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Longitudinal Water-Temperature Profiles in Mill Creek, Mason County, Washington

Scientific Investigations Report 2022–5063

U.S. Department of the Interior
U.S. Geological Survey

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32$$

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Longitudinal Water-Temperature Profiles in Mill Creek, Mason County, Washington

By Andrew S. Gendaszek[1], Richard W. Sheibley[1], Erica Marbet[2], Joe Puhn[2], and Catherine Seguin[1]

Abstract

In streams supporting Pacific salmon (*Oncorhynchus* spp.) within the southern Puget Lowland, high water temperatures during late summer are a primary water-quality concern. The metabolic rates of fish and other ectothermic (in other words, cold-blooded) species are regulated by water temperature; salmon and other cold-water fish have specific thermal tolerances outside of which they are susceptible to infection, disease, increased predation, and decreased reproductive success. Mill and Gosnell Creeks, which collectively drain a 30-square mile area of the Puget Lowland in Mason County, Washington, support several species of anadromous salmonids. Whereas previous studies documented relatively cool water temperatures in Gosnell Creek, which drains the watershed upstream from Lake Isabella, water temperatures in Mill Creek, which heads at the outlet of Lake Isabella, regularly exceed thermal tolerances for cold-water fish. The occurrence and distribution of cold-water anomalies in less-than-ambient water temperatures in Mill Creek, however, have not been assessed. In this report, we present spatially and temporally continuous measurements of near-streambed water temperature measured using fiber-optic distributed temperature sensing for three reaches of Mill Creek during August–September 2020 when the water temperatures of streams in western Washington were near their annual maximum. Water temperature was collected every hour and averaged spatially over 1.015-meter sections of the fiber-optic cable deployed at the streambed of Mill Creek. The lengths of the fiber-optic cables deployed in Reaches A, B, and C were 883, 270, and 1,014 meters, respectively. Daily maximum water temperature and daily temperature variability, as measured by standard deviation of water temperature during the deployment, progressively decreased downstream as distance from Lake Isabella increased. However, no abrupt decreases in daily maximum or standard deviation of water temperature were detected in longitudinal temperature profiles of any of the three reaches. Collectively, these results suggest that warm water discharged from Lake Isabella was progressively buffered downstream as it equilibrated with downstream heat fluxes mediated by physical processes including riparian shading and diffuse groundwater input. Although parts of the surveyed reaches associated with deep pools were cooler than other locations, no large (less than 2 °C) water-temperature anomalies characteristic of discrete sources of cold groundwater or surface-water inputs were measured in any of the three surveyed reaches.

Introduction

Mill and Gosnell Creeks, which are separated by Isabella Lake, collectively drain a 30-square-mile area of the southern Puget Lowland in Mason County, Washington (fig. 1). Mill Creek flows from the outlet of Isabella Lake to Puget Sound at Hammersley Inlet whereas Gosnell Creek originates in the 16-square-mile area of the watershed upstream of Lake Isabella. Both Mill and Gosnell Creeks provide spawning and rearing habitat for several species of Pacific salmon (*Onchorhynchus spp.*), including coho salmon (*O. kisutch*) and chum salmon (*O. keta*), as well as habitat for resident cold-water fish such as cutthroat trout (*O. mykiss*). In parts of Mill Creek, native freshwater mussels (*Margaritifera falcata*) are prolific and form beds across the stream. Water temperature is an important water-quality parameter that controls the metabolic rates of fish and other ectothermic (in other words, cold-blooded) species. Cold-water fish like salmon and trout have specific thermal tolerances outside of which they are susceptible to infection, increased predation, disease, and decreased reproductive success (McCullough, 1999). Temperature requirements for cold-water fish vary between species and across life-history stages; concerning anadromous salmonids, a literature review by McCullough and others (2001) suggested migration of adult salmonids is limited by temperatures exceeding 19–23 °C with acute lethal temperatures estimated between 21 and 24 °C depending on life history stage and acclimation temperature.

[1] U.S. Geological Survey

[2] Squaxin Island Tribe

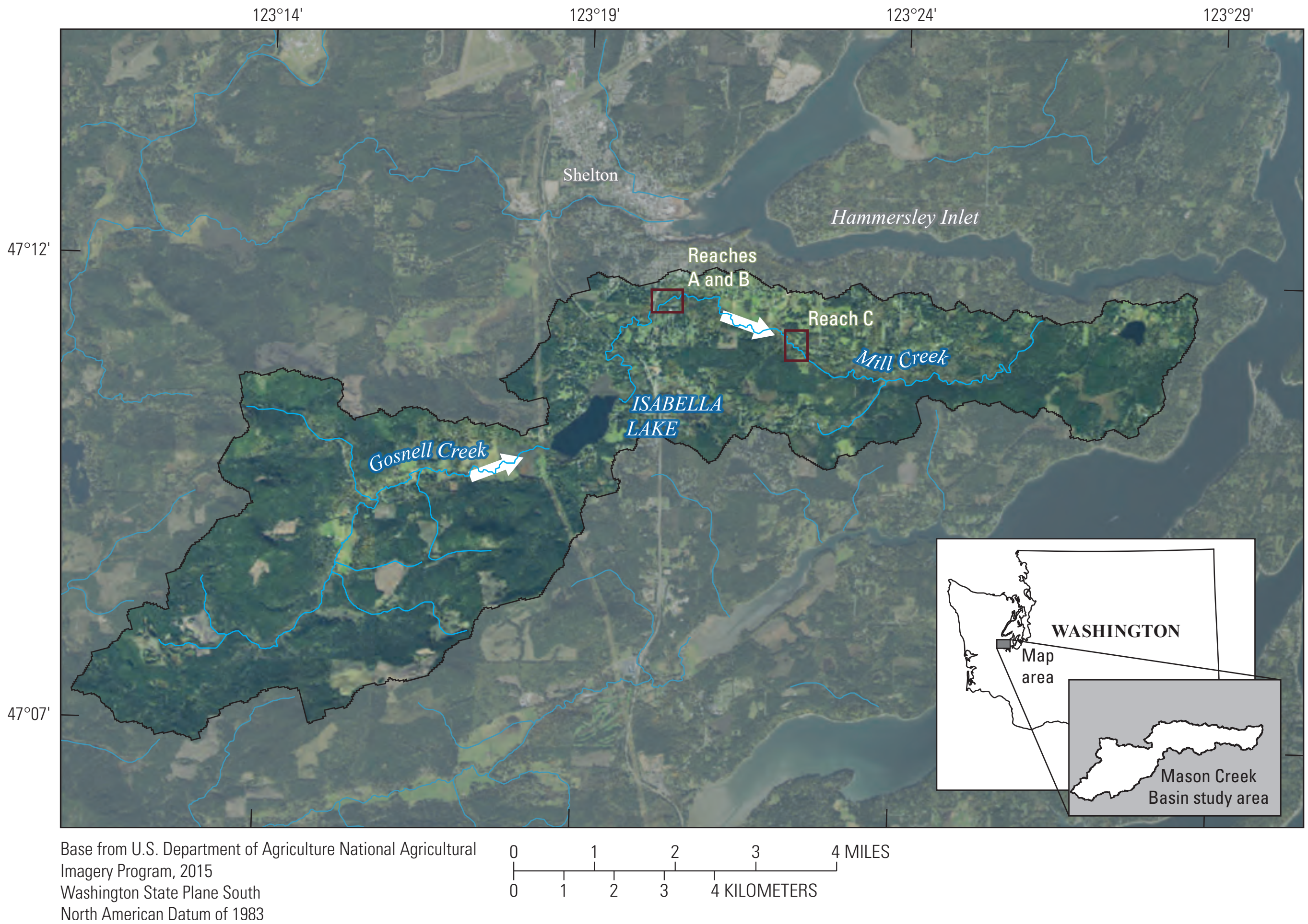


Figure 1. Location of Mill-Gosnell Creek watershed, Mason County, western Washington. Flow direction shown by white arrows.

The non-uniform distribution of summer water temperatures in the Mill-Gosnell Creek watershed reflects differences in the sources of base flow to Mill and Gosnell Creeks. During the summer when precipitation and runoff is minimal, Gosnell Creek base flow is sustained by groundwater discharge, but surface-water outflow from Isabella Lake forms the primary part of Mill Creek's base flow. Because groundwater is buffered from large daily and seasonal fluctuations in temperature, groundwater discharge is generally cooler than surface water during the summer when streams typically reach their annual thermal maximum providing thermal refuge for fish (Hayashi and Rosenberry, 2002). Summer water temperature in Isabella Lake is warmer than Gosnell Creek upstream because the lake receives more solar radiation than Gosnell Creek, which has increased riparian shading. Isabella Lake supports several species of non-native warm-water fish, including largemouth bass (*Micropterus salmoides*) and yellow perch (*Perca flavescens*). Reach-scale and finer variability in water temperature that may provide thermal refuges for cold-water fish within Mill Creek are not known. In order to understand thermal heterogeneity in Mill Creek downstream from Isabella Lake and the distribution of fine-scale cold-water patches that may provide thermal habitat for cold-water fish, longitudinal thermal profiles were measured in three reaches of Mill Creek during August–September 2020 with a fiber-optic distributed temperature sensor.

Purpose and Scope

The purpose of this report is to present longitudinal profiles of near-streambed water temperature measured in three reaches of Mill Creek during August–September 2020 using a fiber-optic distributed temperature sensor. Water-temperature data were measured every hour during three 1-week deployments and spatially averaged over 1.015-meter (m) intervals. Longitudinal profiles were analyzed for downstream changes in the magnitude and variability of water temperature during the deployments. These data were collected and analyzed to support efforts by the Squaxin Island Tribe to address water temperature in the restoration of salmon habitat in Mill Creek.

Description of Study Area

Mill and Gosnell Creeks, which are separated by Isabella Lake, collectively drain a 30-square-mile area of the southern Puget Lowland in Mason County, Washington (fig. 1). Gosnell Creek drains the upper 16-square-mile area of the watershed, which is primarily industrial timberland and some rural residential development, before flowing into Isabella Lake, an unregulated natural lake formed within the remnant glacial topography of the Puget Lowland. Mill Creek flows from the outlet of Isabella Lake to Puget Sound at Hammersley Inlet, and land cover within its watershed downstream from Isabella Lake is primarily rural residential development. During summer base flow, the wetted channel of Mill Creek is typically less than 5 m wide and less than 50 centimeters deep, although some small pools locally exceed 2 m deep. The Mill-Gosnell Creek watershed is largely underlain by unconsolidated Pleistocene glacial sediments with Eocene volcanic rocks of the Crescent Formation basalt also cropping out in the watershed upstream from Isabella Lake (Schasse and others, 2003; Polenz and others, 2010). Mill and Gosnell Creeks largely follow topography established at the end of the Pleistocene following deglaciation and recession of the Puget Lobe of the Cordilleran Ice Sheet, and the watershed is largely underlain by recent alluvium and recessional outwash deposited during that final glacial recession. The U.S. Geological Survey operated a discharge gage on Mill Creek from 1943 to 1951. Named U.S. Geological Discharge Gaging Station 12077500, it was reoccupied by the Squaxin Island Tribe Department of Natural Resources in 2006 with maximum mean monthly discharge of 155 cubic feet per second in January and minimum mean monthly discharge of 13.4 cubic feet per second in August for the period of record from October 2006 to September 2018.

Methods: Longitudinal Temperature Profiles

Near-streambed water temperature was measured using a fiber-optic distributed temperature sensor (FO-DTS) in three reaches of Mill Creek. These reaches were named alphabetically Reach A, Reach B, and Reach C as they were positioned moving in a downstream direction (fig. 1). Water temperature was measured concurrently in the adjacent A and B reaches during a single deployment of the FO-DTS from August 28, 2020, 12:00 PM Pacific Daylight Time (PDT), to September 4, 2020, 11:00 AM PDT. During this period, The FO-DTS unit was located between Reaches A and B with one fiber-optic cable deployed upstream through Reach A and the second fiber-optic cable deployed downstream through the thalweg of Reach B as a single-ended deployment. Water temperature was measured in the thalweg of Reach C during a separate single-ended FO-DTS deployment from August 20, 2020, 5:00 PDT, to August 27, 2020, 1:00 PM PDT. The length of the fiber-optic cable in Reach A was 883 m and included parts of the fiber-optic cable deployed in temperature baths at the upstream and downstream ends of the reach. Excluding the temperature baths, the length of the fiber-optic cable deployed in the reach was 840 m. Reach B was 270 m long and located directly downstream from Reach A. This length included parts of the fiber-optic cable deployed in the temperature baths at the upstream and downstream ends of the reach as well as an 87-m section at one end of a submerged part of the cable that was damaged resulting in signal loss that was unable to be calibrated. Excluding these temperature baths and the damaged sections, the total length of the fiber-optic cable deployed in Reach B was 139 m. In Reach C, the FO-DTS unit was located at the downstream end of the study reach with the fiber-optic cable deployed upstream. The length of the fiber-optic cable in Reach C was 1,014 m and included parts of the fiber-optic cable deployed in the temperature baths at the upstream and downstream ends of the reach. Excluding these temperature baths, the total length of the fiber-optic cable deployed in the reach was 956 m. In each of the three reaches, the FO-DTS unit was programmed to measure water temperature spatially averaged over 1.015-m segments of the fiber-optic cable at 1-hour intervals to resolve diel changes in water temperature.

The FO-DTS measures the temperature of the environment surrounding a fiber-optic cable by emitting a laser pulse at a known wavelength and measuring the intensity of Raman-backscattered light that returns to the FO-DTS unit at a higher (Stokes) and lower (anti-Stokes) wavelength (Selker and others, 2006). The intensity of light that returns at the anti-Stokes wavelength is strongly affected by temperature of the environment surrounding the cable, whereas the intensity of light that returns at the Stokes wavelength is independent of temperature. The temperature of the water surrounding each 1.015-m segment of fiber-optic cable during deployment was determined by calculating the ratio of the intensities of the Stokes and anti-Stokes backscattered light and calculating the time-of-travel of the laser pulse. Hausner and others (2011) described the temperature at a given position of the fiber-optic cable with the following equation:

$$T(z) = \frac{\gamma}{\ln \frac{P_S(z)}{P_{aS}(z)} + C - \Delta\alpha z} \qquad (1)$$

where

T	is temperature,
z	is the position of the fiber-optic cable,
γ	is a constant that represents the shift in energy between a photon of the light emitted by the FO-DTS and the wavelength of the Raman backscattered photon in Kelvin units,
ln	natural logarithm
$P_S(z)$	the power of the Raman Stokes signal at position z,
$P_{aS}(z)$	the power of the Raman anti-Stokes signal at position z,
C	is a calibration parameter (dimensionless)and
$\Delta\alpha z$ (m^{-1})	is the differential attenuation of the Stokes and anti-Stokes signals within the fiber-optic cable.

Prior to each deployment, the fiber-optic cable was initially calibrated by placing both ends of the fiber-optic cable in a constant-temperature ice bath (0.0 °C) verified with a National Institute of Standards (NIST)-certified thermistor with an accuracy of ±0.2 °C. After the deployment, temperature measured by the FO-DTS was dynamically calibrated for each 1-hour time step by solving a set of linear equations based on equation (1) relating raw FO-DTS Stokes and anti-Stokes backscattered light intensity data to three independent water temperature measurements (T_1, T_2, and T_3) at different locations along the cable (z_1, z_2, and z_3; Hausner and others, 2011):

$$\bar{A}\bar{x} = \bar{b} \qquad (2)$$

where

$\bar{A}$	is a matrix, and
$\bar{x}$ and $\bar{b}$	are vectors:

$$\bar{A} = \begin{bmatrix} 1 & -T_1 & T_1 z_1 \\ 1 & -T_3 & T_2 z_2 \\ 1 & -T_3 & T_3 z_3 \end{bmatrix}; \quad \bar{x} = \begin{bmatrix} \gamma \\ C \\ \Delta\alpha \end{bmatrix}; \quad \bar{b} = \begin{bmatrix} T_1 \ln \frac{P_S(z_1)}{P_{aS}(z_1)} \\ T_2 \ln \frac{P_S(z_2)}{P_{aS}(z_2)} \\ T_3 \ln \frac{P_S(z_3)}{P_{aS}(z_3)} \end{bmatrix}; \qquad (3)$$

Water temperature was measured independently of the FO-DTS by data-logging thermistors (Hobo® Water Temp Pro v2) and thermocouples integrated with the FO-DTS unit at least four locations along each cable deployment, including locations in the stream and ice baths at the ends of FO-DTS cables. The distances of independent water-temperature datasets recorded by data-logging thermistors and thermocouples and their use as calibration or validation data are detailed in table 1. At each of the three reaches, three of the independent water-temperature datasets were used to calibrate the raw FO-DTS Stokes and anti-Stokes backscattered light intensity data. FO-DTS data for reaches A and C were validated using a fourth independent water-temperature dataset; at Reach B, no validation dataset was available in the undamaged section of FO-DTS cable. Raw FO-DTS signal data, calibrated FO-DTS water-temperature data, and independent thermistor and thermocouple water-temperature data are available in Gendaszek and others (2021). Calibrated water-temperature data were visualized with the DTSGUI software package (Domanski and Day-Lewis, 2019).

Table 1. Locations of thermocouples and thermistors relative to the fiber-optic distributed temperature sensor (FO-DTS) unit deployed during the FO-DTS deployments for calibration and validation of FO-DTS data, Mason County, Washington.

Reach	Number of thermocouples deployed	Distance of thermocouples from FO-DTS unit (meters)	Number of thermistors deployed	Distance of thermistors from FO-DTS unit (meters)
A	1	22	3	47, 859, and 875
B	1	22	3	91, 125, and 240
C	1	14	3	170, 396, and 998

Reaches A and B: Longitudinal Water Temperature Profiles

Water temperatures in Reaches A and B were measured between August 28, 2020, and September 4, 2020 (figs. 2 and 3). The cold-water baths at both ends of both reaches appear in the figures as ~10-m long sections of fiber-optic cable that remained consistently cooler than the rest of the fiber-optic cable throughout the deployment. At several locations, including in the immediate vicinities of the ice bath, the fiber-optic cables were emergent (not submerged) where obstacles such as channel-spanning logs and vegetation prevented its deployment in the water. Temperatures measured along emergent sections reflected the temperature of the air, which had greater variation than submerged sections of the fiber-optic cable. Data from a 50-m section of Reach B were removed from analysis because signal loss in the fiber-optic cable prevented accurate measurement of water temperature. Root-mean square error (RMSE) calculated at a distance of 22 m from the FO-DTS unit in Reach A was 0.48 °C; however, this measurement was obtained in the ice bath, which may have been subject to thermal stratification between the FO-DTS cable and the data-logging thermistor during the deployment. The lack of an independently collected water-temperature dataset in the undamaged section of the FO-DTS cable in Reach B precluded calculation of RMSE for Reach B.

The time series of longitudinal water-temperature profiles recorded by the FO-DTS recorded diel fluctuations in water temperature influenced by local meteorological conditions and shading from riparian vegetation likely cool warmer water flowing from the outlet of Isabella Lake. In Reaches A and B, no temperature anomalies indicative of discrete inputs of cold-water from substantial groundwater discharge were noted within the FO-DTS profiles. Daily maximum air temperature measured at Olympia Airport, 30 kilometers southeast of the study area, ranged from 22.2 to 30 °C (National Weather Service, 2021). Warm, sunny days such as August 28 and September 4 were characterized by the warmest measured water temperatures, whereas cooler, cloudy days such as September 1 were characterized by cooler water temperatures. On August 28, a warm, clear day when air temperature measured at Olympia Airport reached a maximum of 27.2 °C (National Weather Service, 2021), water temperature at 1900 was warmest at the most upstream part of the Reach A and B longitudinal thermal profile and progressively cooled downstream at a rate of 0.5 °C per kilometer. The progressive downstream cooling coincided with progressively decreased downstream variability in water temperatures during the August 28 to September 4 deployment as measured by a decrease in the standard deviation of water temperature during this time period from 2.4 °C to less than 1.2 °C (fig. 3). Locations where the cable was out of the water were characterized by cool temperatures and relatively high standard deviation. These data suggest that shading from the riparian canopy downstream from Isabella Lake limits solar radiative input to the stream, which coupled with diffuse groundwater discharge may contribute to downstream cooling of water in Reaches A and B. In addition to radiative and advective processes contributing to the heat budget of the stream, other processes including evaporation and conduction also contribute to measured water temperatures. More substantial discrete groundwater inputs are typically characterized by abrupt drops in daytime stream temperature along a reach or by relatively cool late afternoon and evening water temperatures with low variability over the deployment (Mwakanyamale and others, 2012). Those characteristics were absent from both Reaches A and B.

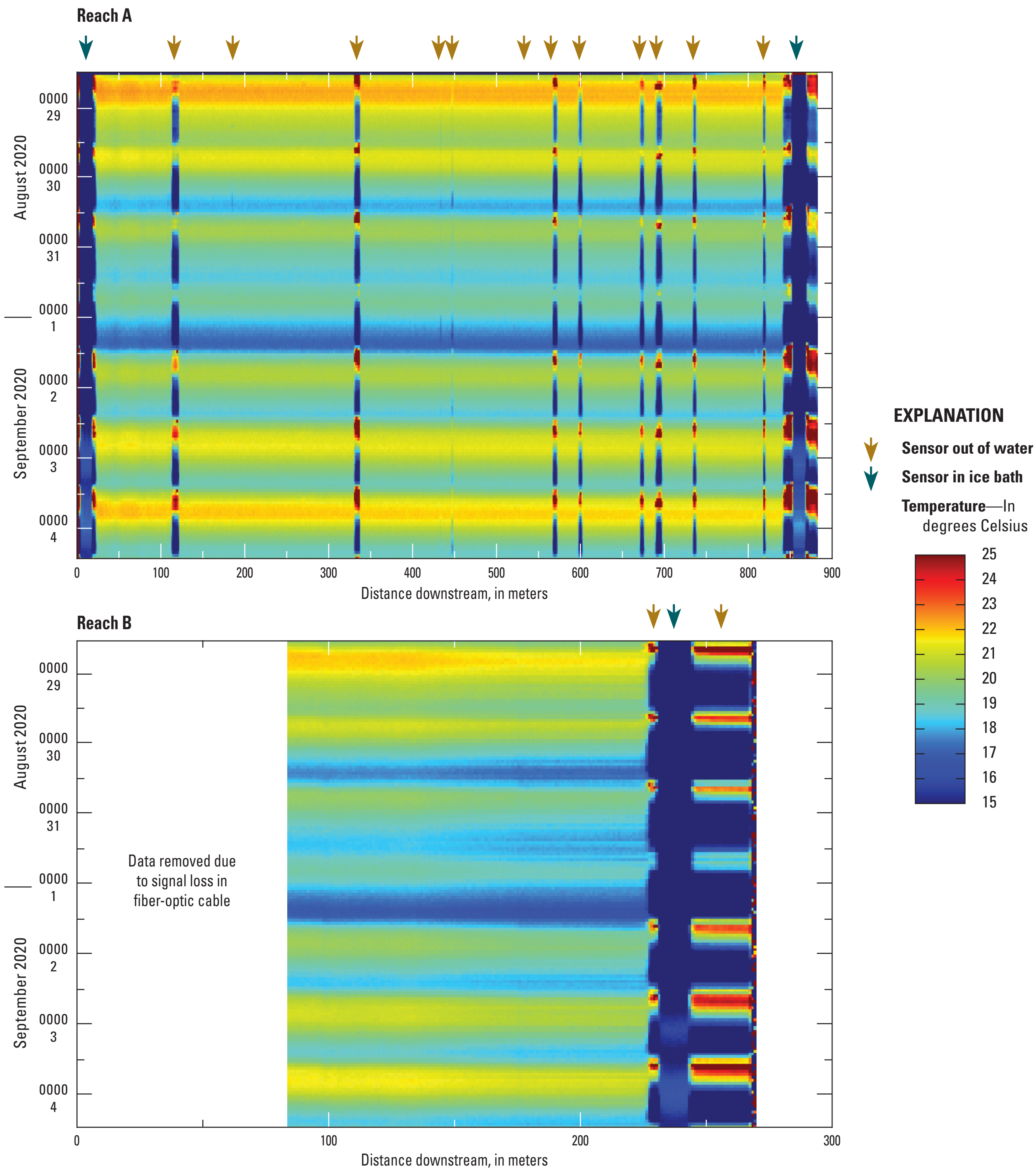
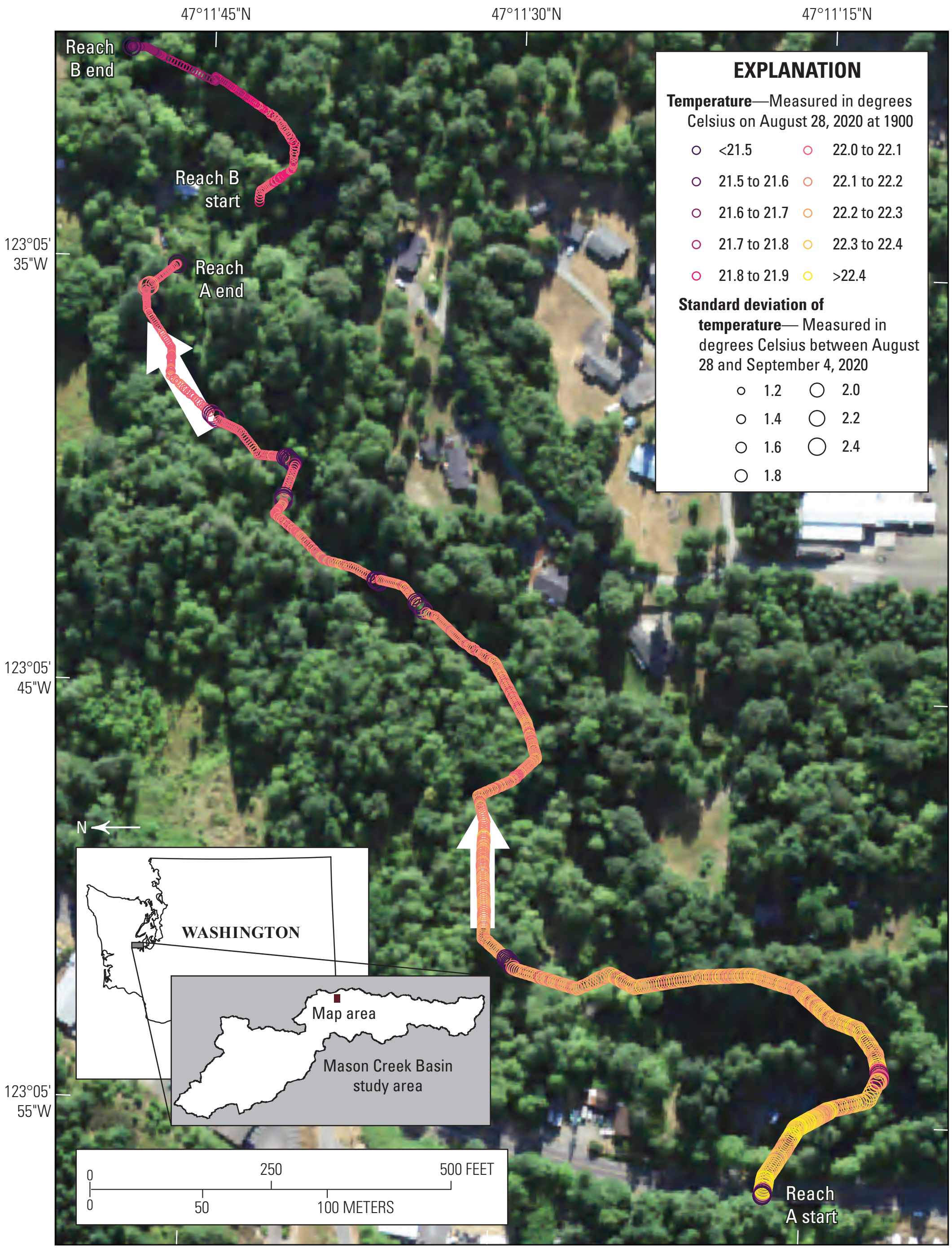


Figure 2. Near-streambed temperature of Reach A and Reach B of Mill Creek, Mason County, western Washington, August 28–September 4, 2020, measured using a fiber-optic distributed temperature sensor. Numbers along the y-axis show hour over day of the month.



Base from U.S. Department of Agriculture National Agricultural Imagery Program, 2015
Washington State Plane South
North American Datum of 1983

Figure 3. Near-streambed temperature measured at 1900, August 28, 2020, and standard deviation of near-streambed water temperature measured between August 28 and September 4, 2020, using a fiber-optic distributed temperature sensor in Reach A and Reach B of Mill Creek, Mason County, western Washington. <, less than.

Reach C: Longitudinal Water Temperature Profile

Water temperature was measured in Reach C between August 20 and 27, 2020, using a single deployment of a 1,014-m fiber-optic cable. Similar to the FO-DTS deployments in Reaches A and B, two ice baths were located at the upstream and downstream ends of the reach with an additional ice bath located near meter 600 in the middle of Reach C. The locations of the ice baths along the cable are indicated by cooler and less variable water temperatures (fig. 4). Locations where the fiber-optic cable was emergent (not submerged) due to obstructions like channel-spanning logs reflect the temperature of the air and were more variable than adjacent submerged sections of the fiber-optic cable. Root-mean square error calculated at a distance of 619 m from the FO-DTS unit in Reach C was 0.12 °C.

Meteorological conditions were cooler and cloudier during the FO-DTS deployment in Reach C than in Reaches A and B and therefore measured water temperatures were typically lower in Reach C. At Olympia Airport, maximum daily temperature during the FO-DTS deployment in Reach C ranged from 20 °C on August 21 to 27.2 °C on August 27 (National Weather Service, 2021). Whereas downstream cooling occurred in Reaches A and B during late evening, water temperatures during August 22 at 1900 were more uniform and increased slightly downstream (fig. 5). Locations where the cable was out of the water are characterized by cool temperatures and relatively high standard deviation. In contrast to Reaches A and B, variation of measured water temperature in Reach C during the deployment was similar along the length of the submerged parts of the fiber-optic cable. The more spatially uniform and less variable water temperatures (standard deviation of water temperature during the deployment was less than 1.0 °C) measured in Reach C during the FO-DTS deployment suggests that the elevated water temperatures in Isabella Lake outflow were largely attenuated by riparian shading and diffuse groundwater discharge along the section of Mill Creek between the lake and Reach C. Additionally, no abrupt drops in daytime stream temperatures were measured in Reach C, suggesting that groundwater discharge was diffuse and minimal and did not contribute substantially to the thermal regime. Water temperatures in Reach C, however, may also reflect cooler and cloudier conditions present during the FO-DTS deployments in Reach C.

Summary and Conclusions

Continuous water-temperature data were collected in three reaches of Mill Creek downstream from Isabella Lake in August and September 2020 and analyzed for spatial differences in the magnitude and variability of water temperature. Water-temperature data were measured at 1-hour intervals, which was adequate to resolve diel changes in water temperature throughout the reaches. No abrupt drops in daytime water temperatures or discrete areas of low variability in temperature, either of which would indicate discrete groundwater discharge, were noted in any of the three reaches. However, in Reaches A and B, variability of water temperature during the entire deployment and daily maximum water temperatures were highest at the most upstream parts of the reach (figs. 2 and 3). Downstream decreases in the variability of water temperatures and daily maximum water temperatures suggest that the temperature of relatively warm outflow from Lake Isabella was being attenuated from mechanisms such as decreased solar radiative input or diffuse groundwater discharge through the extent of the reach. Reach C was far enough downstream from Lake Isabella that no downstream change in the variability or magnitude of temperature was detected from water temperature measured during hydrological and meteorological conditions present during the FO-DTS deployment, although water temperatures measured in Reach C may be influenced by cooler and cloudier conditions during the Reach C deployment. Collectively, these longitudinal water-temperature profiles suggest that although no discrete zones of substantial cold groundwater discharge were measured in any of the three reaches, the late-afternoon water temperatures during summer were attenuated in Mill Creek downstream from Lake Isabella, likely due to the cumulative effect of riparian canopy shading downstream from Lake Isabella or diffuse groundwater input.

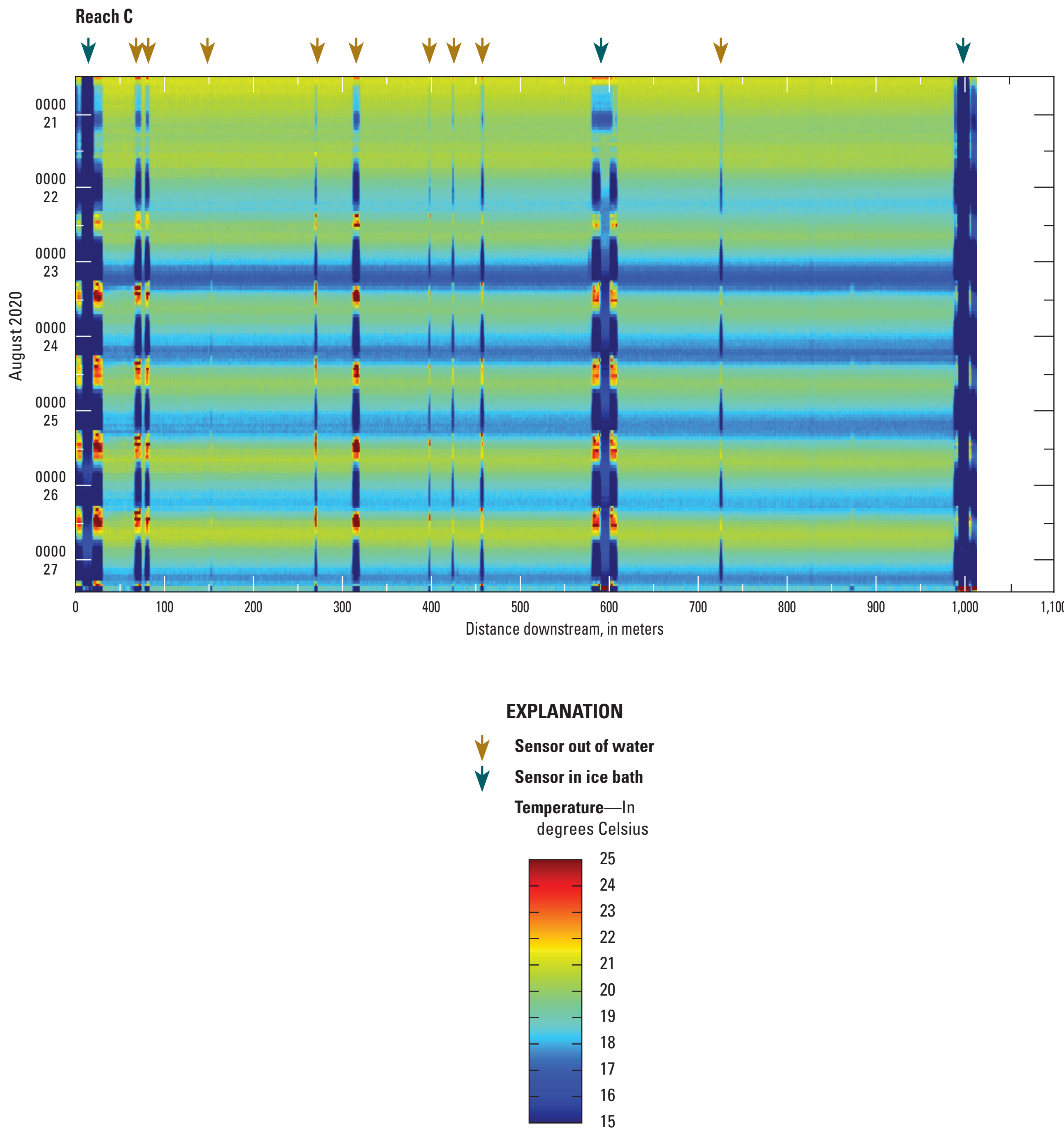
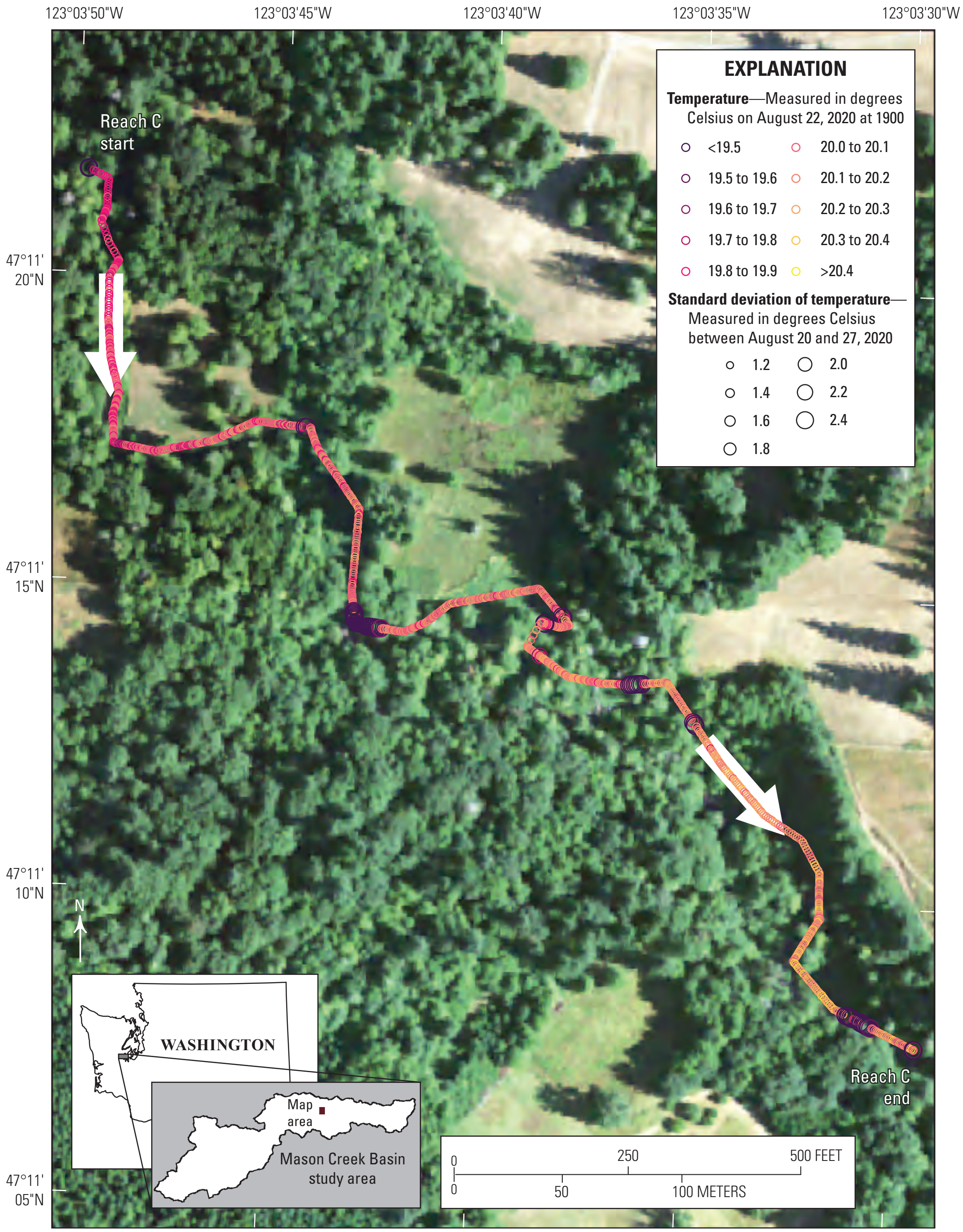


Figure 4. Near-streambed temperature of Reach C of Mill Creek, Mason County, western Washington, August 20–27, 2020, measured using a fiber-optic distributed temperature sensor. Numbers along the y-axis show hour over day of the month. White space at right end of thermograph indicates data removed due to signal loss in fiber-optic cable.



Base from U.S. Department of Agriculture National Agricultural Imagery Program, 2015
Washington State Plane South
North American Datum of 1983

Figure 5. Near-streambed temperature measured at 1900, August 28, 2020, and standard deviation of near-streambed water temperature measured between August 28 and September 4, 2020, using a fiber-optic distributed temperature sensor in Reach C of Mill Creek, Mason County, western Washington. White arrows show flow direction. <, less than, >, greater-than.

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