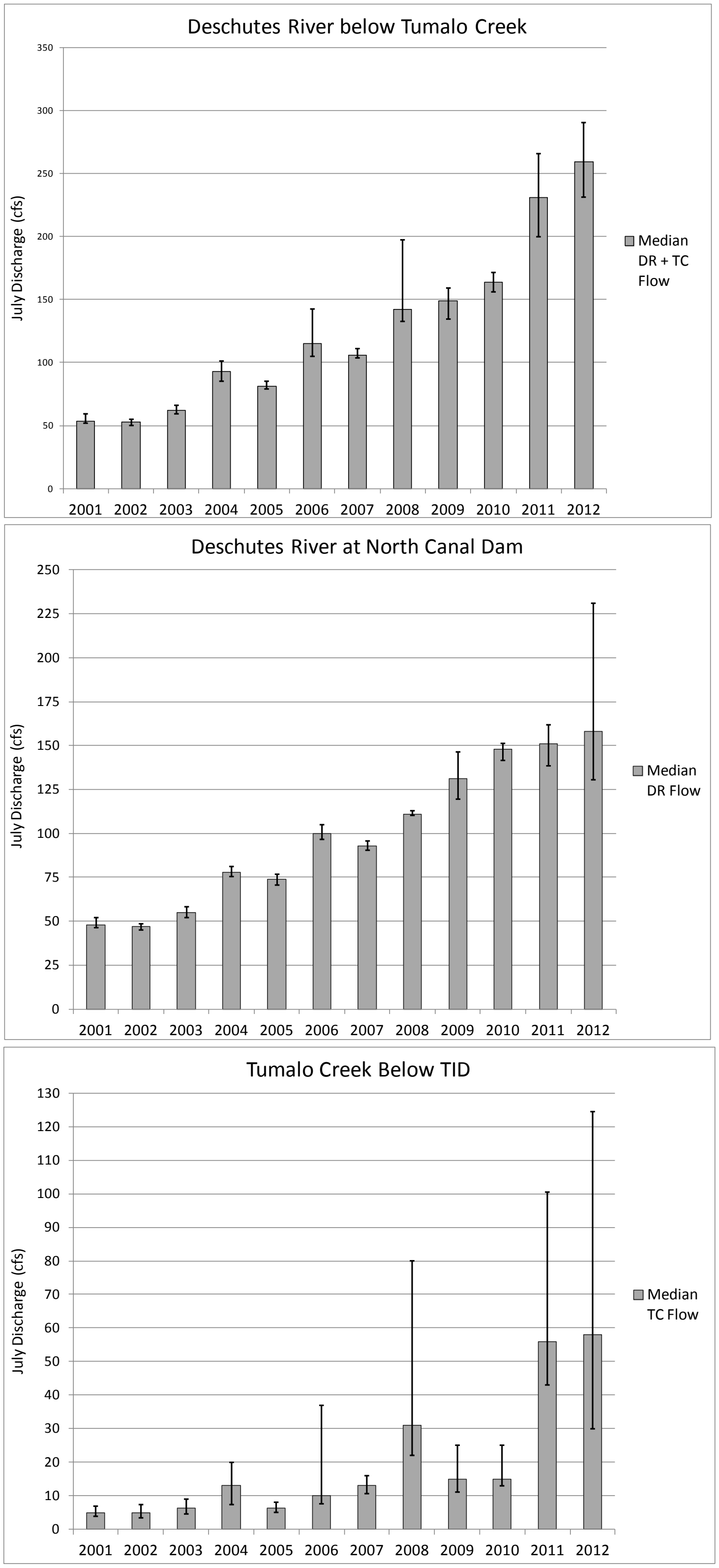


Figure 4. **Deschutes and Tumalo Creek Median July Flows 2001-2012**
Increases in Deschutes River median July flows below the confluence with Tumalo Creek and at North Canal Dam, and Tumalo Creek flows below the TID diversion, from 2001-2012.

Temperatures recorded at the two upstream reference reach stations and the three downstream restoration reach stations from 2005 to 2012 varied among stations and years (Figure 4). Normal plots and Shapiro-Wilks tests of 2005-2012 BACI differences in mean July daily median temperatures showed reference reach and Deschutes restoration reach data to be normally distributed, while distribution of Tumalo restoration reach data was non-normal. Accordingly, we used a paired t-test to statistically compare the Deschutes and reference reaches, and a permutation test to compare the Tumalo and reference reaches.

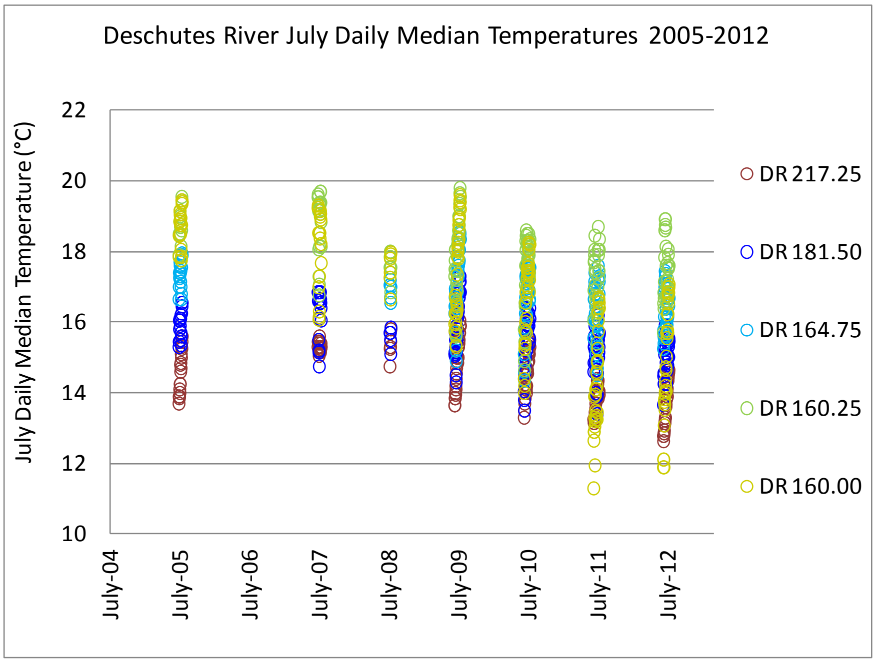


Figure 5. Deschutes River July daily median temperatures from 2005-2012
We used 2005 and 2012 temperatures in a BACI analysis to evaluate temperature response to increases in streamflow between 2005 and 2012.

The mean BACI difference of July daily median temperatures in the Deschutes reach from 2005-2012 was not significantly different than the mean BACI difference for the reference reach from 2005-2012, indicating that changes in temperature in the restoration reach over this interval were statistically no different than changes in temperature in the reference reach over the same period (Table 3); according to this result, despite an approximately 75 cfs increase in streamflow in the restoration reach between 2005 and 2012, temperatures in this reach behaved no differently over that interval than did temperatures in the reference reach, where flows were unmodified from usual irrigation season conditions. This result indicates no detectable cooling effect between at DR 164.75 and DR 160.25 in response to a 75 cfs increase in streamflow from the Deschutes at North Canal Dam. Conversely, the mean BACI difference of July daily median temperatures in the Tumalo restoration reach for 2005-2012 was significantly less than the mean difference for the reference reach, demonstrating a strong cooling response to a three-fold increase in combined flows from the Deschutes at North Canal Dam and from Tumalo Creek, and a dramatic nine-fold increase in Tumalo flows, between 2005 and 2012 (Figure 6).

Table 3. BACI differences of July daily median temperatures

BACI differences and standard deviations of July daily median temperatures for the reference reach and the Deschutes and Tumalo restoration reaches between 2005 and 2012, and T/t-values (permutation/t-test) and p-values for paired tests of significant differences between 2005-2012 reference reach and restoration reach mean BACI differences. Values significantly less than the reference reach mean indicate a cooling trend between 2005 and 2012; values greater than the reference reach mean indicate a warming trend between data years. Asterisks indicate a significant difference between the specified restoration reach and the reference reach.

	2005-2012 n=18, df=17		
	Mean & SD	T/t-value	p-value
Reference reach	**-0.5 ±0.74**		
Deschutes reach	-0.4 ± 0.35	0.5221	0.30
Tumalo reach	-1.4 ± 0.79*	10	0.00

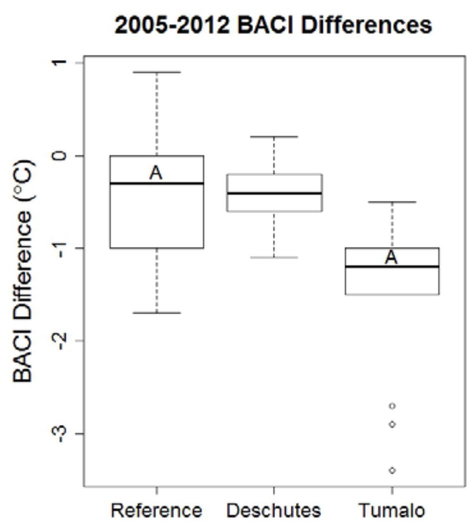


Figure 6. BACI differences for reference and restoration reaches

Letter pairs indicate significant differences between mean values (p <0.05). The mean 2005-2012 BACI difference was significantly lower in the Tumalo restoration reach than the mean 2005-2012 difference in the reference reach, showing a cooling response to increased streamflow. There was no significant difference between Deschutes restoration reach and reference reach 2005-2012 mean BACI differences, suggesting there was no temperature response in this reach to increases in flow between 2005 and 2012.

3.3. Target Streamflow

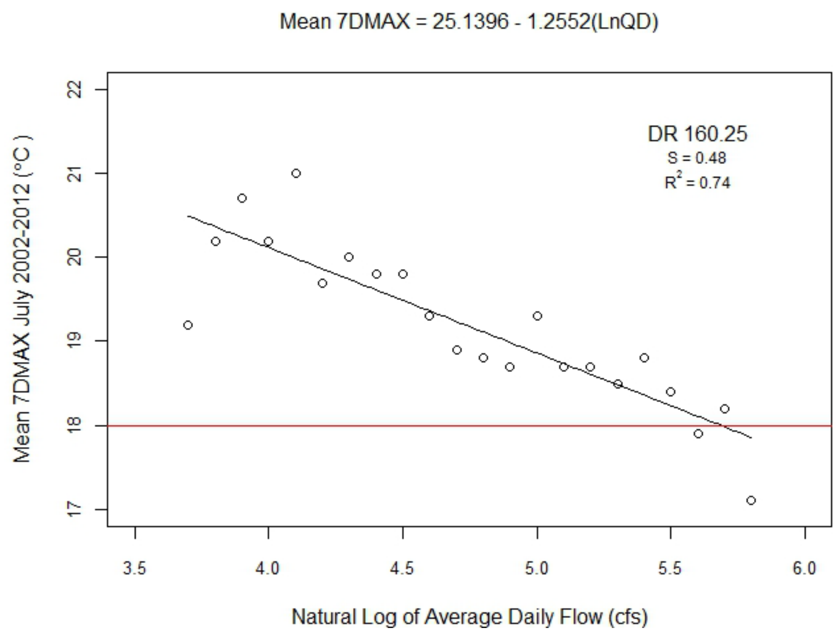
Regression equations for trendlines fitted to July temperature and streamflow data from the middle Deschutes River upstream of the confluence with Tumalo Creek (DR 160.25) and from Tumalo Creek at the mouth (TC 000.25) describe the relationship between flow levels and the average 7DMAX temperature observed at each level (Figure 7). Temperature records were available from DR 160.25 for Deschutes River flows between 41 and 327cfs (3.7-5.8 LnQD), and from TC 000.25 for Tumalo Creek flows between 3.3 and 177 cfs (1.2-5.2 LnQD). A linear regression trendline and equation provided the best fit to DR 160.25 temperature and flow data; a quartic (4th order polynomial) regression trendline and equation best described TC 000.25 data. We used the resulting equations to calculate temperatures for Deschutes flows between 43 and 250 cfs, and for Tumalo flows between three and 177 cfs (Appendix A).

Temperature estimates calculated for five Deschutes River flow scenarios illustrated dramatic gains in temperature reductions in the Deschutes River below the confluence with Tumalo Creek (DR 160.00) as flows in Tumalo increased (Appendix B). At 250 cfs in the Deschutes below North Canal Dam, the ODFW instream water right for the Deschutes below Bend, 26 cfs from Tumalo Creek resulted in 18°C at DR 160.00. At 160 cfs in the Deschutes below North Canal Dam, the flow currently protected instream, 18°C was estimated to occur at DR 160.00 when Tumalo flows were 38 cfs - only 12 cfs more than the volume required to achieve the 18°C standard when Deschutes flows were 250 cfs. The Tumalo Creek ODFW instream water right of 32 cfs resulted in an estimated 18°C at a corresponding Deschutes River flow of 220 cfs.

Estimated temperature gains were magnified as Tumalo flows increased to approximately 60 cfs. Tumalo flows of 45 cfs at Deschutes River flows of 250 cfs resulted in 17.5°C at DR 160.00; the same temperature was achieved at 160 cfs of Deschutes flow by adding five cfs in Tumalo Creek, at a Tumalo flow of 50 cfs. Above 60 cfs, increases in Deschutes flows resulted in equivalent or increased temperatures, such that increasing flows in the Deschutes required commensurate increases in Tumalo flows. For example, at 76 cfs in Tumalo, Deschutes flows of 160 cfs resulted in an estimated temperature of 16.5°C; to obtain the same temperature at 250 cfs in the Deschutes required 82 cfs in Tumalo.

Heat Source model estimates are available for instream water right (ODFW) flows for the Deschutes and for Tumalo Creek. The Heat Source average seven day average daily maximum (7DADM) temperature estimate for Deschutes flows of 250 cfs at the Tumalo instream water right of 32 cfs at approximately DR 160.00 is 17.0°C, almost a full degree lower than the mass balance temperature estimate of 17.9°C for the same flow at the same site. Similarly, the Heat Source average 7DADM for the Deschutes at 250 cfs at approximately DR 160.25, above the confluence with Tumalo, was 17.2, a full degree lower than the 18.2°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, only 0.2°C higher than the 15.5°C calculated from the regression equation for that flow and site.

a)



b)

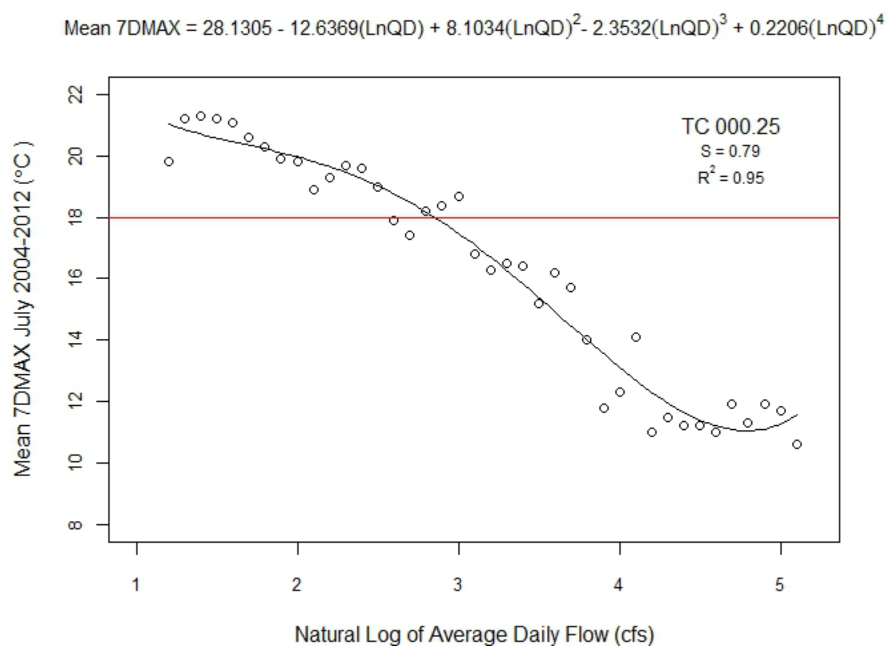


Figure 7. Temperature-Flow Regression Models

Regression models fitted to temperature-flow data describe the relationship between temperature and flow observed during July 2002-2001 at a) DR 160.25, the Deschutes River upstream of the confluence with Tumalo Creek, and during July 2004-2012 at b) TC 000.25, Tumalo Creek upstream of the mouth. We used the corresponding regression equations to calculate temperatures within the observed range of flows for which temperature records were available. The resulting temperature estimates were used with corresponding flow values in a mass balance equation to develop flow scenarios that produce 18°C in the Deschutes downstream of the confluence, at DR 160.00.

4. Discussion

4.1. Temperature Status

Temperatures exceeded the state temperature standard of 18°C at four monitoring locations between DR 164.75 and DR 133.50 in 2012, confirming the temperature impaired status of the middle Deschutes River under Clean Water Act Section 303(d). However, during July 2012, 7DMAX temperatures at DR 160.00 were consistently lower than 18°C while combined flows in the Deschutes downstream of Tumalo Creek remained above 223 cfs, following the pattern observed in 2011. And, while summer temperatures at Lower Bridge Road continue to exceed the state standard, they chart a steadily decreasing trend since 2001. These data suggest that higher flows resulting from streamflow restoration are resulting in temperatures that meet or are very close to the state standard at some sites. When considered with flow data from the Deschutes below North Canal Dam and from Tumalo Creek, 2011 and 2012 temperature data from DR 160.00 suggest that not only higher flows but also different combinations of flow volumes from the Deschutes and from Tumalo will achieve a streamflow scenario that will most effectively result in 18°C at the most impaired sites. Until such a flow scenario is achieved, temperature data suggest that the middle Deschutes River are likely to continue to exceed the state temperature standard during the summer months.

4.2. Restoration Effectiveness

BACI results indicated that temperatures in the Tumalo restoration reach, influenced by flows from both the Deschutes and Tumalo Creek, were significantly cooler relative to the reference reach in 2012 than in 2005. This temperature response suggests a strong cooling effect as a result of the increased contribution of cool Tumalo Creek flows combined with the increase in flows from the Deschutes at North Canal Dam from 2005 to 2012. Streamflow restoration projects that strategically increase flows in Tumalo Creek in proportion to the flow contribution of the upper Deschutes at North Canal Dam may therefore be an effective approach to maximize reductions in temperature in the middle Deschutes downstream of Tumalo Creek.

BACI analysis results for the Deschutes restoration reach from 2005 to 2012 showed no detectable cooling effect along this reach relative to changes in temperature in the reference reach over the same interval, despite the approximately 75 cfs increase in streamflow in the restoration reach between 2005 and 2012. This result suggests that no cooling effect occurred between North Canal Dam and the confluence of the Deschutes River and Tumalo Creek in response to streamflow restoration at North Canal Dam. However, temperature and flow data from DR 160.25, the downstream site for the BACI analysis restoration reach, document stream temperatures decreasing as flows increase, providing empirical evidence for a temperature benefit at DR 160.25 of increased flows at North Canal Dam – according to the temperature-flow regression, approximately a 0.7°C benefit from a 75 cfs increase in streamflow.

Given the observed cooling effect of higher flows at DR 160.25, there are a number of factors that may have contributed to our BACI result indicating no significant difference in change in temperature in the Deschutes restoration reach relative to the reference reach from 2005 to 2012. Despite our BACI analysis failing to show a significant temperature response in the restoration reach relative to the reference reach, the regression of temperature and flow data for DR 160.25 sufficiently demonstrates a cooling effect in response to increased flows resulting from streamflow restoration at North Canal Dam.

4.3. Target Streamflow

Mass balance equation results suggest that the Deschutes River flow target of 250 cfs will achieve the 18°C standard immediately downstream of the confluence with Tumalo Creek at 26 cfs in Tumalo Creek. Alternatively, the Tumalo Creek flow target of 32 cfs will achieve the 18°C standard downstream of the confluence at Deschutes flows of 220 cfs. At the currently protected Deschutes flow of 160 cfs, 38 cfs will be required in Tumalo Creek to meet the 18°C state standard.

Temperature estimates indicate that as flows in Tumalo Creek increase, temperature benefits of higher flows in the Deschutes diminish and ultimately are lost altogether, such that increasing flows in the Deschutes requires commensurate increases in Tumalo flows to achieve the same temperature benefits obtained at lower Deschutes and Tumalo flows. The 13 cfs increase between 24 and 37 cfs in Tumalo Creek results in temperature gains equivalent to increasing Deschutes flows by 90 cfs, from 160 cfs to 250 cfs, to produce a 7DMAX temperature of 18°C below the confluence of the Deschutes and Tumalo. At lower Tumalo Creek flows, increases in Deschutes flows result in comparatively greater temperature gains. Temperature gains of increasing Deschutes flows are greatly reduced once Tumalo flows increase above 50 cfs; above approximately 60 cfs in Tumalo, temperatures *increase* with increases in Deschutes flows. Especially in light of the current status of protected flows, 160 cfs in the Deschutes and 10 cfs in Tumalo, these results suggest that progress to reduce temperatures in the Deschutes may be accelerated by strategically prioritizing Tumalo Creek water transactions; preferentially increasing flows in Tumalo Creek over restoring streamflow in the Deschutes may achieve greater temperature benefits at an equivalent cost.

Regression equations, and the resulting temperature estimates included in the mass balance equation, reflect means of 7DMAX temperatures paired with the natural log of the average daily flow for the middle date of the seven days of temperature data from which the 7DMAX was calculated. Even if pairing the data in this way may allow the flow value to better correspond to the range of temperature values expressed in the 7DMAX, it does not address the problem of attempting to predict temperature from flow without accounting for flows that correspond to the latter three days of temperature values expressed in the 7DMAX. Pairing 7DMAX temperature values with a seven day moving average daily flow statistic instead of a single average daily flow in future analyses may more accurately describe the relationship between temperature and flow and improve the accuracy of the resulting regression equation in predicting stream temperature at a given flow.

The analysis presented identifies flow scenarios that will result in a given temperature at specified Tumalo Creek and Deschutes River flows immediately below the confluence of Tumalo Creek and the

Deschutes. Given available data, future analyses should calculate the rate of change in stream temperature between DR 160.00 and Lower Bridge Road at target flow scenarios to determine what temperature will be required at DR 160.00 to meet the 18°C temperature standard at Lower Bridge. The preliminary mass balance results we present suggest that even by maximizing Tumalo flows and increasing Deschutes flows to 250 cfs, temperatures at DR 160.00 will still be high enough to necessitate a low rate of temperature change between DR 160.00 and DR 133.50, which might also be achieved by increasing flow volume, to obtain 18°C at Lower Bridge. Additionally, estimates of natural average flow for Tumalo Creek in August range from 50 cfs (ODEQ, 2007) to 65 cfs (OWRD 2003); even given the ability to restore flows above this range, higher flows are likely not to exist in some if not many years.

While direct comparison is difficult because of how river miles/kilometers are measured in the two analyses, the Heat Source model for the Deschutes suggests that at instream water right (ODFW) flows for both the Deschutes and for Tumalo, 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 (ODEQ 2007). Both preliminary mass balance equation results and the Heat Source model thus indicate that the instream water right flows for the Middle Deschutes and for Tumalo may be insufficient to meet the state temperature standard in some reaches of the Middle Deschutes between Tumalo Creek and Whychus Creek.

Whether or not it is possible to meet the state temperature standard along every mile of the Middle Deschutes between North Canal Dam and Lower Bridge Road, increases in flow that approach the instream water right and DRC flow targets in both the Deschutes and in Tumalo Creek will nonetheless result in substantial ecological benefits. 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 determine 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 are less well understood. Data on fish response to increased flows and use of habitat including cold-water refugia, to be collected by ODFW in the Middle Deschutes and in Tumalo Creek between 2012 and 2016, will contribute to the ability of restoration partners to discern how flow and temperature affect habitat availability and use and in which locations, and refine streamflow targets accordingly to maximize ecological benefits. Approaches that prioritize increasing Tumalo flows to advance temperature gains should take into account potential strategic long-term trade-offs of deferring greater gains in streamflow volume, and corresponding habitat benefits, 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)	CI (±)	Flow (cfs)	Mean Temp (7DMAX)	CI (±)	Flow (cfs)	Mean Temp (7DMAX)	CI (±)	Flow (cfs)	Mean Temp (7DMAX)	CI (±)
41	20.5	1.8	**94**	19.4	1.8	**147**	18.9	1.8	**200**	18.5	1.8
42	20.4	1.8	**95**	19.4	1.8	**148**	18.9	1.8	**201**	18.5	1.8
43	20.4	1.8	**96**	19.4	1.8	**149**	18.9	1.8	**202**	18.5	1.8
44	20.4	1.8	**97**	19.4	1.8	**150**	18.9	1.8	**203**	18.5	1.8
45	20.4	1.8	**98**	19.4	1.8	**151**	18.8	1.8	**204**	18.5	1.8
46	20.3	1.8	**99**	19.4	1.8	**152**	18.8	1.8	**205**	18.5	1.8
47	20.3	1.8	**100**	19.4	1.8	**153**	18.8	1.8	**206**	18.5	1.8
48	20.3	1.8	**101**	19.3	1.8	**154**	18.8	1.8	**207**	18.4	1.8
49	20.3	1.8	**102**	19.3	1.8	**155**	18.8	1.8	**208**	18.4	1.8
50	20.2	1.8	**103**	19.3	1.8	**156**	18.8	1.8	**209**	18.4	1.8
51	20.2	1.8	**104**	19.3	1.8	**157**	18.8	1.8	**210**	18.4	1.8
52	20.2	1.8	**105**	19.3	1.8	**158**	18.8	1.8	**211**	18.4	1.8
53	20.2	1.8	**106**	19.3	1.8	**159**	18.8	1.8	**212**	18.4	1.8
54	20.1	1.8	**107**	19.3	1.8	**160**	18.8	1.8	**213**	18.4	1.8
55	20.1	1.8	**108**	19.3	1.8	**161**	18.8	1.8	**214**	18.4	1.8
56	20.1	1.8	**109**	19.3	1.8	**162**	18.8	1.8	**215**	18.4	1.8
57	20.1	1.8	**110**	19.2	1.8	**163**	18.7	1.8	**216**	18.4	1.8
58	20.0	1.8	**111**	19.2	1.8	**164**	18.7	1.8	**217**	18.4	1.8
59	20.0	1.8	**112**	19.2	1.8	**165**	18.7	1.8	**218**	18.4	1.8
60	20.0	1.8	**113**	19.2	1.8	**166**	18.7	1.8	**219**	18.4	1.8
61	20.0	1.8	**114**	19.2	1.8	**167**	18.7	1.8	**220**	18.4	1.8
62	20.0	1.8	**115**	19.2	1.8	**168**	18.7	1.8	**221**	18.4	1.8
63	19.9	1.8	**116**	19.2	1.8	**169**	18.7	1.8	**222**	18.4	1.8
64	19.9	1.8	**117**	19.2	1.8	**170**	18.7	1.8	**223**	18.4	1.8
65	19.9	1.8	**118**	19.2	1.8	**171**	18.7	1.8	**224**	18.3	1.8
66	19.9	1.8	**119**	19.1	1.8	**172**	18.7	1.8	**225**	18.3	1.8
67	19.9	1.8	**120**	19.1	1.8	**173**	18.7	1.8	**226**	18.3	1.8
68	19.8	1.8	**121**	19.1	1.8	**174**	18.7	1.8	**227**	18.3	1.8
69	19.8	1.8	**122**	19.1	1.8	**175**	18.7	1.8	**228**	18.3	1.8
70	19.8	1.8	**123**	19.1	1.8	**176**	18.6	1.8	**229**	18.3	1.8
71	19.8	1.8	**124**	19.1	1.8	**177**	18.6	1.8	**230**	18.3	1.8
72	19.8	1.8	**125**	19.1	1.8	**178**	18.6	1.8	**231**	18.3	1.8
73	19.8	1.8	**126**	19.1	1.8	**179**	18.6	1.8	**232**	18.3	1.8
74	19.7	1.8	**127**	19.1	1.8	**180**	18.6	1.8	**233**	18.3	1.8
75	19.7	1.8	**128**	19.0	1.8	**181**	18.6	1.8	**234**	18.3	1.8
76	19.7	1.8	**129**	19.0	1.8	**182**	18.6	1.8	**235**	18.3	1.8
77	19.7	1.8	**130**	19.0	1.8	**183**	18.6	1.8	**236**	18.3	1.8
78	19.7	1.8	**131**	19.0	1.8	**184**	18.6	1.8	**237**	18.3	1.8
79	19.7	1.8	**132**	19.0	1.8	**185**	18.6	1.8	**238**	18.3	1.8
80	19.6	1.8	**133**	19.0	1.8	**186**	18.6	1.8	**239**	18.3	1.8
81	19.6	1.8	**134**	19.0	1.8	**187**	18.6	1.8	**240**	18.3	1.8
82	19.6	1.8	**135**	19.0	1.8	**188**	18.6	1.8	**241**	18.3	1.8
83	19.6	1.8	**136**	19.0	1.8	**189**	18.6	1.8	**242**	18.2	1.8
84	19.6	1.8	**137**	19.0	1.8	**190**	18.6	1.8	**243**	18.2	1.8
85	19.6	1.8	**138**	19.0	1.8	**191**	18.5	1.8	**244**	18.2	1.8
86	19.5	1.8	**139**	18.9	1.8	**192**	18.5	1.8	**245**	18.2	1.8
87	19.5	1.8	**140**	18.9	1.8	**193**	18.5	1.8	**246**	18.2	1.8
88	19.5	1.8	**141**	18.9	1.8	**194**	18.5	1.8	**247**	18.2	1.8
89	19.5	1.8	**142**	18.9	1.8	**195**	18.5	1.8	**248**	18.2	1.8
90	19.5	1.8	**143**	18.9	1.8	**196**	18.5	1.8	**249**	18.2	1.8
91	19.5	1.8	**144**	18.9	1.8	**197**	18.5	1.8	**250**	18.2	1.8
92	19.5	1.8	**145**	18.9	1.8	**198**	18.5	1.8			
93	19.5	1.8	**146**	18.9	1.8	**199**	18.5	1.8			

Tumalo Creek upstream of the mouth (TC 000.25)

Flow (cfs)	Mean Temp (7DMAX)	CI (±)	Flow (cfs)	Mean Temp (7DMAX)	CI (±)	Flow (cfs)	Mean Temp (7DMAX)	CI (±)	Flow (cfs)	Mean Temp (7DMAX)	CI (±)
3	21.2	2.1	**56**	12.9	1.9	**109**	10.9	1.8	**162**	11.3	1.8
4	20.7	2.1	**57**	12.8	1.9	**110**	10.9	1.8	**163**	11.3	1.8
5	20.5	2.1	**58**	12.8	1.9	**111**	10.9	1.8	**164**	11.3	1.8
6	20.2	2.1	**59**	12.7	1.9	**112**	10.9	1.8	**165**	11.4	1.8
7	20.0	2.1	**60**	12.6	1.9	**113**	10.9	1.8	**166**	11.4	1.8
8	19.9	2.1	**61**	12.6	1.9	**114**	10.9	1.8	**167**	11.4	1.8
9	19.7	2.1	**62**	12.5	1.9	**115**	10.9	1.8	**168**	11.4	1.8
10	19.5	2.1	**63**	12.4	1.9	**116**	10.9	1.8	**169**	11.4	1.8
11	19.3	2.1	**64**	12.4	1.9	**117**	10.9	1.8	**170**	11.5	1.8
12	19.1	2.1	**65**	12.3	1.8	**118**	10.9	1.8	**171**	11.5	1.8
13	18.9	2.1	**66**	12.2	1.8	**119**	10.9	1.8	**172**	11.5	1.8
14	18.7	2.0	**67**	12.2	1.8	**120**	10.9	1.8	**173**	11.5	1.8
15	18.5	2.0	**68**	12.1	1.8	**121**	10.9	1.8	**174**	11.6	1.8
16	18.2	2.0	**69**	12.1	1.8	**122**	10.9	1.8	**175**	11.6	1.8
17	18.1	2.0	**70**	12.0	1.8	**123**	10.9	1.8	**176**	11.6	1.8
18	17.9	2.0	**71**	12.0	1.8	**124**	10.9	1.8	**177**	11.6	1.8
19	17.7	2.0	**72**	11.9	1.8	**125**	10.9	1.8			
20	17.5	2.0	**73**	11.9	1.8	**126**	10.9	1.8			
21	17.3	2.0	**74**	11.8	1.8	**127**	10.9	1.8			
22	17.1	2.0	**75**	11.8	1.8	**128**	10.9	1.8			
23	16.9	2.0	**76**	11.7	1.8	**129**	10.9	1.8			
24	16.8	2.0	**77**	11.7	1.8	**130**	10.9	1.8			
25	16.6	2.0	**78**	11.7	1.8	**131**	10.9	1.8			
26	16.4	2.0	**79**	11.6	1.8	**132**	10.9	1.8			
27	16.3	2.0	**80**	11.6	1.8	**133**	10.9	1.8			
28	16.1	2.0	**81**	11.5	1.8	**134**	10.9	1.8			
29	15.9	2.0	**82**	11.5	1.8	**135**	10.9	1.8			
30	15.8	2.0	**83**	11.5	1.8	**136**	10.9	1.8			
31	15.6	2.0	**84**	11.4	1.8	**137**	10.9	1.8			
32	15.5	2.0	**85**	11.4	1.8	**138**	10.9	1.8			
33	15.3	2.0	**86**	11.4	1.8	**139**	11.0	1.8			
34	15.2	1.9	**87**	11.3	1.8	**140**	11.0	1.8			
35	15.1	1.9	**88**	11.3	1.8	**141**	11.0	1.8			
36	14.9	1.9	**89**	11.3	1.8	**142**	11.0	1.8			
37	14.8	1.9	**90**	11.3	1.8	**143**	11.0	1.8			
38	14.7	1.9	**91**	11.2	1.8	**144**	11.0	1.8			
39	14.6	1.9	**92**	11.2	1.8	**145**	11.0	1.8			
40	14.5	1.9	**93**	11.2	1.8	**146**	11.0	1.8			
41	14.3	1.9	**94**	11.2	1.8	**147**	11.0	1.8			
42	14.2	1.9	**95**	11.1	1.8	**148**	11.1	1.8			
43	14.1	1.9	**96**	11.1	1.8	**149**	11.1	1.8			
44	14.0	1.9	**97**	11.1	1.8	**150**	11.1	1.8			
45	13.9	1.9	**98**	11.1	1.8	**151**	11.1	1.8			
46	13.8	1.9	**99**	11.1	1.8	**152**	11.1	1.8			
47	13.7	1.9	**100**	11.0	1.8	**153**	11.1	1.8			
48	13.6	1.9	**101**	11.0	1.8	**154**	11.2	1.8			
49	13.5	1.9	**102**	11.0	1.8	**155**	11.2	1.8			
50	13.4	1.9	**103**	11.0	1.8	**156**	11.2	1.8			
51	13.3	1.9	**104**	11.0	1.8	**157**	11.2	1.8			
52	13.2	1.9	**105**	11.0	1.8	**158**	11.2	1.8			
53	13.2	1.9	**106**	11.0	1.8	**159**	11.2	1.8			
54	13.1	1.9	**107**	11.0	1.8	**160**	11.3	1.8			
55	13.0	1.9	**108**	10.9	1.8	**161**	11.3	1.8			

APPENDIX B Estimated temperatures at five 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)	Mean Temp (7DMAX)	160	180	200	220	250	Flow (cfs)	Mean Temp (7DMAX)	160	180	200	220	250
10	19.5	18.8	18.6	18.5	18.4	18.2	**56**	12.9	17.3	17.3	17.3	17.3	17.2
11	19.3	18.8	18.6	18.5	18.4	18.2	**57**	12.8	17.2	17.2	17.2	17.3	17.2
12	19.1	18.8	18.6	18.5	18.4	18.2	**58**	12.8	17.2	17.2	17.2	17.2	17.2
13	18.9	18.8	18.6	18.5	18.4	18.2	**59**	12.7	17.2	17.1	17.2	17.2	17.1
14	18.7	18.8	18.6	18.5	18.4	18.2	**60**	12.6	17.1	17.1	17.1	17.2	17.1
15	18.5	18.8	18.6	18.5	18.4	18.2	**61**	12.6	17.1	17.1	17.1	17.1	17.1
16	18.2	18.7	18.6	18.5	18.4	18.2	**62**	12.5	17.0	17.0	17.1	17.1	17.1
17	18.1	18.7	18.6	18.5	18.4	18.2	**63**	12.4	17.0	17.0	17.0	17.1	17.0
18	17.9	18.7	18.5	18.4	18.4	18.2	**64**	12.4	17.0	17.0	17.0	17.0	17.0
19	17.7	18.7	18.5	18.4	18.3	18.2	**65**	12.3	16.9	16.9	17.0	17.0	17.0
20	17.5	18.7	18.5	18.4	18.3	18.1	**66**	12.2	16.9	16.9	16.9	17.0	17.0
21	17.3	18.6	18.5	18.4	18.3	18.1	**67**	12.2	16.8	16.9	16.9	16.9	16.9
22	17.1	18.6	18.4	18.4	18.3	18.1	**68**	12.1	16.8	16.8	16.9	16.9	16.9
23	16.9	18.6	18.4	18.3	18.3	18.1	**69**	12.1	16.8	16.8	16.9	16.9	16.9
24	16.8	18.5	18.4	18.3	18.2	18.1	**70**	12.0	16.7	16.8	16.8	16.9	16.8
25	16.6	18.5	18.4	18.3	18.2	18.1	**71**	12.0	16.7	16.7	16.8	16.8	16.8
26	16.4	18.5	18.3	18.3	18.2	18.0	**72**	11.9	16.7	16.7	16.8	16.8	16.8
27	16.3	18.4	18.3	18.2	18.2	18.0	**73**	11.9	16.6	16.7	16.7	16.8	16.8
28	16.1	18.4	18.3	18.2	18.1	18.0	**74**	11.8	16.6	16.6	16.7	16.7	16.7
29	15.9	18.4	18.2	18.2	18.1	18.0	**75**	11.8	16.6	16.6	16.7	16.7	16.7
30	15.8	18.3	18.2	18.1	18.1	17.9	**76**	11.7	16.5	16.6	16.6	16.7	16.7
31	15.6	18.3	18.2	18.1	18.1	17.9	**77**	11.7	16.5	16.5	16.6	16.7	16.7
32	15.5	18.2	18.1	18.1	18.0	17.9	**78**	11.7	16.5	16.5	16.6	16.6	16.6
33	15.3	18.2	18.1	18.1	18.0	17.9	**79**	11.6	16.4	16.5	16.6	16.6	16.6
34	15.2	18.2	18.1	18.0	18.0	17.8	**80**	11.6	16.4	16.4	16.5	16.6	16.6
35	15.1	18.1	18.0	18.0	17.9	17.8	**81**	11.5	16.4	16.4	16.5	16.6	16.6
36	14.9	18.1	18.0	18.0	17.9	17.8	**82**	11.5	16.3	16.4	16.5	16.5	16.5
37	14.8	18.1	18.0	17.9	17.9	17.8	**83**	11.5	16.3	16.4	16.4	16.5	16.5
38	14.7	18.0	17.9	17.9	17.9	17.7	**84**	11.4	16.3	16.3	16.4	16.5	16.5
39	14.6	18.0	17.9	17.9	17.8	17.7	**85**	11.4	16.2	16.3	16.4	16.5	16.5
40	14.5	17.9	17.8	17.8	17.8	17.7	**86**	11.4	16.2	16.3	16.4	16.4	16.5
41	14.3	17.9	17.8	17.8	17.8	17.7	**87**	11.3	16.2	16.2	16.3	16.4	16.4
42	14.2	17.8	17.8	17.8	17.7	17.6	**88**	11.3	16.1	16.2	16.3	16.4	16.4
43	14.1	17.8	17.7	17.7	17.7	17.6	**89**	11.3	16.1	16.2	16.3	16.4	16.4
44	14.0	17.8	17.7	17.7	17.7	17.6	**90**	11.3	16.1	16.2	16.3	16.3	16.4
45	13.9	17.7	17.7	17.7	17.6	17.5	**91**	11.2	16.1	16.1	16.2	16.3	16.3
46	13.8	17.7	17.6	17.6	17.6	17.5	**92**	11.2	16.0	16.1	16.2	16.3	16.3
47	13.7	17.6	17.6	17.6	17.6	17.5	**93**	11.2	16.0	16.1	16.2	16.3	16.3
48	13.6	17.6	17.5	17.6	17.5	17.5	**94**	11.2	16.0	16.0	16.2	16.2	16.3
49	13.5	17.6	17.5	17.5	17.5	17.4	**95**	11.1	15.9	16.0	16.1	16.2	16.3
50	13.4	17.5	17.5	17.5	17.5	17.4	**96**	11.1	15.9	16.0	16.1	16.2	16.2
51	13.3	17.5	17.4	17.4	17.4	17.4	**97**	11.1	15.9	16.0	16.1	16.2	16.2
52	13.2	17.4	17.4	17.4	17.4	17.3	**98**	11.1	15.9	15.9	16.1	16.1	16.2
53	13.2	17.4	17.4	17.4	17.4	17.3	**99**	11.1	15.8	15.9	16.0	16.1	16.2
54	13.1	17.4	17.3	17.3	17.4	17.3	**100**	11.0	15.8	15.9	16.0	16.1	16.2
55	13.0	17.3	17.3	17.3	17.3	17.3							