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HCFF Middle Provo Temperature Monitoring Project 2022-2024

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High Country Fly Fishers

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INTRODUCTION

Water released from the Jordanelle dam into the Middle Provo River presently meets state-required nutrient standards, but additional nutrients and other pollutants are being added both upstream and downstream from sources associated with the development of residential subdivisions around the Jordanelle Reservoir and rapid urbanization of the Heber Valley. The Middle Provo River has also been adversely affected by a persistent 20-year megadrought in the Intermountain Basin or, more accurately, the *aridification* of the Western United States due to global climate change. Water quality and the health of the Middle Provo fishery are at risk from reduced flows and the associated warmer water and dissolved oxygen reductions caused by potential future climate change.

Because of the effects of a continuing drought and the ongoing rapid urbanization of the Heber Valley on the health of the trout fishery in the Middle Provo River, the High Country Fly Fishers (HCFF), a chapter of Trout Unlimited in Park City, Utah, initiated a 2-year conservation project in Spring 2022 to continuously monitor water temperatures along the full course of the Middle Provo River. This river, a high-quality, blue ribbon, brown trout tailwater fishery, runs through Utah's Heber Valley between the Jordanelle and Deer Creek Reservoirs and is fed by water discharged from the Jordanelle Reservoir, which was built by the U.S. Bureau of Reclamation in the years 1987-1993.

The project was proposed jointly with Wasatch High School's Center for Advanced Professional Studies (CAPS) program in Heber City, Utah, which introduces high school students to various professional fields of study. The high school program entrains students into a program of Environment and Agriculture run by high school teacher Matthew Zierenberg. Within this program selected students receive training in aquatic entomology by retired entomologist Professor Roger Gold. The students assist the HCFF program by helping download temperature dataloggers placed in the river by HCFF and by collecting and categorizing aquatic invertebrates along the river to monitor the health of the aquatic insects that are the primary diet of trout. The HCFF project received a permit from the U. S. Bureau of Reclamation and concurrent approval from the Mitigation Commission.

The two-year project had the good fortune to sample both low (2022) and high (2023) water years. Here, we provide a report of the findings of the water temperature monitoring project while also providing a context for that data by utilizing supporting data from the Central Utah Water Conservancy District (CUWCD) and the United States Geological Survey (USGS). Additional supporting weather data came from the Wasatch campus of Utah Valley University (UVU) and a station near the Trestle Bridge operated in the years 2014 to 2018 by Brigham Young University (BYU). We thank the CUWCD, USGS, UVU and BYU for access to this supporting data.

A related document introduces fisherman to the Middle Provo River and includes historical information on the Central Utah Project, the Jordanelle Dam, the river and its rehabilitation after the Jordanelle Dam was built, the geology, the climate and weather, the water quality, the fishery and the benthic macro-invertebrates on which the trout depend for sustenance. Additionally, a fly-by video tour of the Middle Provo River shows the locations where temperature dataloggers were placed in the river. A second video provides examples of macro-invertebrates collected by the CAPS students in early December 2023.

WHY MEASURE STREAM TEMPERATURES?

Water temperature is a key environmental and water quality parameter that affects both trout and the macroinvertebrates on which trout feed. High temperatures are associated with lower dissolved oxygen levels in the water that support the respiration of macroinvertebrates and trout. The health of the macro-invertebrates and their times of hatching or *emergence* depend on water temperature. Trout slow down when water temperatures reach into the range of 65-68°F and become stressed at temperatures above 68°F (**Figure 1**). Continuous temperatures in the upper 70s can be lethal.

Other agencies have collected water temperature data in the Middle Provo River. This High Country Fly Fishers project extends these prior studies temporally and spatially by collecting temperature data at 15-minute intervals at multiple sites along the entire course of the river and in its major tributaries to gain an understanding of water temperature relationships within the drainage and to prepare a baseline for future such measurements in case the watershed comes under further stress due to climate change (droughts), rapid urbanization or other factors. The HCFF data will be made publicly available through a database at the Utah Division of Water Quality (DWQ).

TEMPERATURE DATALOGGERS

Water temperatures in the Middle Provo River and its major tributaries were monitored using HOBO Pendant® MX2201 temperature data loggers (Onset Computer Corporation, Bourne, MA) that were attached to permanent in-stream infrastructure or were secured to concrete pavers (**Figure 2**) that were temporarily placed into the water. Several of the pavers were lost by the extremely high and long-lived water discharges in 2023, so that the loggers placed on permanent in-stream infrastructures were critical to the project. The dataloggers recorded instantaneous temperatures at 15-minute intervals. They were removed from the water periodically and data were downloaded to a cell phone using the Bluetooth LE communications protocol.

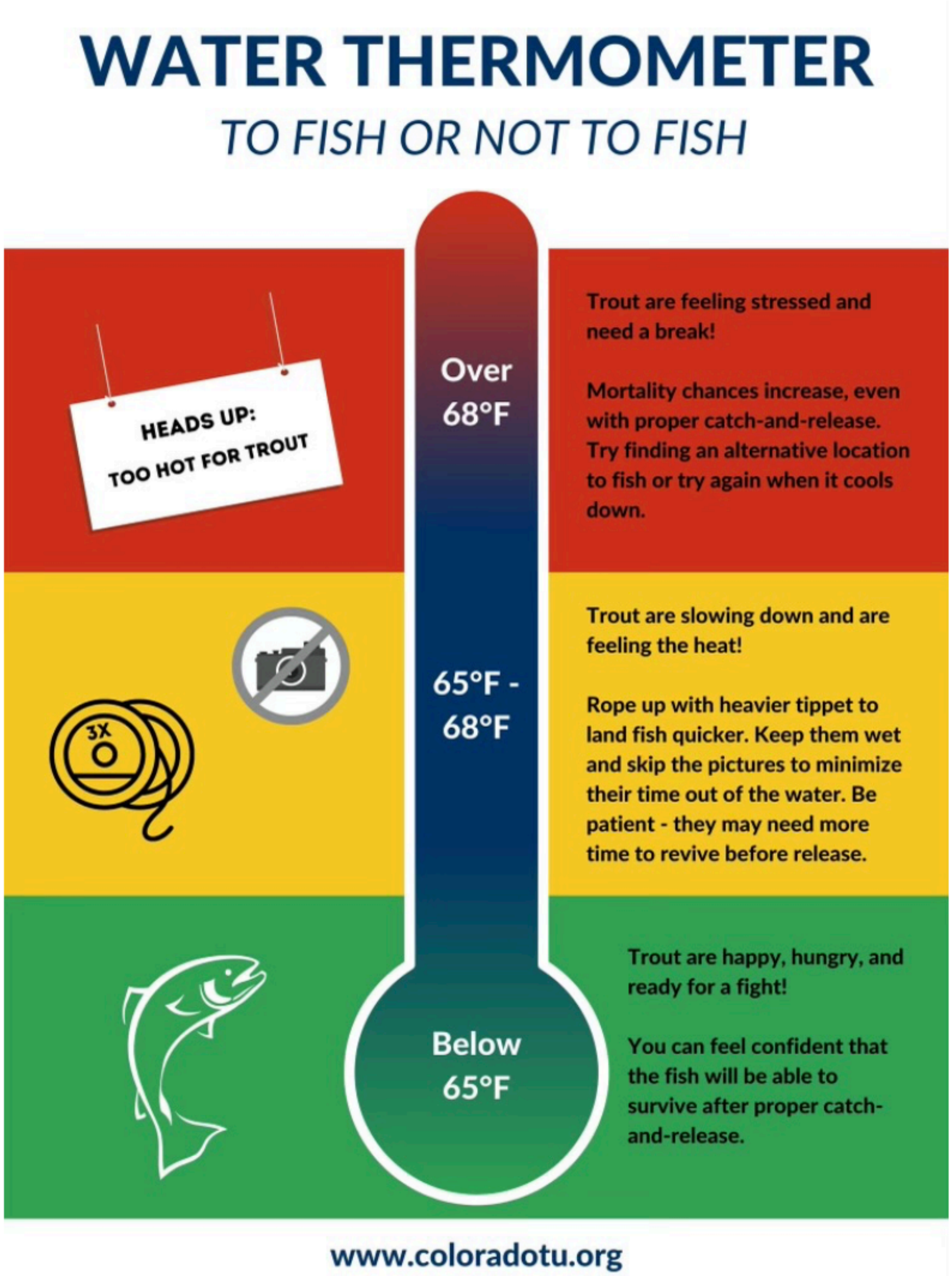


Figure 1. Effects of water temperature on trout. From Colorado Trout Unlimited.

Figure 2. HOBO pendant® temperature datalogger secured to a paver. The paver is inserted and removed from the water using a stick with a hook on the end that is inserted into the eyebolt. Once in the stream, the paver is soon covered by algae making it hard to distinguish from the rocks in the streambed.

THE DATALOGGER NETWORK

The Middle Provo River is fed by the discharge from the Jordanelle Reservoir and flows southward for 12 miles (19 km) through the Heber Valley to Deer Creek Reservoir. Heber City and Midway are nearby cities located east and west of the river. The topographic map in Figure 3 shows the datalogger locations and site names. Names used in this report for streamside infrastructure and fishing locations on the Middle Provo River are taken from Streamline's *Provo River Fishing Map©* (Appendix A in The Middle Provo River – An introduction for the fisherman).

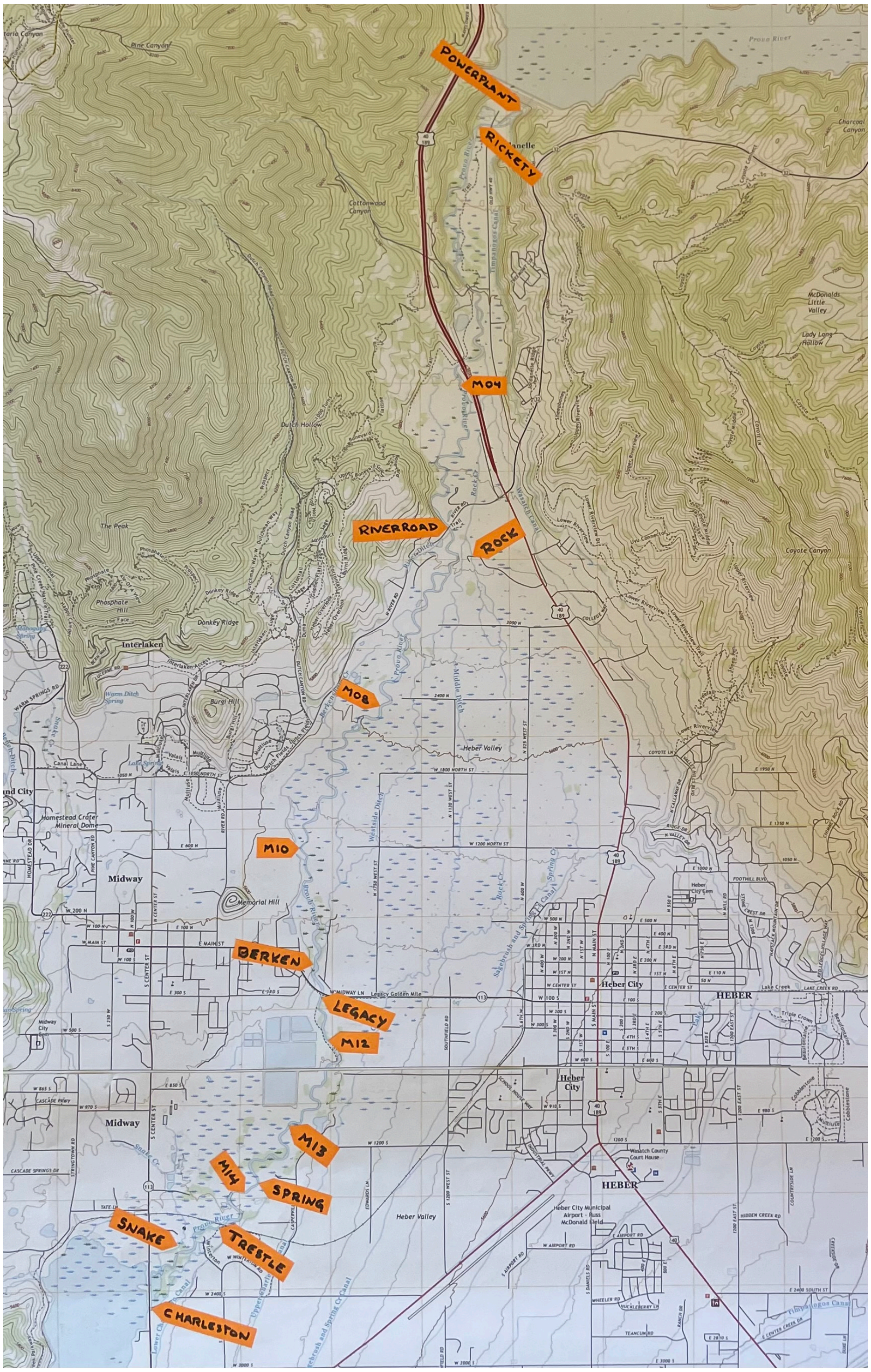


Figure 3. Middle Provo River topography and the locations and names of the water temperature sampling sites. The powerplant temperature was measured by CUWCD; temperatures at the remaining 15 sites were measured with HOBO dataloggers. Base map from USGS 7.5 min 2020 Charleston and 2020 Heber quadrangles.

The GPS positions of the sites and their down-river distances from the Jordanelle Dam are presented in **Table 1**. CUWCD operates the dam for the U.S. Bureau of Reclamation and measures water temperature and discharge at the power plant. HOBO dataloggers measure the temperature at the other sites. Three HOBOs in tributaries (Berkenshaw, Spring and Snake creeks) were positioned just upstream of their confluences with the Middle Provo. One HOBO site (Rock Creek ditch) was in an irrigation diversion. The remaining 11 HOBO sites were in the main channel of the Middle Provo River.

Table 1. GPS coordinates and down-stream distances of the water temperature measuring sites. Tributary sites in blue; irrigation diversion site in red. Sites M08, M10, M12, M13, and M14 were co-located with CAPS macro-invertebrate sampling sites. Sites M12 and M14 were difficult to access, collected redundant data and were decommissioned early in the project.

Abbreviated Site Name	Site	No.	River distance (mi, km)	Latitude (°N) & longitude (°E)	Notes
Powerplant	Jordanelle powerplant	1	0.00, 0.00	40.59643, -111.42360	
Rickety	Rickety Bridge, USGS gage	2	0.395, 0.64	40.59484, -111.42914	
M04	Macro Site 04	3	2.562, 4.12	40.56821, -111.43110	
RiverRoad	River Rd Bridge, USGS gage	4	3.880, 6.24	40.55411, -111.43331	
Rock	Simmons Rock Creek Bridge	5	3.837, 6.18	40.55125, -111.43050	
M08	Macro Site 08	6	5.645, 9.08	40.53616, -111.44247	
M10	Macro Site 10	7	7.241, 11.65	40.52194, -111.45293	
Berken	Berkenshaw Crk confluence	8	8.149, 13.11	40.51043, -111.45120	
Legacy	Legacy Bridge, USGS gage	9	8.495, 13.67	40.50699, -111.44975	
M12	Macro Site 12	10	8.784, 14.14	40.50189, -111.44801	Site deactivated
M13	Macro Site 13	11	9.604, 15.46	40.49489, -111.45396	
Spring	Spring Creek confluence	12	10.159, 16.35	40.48880, -111.45857	
M14	Macro Site 14	13	10.259, 16.51	40.48842, -111.46032	Site deactivated

Trestle	Trestle Bridge, USGS gage	14	10.727, 17.26	40.48501, -111.46258	
Snake	Snake Creek confluence	15	11.327, 18.23	40.48135, -111.47027	
Charleston	Charleston bridge	16	11.709, 18.84	40.47704, -111.47170	

The longitudinal stream elevation profile in **Figure 4** shows the elevation gradient along the river (44 ft/mile above the Legacy Bridge; 28 ft/mi below the Legacy Bridge), the stream infrastructure located along the river, and datalogger locations. The river begins at an elevation of 5880 ft at the dam power plant and enters Deer Creek Reservoir at approximately 5400 ft, depending on the water level in the reservoir. At the upper end of the river, water is diverted into the Timpanogos, Rock Creek and Wasatch Canals. The river receives inflows from 3 tributaries in the lower half of the river – Berkenshaw Creek, Spring Creek and Snake Creek, as well as occasional stormwaters that flow into the river just above the Charleston bridge. The river flows through alluvium with boulders and cobbles throughout, but with increasing gravels and sands in the lower river.

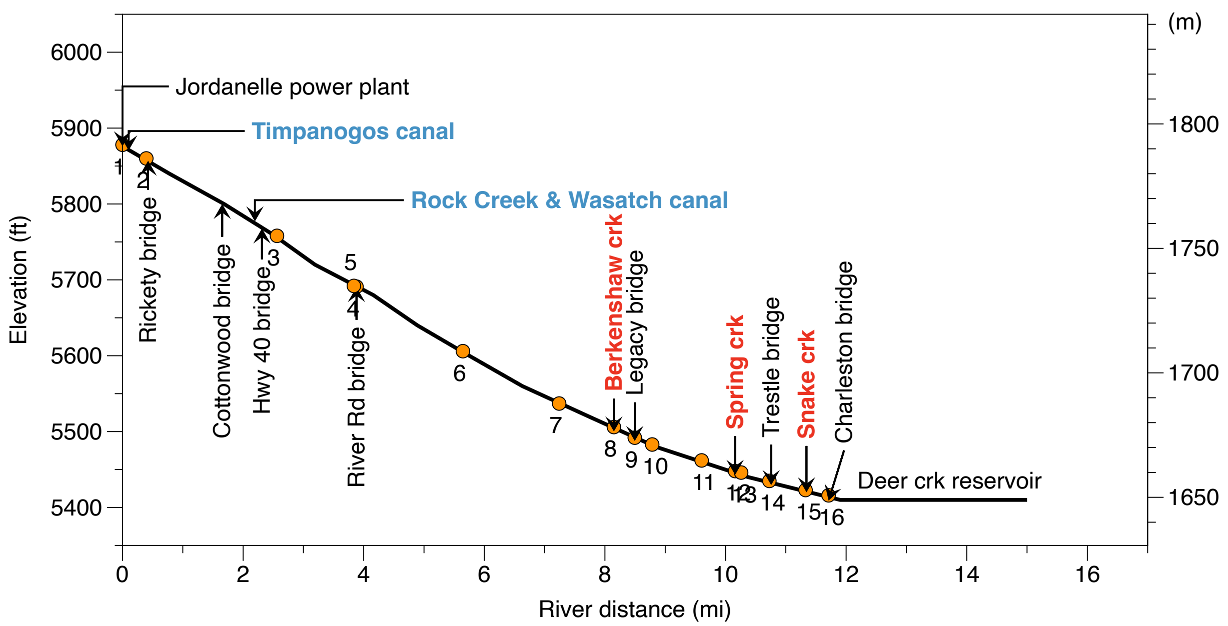


Figure 4. Elevation profile along the Middle Provo River, indicating locations of major irrigation diversions (blue), tributaries (red), power plant and bridges (black) and temperature dataloggers (numbered orange dots). Elevation data from USGS 2020 Heber City and 2020 Charleston quadrangle maps with 40 ft contour intervals.

WATER DISCHARGE RATE AND TEMPERATURE FROM THE JORDANELLE DAM

Water entering the Middle Provo River comes from the foot of the Jordanelle dam, with its flow rate and temperature determined by CUWCD. The discharge rate and water temperature for the 2022-2024 years of the HCFF study are shown in **Figure 5**. The discharge rate at the dam is varied by adjusting the opening of gates at different elevations on a tower in the reservoir adjacent to the dam to feed the dam's penstock. The temperature is adjusted by selecting input gates at different depths in the reservoir. The vertical temperature profiles in the reservoir change with season. In summer, when CUWCD tries to keep the water at a steady ~50-53°F temperature range that is ideal for trout, frequent changes to gate depth and openings are required.

In 2022, a severe drought year, discharge barely exceeded 300 cfs as water flow was reduced to water rights holders downstream. 2023, on the other hand, was an unusually wet year, with discharges exceeding 2000 cfs. While the discharge rates were quite different in 2022 and 2023, the seasonal water temperature curves of the two years were similar. The winter temperatures were near 37°F, with a steady rise to about 45°F in mid-June (2022) or early July (2023), followed by an abrupt 5-6°F rise to a relatively steady summer and early fall temperature range of 50-53°F. In late September the water temperatures began a steady fall to the wintertime value of 37°F by early January.

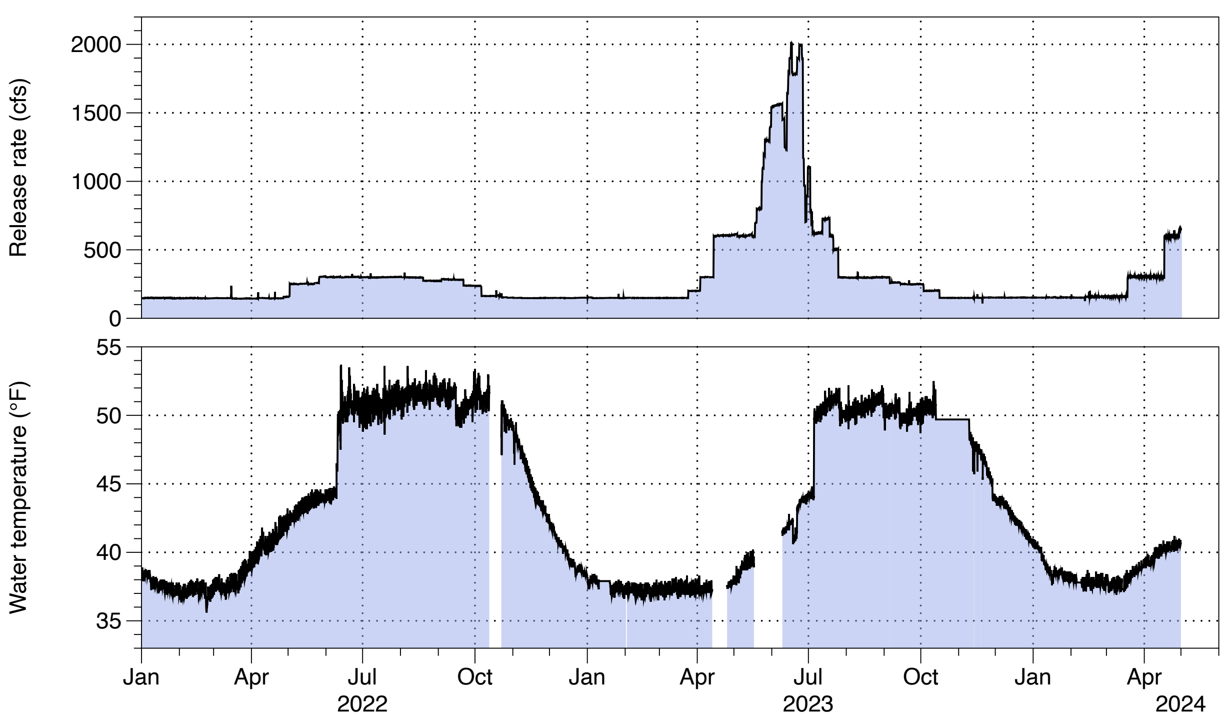


Figure 5. Jordanelle dam water release rate (upper figure) and temperature (lower figure) during 2022-2024.

These 2022-2024 discharge rates are compared to previous years in **Figure 6**. The unusually low discharge in 2022 and the unusually high and summer-long output in 2023 are apparent in this figure. Also apparent are the stepwise changes in discharge in the spring and early summer. Fish take several days to adjust to these stepwise changes in water depths by finding new lies.

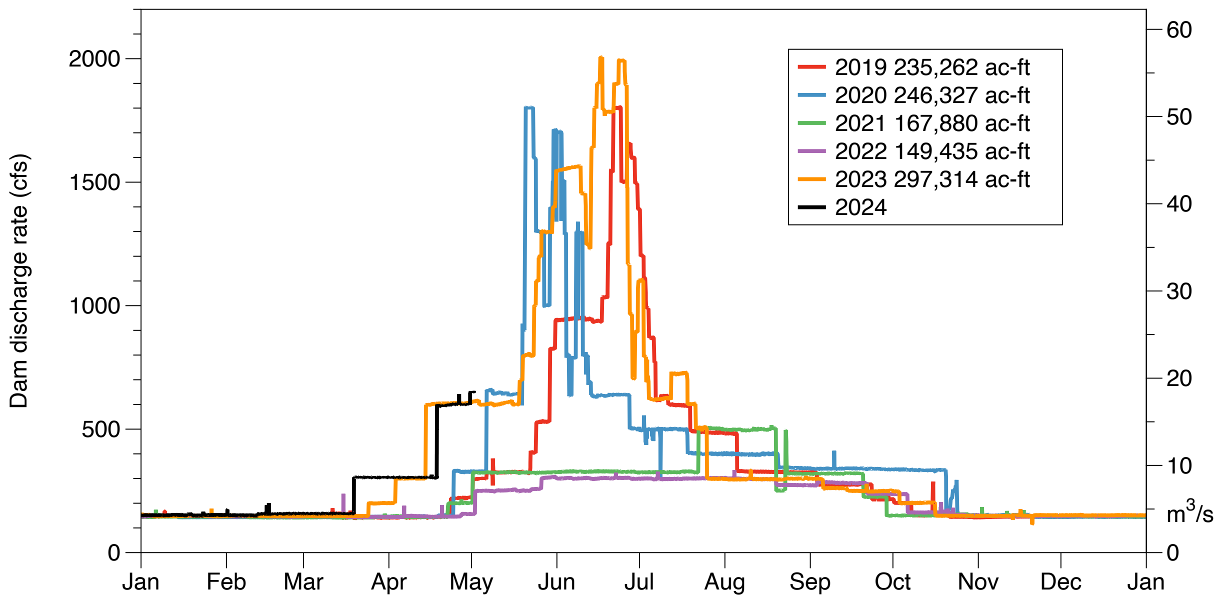


Figure 6. Release rates from the Jordanelle Reservoir as a function of time for years 2019-2024. Also shown in the legend is the yearly total release.

MIDDLE PROVO RIVER FLOWS

Three streamflow gages are located along the main river channel. In addition to the CUWCD gage at the dam, discharge measurements are made at USGS gages at the River Road Bridge 3.9 miles downstream and at a site just a stones-throw below the Trestle Bridge 10.7 miles downstream. The gage near the Trestle Bridge is called the Charleston gage by the USGS, but we will refer to it as the Trestle gage.

CUWCD maintains a year-around minimum flow of at least 125 cfs at the River Road gage to protect the fishery. The 2022-2024 history of stream flows at these three sites is shown in **Figure 7**. The streamflow decreases between the dam and the River Road gage but then increases between the River Road and Trestle gages. These changes in streamflow are caused by irrigation diversions, and by tributary and groundwater inflows.

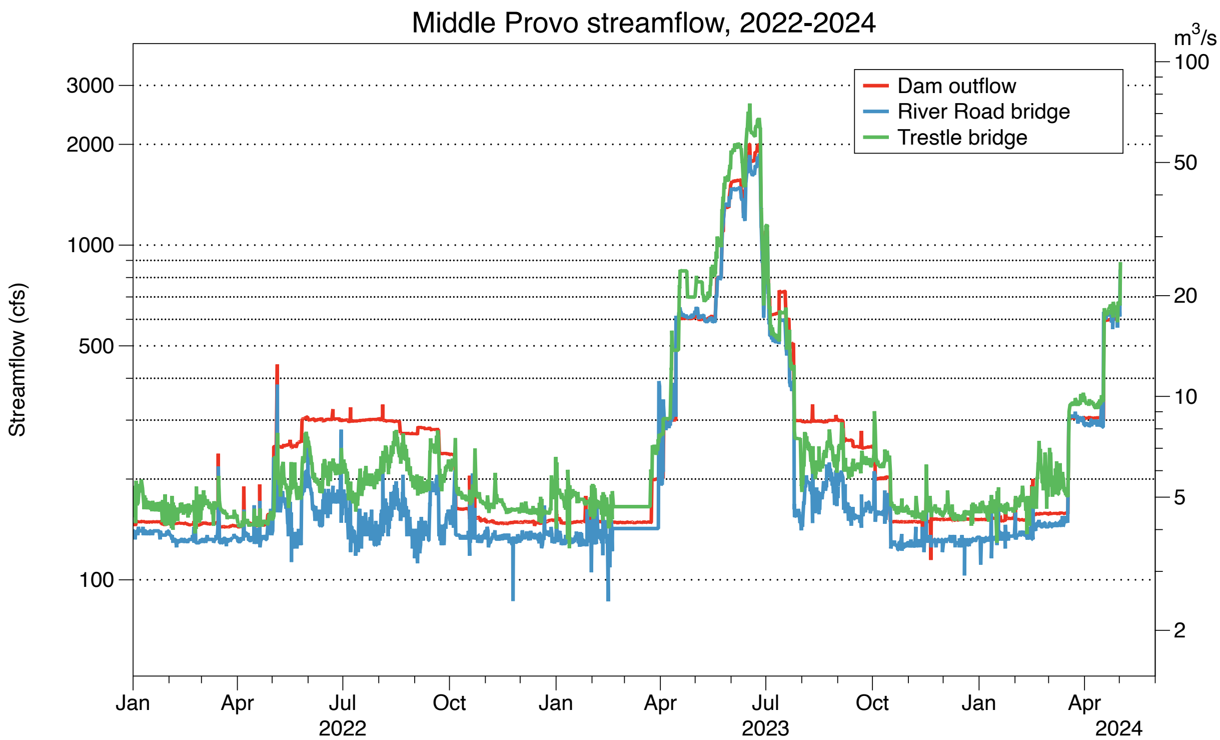


***Figure 7**. Dam discharge and streamflow in the Middle Provo River at the River Road Bridge and Trestle gages in 2022-2024. Note the logarithmic scale. Data from CUWCD and USGS.*

Vertical spikes in the discharge rate at the dam, as seen in **Figure 7**, indicate short-term water surges caused by maintenance operations at the dam. These surges travel downstream to the River Road Bridge and Trestle gages. Their arrival at the gages can be used to estimate flow velocity and the time required for water released from the dam to reach downstream locations (**Figure 8**). Their rate of travel depends on the rate of discharge. The water flow velocity at 145 cfs (upper two and lower left sub-figures) is 1.6 and 2.1 mph between the Jordanelle Dam and the River Road gage and between the River Road and Trestle gages, respectively. At 250 cfs (lower right sub-figure) the respective velocities are 1.7 and 2.5 mph. The river gradient between the dam and the River Road gage is 56 ft/mile, while it is 34 ft/mile between the River Road and Trestle gages. At the flow rates sampled, it takes about 5-6 hours for water released from the dam to travel to the Trestle gage, and an additional 24-30 minutes to reach Deer Creek Reservoir. Interestingly, the spikes change their amplitude and width (i.e., duration) as they move downriver. The surge passes quickly at the River Road gage and a dip in streamflow often occurs after the surge passes. Anglers who have experienced these water passages will note the discoloration of the water and the transport of debris in the enhanced flow.

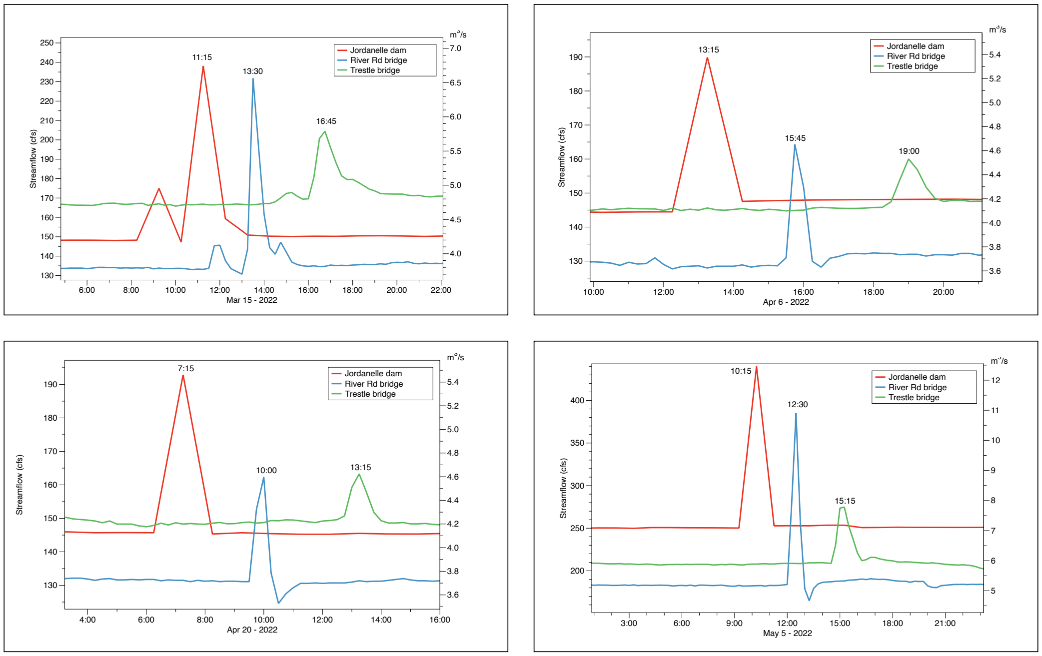


Figure 8. Sudden discharge surges from the power plant (red curves) associated with dam maintenance, etc. travel down the main channel and are visible in downstream hydrographs at the River Road Bridge (blue curves) and Trestle (green curves) gages. 15-min time resolution. Data from CUWCD and USGS.

Another method of determining water transport velocity uses data from the concrete weir located under the River Road Bridge. The weir extends between the two banks and the height of the water flowing over the horizontal surface of the weir (the "stage") is measured continuously and can be related to the reported river flow there in cubic feet per second (cfs). Knowing the stage in feet and the width of the weir, one can divide the streamflow by the product of stage and width to calculate the mean river velocity. The relationship between stream velocity and streamflow or discharge (the "ratings curve") is shown in **Figure 9**. Using this relationship and discharge data from 2019 to present, the temporal variation in stream velocity can be determined (**Figure 10**). Enhanced releases from the dam in May and June at the beginning of the irrigation season can result in mean stream velocities exceeding 6 mph. The water, on its way downstream, increases its velocity if it flows through a narrow constriction and decreases its velocity if the stream widens. Variable and, especially, sudden changes in discharge rates affect the fishing for up to several days, as fish seek new fishing lies when water depths change. An angler can determine whether changes in discharge have occurred recently by accessing the discharge graph for the USGS River Road gage (you have to select discharge, rather than stage to get the desired plot). A comprehensive CUWCD webpage provides information on the flows over their entire district, including the Jordanelle dam and the Upper and Lower Provo. Anglers should ignore the discharge data on this website at their Lower Midway (i.e., Legacy Bridge) site, which was decommissioned years ago and is producing bogus numbers.

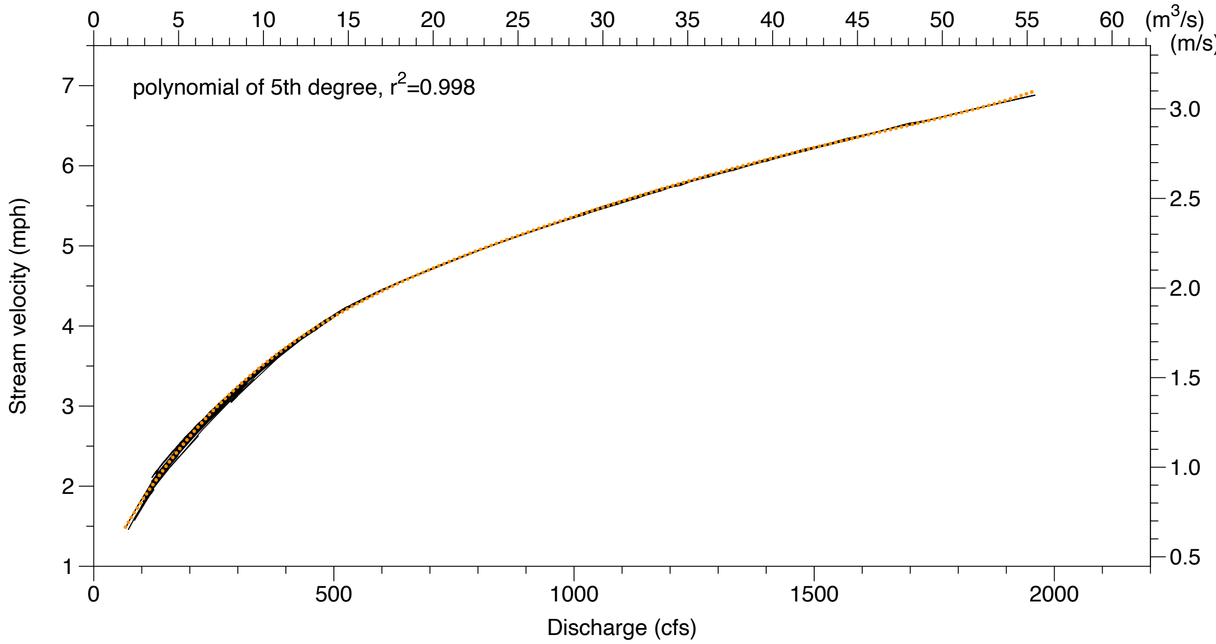


Figure 9. The relationship between discharge and stream velocity at the River Road gage.

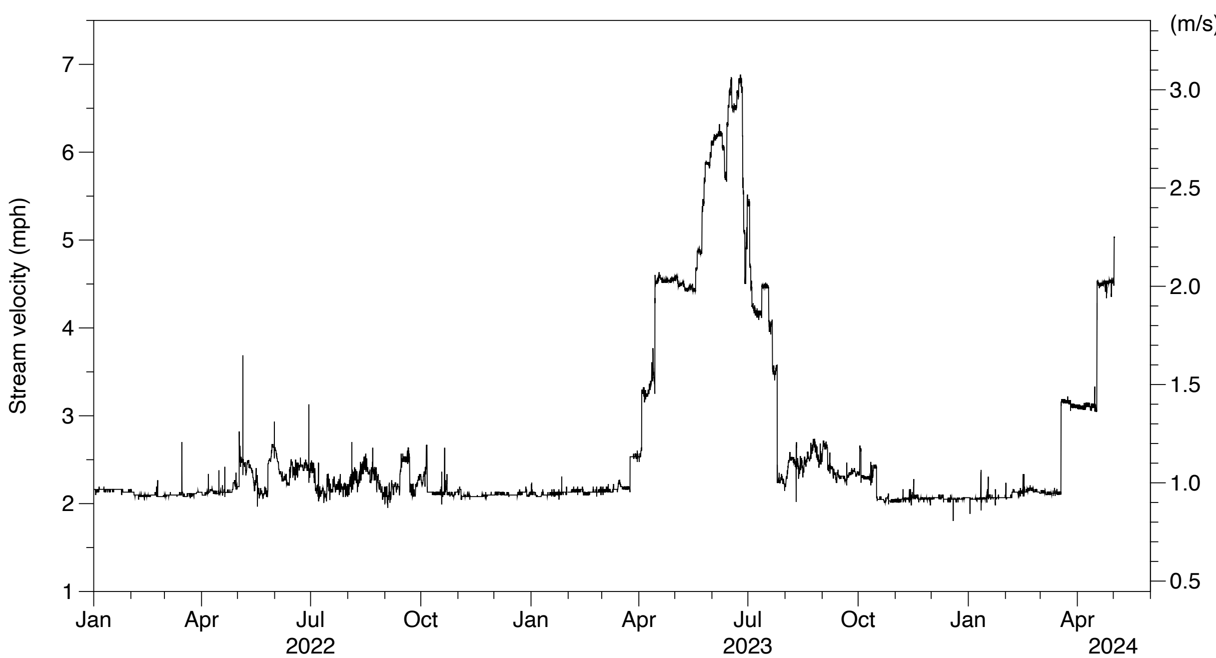


Figure 10. Variation in stream velocity at the River Road gage for the project years 2022-2024.

WATER TEMPERATURES ALONG THE RIVER AND THEIR DIURNAL OSCILLATIONS

Water temperature changes as it travels downstream from the dam as heat inputs and outputs change during the river's course. The tributaries, irrigation diversions, groundwater and overland flows into the river vary its volume and have a secondary effect on water temperatures.

Water temperature data are now available from the network of HCFF temperature dataloggers from Spring 2022 into March 2024 (**Figure 11**). Water temperatures are governed primarily by the temperature of the water released from the dam, as indicated in the figure by the black curve. The water temperature released from the dam begins a slow decrease to wintertime values in mid-October as the water in the reservoir cools. Winter water release temperatures reach as low as the upper 30s. A stepwise water temperature increase from the winter temperatures to the summer temperatures is made in June (2022) or July (2023). Temperatures in the lower 50s are maintained throughout the summer and early fall by actively mixing reservoir water from various gates at different depths in the reservoir.

The seasonal variation in dam discharge temperature provides a baseline on which downriver temperature oscillations are superimposed. Because cold water released from the dam in summer transits the length of the river during nighttime when sunlight cannot heat the water, by sunrise all dataloggers tend to report daily minimum temperatures that are close to the temperature of water released from the dam. Individual day-night oscillations are difficult to see in this figure because of the long period of record on the x-axis, but daytime summer temperature oscillations from the nighttime temperature baseline can reach into the range of 15-20°F at sites on the lower river. These positive daytime temperature excursions increase with downriver distance in the summer half-year, with values increasing from the dam to the River Road Bridge and on to the Legacy Bridge. Interestingly, however, the daily maximum temperatures change little between the Legacy Bridge and the Trestle Bridge. In the winter half-year, on the other hand, temperature minimums decrease with downstream distance, falling below the release temperature at the dam. In this season, the dam discharge constitutes a relatively warm input to the river. The wintertime cooling as water travels down the river is clearly not as great as the summertime warming. Higher time-resolved data from selected case studies will follow in a later section to illustrate the day-night or *diurnal* oscillations.

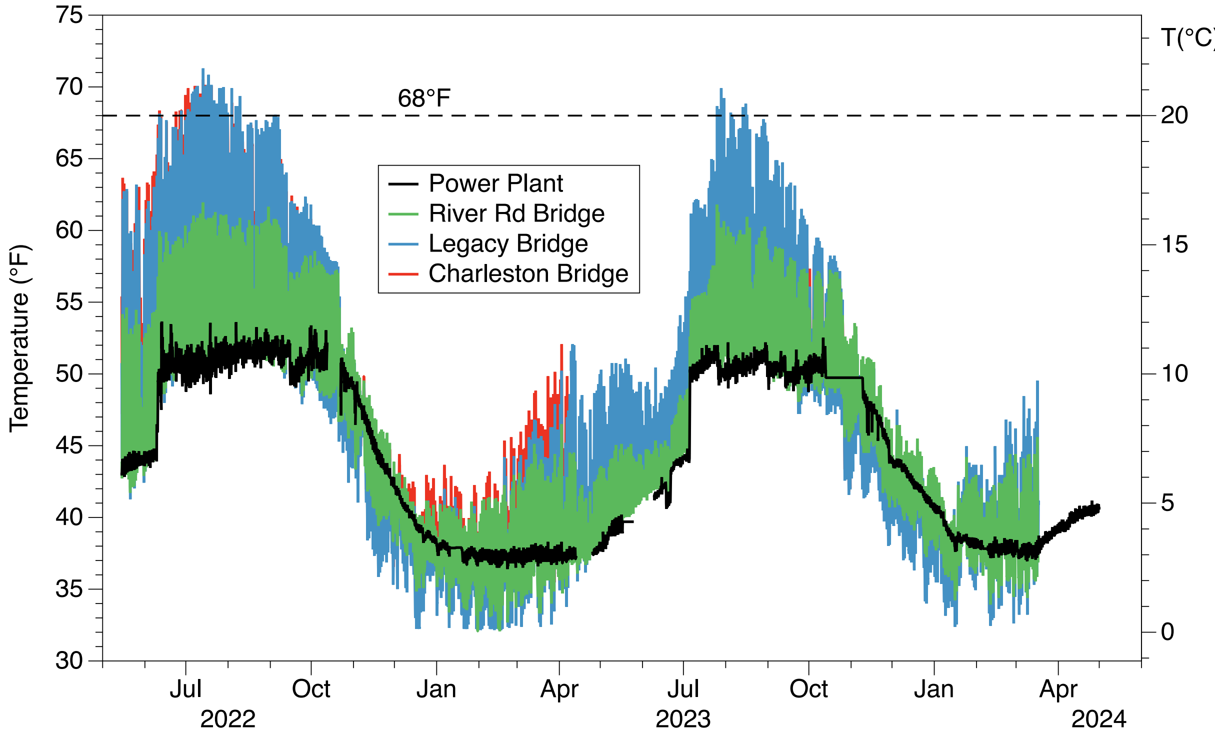


Figure 11. Water temperatures at the power plant and the River Road, Legacy and Charleston Bridges. HCFF data.

Of interest to fishermen is the fact that, in 2022 and 2023, sites lowest in the river near the Legacy and Charleston Bridges clearly attain maximum temperatures that exceed the trout stress threshold of 65-68°F. The exceedances occurred as early as mid-June and as late as early September, but the bulk of the exceedances occurred in July and early August. July and August had unusually warm weather and clear skies. The temperature exceedances in the lower river should be viewed within this climatological context. In contrast to the lower river, no exceedances occurred farther up-river at the River Road Bridge, illustrating a key feature of the summer half-year river temperature behavior – sites closer to the cold water released from the dam have lower daily temperature maxima since cold water released from the dam is heated by the sun as it travels downstream and the downstream travel distance is short. In contrast, during the winter half-year when solar radiation is weaker, cloud cover is more frequent, and air temperatures are lower the water temperatures can decrease with distance downriver as the water cools by evaporation and net radiation loss during its travel. These points will be illustrated in the next sections by focusing on the day-night temperature oscillations during periods in May, July and November of 2022.

FLOWS AND WATER TEMPERATURES IN THE IRRIGATION DIVERSIONS AND TRIBUTARIES

Flows

The Middle Provo River supplies seasonal outflows into two major irrigation diversions and receives water year-around from three tributaries (**Figure 12**).

During the irrigation season some water is channeled into the Timpanogos Canal at the foot of the dam to provide water to agricultural water rights holders in the upper eastern portion of the Heber Valley. A diversion into the Rock Creek ditch occurs 2.2 miles downstream to provide irrigation water to the lower east side of the Heber Valley. Soon after the ditch leaves the Middle Provo, the ditch feeds the Wasatch Canal, which again is used to irrigate the east side of the valley. The irrigation season generally runs from early May through September and both the Timpanogos Canal and Rock Creek carry irrigation flows from 30 to 70 cfs. Rock Creek typically has a non-irrigation-season flow of 10 cfs and an irrigation season flow of 30 cfs. Excess water in Rock Creek eventually feeds into Spring Creek, a tributary that enters the Middle Provo from the east side of the river 10.2 river miles downstream from the dam (0.6 miles above the Trestle Bridge). A minor irrigation diversion (~ 6 cfs) close to the dam feeds the Jordanelle wetlands on the west side of the river.

There are three tributaries to the Middle Provo River. Spring Creek enters the river from the east side of the valley, while Berkenshaw and Snake Creeks enter from the west. The tributaries, like the irrigation ditches, cross private lands. A short section of Snake Creek just above its confluence with the Middle Provo is fishable, and there is a nearby parking lot for fishermen. In summer, the tributaries mix warmer water into the main river. The volume of tributary water is such that they do not greatly increase the temperature in the main river.

Berkenshaw Creek is a minor tributary that carries excess irrigation water from a canal on the west side of the river, entering 8.1 miles below the dam, 0.3 miles above the Legacy Bridge. No discharge measurements are made on this creek, and the inflows are minimal.

Spring creek is a natural stream supplemented by excess irrigation water and has a diurnal (day-night) flow oscillation in the winter with a decrease in flow as its water supply dries up in the summer. It enters the river 10.2 miles downstream from the dam, 0.6 miles above the Trestle Bridge.

The major Snake Creek tributary enters the Middle Provo 11.3 mi below the dam, 0.4 miles above the Charleston Bridge. Snake Creek has a relatively uniform flow through winter and mid-summer. Snake Creek carries high nutrient loads from hot springs and grazing operations on the west side of the valley and is usually choked with vegetation (macrophytes) in the growing season.

Finally, some water is lost in the upper segment of the river through ground water recharge. This water re-emerges in the lower half of the river, partly through weak seeps, springs and drainages coming through wetlands, especially on the east side of the river. Further information on the operation of the reservoir and dam, the geography, soils, tributaries, irrigation diversions, etc. is available in the accompanying report, which provides a broader description of the Middle Provo River and its surroundings.

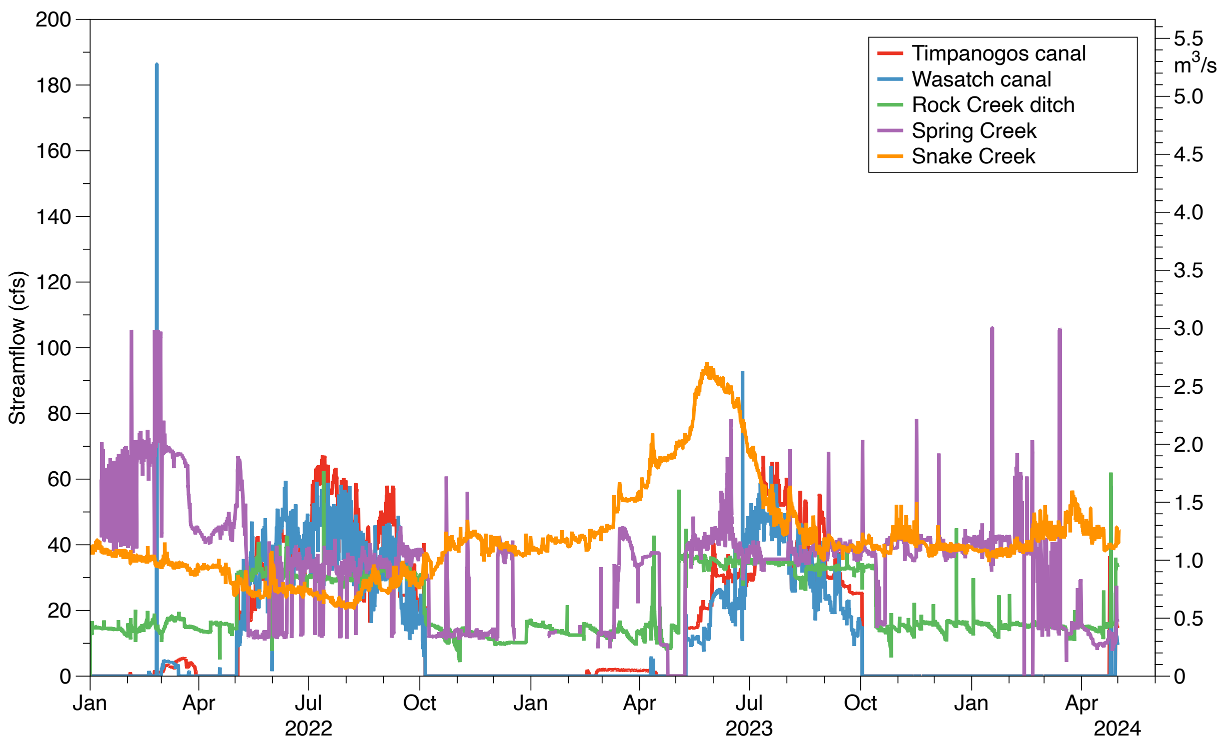


Figure 12. 2022-2024 irrigation diversion and tributary flows. Data from CUWCD and USGS.

Water temperatures

Water temperatures in the three tributaries are shown in **Figure 13**. The shallow, slow-moving tributary waters generally have higher temperatures in the summer than those in the main river channel. The maximum tributary temperatures rise from about 50°F in April and May to a peak well above the 65-68°F trout stress threshold later in the summer, with the highest temperatures in mid-July. The highest temperatures, as in the main channel, occur late in the day as the water accumulates heat by absorption of the incoming sunlight. The attained temperature depends on the width and depth of the stream, as smaller volumes of water heat up more quickly than larger volumes, given equivalent solar radiation input at the water surface. Variations in maximum temperatures from day to day are primarily due to changes in cloudiness affecting this solar radiation input (see daily total solar radiation values for 2022-2024 in **Appendix A**). High temperatures in the tributaries preclude the trout in the main channel from going up the tributaries to find cooler water with higher dissolved oxygen content. As we will see, however, maximum water temperatures, sometimes above the trout stress threshold, are relatively invariant along the lowest couple miles of the river, so fish would have to swim a long way from the lower river to find cooler water in the main stream.

If the temperatures in the tributaries are higher than in the mainstream, the temperature of the water downstream of the confluence will increase. The increase depends on the relative flow volumes of the merging waterways and the temperature differences between the merging flows. Consider, for example, water in the Middle Provo with temperature T_1 and volume flux (i.e, discharge) Q_1. The temperature and volume flux in the tributary are T_2 and Q_2. After the flows combine in the main river, the final volume flux is $Q_f = Q_1 + Q_2$ and the final temperature T_f is intermediate between the two temperatures and is given by $T_f = T_1 (Q_1/Q_f) + T_2 (Q_2/Q_f)$.

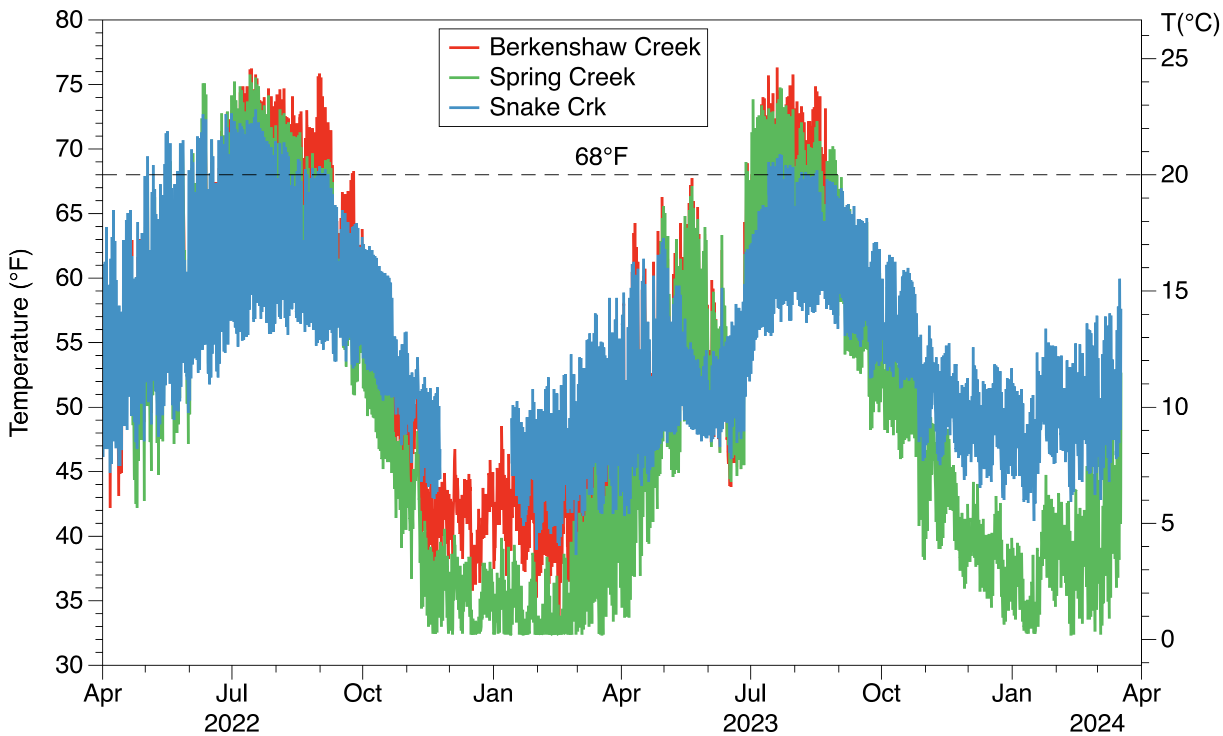


Figure 13. Water temperatures in the Berkenshaw, Spring and Snake Creek tributaries. Berkenshaw Creek flow was stopped in August 2023 to facilitate canal repairs. HCFF data.

In actuality, the thermal energy balance of a stream that leads to the temperature maximum is a combination of other factors besides incoming solar radiation, including the reflectivity of sunlight from the water surface, shading by streamside trees, net longwave radiation, advection of water temperatures from upstream, sensible heat flux to and from the atmosphere above the stream, latent heat fluxes as water evaporates from the stream, and groundwater import into the stream. Nonetheless, the major factor affecting water temperatures in the summer half-year is incoming solar radiation, as will be shown in a later section of this report. First, however, several case studies will illustrate temperature variations with time and river distance in different seasons.

CASE STUDIES

Water temperatures during a period in May 2022

Water temperatures for a selected fair-weather period of 8 days in May 2022 for 8 sites (L to R) that are arrayed along the river at distances 0, 0.40, 2.56, 3.88, 5.65, 6.31, 8.50, 11.71 miles below the Jordanelle dam are plotted in **Figure 14**. Diurnal temperature ranges increase with distance downriver and reach 15-20°F at the Legacy Bridge. Daytime temperature rises tend to occur at about the same time at all sites. Variation in the time of rise from site to site may be related to shading by streamside trees. Variation in the temperature curves is also caused by temporary reductions in incoming solar radiation due to cloud cover. As one progresses downstream, there is a distinct time lag in late afternoon and nighttime cooling relative to sites closer to the cold water released from the dam. While the water released from the dam is cold, the water downriver from the dam occasionally becomes a couple of degrees F colder at night than the water released from the dam. This is likely due to nighttime sensible heat losses from the water to the colder air above or to evaporative cooling of the water during transport. Water at the Charleston Bridge site remains warmer at night than other sites, possibly due to warmer water flowing into the river above the bridge from the Spring Creek and Snake Creek tributaries or groundwater inflows.

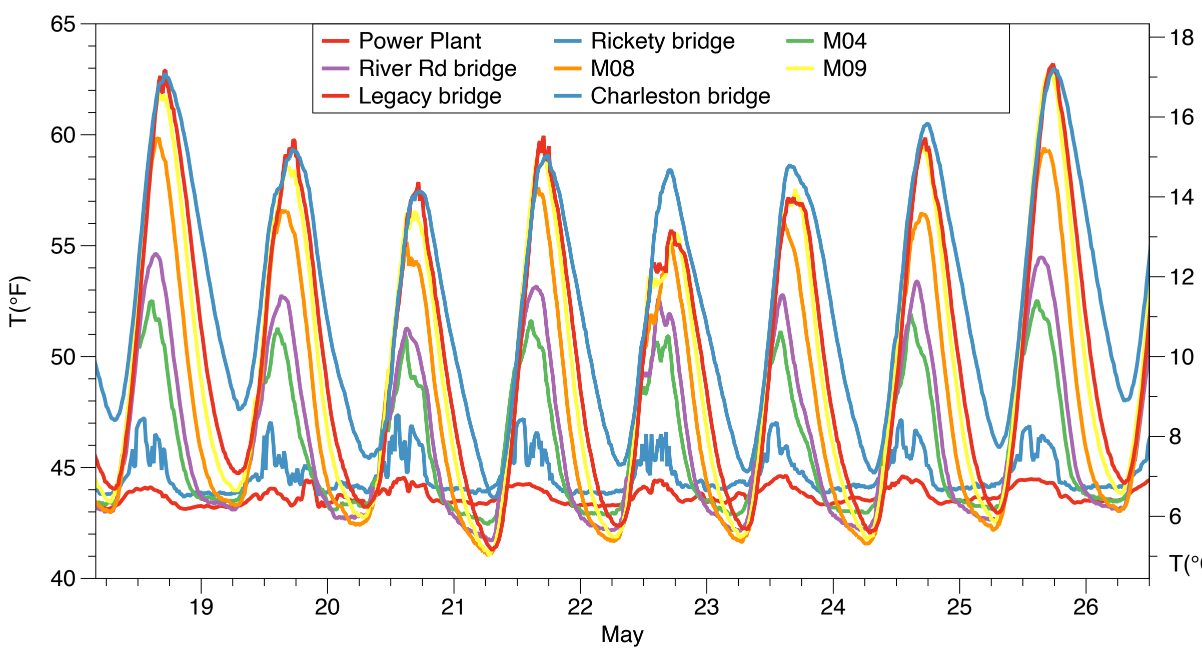


Figure 14. Water temperatures during the period 18-26 May 2022 at the Jordanelle power plant, the Rickety Bridge, M04, the River Road Bridge, M08, M09, the Legacy Bridge and the Charleston Bridge. HCFF data.

A more highly resolved temperature plot using data from additional sites is shown for 25-26 May in **Figure 15**. Minimum temperatures are reached near sunrise at all sites. Minimum temperatures at sites downriver from M13 do not fall below the discharge temperature at the dam, while temperatures fall below the dam discharge temperature at sites above M14.Temperature rises begin at all sites within a couple of hours following sunrise and climb in tandem. The temperature maxima increase with distance downriver but their timing lags with distance, occurring between 1430 and 1800 MDT. Temperatures fall gradually following the late afternoon maxima. At the Charleston Bridge the temperature does not decay to the temperature of water released from the dam, probably because of the inflow of warmer water from Snake Creek and from groundwater. A simple analytical model of temperatures in an idealized tailwater fishery such as the Middle Provo River is described in **Appendix B**. This model accounts for many of the features seen in these and other observed temperature curves.

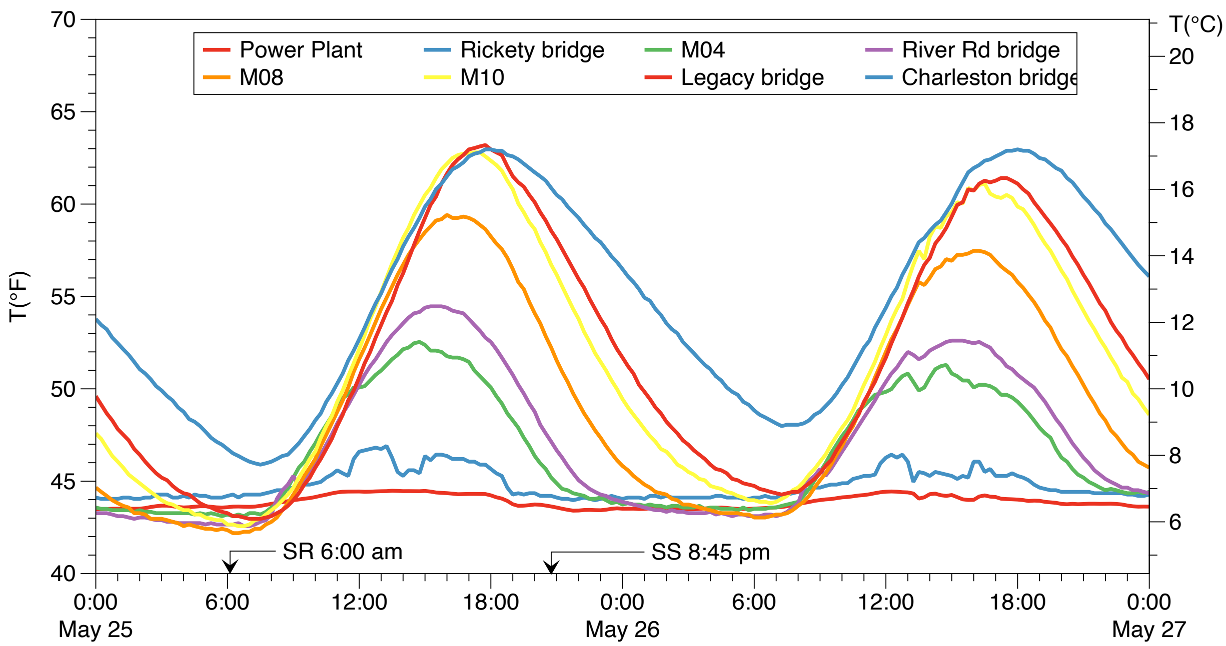
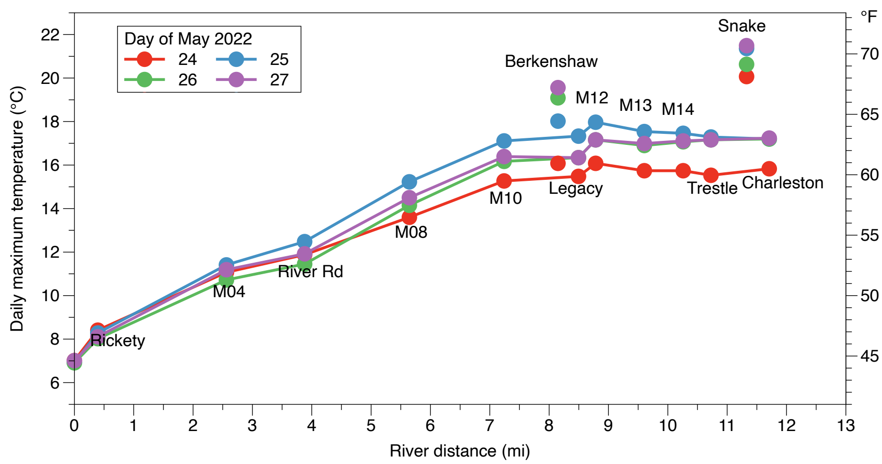
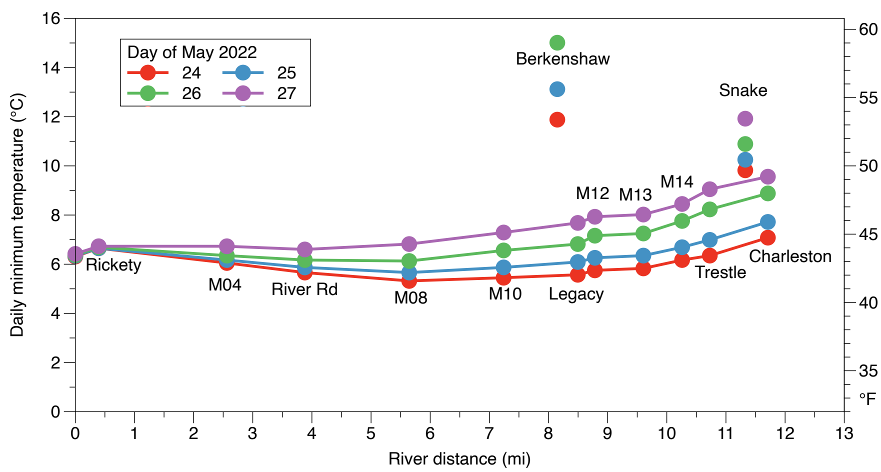


Figure 15. Observed stream temperatures as a function of time for a 25-26 May 2022 period of clear to partly cloudy days. HCFF data.

Daily temperature maxima, temperature minima and daily temperature ranges are a function of downstream distance from the Jordanelle dam. These distance dependencies are illustrated in **Figure 16** for the two days chosen in **Figure 15** and for one day on either side of the chosen days (four days total). The daily maximum temperatures for sites along the Middle Provo River during the four-day period are between 45 and 64°F, although maximum temperatures are somewhat higher in the Berkenshaw and Snake Creek tributaries. Maximum temperatures increase from the dam to site M12 and then decrease slowly with further downstream distance. The decreases beyond site M12 are likely due to groundwater inflows having rather steady temperatures between the daily maxima and minima at these sites. This supposition is supported by the increase in daily minima at the same sites. The daily minimum temperatures for sites along the river are between 41 and 49°F, with minimum water temperatures dropping between the dam and site M08 and then rising with further downstream distance. The Berkenshaw and Snake Creek tributaries exhibit warmer minimum temperatures than those in the Middle Provo River. The daily range of water temperatures (i.e., the difference between the daily maximum and daily minimum temperatures) increases from near zero at the dam, where the release temperature is nearly constant, to over 20°F at site M10. The daily temperature range then decreases with further downstream distance. The Berkenshaw Creek tributary has a much smaller temperature range than sites in the main river at the same distance downstream, while Snake Creek has a somewhat higher daily temperature range than the Middle Provo at the same distance downriver.





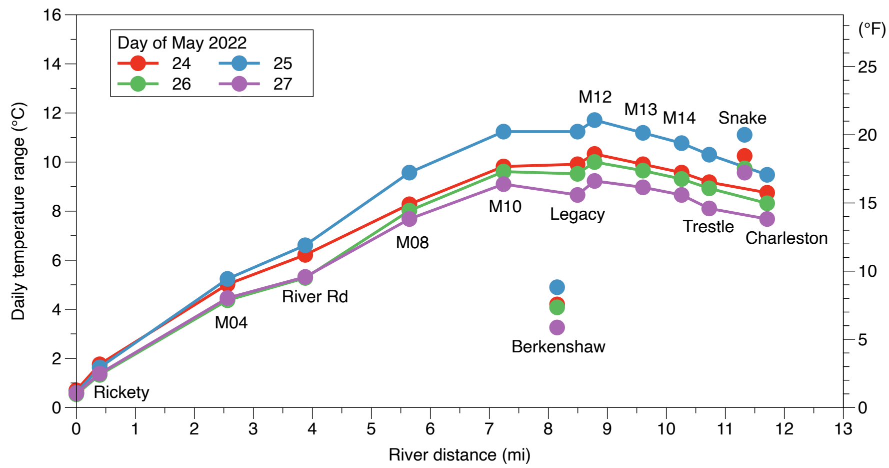


Figure 16. Daily maximum (upper) and minimum (middle) water temperatures and temperature range (lower) versus river distance for 24, 25, 26 and 27 May 2022. HCFF data.

Water temperatures during a period in July 2022

Temperatures during a 19-day period of clear to partly cloudy days in mid-July are shown in **Figure 17**. During this period, maximum temperatures often reached above the 68°F trout stress threshold between the Legacy and Charleston Bridges.

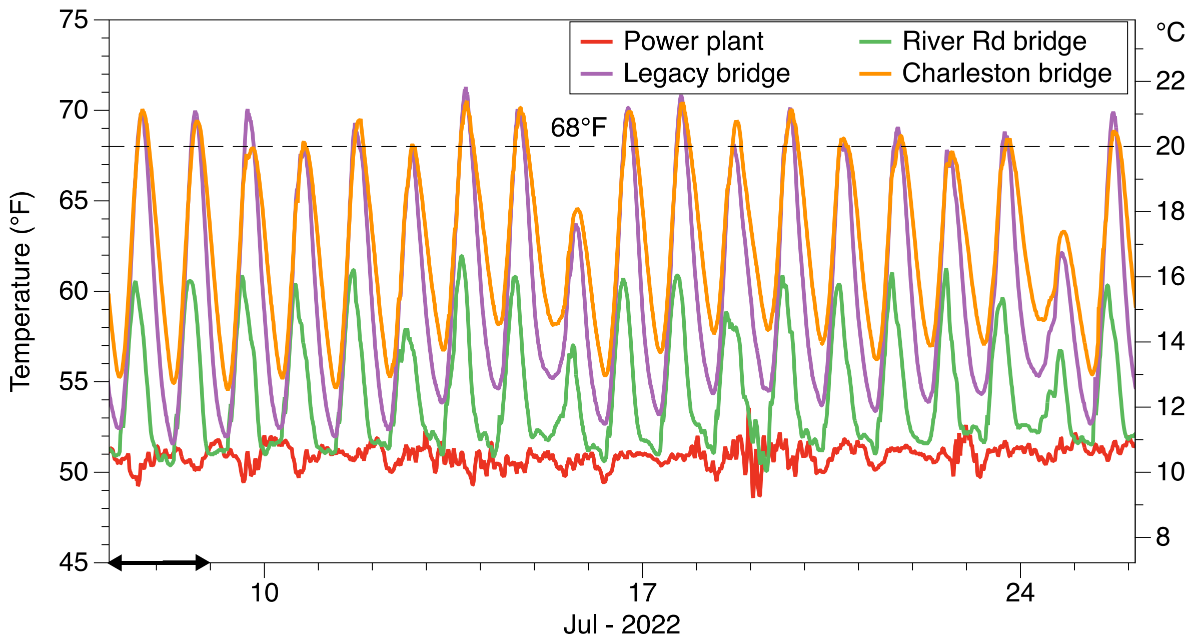


Figure 17. Example of observed stream temperatures during a period in mid-July 2022 at the Rickety, River Road, Legacy and Charleston Bridges. A higher time resolution plot follows for the 7-8 July period indicated by the arrows. HCFF data.

Observed river temperatures on the 7th and 8th of July 2022 (within the double arrowhead line in **Figure 17**) are shown in **Figure 18**. The sunrise and sunset times (and solar irradiation) are nearly identical to those in the May example, as the two periods are nearly equidistant in time from the June 21 summer solstice. While maximum temperatures are higher and reach above 68°F below M10, the maxima occur at about the same time (1500 to 1900 MDT) as in May, with the earliest maximums closest to the dam. The temperature of the water released from the dam is 51°F during this period, compared to 44°F in the May period, so the daytime temperature rises in July are imposed on warmer water. Minimum temperatures are reached near sunrise. A much bigger difference in minimum temperatures occurs between sites in July than in May, with much higher nightly minimums downstream. The sites farthest downstream thus reach trout stress threshold temperatures earlier than sites upstream. In both May and July, the daily water temperature range is much reduced in the river above M10 compared to the river below the Legacy Bridge. Trout thus have a more confined or consistent temperature environment in the colder water above the Legacy Bridge and are not exposed to temperatures that exceed the trout stress threshold.

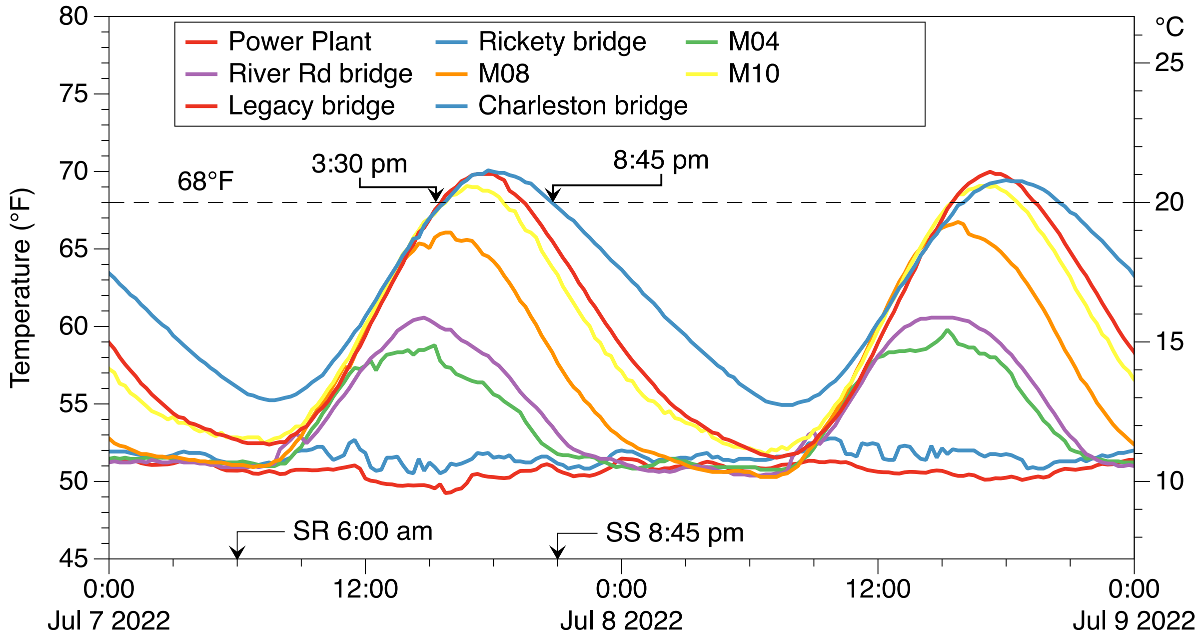


Figure 18. Observed stream temperatures as a function of time for a 7-8 July 2022 period of clear to partly cloudy days. HCFF data.

The distance dependency of daily maximum and minimum temperatures and temperature ranges are shown in **Figure 19**. The daily maximum temperatures increase strongly with downstream distance from 52°F at the dam to 72°F at site M13. Daily maximum temperatures then fall 3 or 4°F farther downstream despite the warm water input from Snake Creek, most likely because of cool groundwater inputs. Berkenshaw Creek has marginally higher maximum temperatures than any sites on the Middle Provo River. Daily minimum temperatures range between 49 and 58°F, with minimum water temperatures increasing monotonically with downstream distance. Berkenshaw Creek has much higher minimum temperatures than any site in the Middle Provo. Snake Creek, on the other hand, has minimum temperatures quite close to those at the nearby Charleston Bridge. The daily temperature *range* is similar to that in the May period with an increase with downstream distance to a maximum of around 19°F at site M13 and with a decrease farther downstream. Berkenshaw Creek has a lower temperature range, while Snake Creek has a marginally higher temperature range than at the nearby Charleston Bridge. The daily minimum and maximum water temperatures differ between the cooler May and warmer July periods, while the daily water temperature ranges and solar inputs are quite similar. This supports the hypothesis that the water temperature behavior is primarily governed by solar radiation input rather than air temperatures.

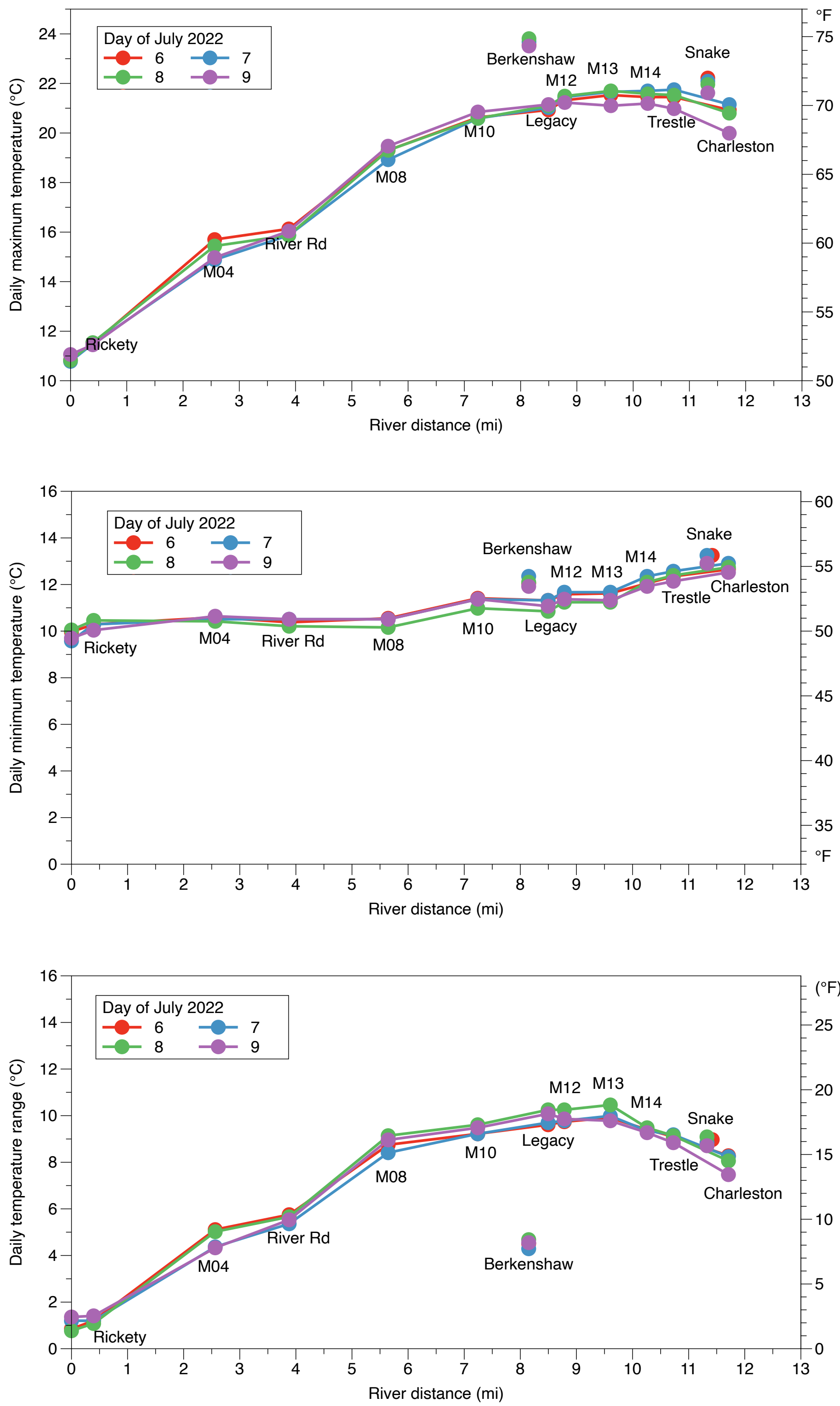


Figure 19. Daily maximum (upper) and minimum (middle) water temperatures and temperature range (lower) versus river distance for 6-9 July 2022. HCFF data.

Water temperatures during a period in November 2022

The winter half-year water temperature behavior is quite different from the summer behavior, as water leaving the dam cools as it travels downstream during the long, cold nights and is limited in its daytime heating by the shorter period of sunshine. Nighttime and daytime evaporation is one source of cooling, as the heat required to evaporate water comes from the stream. This process can sometimes be visualized when tendrils of "steam fog" rise from the water surface. Additionally, the stream, being warmer than the air above, loses heat by convection. And there is a loss of longwave radiation from the warm water that is not countered by the opposing weaker downward longwave radiation from the cold sky above. Only during daytime can solar radiation, even though some is reflected back to space, heat the water. These effects can be illustrated using data from a period in November 2022 when the temperature of water leaving the dam is steadily decreasing toward wintertime values (**Figure 20**).

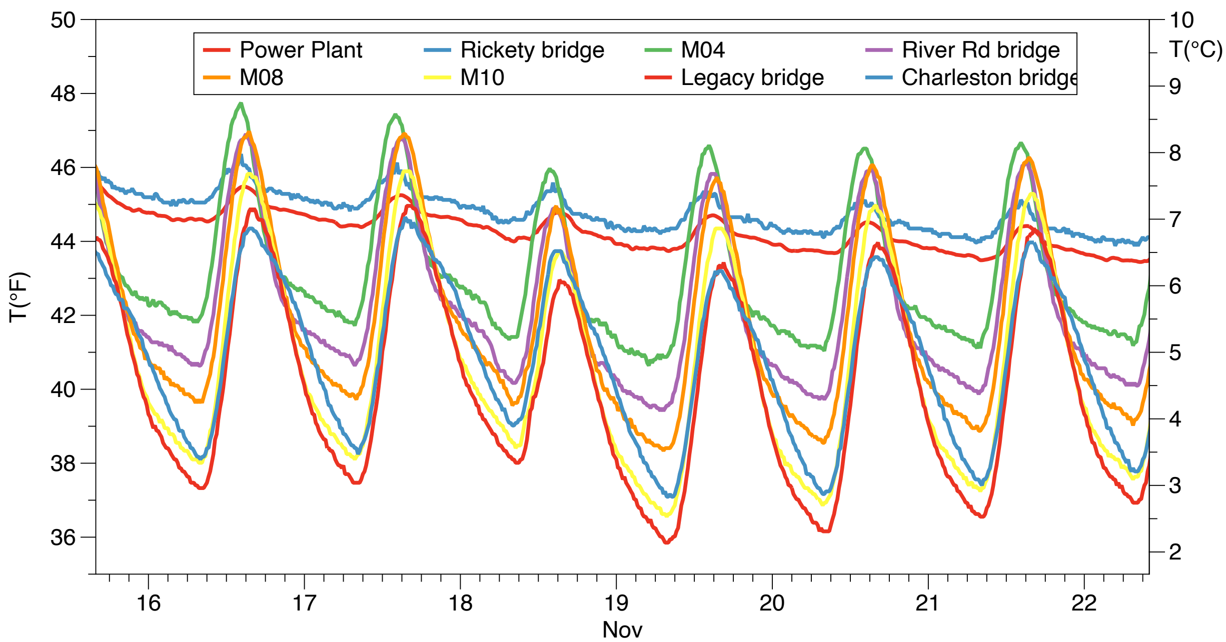


Figure 20. Example of observed stream temperatures during a period in November 2022. HCFF data.

Further discussion will be focused on a 19th and 20th November sub-period in **Figure 21**. Minor temperature oscillations occur at the power plant caused by temperature oscillations within the Jordanelle Reservoir. The power plant and Rickety Bridge sites are quite close together, but it is surprising that temperatures at the Rickety Bridge are consistently warmer by about 0.5°F than the water released from the dam. In wintertime, discharge from the dam is a source of *warm* water, not cold water. The warmest water is thus found closer to the dam. The diurnal temperature oscillations at sites downriver from the Rickety Bridge are only about 7°F, in comparison with mid-summer oscillations that reach 20°F. A clear signal of daytime solar heating is seen at all sites, with temperature increases following sunrise and temperature maxima lagging with downstream distance (as in summer). The lowest minimum temperatures are found far downstream, and it is only at the sites nearest the dam that maximum temperatures rise above the release temperature at the dam.

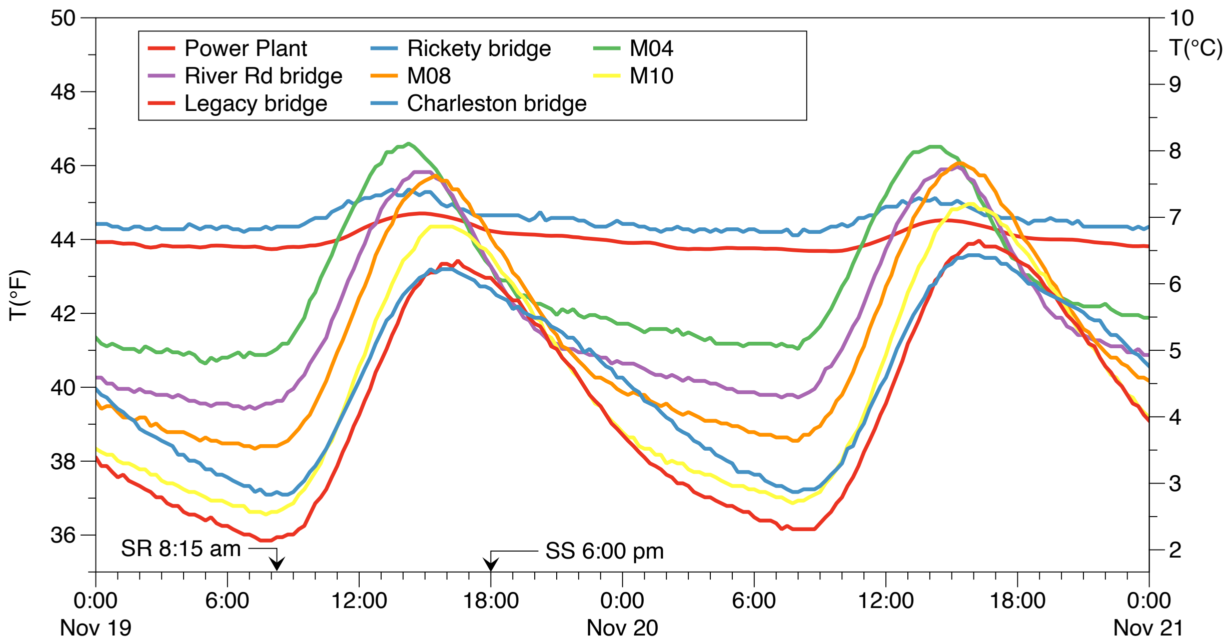


Figure 21. Observed stream temperatures as a function of time for a 19-20 November 2022 period of clear to partly cloudy days. HCFF data.

Daily minimum and maximum temperatures and the temperature ranges as a function of distance downstream are shown for a 4-day period encompassing November 19 and 20 in **Figure 22.** Daily maximum temperatures rise to site M04, then decrease to the Trestle Bridge, and finally rise to the Charleston Bridge. Snake Creek has higher maximum temperatures than any sites on the main river, while Berkenshaw Creek maxima are consistent with nearby river sites. Middle Provo maxima are generally between 46 and 42°F, decreasing with downstream distance, but with a rise between the Trestle and Charleston Bridges. Snake Creek minimums are warmer than any other sites. Berkenshaw minimums are consistent with nearby main river sites. The daily temperature range is only 3-5°F at all sites, with the range increasing to M10 and then decreasing to the Charleston Bridge. Snake Creek, while having higher minimum and maximum temperatures, has about the same small daily temperature range as the other sites.

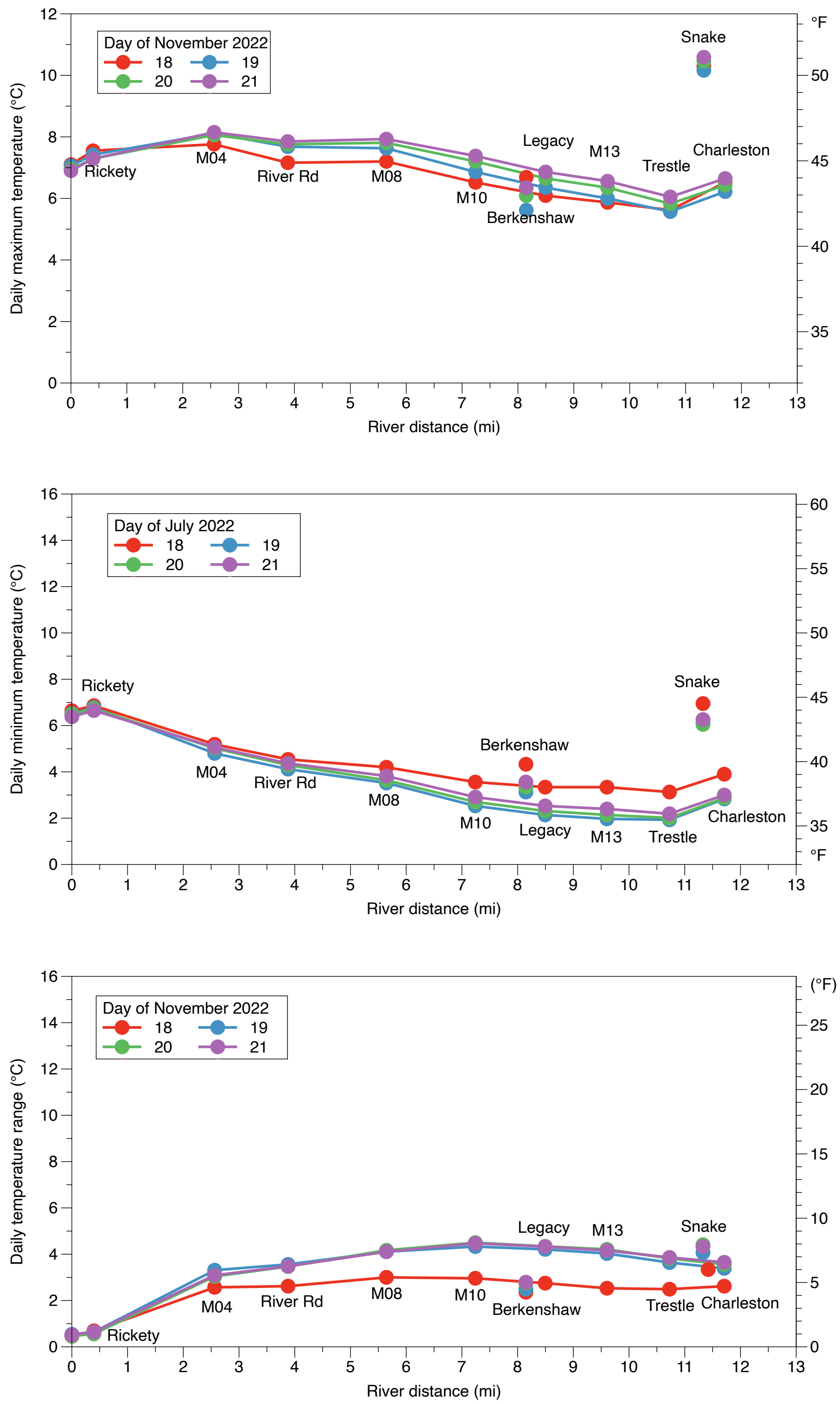


Figure 22. Daily maximum (upper) and minimum (middle) water temperatures and temperature range (lower) versus river distance for 18, 19, 20, and 21 November 2022. HCFF data.

DAILY AIR AND WATER TEMPERATURE RANGES AND THEIR RELATIONSHIP TO DAILY TOTAL SOLAR FLUX

Air temperatures in the Heber Valley are quite variable in winter and spring as weather systems come and go, as seen from the weather station at the Utah Valley University Wasatch campus in Heber City (**Figure 23**). 2022 and 2023 were unusually warm years, especially in July and August, when daytime temperatures in the Heber Valley frequently crept in the 90's. In nearby Salt Lake City, where temperature records have been kept for many years, the mean July maximum temperature in 2022 was 99.7°F – the hottest monthly maximum ever. The mean July minimum temperature was 74.9°F. This was 1.8°F higher than the previous record in 2021 and was the highest mean monthly minimum temperature in the 20th century. The mean July temperature was 87.3°F, 6.1°F higher than the highest mean July temperature observed in the 20th century! 2023 was again a warm year.

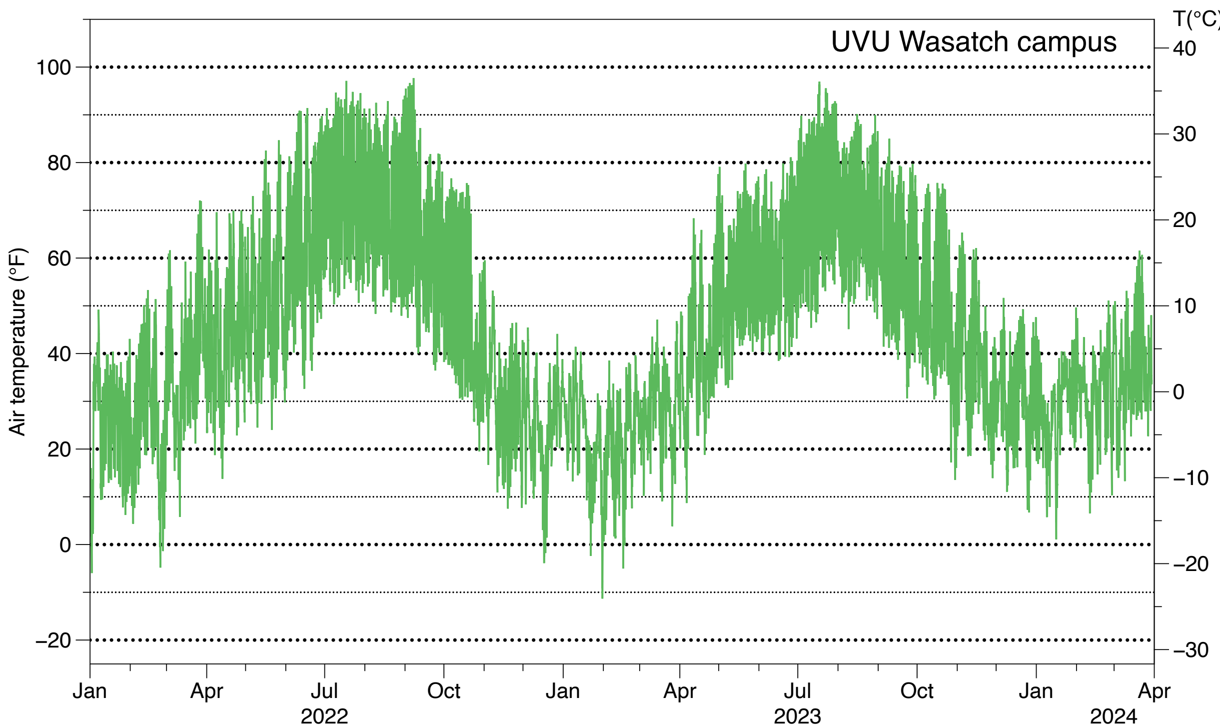


Figure 23. Air temperatures in the Heber Valley, 2022-2024.

One might expect that the gain or loss of heat in the water as it flows downstream from the dam would depend on *air temperature*, with water temperatures increasing with air temperatures. This relationship is much weaker than one might expect, as a multitude of factors affect the daily air temperatures and daily temperature range, including the transit of large-scale weather systems and fronts, windspeed, precipitation, etc. The stronger relationship is with daily total incoming solar radiation. As an example, consider the interrelationships (**Figure 24**) between the daily water temperature range at the River Road Bridge site and the incoming solar radiation and air temperature ranges measured at the nearby UVU weather station (1.15 mi west-southwest and 70 ft higher).

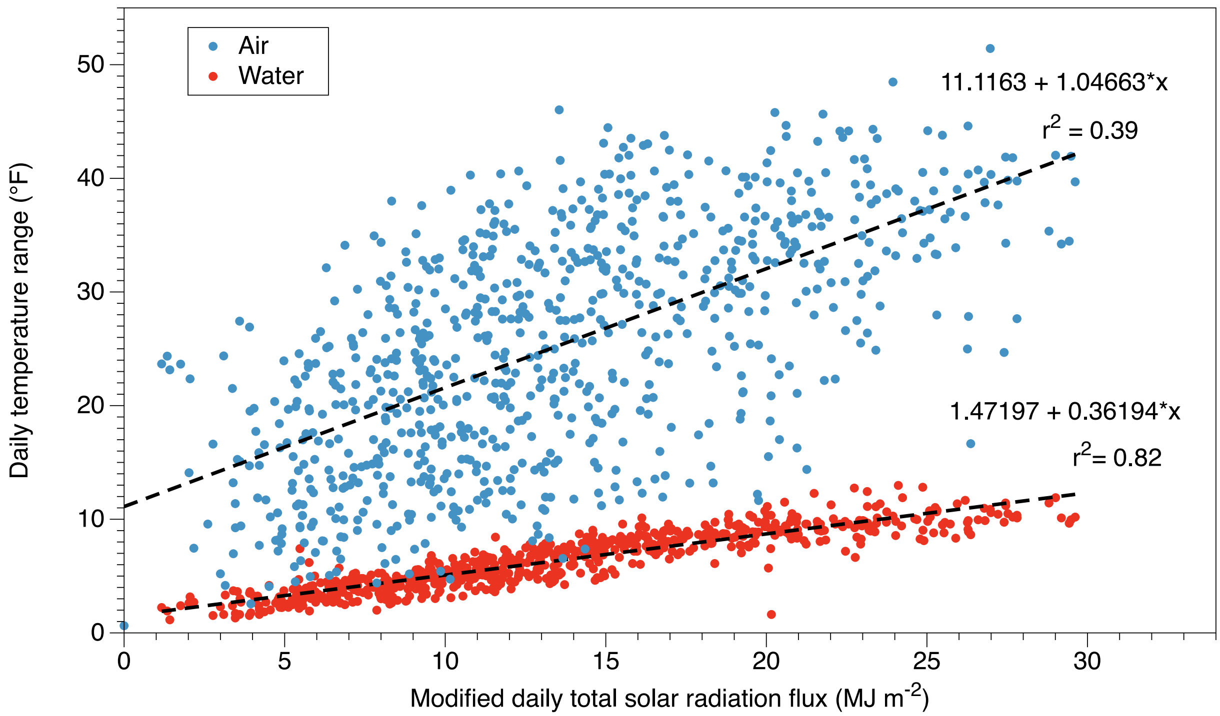


Figure 24. Relationships between modified daily incoming total solar radiation and the daily ranges of water temperatures at the River Road Bridge and air temperatures at the nearby UVU Wasatch campus. UVU, USGS and HCFF data.

For this comparison the daily incoming solar radiation must be modified to account for the fact that the amount of incoming solar radiation accumulated by water traveling downstream from the dam depends on water velocity, as water that is moving faster will accumulate less solar radiation as it travels downstream from the dam. For this purpose, the daily total solar radiation is multiplied by the ratio of the daily mean winter water velocity divided by the actual daily mean water velocity of the day in question. **Figure 24** shows a strong relationship between the daily range of water temperature and the modified daily total solar radiation flux for the entire data set, which includes winters and summers. But there is only a weak relationship between daily water and air temperature ranges. For example, a water temperature range of 15°F can be associated with air temperature ranges between 7 and 40°F.

Factors other than solar radiation play supporting roles, as mentioned previously, but solar radiation input and water velocity are the key factor affecting daytime water temperature rises. Note that only small amounts of solar radiation are absorbed directly by the shallow water, which is largely transparent to solar radiation, but radiation received by suspended particulates in the water and, more importantly, on the streambed is efficiently converted to heat and mixed throughout the water column by the moving water.

TAKEAWAYS FOR FISHERMEN

Water temperature along the Middle Provo River tailwater is strongly affected by the rate of discharge and temperature of the discharged water from the Jordanelle Dam. Both variables are controlled by the dam operator. The rates of discharge and discharge temperatures vary with season, but they are nearly constant on most days, and in summer the discharge temperature is usually maintained within the range of 51-53°F.

Following sunset, the cold water discharged, even at the minimum flow rate of 125 cfs, has sufficient velocity to travel all the way down the Middle Provo River to Deer Creek Reservoir by sunrise. During this nighttime travel the cold water released from the dam undergoes relatively minor water temperature changes as it travels downstream, although the groundwater inputs in the lower river plays a significant role. Thus, by sunrise the water temperature varies only weakly with downstream distance.

Following sunrise, on the other hand, water traveling downstream accumulates heat from incoming solar radiation, producing rising temperatures and increasing temperature ranges with downstream distance. Day to day variations in temperature ranges with downstream distance are produced mainly by variable cloudiness. In the lower river on sunny summer days when outflows from the dam are relatively weak, the diurnal temperature range of up to 20°F, when superimposed on the release temperature can cause water temperatures in the lower river to exceed the trout stress threshold temperature range of 65-68°F. Higher release rates increase the flow velocity and leave less time for the sun's radiation to heat the water during its travel downstream, so that temperature ranges and temperatures are lower with higher release rates.

The elevated water temperatures in the lower river decrease the survival of caught-and-released trout. Anglers should refrain from fishing there during afternoons when water temperatures rise into or above the trout stress range. Fishing success will be lower at those times anyway since the stressed trout will be less active. To measure water temperatures, anglers should carry and use a stream thermometer. There are inexpensive miniature infrared thermometers and mercury or alcohol stream thermometers that can be carried easily in fishing vests. A better solution than having individual anglers carry thermometers would be to develop a website for use by anglers that would show a week's history of stream temperatures in the lower river. The Trestle gage site would be a good site to install such a temperature sensor since access to the internet is already available there and much of the required electronics and hardware is already in place to put this information up on the web.

The key features of the spatial and temporal variability of water temperatures within the Middle Provo River are the increase in diurnal temperature range and the delay in the temperature maximum with downstream distance. These features are superimposed on the temperature of water released from the dam. Case studies in the summer half-year show that daytime temperature maxima increase linearly with distance downstream to site M10 (just above the Legacy Bridge) while minimum temperatures are nearly constant, causing the temperature range to increase linearly with downstream distance to M10. Below M10, however, the minimum temperatures increase from the values at M10 while the maximum temperatures remain near-constant or decrease slightly. This causes the daily temperature ranges for the lower river to remain constant or decrease with downstream distance. This behavior is consistent with groundwater inputs in the lower river. The groundwater inputs have temperatures intermediate between the maxima and minima, thus decreasing the maxima and increasing the minima.

Appendix B digs into these questions further, providing a heuristic explanation for the observed temperature behavior as well as a simplified numerical model that captures the key physics of the phenomenon.

For the Middle Provo River, the fishery above site M10 does not suffer from high temperatures that stress trout even on clear or partly cloudy summer days because the cold water released from the Jordanelle dam has not accumulated large inputs of solar radiation by the time it reaches these sites. Below site M10 temperatures can exceed the trout stress threshold in mid to late afternoon on sunny mid-summer days. Anglers could fish in the morning but stop fishing before about 2 pm when water temperatures become stressful to the fish (the so-called *hoot owl* strategy). Depending on distance below site M10, the water falls below the stress level only by 7 to 9 pm, leaving little time for fishing before dark. Anglers, as a conservation alternative, should reduce or forego fishing at these times.

SUGGESTED ACTIONS

Several suggestions for future work come from this project. First, it would be prudent to continue to work together with other stakeholders to monitor the temperatures and other water quality parameters in this valuable fishery, which is seeing increasing angler use as drought and excess temperatures cause anglers to abandon other non-tailwater fisheries. The temperature dataloggers are still available and, if there is interest, the project could be carried on by another volunteer. Current use permits could be extended, and the project could be greatly simplified by installing dataloggers at four streamside infrastructure locations - at the Rickety Bridge, River Road Bridge, Legacy Bridge and Trestle Bridge sites. These secure sites would not need to be downloaded frequently and the data could be used to extend the findings of this project into future years.

Second, some additional installations from our partners, CUWCD and USGS, could greatly enhance the information available to Middle Provo fishermen. The non-functional Lower Midway site on the CUWCD webpage could be removed. It is confusing to fishermen. The CUWCD website could include a new figure showing the discharge water temperature at 15-min intervals and its course over the last week, using the CUWCD sensor that is already monitoring discharge temperature. This data could support models of water temperature along the river's course and could be used to predict hatches. Further, a water temperature sensor could be added to the USGS Charleston (Trestle) site, where the web connection and a suitable webpage are already on-line. This sensor would have to be placed in the river in such a way that it would not be fouled by drifting vegetation. Perhaps HCFF could purchase a suitable new sensor for this installation. The webpage would inform fishermen when water temperatures are above the trout stress threshold. Finally, if feasible, it would be a great boon to fishermen if the CUWCD webpage could warn fishermen of planned upcoming changes to the Jordanelle discharge rate.

THE DATA

Temperature and supporting data collected as part of this HCFF project are publicly available through the Utah Division of Water Quality's water quality dashboard.

ABOUT THE AUTHOR

This report was prepared by Dr. Dave Whiteman, a member of the High Country Fly Fishers club in Park City, Utah, since 2016. He is a fly fisherman and fly tyer and often fishes the Middle Provo River. Dr. Whiteman is an Emeritus Research Professor in the Department of Atmospheric Sciences at the University of Utah in Salt Lake City.

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Mitigation Commission: Mark Holden
TU: Jordan Neilson
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REFERENCES

Whiteman, C. D., and J. Allwine, 1986: Extraterrestrial solar radiation on inclined surfaces, *Environ. Software*, 1 (3), 164-169.

APPENDIX A: SOLAR RADIATION

Extraterrestrial solar fluxes

Theoretical solar flux as a function of time of day at the edge of the Earth's atmosphere at the latitude and longitude of the River Road Bridge, called the *extraterrestrial solar flux*, is shown for the winter and summer solstices and equinoxes in **Figure A1**. Sunrise and sunset times are where the curves touch the x-axis. These curves illustrate the difference between the intensity and timing of solar radiation at the times of year when radiation is maximized (summer solstice), when it is minimized (winter solstice) and when the day length and night length are equal (12 hours). The area under each of these curves is proportional to the daily total extraterrestrial solar flux.

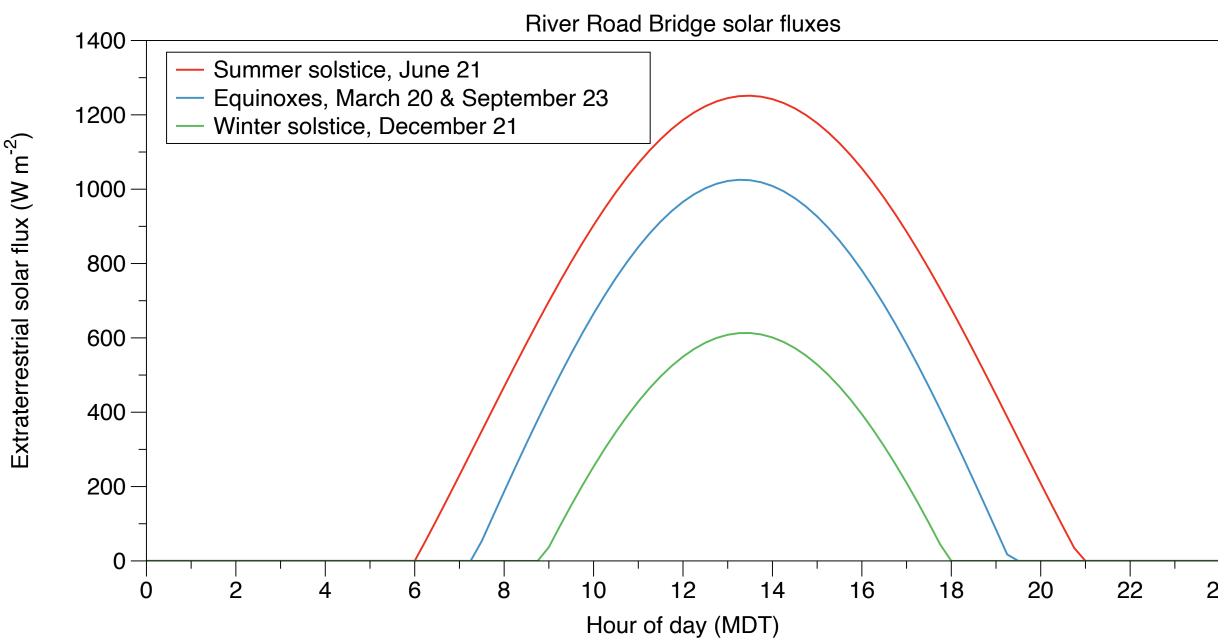

Figure B1. Extraterrestrial solar fluxes at the latitude and longitude of the River Road Bridge as a function of the hour of the day (MDT) at the summer solstice, equinoxes and winter solstice. Areas under the curves are 41.5, 28.2, and 13.1 MJ, respectively.

Observed daily solar flux totals at UVU Wasatch campus

The daily total extraterrestrial radiation, the daily total after allowing for an estimated 27% depletion as the solar beam passes through the Earth's atmosphere on a clear day, and the observed daily totals at the Midway weather station on the UVU Wasatch campus in the Heber Valley are plotted in **Figures A2 and A3**. Daily total solar radiation is closely correlated with the daily range of water temperatures in the Middle Provo River, which varies from day to day because of cloudiness. Low totals occur on cloudy days. Higher totals approaching the 73% extraterrestrial curve are clear days.

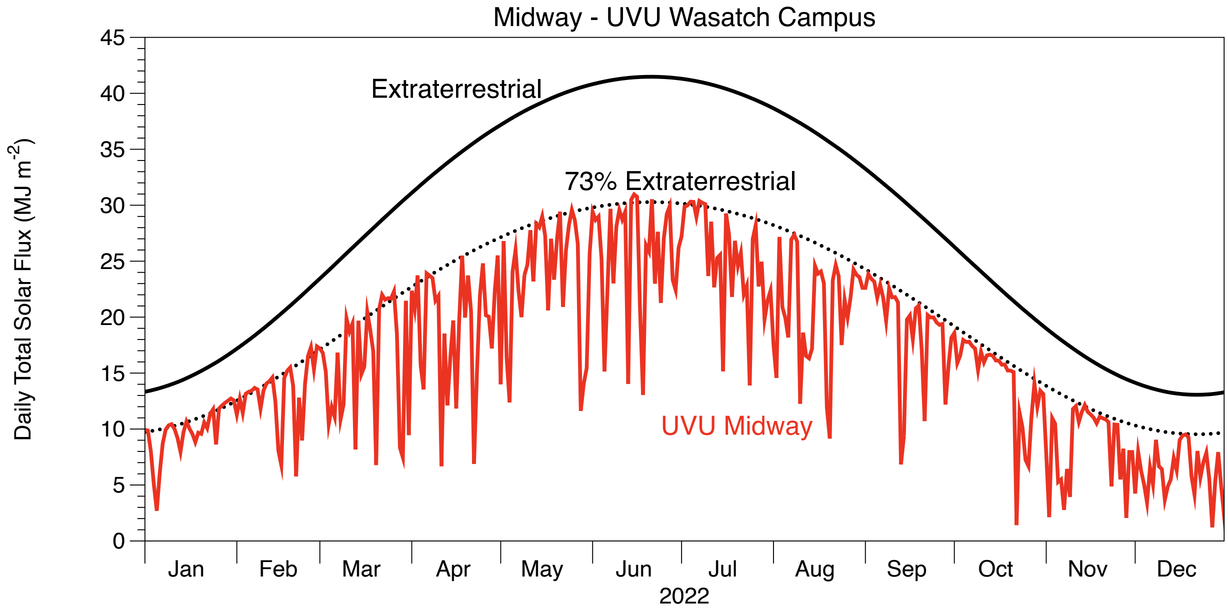

Figure A2. Daily total theoretical (or extraterrestrial) insolation (i.e., instantaneous solar radiation integrated over the day from sunrise to sunset) that would be received at River Road Bridge if the Earth had no atmosphere. The dotted curve accounts for an estimated 27% depletion of the daily total solar radiation caused by absorption of the solar beam as it traverses the Earth's atmosphere. The final curve (red) shows the measured daily total solar radiation at the UVU Wasatch campus in the Heber Valley in 2022. Extraterrestrial curves are from Whiteman and Allwine's (1986) solar model, and daily total insolation comes from the Midway weather station at the UVU Wasatch campus in the Heber Valley. UVU data.

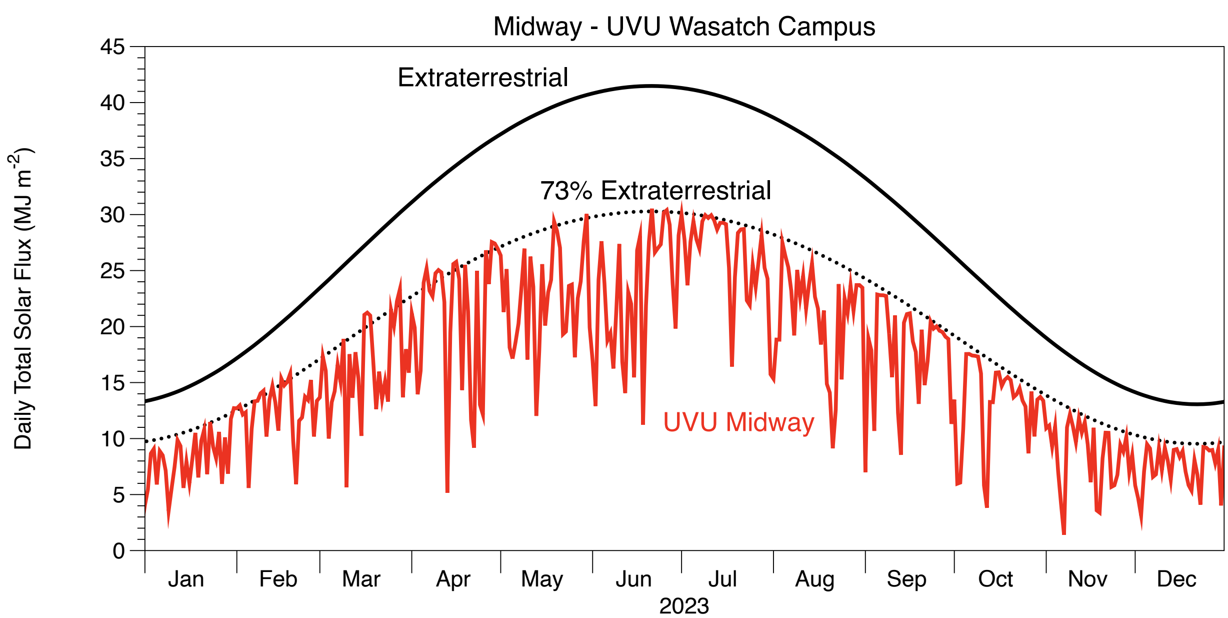

Figure A3. Same as Figure B2, but for 2023. UVU data.

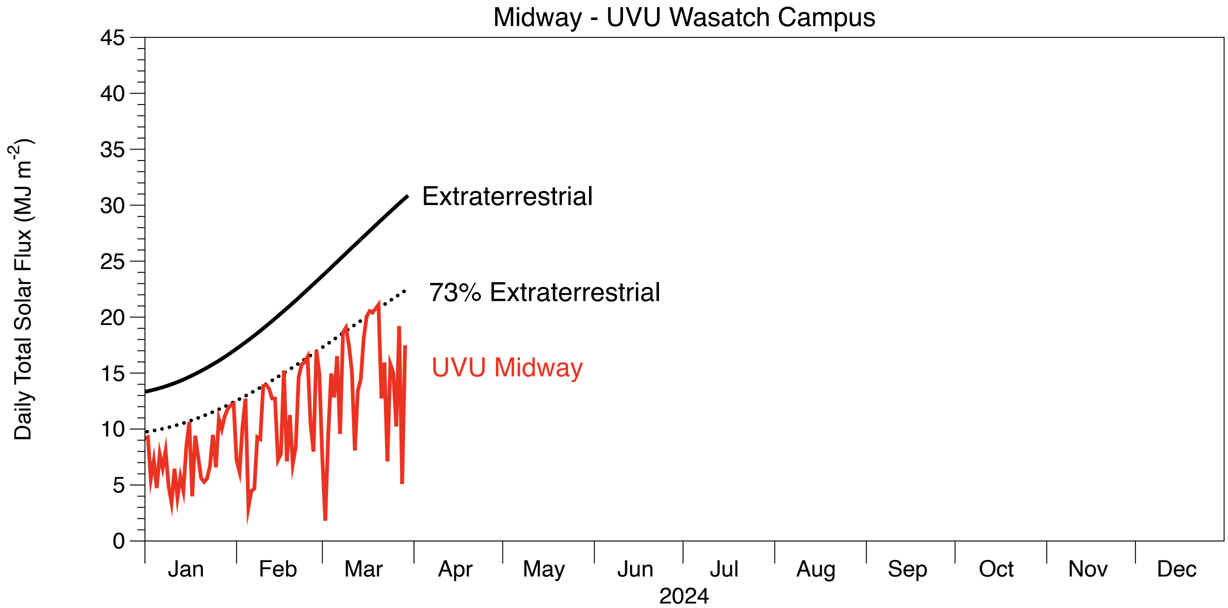

Figure A4. Same as Figure B2, but for 2024. UVU data.

APPENDIX B: SIMULATION OF TEMPERATURES IN A TAILWATER STREAM

A Lagrangian approach, commonly used in physics, allows one to visualize the effect of solar radiation on water temperatures along the river by following moving unit volumes of water released at successive times from the dam. The unit water volume depicted in **Figure B1** has a mean depth *D*, a mean width at the water surface *W*, and a 1 m length *L*, resulting in an area $A = W * L$ at the top of the volume and a volume $V = W * D * L$.

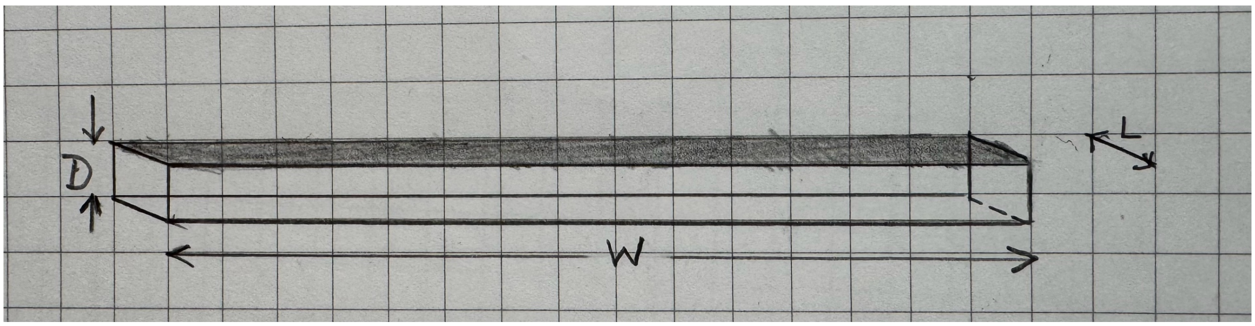

Figure B1. Unit volume. Not to scale.

A unit water volume released from the dam with an initial temperature T_0 will travel downstream at a velocity *v* that depends on the discharge rate from the dam – the higher the discharge rate the faster the volume moves downstream. An estimate of the velocity in the main river channel can be obtained from discharge measurements at the River Road Bridge weir using **Figure 9**. During its downstream travel the volume receives heat from the incoming solar radiation coming across the area *A* at the top of the moving volume, which warms the underlying volume *V*. Slow traveling parcels leaving the dam will receive more solar radiation during travel to a point downstream than fast traveling water since the accumulation of incoming solar radiation will be greater in the slow traveling parcel. The warming rate will vary during the day with incoming solar radiation and the volume when reaching a point downstream will gain a temperature increment ΔT so that the temperature at that point will be $T_0 + \Delta T$.

Volumes released early in the day when solar radiation is weak will accumulate low temperature increments, while volumes traveling in mid-day will accumulate more solar radiation during travel, thus acquiring higher temperature increments. The temperature increments depend on the *accumulated* solar input during the travel. The net result of tracking a series of moving volumes is that the water temperature will undergo a daytime temperature oscillation, rising from the nighttime value to a peak in mid- to late-afternoon, with a drop-off in the evening to the nighttime value as the cold water from the dam is advected downstream. The amplitude of the daily temperature oscillation will be low at locations near the dam, as cold water released from the dam has little time in the sun, while the amplitude of daily temperature oscillations in the lower parts of the river will be much higher. In fact, as we have seen, temperature oscillations in the lower river on clear sunny days reach amplitudes of 17 or 18°F. These oscillations in the lower river in summer when the release temperature is near 51°F can bring actual water temperature into the 65-68°F trout stress range. A reduction in the temperature of the water released from the dam by a few degrees may well bring the water temperatures in the lower river below this range.

A heuristic way of illustrating how temperatures increase with downstream distance and how peak water temperatures occur later in the day at distances farther downstream requires a focus on incoming solar radiation and the use of the Lagrangian approach. For illustration, we use typical values for the Middle Provo River and assume that the temperature of water released from the dam, T_0, is unchanging during the simulation and that during the night the river has attained this constant temperature along its entire length. We wish to track unit water volumes that leave the dam at a constant speed of 5 km/h at different times of day. We want to determine the temperature increment added by incoming solar radiation to the volume as it reaches two sites – a blue site 5 km downstream and a red site 10 km downstream. It will take one hour for the water volume to reach the blue site after its release from the dam and two hours to reach the red site. Consider **Figure B2** in which we plot an idealized incoming solar radiation curve on a clear day at River Road (the black curve) that accounts for a 27% loss of radiation as the incoming solar radiation at the edge of the Earth's atmosphere (i.e., extraterrestrial radiation) penetrates the Earth's atmosphere to reach the River Road Bridge. While we can choose any time of day and track the volume as it moves, here we track unit volumes leaving the dam at chosen specific times, illustrated by blue and red areas that represent the total solar radiation input between the starting and stopping times of the transits.

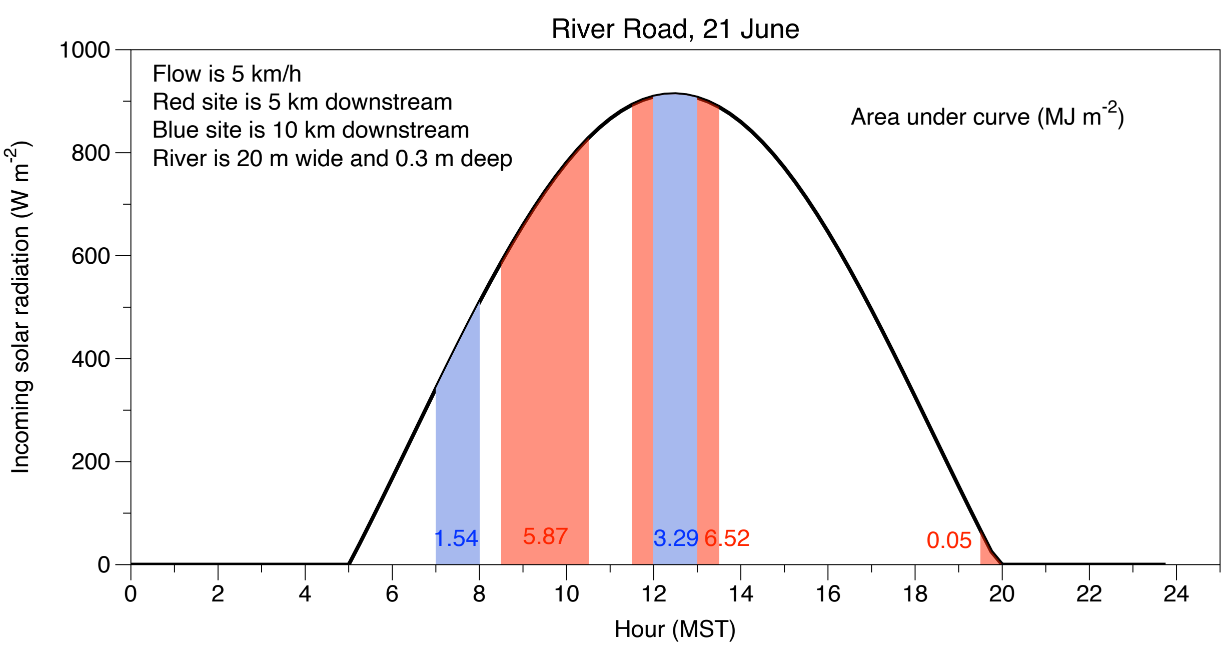

Figure B2. Simulated clear day incoming solar flux at River Road Bridge on 21 June. The areas under the curve (MJ) are indicated for various situations discussed in the text.

Consider a unit water volume in which W = 20 m, D = 0.3 m (the *mean* water depth across the stream) and L = 1 m (hence the term *unit volume*). The unit volume leaving the dam at 7 am would reach the blue site at 8 am and the heat gained per square meter of water surface area by the input of solar radiation during this transport would be the blue area under the incoming solar radiation curve in **Figure B2** between 7 and 8 am (Q = 1.54 MJ m^{-2}). Solar radiation comes across the area (A = L * W =20 m^2) at the top of the volume so that the total heat $H = Q * A$ = 30.8 M is added to the unit volume ($V = A * D * L$ = 6 m^3). The mass of the unit volume would be $M = \rho * V$ = 6000 kg, where ρ = 1000 kg m^{-3} is the density of water. The temperature increment added to the volume during its transport would then depend on the specific heat of water c = 4182 J kg^{-1} °C^{-1} using the formula

$$\Delta T = A * Q / (M * c) = H / (M * c) = 30.8 \times 10^6 \text{ J} / (6000 \text{ kg} * 4182 \text{ J kg}^{-1} \text{ °C}^{-1}) = 1.23\text{°C}$$

Thus, at 9 am the temperature at the blue site would be T_0 + 1.23°C. Temperature increments (and, thus, temperatures) at the blue site would increase during the morning as incoming sunlight increases. The maximum temperature increment at the blue site would occur when the one-hour travel time spans the maximum value of incoming solar radiation. This would occur when the volume leaves the dam at 12 pm and arrives at the blue site at 1 pm. The temperature increment at 1 pm would then be the maximum daily value of 2.62°C. Temperature increments would then decrease for release times after the 12 pm maximum. The numerical values appropriate for the equation above are given for all examples in **Table B1**.

Table B1. Values of variables for the different simulations illustrated in Figure C2.

Site	Times	Q (MJ m-2)	H (MJ)	ΔT (°C)	ΔT (°F)
blue	0800-0900	1.54	30.8	1.23	2.21
blue	1200-1300	3.29	65.8	2.62	4.72
red	0830-1030	5.87	117.4	4.68	8.42
red	1130-1330	6.52	130.4	5.20	9.36
red	1930-2130	0.05	1.0	0.040	0.07

The red site accumulates heat from incoming solar radiation during the longer (2-h) travel time (**Figure B2**). During the transport from 08:30 to 10:30 the traveling volume arriving at the red site would have received 117.4 MJ for a temperature gain of 4.68 °C. The temperature at this site at 10:30 would thus be this temperature increment added to the temperature of the water released from the dam. As was shown for the blue site, the maximum temperature increment attained by the red site occurs when the maximum in the solar curve was midway through the travel time. Its 2-hour transport time will include the maximum in the incoming solar radiation curve if it leaves the dam at 11:30 am to attain a heat input of 130.4 MJ and a temperature increment of 5.20°C at 1:30 pm. This 1:30 pm peak temperature is later than the 1 pm arrival of the peak temperature at the blue site. Longer transport times required to reach sites farther downriver accumulate more solar heat during transport and maximum temperatures will occur later in the day. Any releases after this time of the maximum temperature increment will have lower values of accumulated solar fluxes during transport so the temperature will start to fall back towards the nighttime value.

The final red area in **Figure B2** illustrates what will happen at the red site for volumes released from the dam late in the day (7:30 pm). When the unit volume reaches this site at 9:30 pm the heat input is 1.0 MJ and the temperature increment is only 0.04 °C, as no solar radiation enters the volume after sunset. A unit volume released from the dam at 8 pm will have no heat input from solar energy during its transport and the temperature will be the same as the release temperature at the dam at and after 10 pm.

The heuristic approach illustrated using the solar radiation curve of **Figure B2** can be coded into a simple Lagrangian mathematical model of an idealized tailwater stream in which successive units of water are released at 15-min intervals from the dam and tracked downstream while gaining heat from the sun's radiation. We consider an idealized stream on 7-8 July 2022 with the physical characteristics of the Middle Provo supplied by continuous discharge of water at 11°C (51°F) and with this same temperature along the river's length at the beginning of the simulation. There are no irrigation diversions or tributaries and the idealized stream is 20 m (66 ft) wide (W = 20) with a mean depth 0.2 m or 0.7 ft (D = 0.2) and a mean velocity of 1 m/s or 2.2 mph (v = 1), similar to flows at the River Road weir on this date. The heat flux into the river as it travels downstream is specified as 42% of the extraterrestrial solar radiation flux to match the actual observed temperature maximum at the last grid element on the day in question. The model is run at 15-min timesteps to match the output from a solar model (Whiteman and Allwine, 1986) and the 15-min observational data from the Middle Provo River.

The formula for determining the temperature increment added as a unit of water travels downstream is given by:

$$\Delta T(t; v; date) = \frac{A}{\rho v c} \int_{t-\frac{\Delta x}{v}}^{t} H(t)\, dt$$

where T is temperature, v is water velocity, t is time, $\Delta x = 900 * v$ is distance between grid elements and $\Delta x/v$ is the travel time between grid elements (15 minutes or 900 s), date is day of year (1 - 365), $A = 20\ m^2$ is area at the top of the unit water volume, ρ is water density, c is specific heat of water, and H is heat added between time steps at the date specified.

Simulated temperatures for a 1 m s^{-1} flow are shown in **Figure B3** for comparison with actual data on the same date in **Figure B4**.

Key features of the temperature curves in both the simulation and observations include:

- The temperature of water released from the dam is constant throughout the simulation
- The rise in temperature starts at the same time at all points downstream because the sun, when it rises, adds heat along the whole river at the same rate.

- Sites closest to the dam reach temperature maxima earlier than sites farther downstream
- Temperature maxima increase with downstream distance
- Temperature maxima exhibit a time lag with distance downstream
- It takes longer for the temperatures to decay from their maxima at the downstream sites

The heat gained is parameterized as a fraction of the solar radiation input, which varies with time as the sun transits across the southern sky (**Appendix A**). Other physical processes that add or subtract heat during the transport (net long- and short-wave radiation, sensible heat flux, evaporation, heat gain or loss through irrigation diversions or confluences, etc.) are subsumed into the solar parameterization or are neglected. Comparison of the simulation with actual data on the same date can provide insight into neglected heat inputs or outputs in the idealized model. Note, however, that the model outputs temperatures at regular distance intervals, while the observational data is at fixed, and different, distances downriver.

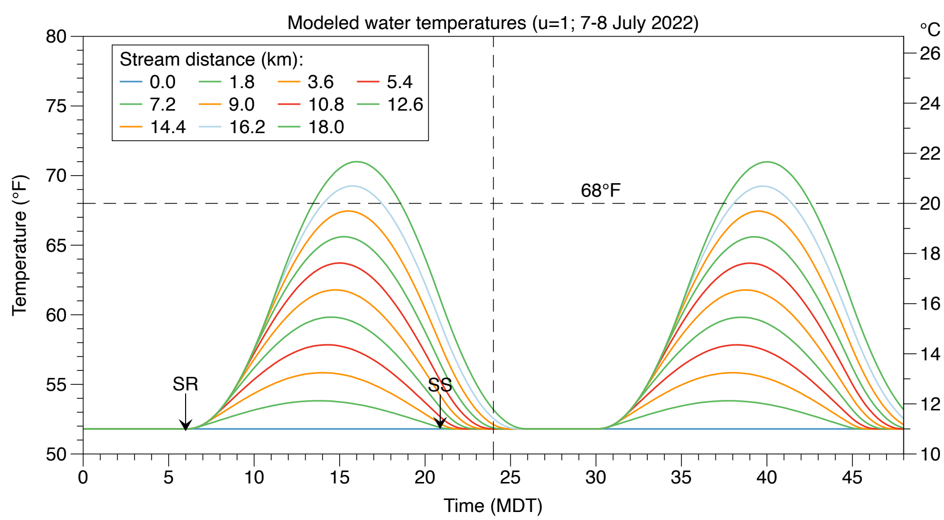

Figure B3. Model output for 7-8 July with water velocity at 1 m/s. SR=sunrise; SS=sunset

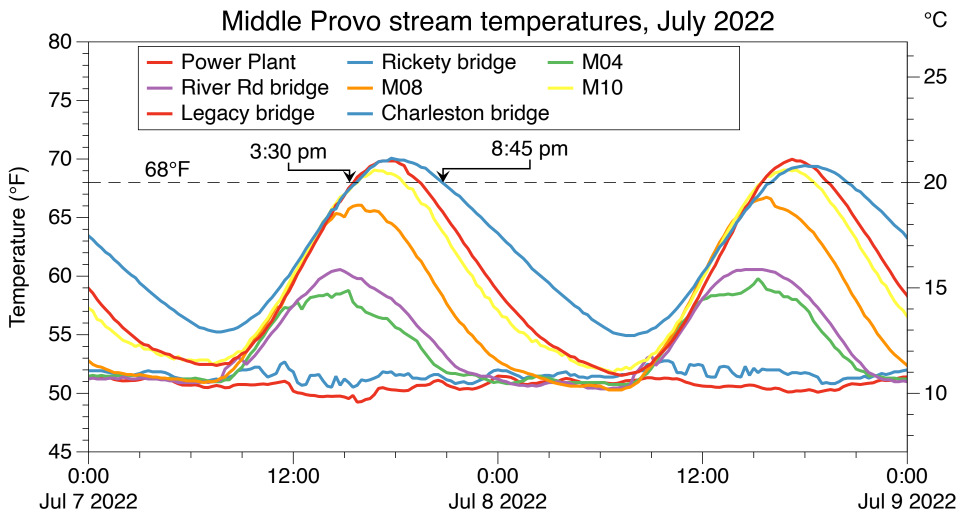

Figure B4. Middle Provo measured water temperatures on July 7-8, 2022.

Simulated temperatures obtained with a 2 m s^{-1} (4.5 mph) stream velocity are shown, for comparison, in **Figure B5**. This velocity is attained by increasing the discharge from the dam. It results in lower maximum temperatures, earlier daytime maxima, less time lag between grid elements and quicker nighttime recovery to the temperature of the water released from the dam. Takeaways from the model are that downstream temperatures can be reduced by increasing the discharge rate at the dam or by discharging colder water.

This model simply illustrates the key physical processes but neglects many others. The model could be expanded to account for better initial conditions (temperatures at sunrise are not the same along the entire river's length) and the influence of groundwater inputs with different temperatures in the lower river.

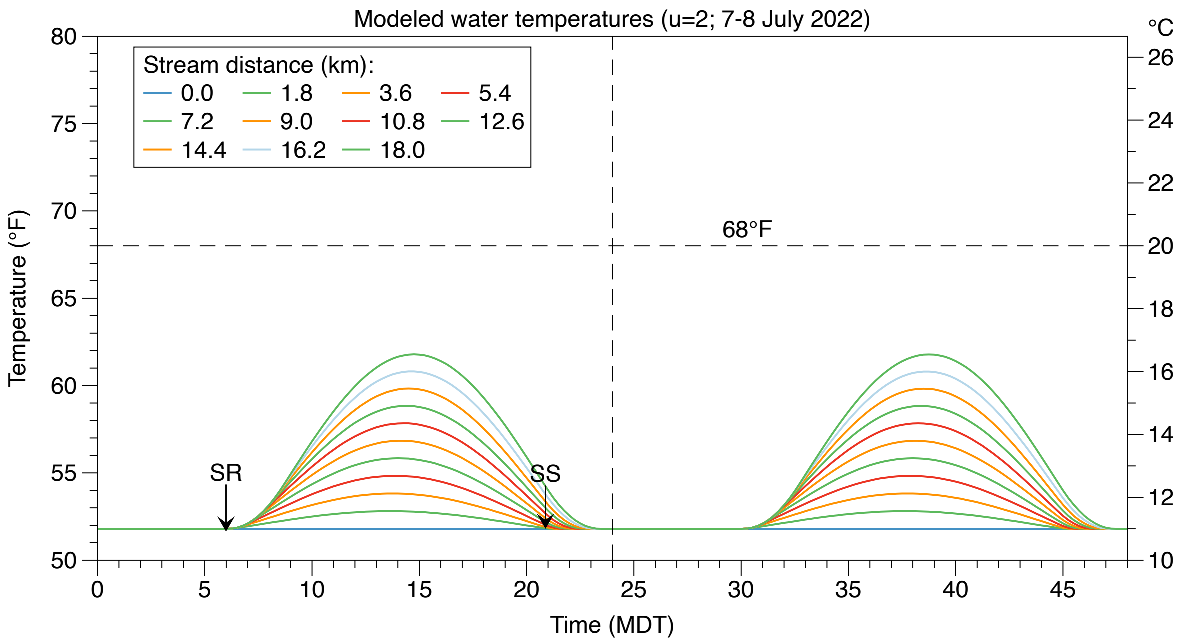

Figure B5. Model output for 7-8 July with water velocity at 2 m/s. SR=sunrise; SS=sunset