City of Steamboat Springs

Yampa River Health Assessment & Streamflow Management Plan

Water Temperature Management Opportunities on the Yampa River

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Overview

Purpose and Scope

The principal purpose of the Yampa River Health Assessment and Streamflow Management Plan is to better understand drivers of river health impairment and the land and water management opportunities best suited to respond to those impairments on the Yampa River near Steamboat Springs. Anecdotal evidence and several years of water temperate data collection by the City of Steamboat Springs and Colorado Parks and Wildlife (CPW) staff indicate regular exceedance of State of Colorado water temperature standards meant to protect local fisheries and other aquatic life. This issue was highlighted in the Yampa River Health Assessment Report, but the cause of elevated stream temperatures could not be diagnosed. The difficulty encountered in attributing elevated water temperatures to some water management or geographic condition encouraged further investigation into the underlying processes at work. The findings presented here intend to support future management decisions regarding management of water temperature to meet stakeholder-identified targets for the protection of sport fish and native fish populations on the Yampa River near Steamboat Springs.

Investigative Approach

The frequency, duration and magnitude of elevated water temperatures on this section of the Yampa River are well documented. Unfortunately, the physical processes driving exceedances of water quality standards were poorly understood at the inception of this project. This information gap produced significant uncertainty in management outcomes for recent activities undertaken by the City of Steamboat Springs and the Colorado Water Trust to limit the number of days local aquatic fauna experienced elevated water temperatures. This investigation developed and integrated results from 1) empirical models of observed streamflow, water temperature, and air temperature from several key locations on the Yampa River and 2) an energy balance model for water temperature representing the section of the Yampa River between Lake Catamount and the wastewater treatment plant (WWTP) outfall above the confluence with the Elk River. The combined approach to modeling system behavior helped identify the types and locations of management activities most likely to yield decreased mid- and late-summer river temperatures.

Summary of Findings

Modeling results suggest that streamflow management activities (e.g. contracted releases of water from Stagecoach Reservoir) aimed at mitigating high water temperatures on the Yampa River will require substantial increases in mid- to late-summer flows below Lake Catamount. Critically, while modeling indicates that it may be possible to control water temperature by increasing streamflows, the flow rates required are significantly higher than either existing or natural conditions. Exposing the river to such abnormally high flows may produce unintended consequences for other aspects of river health. The beneficial impacts of more moderate increases in streamflow on the Yampa River appear limited to the time period between mid-August and mid-September. Energy balance modeling indicates radiative warming of the channel may be positively reduced through increased shading of the river channel, thereby making efforts to manage flows to control temperature more effective. Widespread increases in shading may be achieved through long-term efforts floodplain management efforts that encourage the recruitment of large woody species (e.g. cottonwood) in the area between Lake Catamount and the Yampa River's confluence with Walton Creek.

Assessment Methodologies and Results

Data Availability

Characterization of stream temperature patterns on the Yampa River required development of several linear regression models and an energy balance model. Each assessment was built upon observed records of streamflow, meteorological conditions, and water temperature available for the project area between 2011 and 2018. Daily average streamflow data was procured from the USGS for locations on the Yampa River below Stagecoach Reservoir (USGS 09237500) and in Steamboat Springs (USGS 09239500). The USGS also provided daily streamflow data from Fish Creek below Fish Creek Reservoir (USGS 09238900). Colorado Division of Water Resources provided streamflow data at the spillway (YAMBELCO) and outlet works (YAMOUTCO) on Lake Catamount. The National Oceanographic and Atmospheric Administration (NOAA) publishes 20-minute meteorological data (e.g. wind speed/direction, humidity, cloud cover, air temperature, etc.) from a station located in Steamboat Springs (KSBS). Water temperature data was collected intermittently over a period of several years by CPW at Chuck Lewis State Park and locations near Tree Haus bridge, the mouth of Fish Creek, and Dream Island Plaza. This data covered the period between 2012 and 2015. Un-censored data records for each location were secured from CPW staff. The City of Steamboat Springs collected water temperature data between the fall of 2016 and the winter of 2017/18 below the outlet of Lake Catamount, above the confluence with Oak Creek, near Dougherty Road, at the KOA campground west of downtown, and above the outfall from the WWTP. Un-censored data records for each location were secured from City staff. Time series water temperature data for the Yampa River below Stagecoach Reservoir for the period covering 2011-2017 was supplied by the Upper Yampa Water Conservancy District. All time series data was quality checked through visual analysis in the R statistical computing environment and anomalous data was removed. All sub-daily data was aggregated to daily means using the HydroTSM and Zoo libraries in R. Further aggregation of daily data yielded rolling means of weekly air temperature (7-day, center aligned), weekly water temperature (7-day, center aligned), weekly streamflow (7-day, center aligned), and monthly air temperature (30-day, left aligned). All processed data was organized as a time series matrix to facilitate linear regression modelling.

Development of an energy balance model required stream geometry and riparian shading information in addition to the data described above. Average stream geometries, reach lengths, and relationships between channel top-width and discharge were retrieved from a HEC-RAS model provided by City of Steamboat Springs staff. Reach-integrated estimates of riparian and topographic shading were informed by field surveys and GIS analysis. No data was available to estimate groundwater inflows or temperatures, so they were not included in the energy balance model.

Empirical Relationships

Linear regression modeling is a fairly typical approach for identifying significant relationships between water temperature and other environmental variables like air temperature (Benyahya, et al., 2007; Caissie, et al., 1998; Li, et al., 2014; Neumann, et al., 2003; Sahoo, et al., 2009). Regression models were developed for predicting weekly average temperatures at the outlet of Lake Catamount, the mouth of Fish Creek, and at Dream Island Plaza. Locations were selected due to the availability of data and their relative importance as upstream or downstream boundary conditions for the project area.

Outlet of Lake Catamount

Water temperatures at the outlet of Lake Catamount represent a critical upstream boundary control on water temperatures on the section of the Yampa River that flows through Steamboat Springs. Unfortunately, only limited water temperature data is available for that location. The City of Steamboat Springs collected data below the mixing zone of the outlet works and the spillway at Lake Catamount between September of 2016 and the winter of 2017. This period of record provides enough information to create empirical models of water temperatures but does not cover the breadth of possible environmental conditions experienced at this location necessary to support predictions across a broad range of possible future conditions. Nonetheless, even a cursory understanding of the controls on water temperature at this location is necessary for guiding water management actions designed to mitigate elevated water temperatures in downstream river sections. Therefore, we sought to develop an empirical relationship between water temperature, air temperature, and streamflows below Stagecoach Reservoir (USGS 09237500).

We curated the available data to include only subsets between the months of June and September across the period of record. We then fit a linear temperature model to the data. We used a linear model formulation common to similar studies similar in the scientific literature (e.g. Toffolon and Piccolroaz, 2015):

$$1)\ \overline{T_w} = \alpha_1 + \alpha_2\overline{T_a} + \alpha_3 ln\overline{\mathrm{Q}} + \alpha_4[\,\overline{T_A} + \left(T_{A_{max}} - T_{A_{min}}\right) * (\cos\left(\frac{2\pi}{t} * (t_i - S)\right)]$$

Where:

$\overline{T_w}$ = Weekly average water temperature below Lake Catamount
$\overline{T_a}$ = Weekly average air temperature at Steamboat Springs
$\overline{\mathrm{Q}}$ = Weekly average streamflow below Stagecoach Reservoir
$\overline{T_A}$ = Annual average air temperature at Steamboat Springs
$T_{A_{max}}$ = Annual maximum daily average air temperature at Steamboat Springs
$T_{A_{min}}$ = Annual minimum daily average air temperature at Steamboat Springs
t = The total number of time steps modeled in a year
t_i = The ith time step in the model
S = Phase shift parameter (fitted manually)
$\alpha_1, \alpha_2, \alpha_3, \alpha_4$ = Model parameters fitted by linear regression

The fitted model yielded an excellent fit to the observed data as indicated by Figure 1. Unfortunately, the data set was not long enough to effectively divide into calibration and validation periods, so we did not assess model fit outside of the model training set. All predictor variables were found to be significant ($p \leq 0.05$). However, the p-value for weekly average streamflow below Stagecoach Reservoir was lower than for parameters associated with air temperature. In response, we tested alternate formulations of the model. We substituted daily average flows at USGS 09237500 for the combined daily average flows from YAMBELCO and YAMOUTCO. We also developed a simplified model that eliminated the third term on the right side of the Equation 1 altogether.

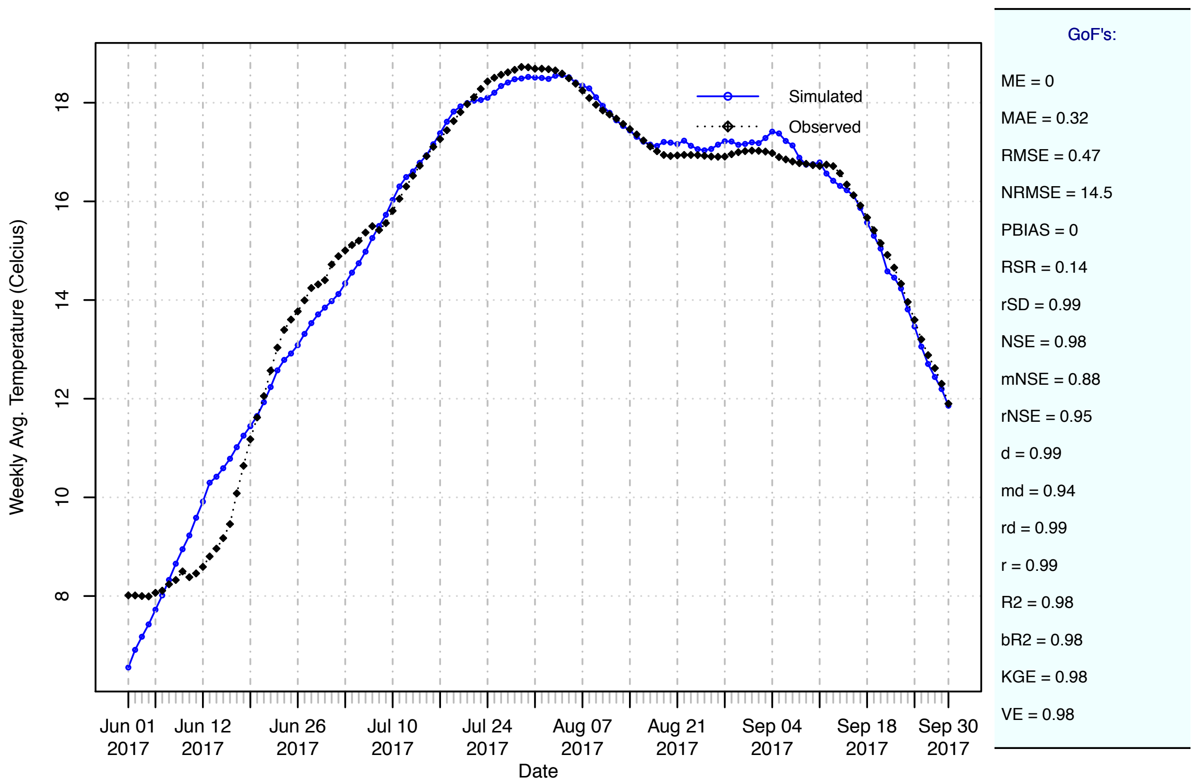

Figure 1. Observed and simulated weekly average water temperatures on the Yampa River below Lake Catamount. Simulations included releases from Stagecoach Reservoir as a predictor variable. Various goodness of fit measures indicated in light blue legend on tge right.

The model that utilized flows below Lake Catamount instead of flows below Stagecoach Reservoir performed more poorly than the original model. The simplified model (i.e. no term for streamflow) performed nearly as well as the original model (Figure 2), suggesting the diminutive role that flow releases from Stagecoach Reservoir may play in governing water temperatures below Lake Catamount. The relationships (or lack thereof) visibly evident between flows, daily air temperatures, and water temperature at this location initially led us to us use of a left-aligned calculation of air temperatures for $\overline{T_a}$. Alternate models that used computations of rolling 7-day average air temperatures yielded much poorer fits to the observed data.

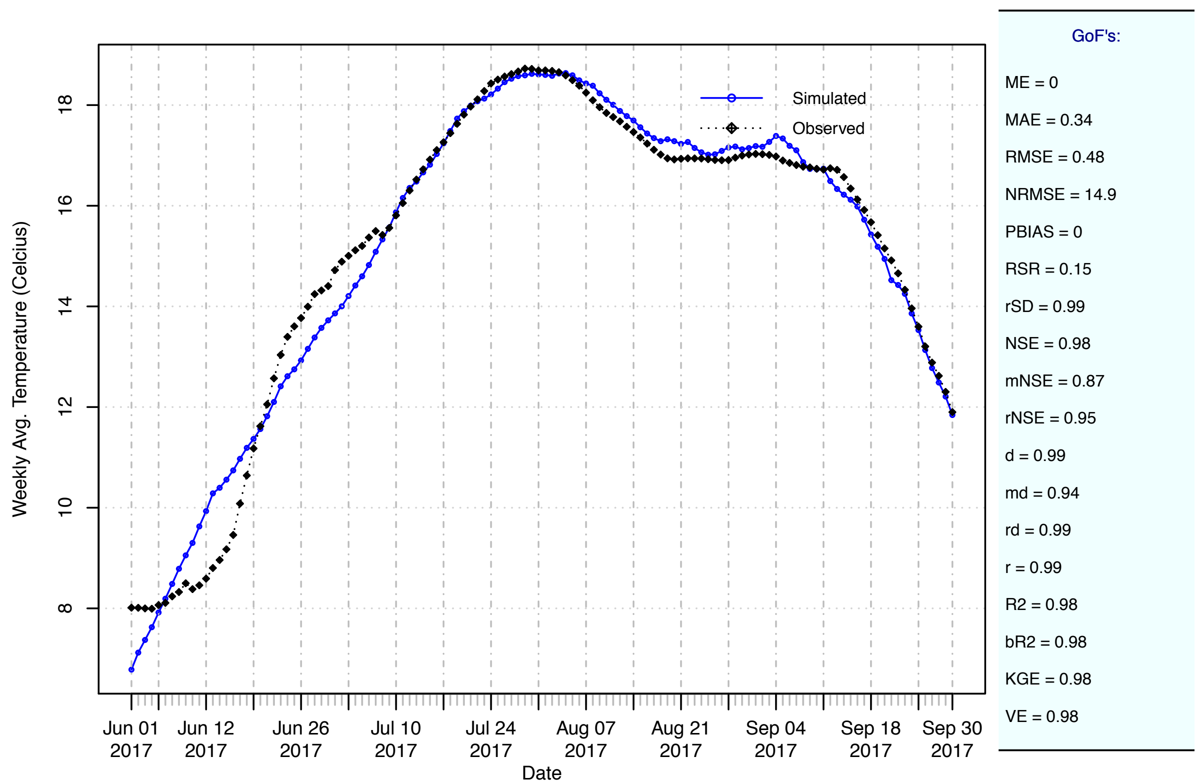

Figure 2. Observed and simulated weekly average water temperatures on the Yampa River below Lake Catamount. Simulations did not include releases from Stagecoach Reservoir as a predictor variable. Various goodness of fit measures indicated in light blue legend on the right.

Dream Island Plaza

Elevated summer water temperatures near Dream Island Plaza drive concerns at the City of Steamboat Springs over discharge permit violations for temperature at the WWTP outfall located downstream. This location also integrates temperature changes that occur between Lake Catamount and the City of Steamboat Springs as they are affected by solar irradiance and relatively-cool tributary inflows (e.g. Fish Creek). Colorado Parks and Wildlife collected water temperature data at this location between September of 2011 and the winter of 2015. Data collected by the City of Steamboat

Springs near the KOA campground was added to the CPW dataset to extend the record to the 2016 and 2017 summers. Minimal temperature changes were assumed between these two locations. Streamflow data from USGS 09239500 was assumed representative of the temperature monitoring locations. The data set was curated to include only periods between the months of June and September. The resultant period of record provided a wide range of possible environmental conditions for model training.

We used daily streamflow, water temperature, and air temperature data to initially create a linear model of water temperatures in the R statistical computing environment. We used the same linear model formulation presented previously:

$$2)\ \ \overline{T_w} = \alpha_1 + \alpha_2\overline{T_a} + \alpha_3 ln\overline{\mathrm{Q}} + \alpha_4[\,\overline{T_A} + \left(T_{A_{max}} - T_{A_{min}}\right) * (\cos(\tfrac{2\pi}{t} * (t_i - S))]$$

Where:

$\overline{T_w}$ = Weekly average water temperature at Dream Island Plaza
$\overline{T_a}$ = Weekly average air temperature at Steamboat Springs
$\overline{\mathrm{Q}}$ = Weekly average streamflow at Steamboat Springs

$\overline{T_A}$ = Annual average air temperature at Steamboat Springs
$T_{A_{max}}$ = Annual maximum daily average air temperature at Steamboat Springs
$T_{A_{min}}$ = Annual minimum daily average air temperature at Steamboat Springs
t = The total number of time steps modeled in a year
t_i = The ith time step in the model
S = Phase shift parameter (fitted manually)
$\alpha_1, \alpha_2, \alpha_3, \alpha_4$ = Model parameters fitted by linear regression

The linear model fit the observed data well (Figure 3) with an overall p-value of 2.2e-16 and an F-statistic of 3020 on 3 and 574 degrees of freedom. The adjusted R-squared for the model was 0.94. The model predicted that for every one degree increase in weekly average air temperature, water temperature increases 0.32 degrees. For every unit increase in the natural log of streamflow, the model indicates a 2.27 degree decrease in water temperature.

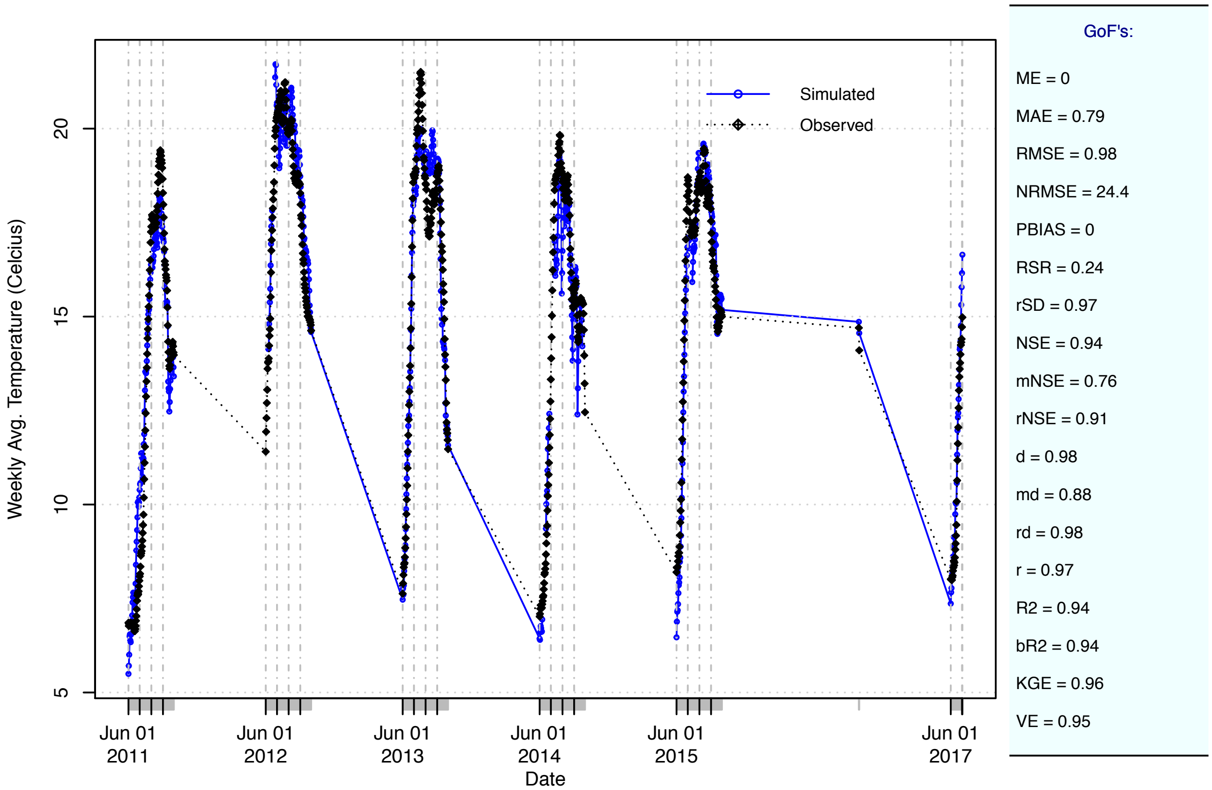

Figure 3. Observed and simulated weekly average water temperatures on the Yampa River near Dream Island. Various goodness of fit measures indicated in light blue legend on the right.

We then used the same data set to create a logistic regression model in R for understanding the probability that water temperatures exceeded some threshold across changing streamflow and air temperature conditions. Logistic regression models can be effective tools for informing management actions. Presentation of outcomes as probabilities of occurrence allows for some consideration of risk in the decision-making process. The basic model formulation did not change, but instead of solving for $\overline{T_w}$, we solved for $P(y = 1|X)$, the probability that water temperatures at Dream Island Plaza exceeded 18.3 degrees Celsius. Checks on logistic model validity indicated an overall accuracy of 89%. The model predicted that for every one degree increase in weekly average air temperature, the ln(odds) of a weekly average water temperature above 18.3 degrees Celsius increased by 1.10. For every unit increase in the natural log of streamflow, the ln(odds) of a weekly average water temperature above 18.3 degrees Celsius decreased by 1.91.

Mouth of Fish Creek

Cooler tributary water from Fish Creek moderates water temperatures near downtown City of Steamboat Springs and represents an important thermal refuge for native mountain whitefish during low-water conditions. Colorado Parks and Wildlife collected water temperature data at the mount of Fish Creek in the summers 2011 and 2012. We used this data to develop a linear model of water temperature, air temperature and discharge on Fish Creek to extend the record of water temperatures on Fish Creek. This was an important contribution to the development of the energy balance model discussed in the next section. We used the same linear model formulation presented previously:

$$3)\quad \overline{T_w} = \alpha_1 + \alpha_2\overline{T_a} + \alpha_3 ln\overline{\mathrm{Q}} + \alpha_4[\overline{T_A} + \left(T_{A_{max}} - T_{A_{min}}\right) * (\cos(\frac{2\pi}{t} * (t_i - S))]$$

Where:

$\overline{T_w}$ = Weekly average water temperature at the mouth of Fish Creek
$\overline{T_a}$ = Weekly average air temperature at Steamboat Springs
$\overline{\mathrm{Q}}$ = Weekly average streamflow below Fish Creek Reservoir

$\overline{T_A}$ = Annual average air temperature at Steamboat Springs
$T_{A_{max}}$ = Annual maximum daily average air temperature at Steamboat Springs
$T_{A_{min}}$ = Annual minimum daily average air temperature at Steamboat Springs
t = The total number of time steps modeled in a year
t_i = The ith time step in the model
S = Phase shift parameter (fitted manually)
$\alpha_1, \alpha_2, \alpha_3, \alpha_4$ = Model parameters fitted by linear regression

While the data record for Fish Creek was limited, the linear model fit the observed data reasonably well (Figure 4) with an overall p-value of 2.2e-16 and an F-statistic of 2208 on 3 and 341 degrees of freedom. The adjusted R-squared for the model was 0.95. The model predicted that for every one degree increase in weekly average air temperature, water temperature increases 0.47 degrees. For every unit increase in the natural log of streamflow, the model indicates a 2.03 degree decrease in water temperature.

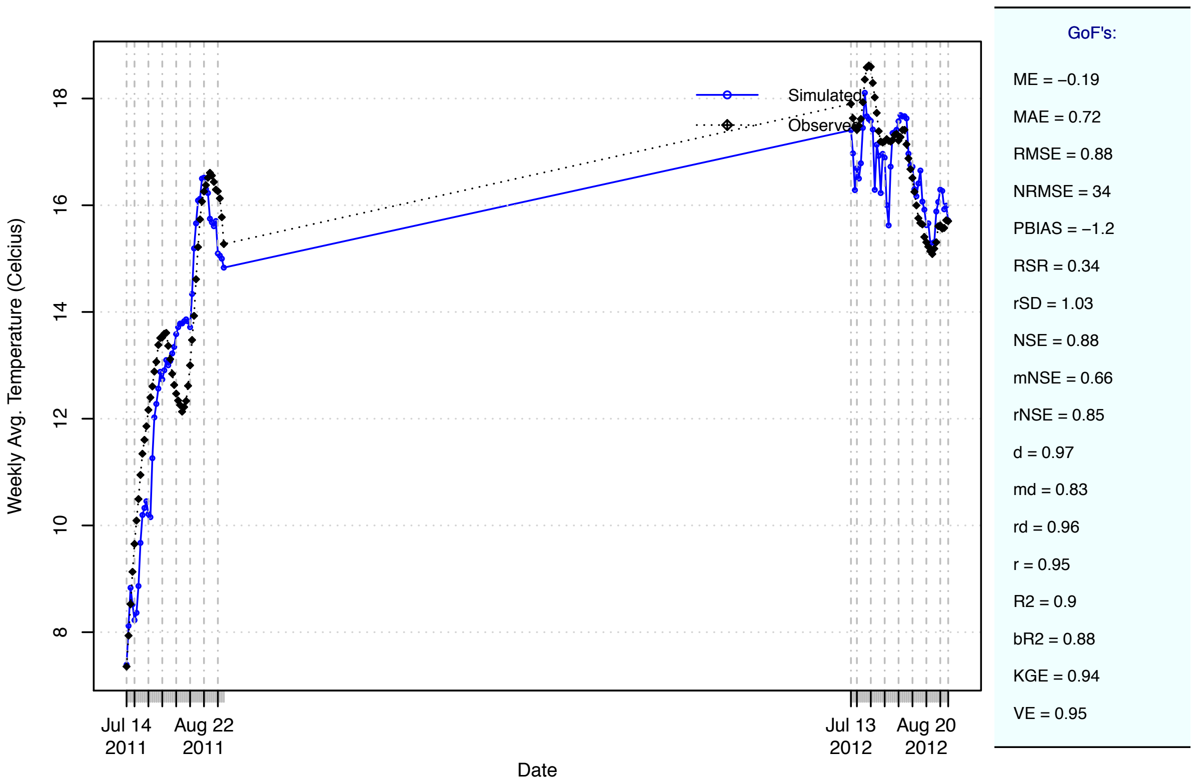

Figure 4. Observed and simulated weekly average water temperatures at the mouth of Fish Creek. Various goodness of fit measures indicated in light blue legend on the right.

Energy balance modeling

Supplementation of the empirical models was necessary to understand the potential implications of management actions that alter riparian shading or stream channel dimensions on water temperatures. Modeling the physical processes that govern stream water temperature is typically understood to be more reliable and informative than empirical modeling, but the data requirements present a significant barrier to entry in most systems. A fully parameterized stream temperature model requires knowledge of solar irradiance, longwave radiation to and from the stream, the degree of shading and channel dimensions at any given channel position, the conduction between the water in the channel and the streambed, convective exchanges of heat driven by wind, and the quantity and temperature of inflowing groundwater and tributary inflows (Figure 5).

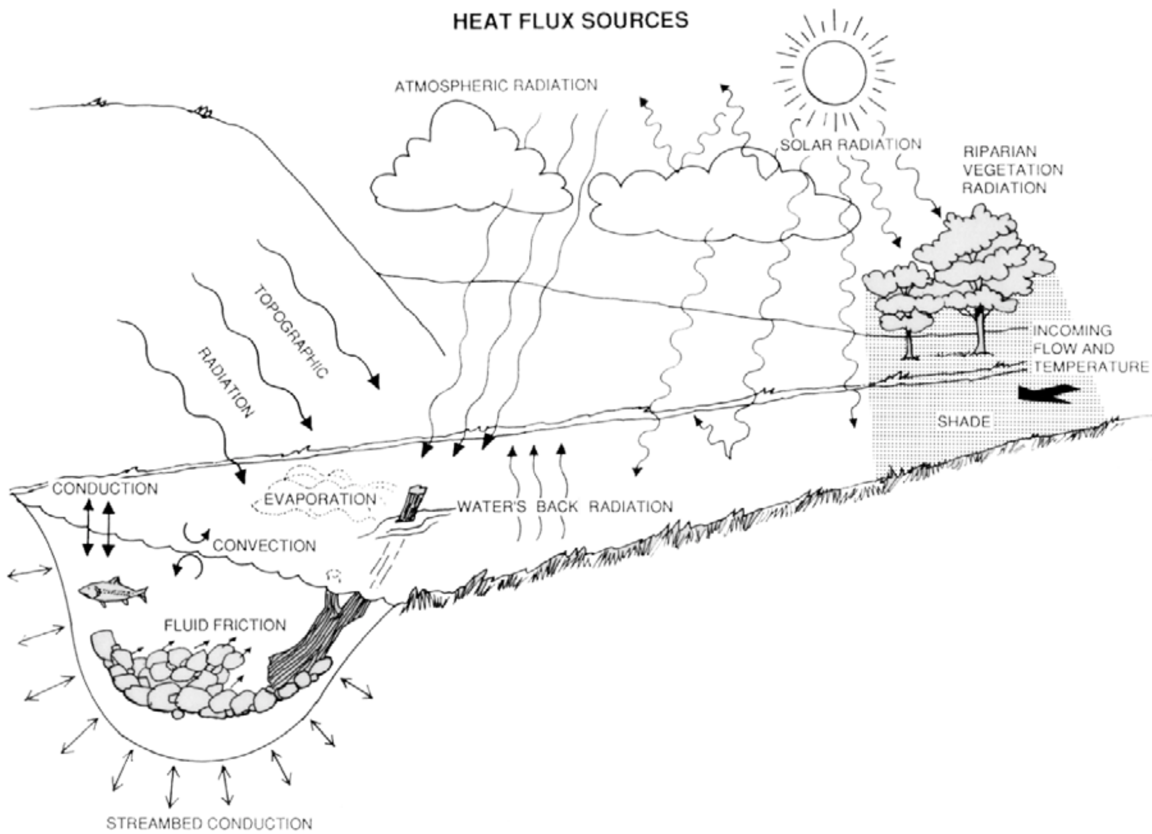

Figure 5. Conceptual model of the heat fluxes that control stream water temperature (From Theurer, et al. 1984).

Data available for the Yampa River enabled creation of a sparsely parameterized—and, thus, generalized—model of heat exchanges on the section of the river between Lake Catamount and the WWTP outfall. The energy balance model was implemented in the StreamTemp software (Version 1.0.4), a derivation of the SNTEMP software produced by the USGS and the U.S. Fish and Wildlife Service (Bartholow, 1989; Theurer, et al., 1984). The model was constructed to include five reaches on the Yampa River: 1) Lake Catamount to Chuck Lewis SWA, 2) Chuck Lewis SWA to Dougherty Road, 3) Dougherty Road to Fish Creek, 4) Fish Creek to the KOA campground, 5) and the KOA campground to the WWTP outfall. Fish Creek was the only tributary included in the model. The physical characteristics of each reach were assumed internally homogenous. Upstream boundary streamflows were calculated by summing observed daily average flows from YAMBELCO and YAMOUTCO. Average daily flows on Fish Creek were calculated by aggregated 15-minute data USGS 09238900. The heights and densities of streamside vegetation and features contributing to topographic shading on each reach were initially calculated via GIS analysis, assessment of aerial imagery, and review of field data collection notes. Relationships between channel width and streamflow were derived from a 1D hydraulic model. No estimates of groundwater inflow volumes or temperatures were included. Water temperature data collected over the 2017 summer season on the Yampa River below Lake Catamount provided the upstream water temperature boundary condition. The linear regression model for weekly average streamflow temperatures on Fish Creek was used to predict water temperatures above that tributary's confluence with the Yampa River. The NOAA KSBS weather station provided observations of air temperature, humidity, wind speed, and cloud cover. Fixed values were assumed for atmospheric dust and ground reflectance.

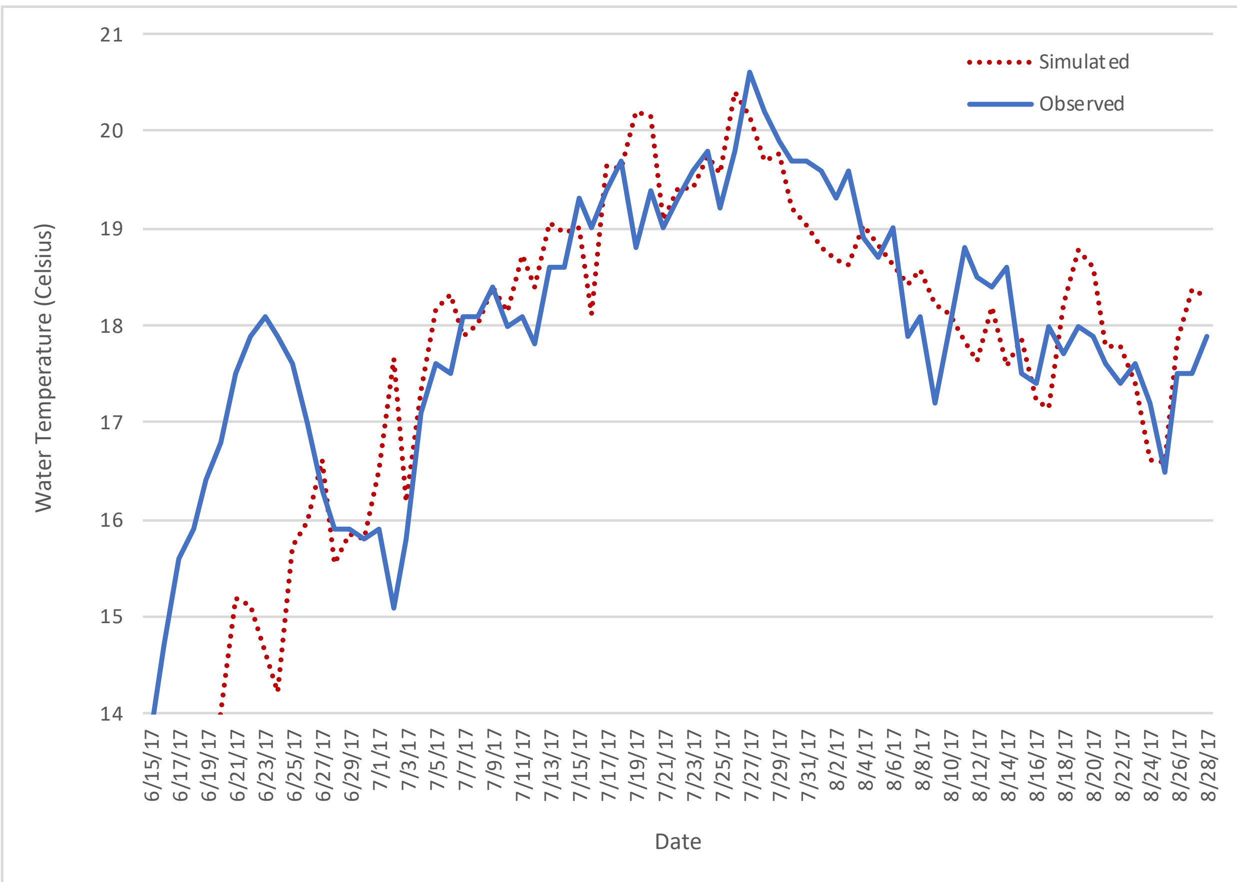

Figure 6. Energy balance model calibration results at the Chuck Lewis SWA.

The model was calibrated using water temperature data collected over the 2017 summer season on the Yampa River below Lake Catamount, at Dougherty Road, at the KOA campground, and above the WWTP outfall. Improvements in model fit were made through manual adjustment of riparian shading and channel dimension parameters.

The fully calibrated model predicted patterns of daily water temperature with a reasonable degree of accuracy (Figures 6, 7). The model did not capture an observed period of warming in the last half of June at the Chuck Lewis SWA. However, we believe this data may be anomalous because the pattern is not replicated at downstream locations. Critically, successful application of the energy balance model as a decision support tool does not require perfect symmetry between model result and observed conditions. Rather, the physical processes at work in the system must be sufficiently captured to enable "what-if" scenario testing.

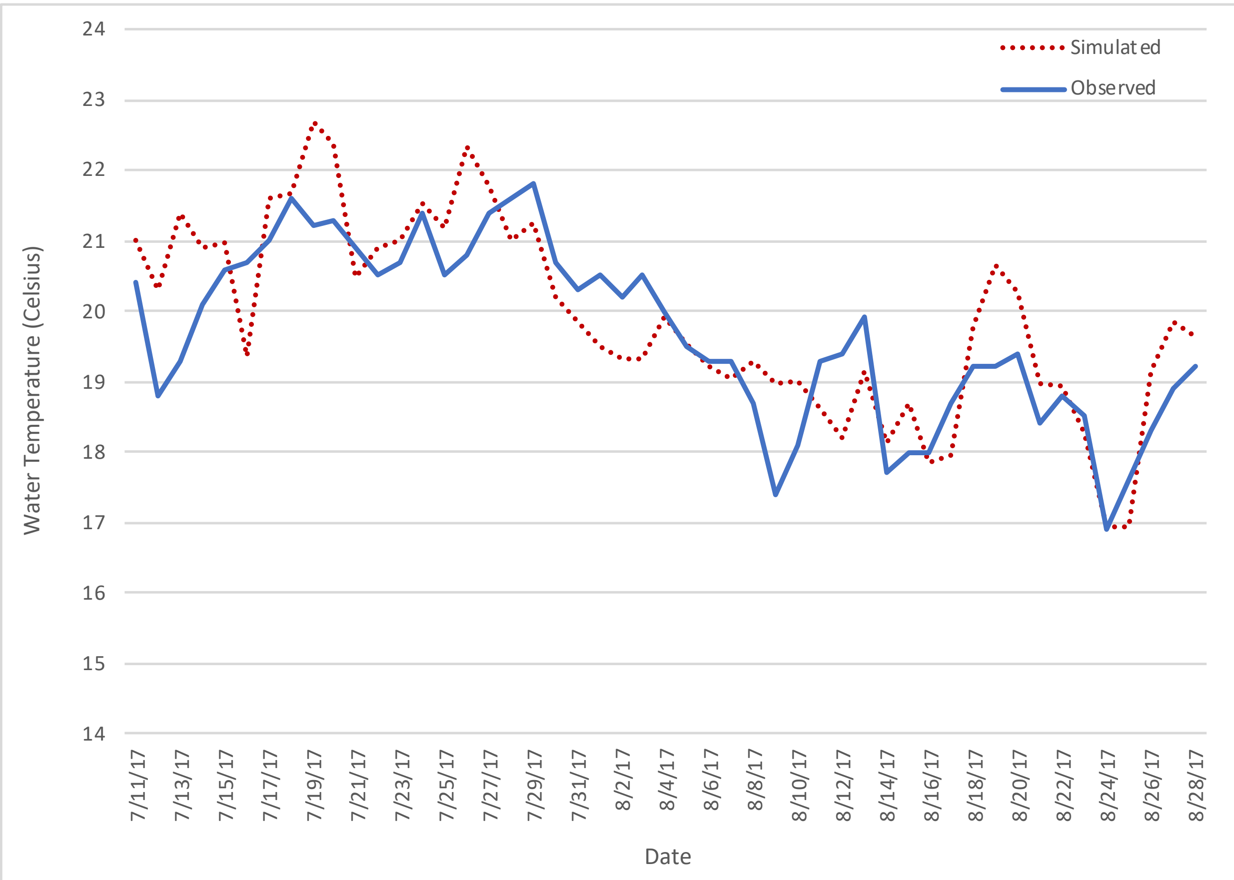

Figure 7. Energy balance model calibration results of above the WWTP outfall.

In addition to the energy balance model for the section of the Yampa River below Lake Catamount, some effort was made to parametrize a model for the section of the river between Stagecoach Reservoir and the outlet to Lake Catamount. The StreamTemp model is not well suited to simulating complex reservoir temperature dynamics (e.g. stratification), except in small, run-of-river reservoirs without controlled releases. While Lake Catamount may fit this definition, we were unable to successfully simulate the observed changes in stream temperature between Stagecoach Reservoir and the outlet of Lake Catamount. Our inability to model the system in this way suggests the presence of complicated thermal processes at work in Lake Catamount. The dearth of data bounding the thermal conditions and describing the physical characteristics of Lake Catamount itself precluded further investigation of this issue during this project, but may be a useful line of study in the future.

Management Implications

Stakeholders involved in the Yampa Streamflow Management planning process identified several river health and community needs management objectives that impact elevated water temperatures on the Yampa River. Stakeholders identified the Water Quality Control Division’s Coldwater Tier-II standard for aquatic life use protection as an appropriate metric for measuring the success of proposed or implemented management actions against. Specifically, stakeholders identified a desire to eliminate exceedances of the Coldwater Tier-II standard on the Yampa River through Steamboat Springs during average (non-drought) hydrological year types. Stakeholders also identified a stretch goal of eliminating exceedances on the Yampa River during moderate (1-in-4 year) drought conditions. The models discussed in the previous section provide useful tools for informing stakeholders on the potential effectiveness of various management actions intended to meet stated water temperature goals.

The logistic regression model created for the Yampa River at Dream Island Plaza enables assessment of the effectiveness of using increased streamflows as a tool for managing weekly average water temperatures. Applying the model to a sequence of increasing streamflows during a representative year type produces a matrix of probabilities for temperature exceedances. These probabilities represent the likelihood that the 18.3 degree Celsius threshold is exceeded. Plotting these results in a heatmap (Figure 8) illustrates the high streamflows (> 400 cfs) necessary to achieve favorable (< 50%) probabilities of exceedance at certain times of year. It is important to note that flows of this magnitude during the late summer were not observed in the time series record used to fit the model. Such results are, therefore, extrapolations. Using linear models for extrapolation of conditions beyond the observed datasetis considered problematic and any extrapolated results should be treated with caution. There are other short periods when flows between 100-150 cfs reduce the risk of temperature exceedance. These conditions, which reflect median August flows at the gauge below

Soda Creek, do appear in the time series record used to fit the model and are more reliable than predictions for the impacts of higher streamflows.

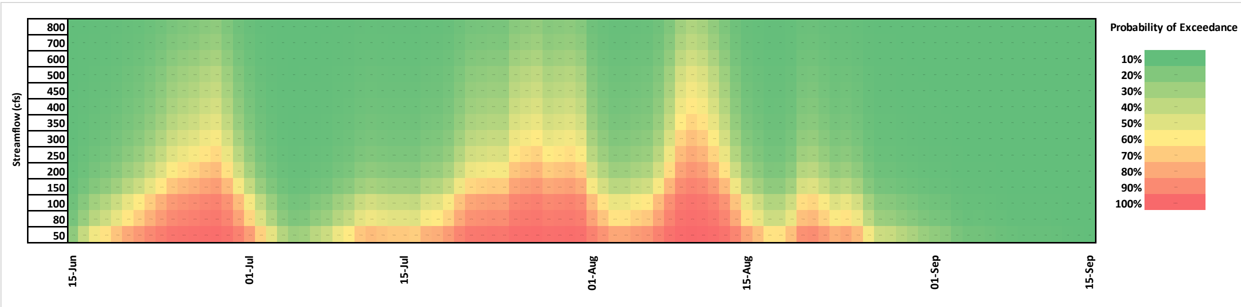

Figure 8. Logistic regression results for predicting the probability that water temperatures exceed 18.3 degrees Celsius as a function of observed 2015 air temperature and fixed flow rates in downtown Steamboat Springs.

The problems with linear model extrapolation partly motivated the development of the energy balance model. We used the parameterized model to predict the impact of increased streamflows or riparian shading on longitudinal (upstream-downstream) increases in stream temperature. Initially, we ran the model forward and increased flows out of Lake Catamount and, alternately, out of Fish Creek. We assumed that increases in flow did not alter the upstream water temperature boundary conditions at either location. Results indicated that increased flows at either location introduce sufficient thermal inertia into the system to somewhat limit downstream temperature increases. However, increased flows up to 150 cfs at Lake Catamount and 60 cfs on Fish Creek (when the temperature of those flows mirrored existing patterns of water temperature) were insufficient to meet stakeholder management targets (Figure 9, 10). As an alternative, we modified the amount of riparian shading in the model for reaches between Lake Catamount and the Fish Creek confluence to mimic a future 'best-case' scenario where revegetation and streambank restoration/management activities produce contiguous cottonwood galleries throughout these reaches (Figure 10). Increased riparian shading did achieve reductions in downstream warming, but of an insufficient degree to meet stakeholder management targets. Reduction of channel top-width dimensions in the model (as might be a goal of channel modification projects) did not result in lower water temperatures.

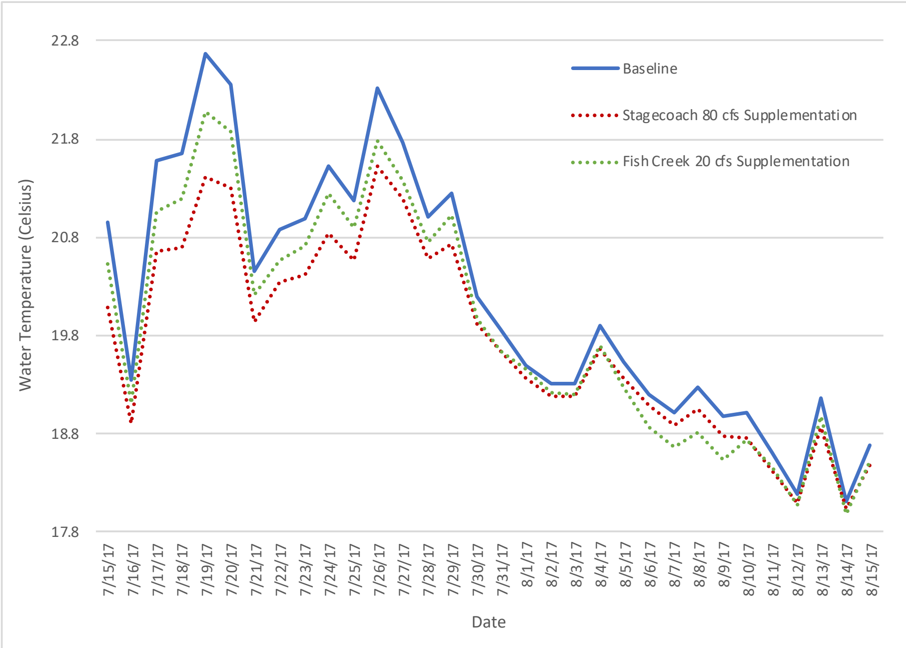

Figure 9. Energy balance modelling results for multiple management scenarios at the WWTP outfall.

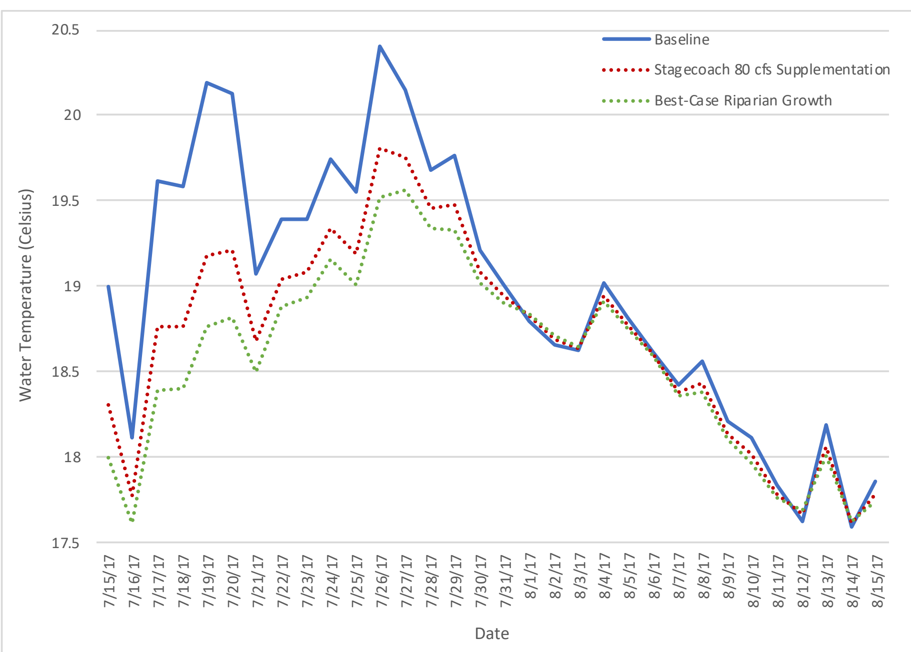

Figure 10. Energy balance modelling results for multiple scenarios at the Chuck Lewis SWA.

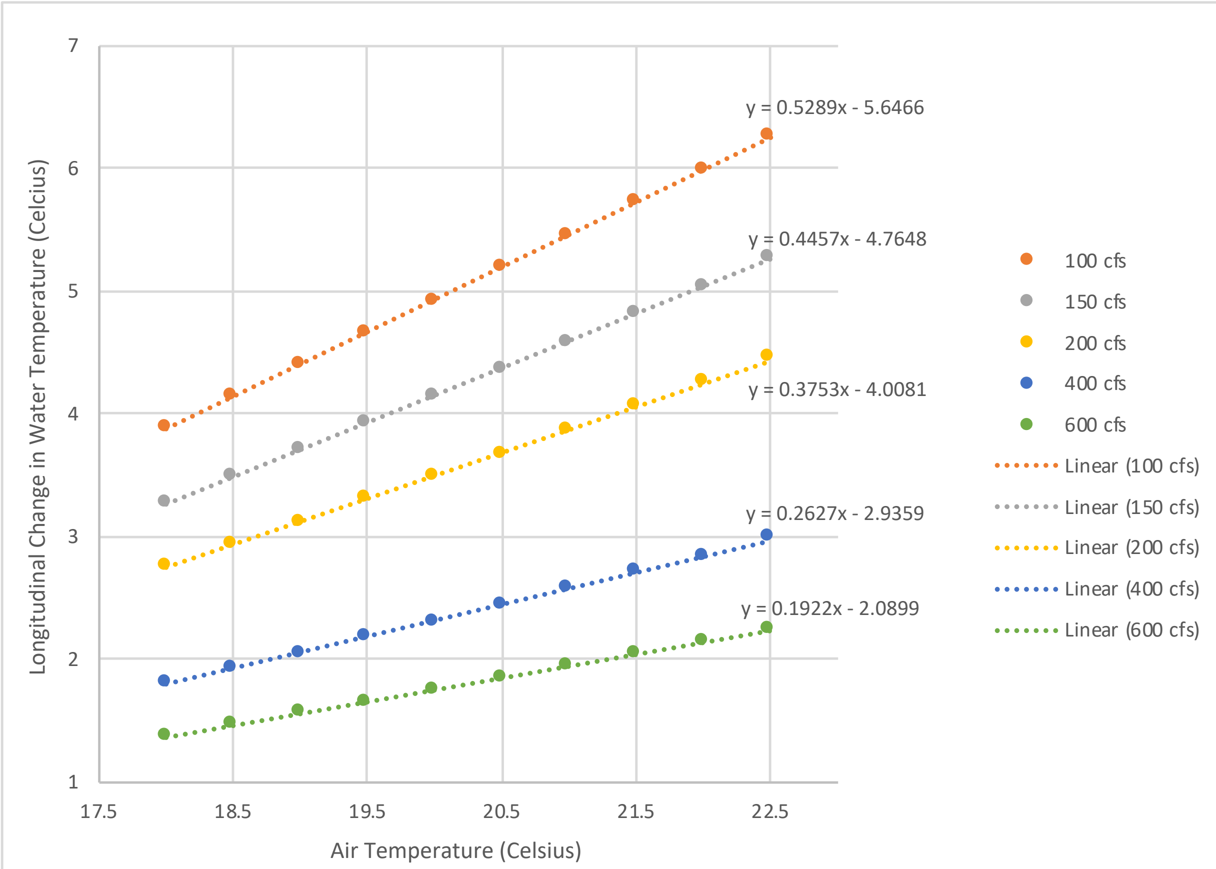

Figure 11. Changes in water temperature predicted by the energy balance model for the section of the Yampa River between Lake Catamount and the WWTP outfall as a function of air temperature and streamflow. All model runs performed with fixed atmospheric conditions (i.e. cloud cover, humidity, wind speed) and a constant upstream boundary water temperature of 17 degrees Celsius. Flatter slopes of high-flow lines indicate increased thermal inertia (resistance to heat gain) with increasing streamflows.

Subsequently, we ran the model forward with fixed atmospheric conditions and a moderately reduced constant temperature at the outlet of Lake Catamount, while varying air temperature and streamflow. We selected 17 degrees Celsius as our upstream boundary temperature as it seems that the most significant exceedances in water quality standards on downstream segments occur during periods (mid-July to mid-August) when the temperature of releases from Lake Catamount exceed this threshold (See Figure 1). Flows from Fish Creek were set to zero for these model runs. Results indicated that the combination of upstream water temperatures at 17 degrees and flows of 600 cfs may be ineffective at eliminating water temperature exceedances when average air temperatures exceed 19 degrees Celsius (Figure 11). While this outcome does not suggest flow-management is an ineffective tool for controlling water temperatures in the Yampa River at all times and under all conditions, it does suggest that the upstream boundary condition (i.e. water temperatures at Lake Catamount) represents a critical control on downstream temperature patterns.

We were somewhat surprised by these results but recognized the assumption that upstream boundary water temperatures do not change with changing discharge may be problematic. If we, therefore, assume a hypothetical case where minimum potential water temperature at the outlet of Lake Catamount is identical to typical summer water temperatures below Stagecoach Reservoir (Figure 13), then we can use a similar approach to that presented above to anticipate the impact of variable Lake Catamount release temperatures on water temperature on the Yampa River through Steamboat Springs. We ran the energy balance model forward with fixed atmospheric conditions and streamflows below Stagecoach Reservoir, while varying air temperature and the temperature of Stagecoach Reservoir releases. We selected 80 cfs as our upstream boundary streamflow condition as it is a typical flow observed at USGS 09237500 in late summer. Flows from Fish Creek were set to zero.

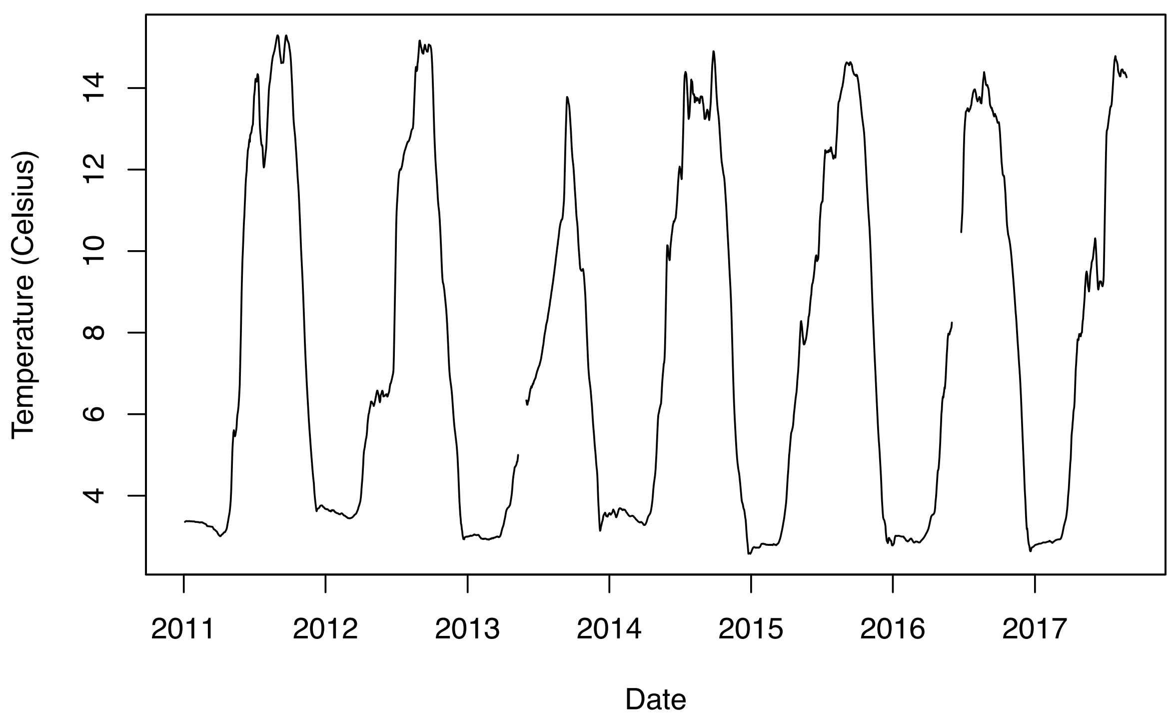

Figure 13. Weekly average water temperatures observed below Stagecoach Reservoir.

Model results showed a general insensitivity to changing upstream water temperature conditions. Modeled water temperatures at the WWTP were approximately equal, for each model run (and substantially higher than stated management targets), regardless of the boundary condition temperatures below Lake Catamount (Figure 14).

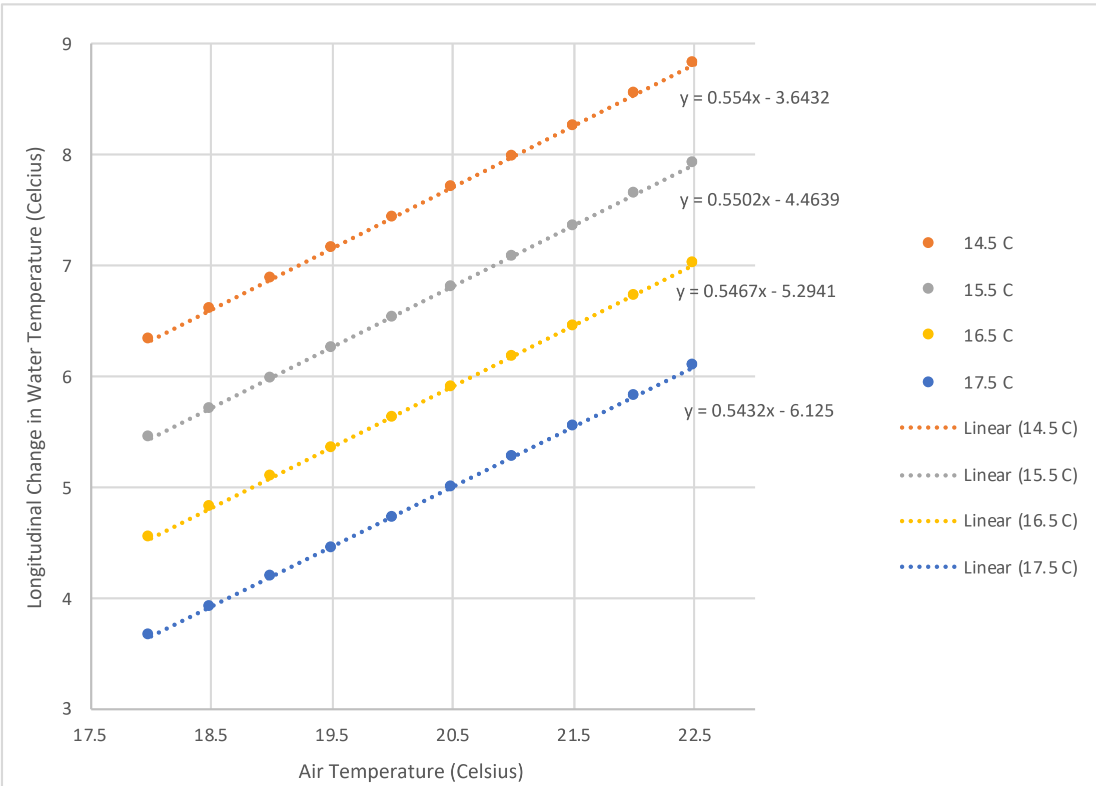

Figure 14. Changes in water temperature predicted by the energy balance model for the section of the Yampa River between Lake Catamount and the WWTP outfall as a function of air temperature and water temperatures below Lake Catamount between 14.5 and 17.5 degrees Celsius. All model runs performed with fixed atmospheric conditions (i.e. cloud cover, humidity, wind speed) and a constant upstream streamflow of 80 cfs.

Interactive effects of increased streamflow and decreased temperature were also tested in the model. These model runs showed some success at meeting management objectives across a range of air temperatures above Dougherty Road, but did not yield successful outcomes downstream at the WWTP outfall. Restricting the upper temperature of Lake Catamount releases to 17 degrees Celsius and increasing flows to 300 cfs reduced modeled temperature exceedances at Dougherty Road for air temperatures below 20 degrees Celsius, but not for warmer atmospheric conditions.

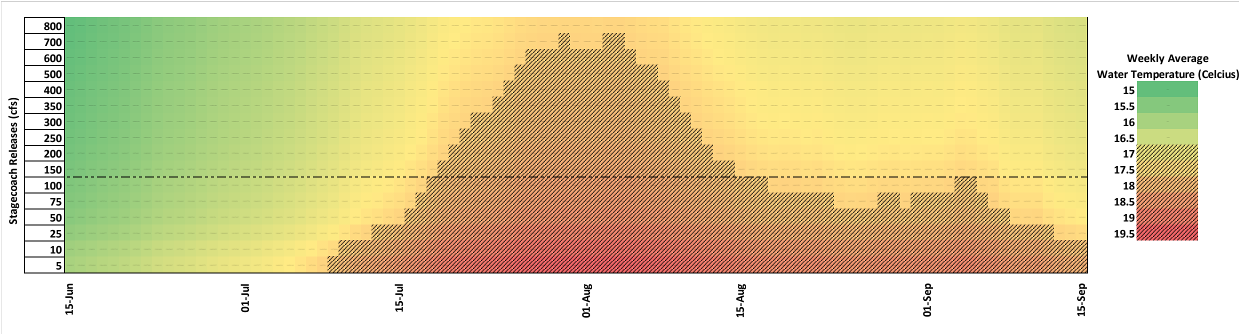

Figure 15. Multiple linear regression results predicting water temperatures below Lake Catamount as a function of air temperature and water releases from Stagecoach Reservoir. Dashed line indicates potential water temperature management threshold for keeping Lake Catamount releases below 17 degrees Celsius in late summer. Figure displays the fitted model predictions, not upper confidence or prediction intervals.

The outlet works at Stagecoach Reservoir can pull water from multiple layers in the water column. Therefore, it is not unreasonable to expect that some management of water temperatures at Lake Catamount can be achieved through active water temperature management at Stagecoach Reservoir. Insufficient data exists to examine the physical processes that would govern/limit this type of management strategy. However, application of our regression model for water temperature below Lake Catamount (Equation 1) allows us to use the limited data available to examine relationships between releases of water from Stagecoach Reservoir and water temperatures above Steamboat Springs. Using a typical pattern of air temperature—in this case, the time series from 2015—and by sequentially varying release rates from Stagecoach Reservoir, we used Equation 1 to predict changes on downstream water temperatures (Figure 15). Results suggest that for significant periods of the year (approx. mid-August to mid-September), flow releases of approximately 100 cfs may help keep temperatures at the Lake Catamount outlet below 17 degrees Celsius. During the hottest part of the summer (mid-July to mid-August), and the period when water temperatures in the Yampa River near Steamboat Springs most regularly exceed the stated management targets, the model indicates that significantly more water is required to reduce downstream temperatures. Once again, these predictions are extrapolations well beyond the observed conditions used to train the linear model and should, therefore, be treated with caution. It is also worth pointing out that streamflows were not found to be an extremely important driving variable for downstream water temperatures (see Figure 2 and accompanying discussion). Conversely, it is possible that complex non-linear effects exist between Stagecoach

Reservoir releases and temperatures in Lake Catamount and that better prediction models can be created following the procurement of additional data.

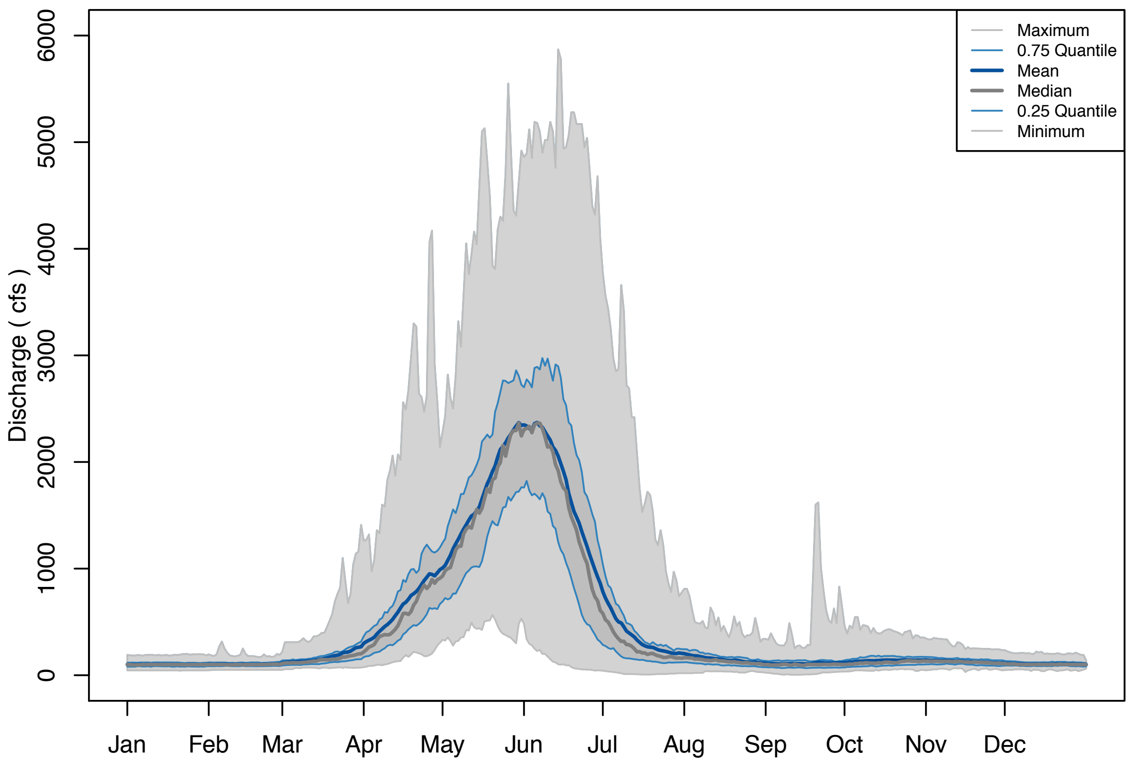

Figure 16. Historical hydrological regime behavior calculated from approximately 50 years of observed daily streamflows at USGS 09239500.

The significant flow seemingly required to mitigate elevated water temperatures on the Yampa River through Steamboat Springs presents several challenges. First securing releases of water of between 100 and 600 cfs may prove cost prohibitive. Second, significantly increasing late summer baseflows beyond the range of existing conditions (or the historical "natural" condition) may produce unintended consequences for other aspects of river health. For example, increasing late summer flows for extended periods may interfere with the environmental signals that some woody riparian species use to time seed dispersal. Elevated late-season flows may also scour bar surfaces home to new vegetative growth. In recognition of the importance of protecting the relatively unaltered hydrology in Yampa River through Steamboat Springs, stakeholders identified several measures of hydrological regime behavior as important river health management metrics. Specifically, stakeholders identified a target of no greater than 5% alteration above and/or below the 25th and 75th percentile of weekly average streamflows. Management actions or future water development projects projected to exceed this target should thus be flagged as problematic. While records at USGS 09239500 indicate that flows on the Yampa River between July and September have been significantly higher than the amount predicted to moderate water temperatures through Steamboat Springs (Figure 16), these conditions are well outside of the typical condition (i.e. 25th to 75th percentile daily flows). Therefore, if the City of Steamboat Springs and local stakeholders elect to manage conditions to produce large flow increases in the Yampa River, these activities should occur only infrequently so as not to alter 25th to 75th percentile annual 7-day minimum flows. Even if large flow increases are used infrequently, riparian and geomorphological conditions should be monitored carefully to identify undesirable shifts in behavior or condition.

Conclusion

Short-term water management options for mitigating stream temperatures on the Yampa River through Steamboat Springs appear limited to large releases of water from Stagecoach Reservoir and/or Fish Creek Reservoir. Further data collection and investigation into the thermal processes at work in Lake Catamount may indicate new opportunities or help refine predictions of the impacts of flow releases from Stagecoach Reservoir. While regular large-scale water releases over long periods of the summer may not be feasible (or even desirable if the potential unintended consequences are considered) smaller releases of water from Stagecoach Reservoir that keep flows in Steamboat Springs above 100 cfs do appear somewhat effective at reducing the likelihood of undesirable water temperature conditions during cooler atmospheric conditions in late August and early September. The lookup table provided below (Table 1) includes estimates of water temperature generated by fitting Equation 2 with synthetic air temperature values and a range of expected streamflow values for the summer months. This table can help inform managers about the effectiveness of modest streamflow supplementation efforts on the Yampa River. Efforts to increase riparian shading through passive land management or active streambank revegetation should yield stream temperature reduction benefits that, ultimately, make water management activities more effective at reducing peak water temperatures. It does not appear that channel modification efforts to reduce channel top-width will significantly alter patterns of water temperature.

Table 1. Water temperature predictions from Equation 1 using a synthetic air temperature profile and a range of possible streamflows for the late summer months. Estimates do not reflect the 95% confidence or prediction intervals that bound the fitted values.

Streamflow (cfs)	15-Jun	16-Jun	17-Jun	18-Jun	19-Jun	20-Jun	21-Jun	22-Jun	23-Jun	24-Jun	25-Jun	26-Jun	27-Jun	28-Jun	29-Jun	30-Jun	1-Jul	2-Jul	3-Jul	4-Jul	5-Jul	6-Jul	7-Jul	8-Jul	9-Jul	10-Jul	11-Jul	12-Jul	13-Jul	14-Jul	15-Jul
115	17.3	17.5	17.6	17.9	18.3	18.5	18.8	18.9	19.0	19.2	19.3	19.4	19.5	19.6	19.6	19.7	19.8	19.9	19.8	19.8	19.9	19.9	20.0	20.0	20.0	19.9	20.0	20.0	20.2	20.4	20.4
110	17.4	17.6	17.7	18.0	18.4	18.6	18.9	19.0	19.1	19.3	19.4	19.5	19.6	19.7	19.7	19.8	19.9	20.0	19.9	19.9	20.0	20.0	20.1	20.1	20.1	20.0	20.1	20.1	20.3	20.5	20.5
105	17.5	17.7	17.8	18.1	18.5	18.7	19.0	19.1	19.2	19.4	19.5	19.6	19.7	19.8	19.8	19.9	20.0	20.1	20.1	20.0	20.1	20.1	20.2	20.2	20.2	20.1	20.2	20.2	20.4	20.6	20.6
100	17.7	17.8	18.0	18.3	18.6	18.8	19.1	19.2	19.3	19.5	19.6	19.7	19.8	19.9	20.0	20.0	20.1	20.2	20.2	20.1	20.2	20.2	20.3	20.3	20.3	20.3	20.3	20.3	20.5	20.7	20.8
95	17.8	17.9	18.1	18.4	18.7	18.9	19.2	19.3	19.5	19.7	19.7	19.8	19.9	20.0	20.1	20.2	20.2	20.3	20.3	20.2	20.3	20.4	20.4	20.4	20.4	20.4	20.4	20.5	20.6	20.8	20.9
90	17.9	18.0	18.2	18.5	18.8	19.1	19.4	19.5	19.6	19.8	19.9	20.0	20.0	20.1	20.2	20.3	20.4	20.4	20.4	20.3	20.4	20.5	20.5	20.6	20.5	20.5	20.5	20.6	20.8	20.9	21.0
85	18.0	18.1	18.3	18.6	18.9	19.2	19.5	19.6	19.7	19.9	20.0	20.1	20.2	20.2	20.3	20.4	20.5	20.6	20.5	20.5	20.5	20.6	20.7	20.7	20.7	20.6	20.7	20.7	20.9	21.1	21.1
80	18.2	18.3	18.5	18.8	19.1	19.3	19.6	19.7	19.9	20.0	20.1	20.2	20.3	20.4	20.5	20.5	20.6	20.7	20.7	20.6	20.7	20.7	20.8	20.8	20.8	20.8	20.8	20.9	21.0	21.2	21.3
75	18.3	18.4	18.6	18.9	19.2	19.5	19.8	19.9	20.0	20.2	20.3	20.4	20.4	20.5	20.6	20.7	20.8	20.8	20.8	20.8	20.8	20.9	21.0	21.0	20.9	20.9	20.9	21.0	21.2	21.4	21.4
70	18.5	18.6	18.8	19.1	19.4	19.6	19.9	20.0	20.2	20.3	20.4	20.5	20.6	20.7	20.8	20.8	20.9	21.0	21.0	20.9	21.0	21.0	21.1	21.1	21.1	21.1	21.1	21.2	21.3	21.5	21.6
65	18.6	18.8	18.9	19.2	19.5	19.8	20.1	20.2	20.3	20.5	20.6	20.7	20.8	20.9	20.9	21.0	21.1	21.2	21.1	21.1	21.1	21.2	21.3	21.3	21.3	21.2	21.3	21.3	21.5	21.7	21.7
60	18.8	18.9	19.1	19.4	19.7	20.0	20.3	20.4	20.5	20.7	20.8	20.9	21.0	21.0	21.1	21.2	21.3	21.3	21.3	21.3	21.3	21.4	21.5	21.5	21.4	21.4	21.4	21.5	21.7	21.9	21.9
55	19.0	19.1	19.3	19.6	19.9	20.2	20.5	20.6	20.7	20.9	21.0	21.1	21.2	21.2	21.3	21.4	21.5	21.5	21.5	21.5	21.5	21.6	21.7	21.7	21.6	21.6	21.6	21.7	21.9	22.1	22.1
50	19.2	19.3	19.5	19.8	20.1	20.4	20.7	20.8	20.9	21.1	21.2	21.3	21.4	21.5	21.5	21.6	21.7	21.8	21.7	21.7	21.7	21.8	21.9	21.9	21.9	21.8	21.9	21.9	22.1	22.3	22.3

Streamflow (cfs)	15-Jul	16-Jul	17-Jul	18-Jul	19-Jul	20-Jul	21-Jul	22-Jul	23-Jul	24-Jul	25-Jul	26-Jul	27-Jul	28-Jul	29-Jul	30-Jul	31-Jul	1-Aug	2-Aug	3-Aug	4-Aug	5-Aug	6-Aug	7-Aug	8-Aug	9-Aug	10-Aug	11-Aug	12-Aug	13-Aug	14-Aug
115	20.4	20.5	20.6	20.6	20.7	20.7	20.6	20.6	20.6	20.7	20.7	20.7	20.6	20.4	20.4	20.4	20.4	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.4	20.4	20.4	20.3	20.2
110	20.5	20.6	20.7	20.7	20.8	20.8	20.7	20.7	20.7	20.8	20.8	20.8	20.7	20.5	20.5	20.5	20.5	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.5	20.5	20.5	20.4	20.3
105	20.6	20.7	20.8	20.8	20.9	20.9	20.8	20.8	20.8	20.9	20.9	20.9	20.8	20.6	20.7	20.6	20.6	20.7	20.7	20.7	20.7	20.7	20.7	20.7	20.7	20.7	20.6	20.6	20.6	20.5	20.4
100	20.8	20.9	20.9	20.9	21.0	21.0	20.9	20.9	20.9	21.0	21.0	21.0	20.9	20.8	20.8	20.7	20.7	20.8	20.8	20.8	20.8	20.8	20.8	20.8	20.8	20.8	20.8	20.7	20.7	20.6	20.5
95	20.9	21.0	21.0	21.1	21.1	21.1	21.0	21.0	21.1	21.1	21.1	21.1	21.0	20.9	20.9	20.9	20.9	20.9	20.9	21.0	20.9	20.9	20.9	20.9	20.9	20.9	20.9	20.9	20.8	20.8	20.6
90	21.0	21.1	21.1	21.2	21.2	21.2	21.1	21.2	21.2	21.2	21.2	21.2	21.1	21.0	21.0	21.0	21.0	21.0	21.1	21.1	21.1	21.1	21.1	21.0	21.0	21.0	21.0	21.0	21.0	20.9	20.7
85	21.1	21.2	21.3	21.3	21.3	21.4	21.3	21.3	21.3	21.3	21.4	21.4	21.2	21.1	21.1	21.1	21.1	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.1	21.1	21.1	21.1	21.0	20.9
80	21.3	21.4	21.4	21.4	21.5	21.5	21.4	21.4	21.5	21.5	21.5	21.5	21.4	21.3	21.3	21.2	21.3	21.3	21.3	21.3	21.3	21.3	21.3	21.3	21.3	21.3	21.3	21.2	21.2	21.1	21.0
75	21.4	21.5	21.6	21.6	21.6	21.6	21.5	21.6	21.6	21.6	21.6	21.7	21.5	21.4	21.4	21.4	21.4	21.4	21.5	21.5	21.5	21.5	21.5	21.5	21.4	21.4	21.4	21.4	21.4	21.3	21.1
70	21.6	21.7	21.7	21.7	21.8	21.8	21.7	21.7	21.8	21.8	21.8	21.8	21.7	21.6	21.6	21.5	21.6	21.6	21.6	21.6	21.6	21.6	21.6	21.6	21.6	21.6	21.6	21.5	21.5	21.4	21.3
65	21.7	21.8	21.9	21.9	22.0	22.0	21.9	21.9	21.9	21.9	22.0	22.0	21.9	21.7	21.7	21.7	21.7	21.8	21.8	21.8	21.8	21.8	21.8	21.8	21.8	21.8	21.7	21.7	21.7	21.6	21.5
60	21.9	22.0	22.1	22.1	22.1	22.1	22.1	22.1	22.1	22.1	22.2	22.2	22.0	21.9	21.9	21.9	21.9	21.9	22.0	22.0	22.0	22.0	22.0	22.0	21.9	21.9	21.9	21.9	21.9	21.8	21.6
55	22.1	22.2	22.3	22.3	22.3	22.3	22.2	22.3	22.3	22.3	22.3	22.4	22.2	22.1	22.1	22.1	22.1	22.1	22.2	22.2	22.2	22.2	22.2	22.2	22.1	22.1	22.1	22.1	22.1	22.0	21.8
50	22.3	22.4	22.5	22.5	22.5	22.6	22.5	22.5	22.5	22.5	22.6	22.6	22.4	22.3	22.3	22.3	22.3	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.3	22.3	22.3	22.3	22.2	22.1

Streamflow (cfs)	15-Aug	16-Aug	17-Aug	18-Aug	19-Aug	20-Aug	21-Aug	22-Aug	23-Aug	24-Aug	25-Aug	26-Aug	27-Aug	28-Aug	29-Aug	30-Aug	31-Aug	1-Sep	2-Sep	3-Sep	4-Sep	5-Sep	6-Sep	7-Sep	8-Sep	9-Sep	10-Sep	11-Sep	12-Sep	13-Sep	14-Sep
115	19.9	19.7	19.6	19.6	19.5	19.5	19.5	19.6	19.5	19.3	19.2	19.1	19.0	18.9	18.8	18.7	18.6	18.6	18.5	18.4	18.1	17.9	17.8	17.7	17.6	17.4	17.2	17.1	17.0	16.7	16.3
110	20.0	19.8	19.7	19.7	19.6	19.6	19.6	19.7	19.6	19.4	19.3	19.2	19.1	19.0	18.9	18.8	18.7	18.7	18.6	18.5	18.2	18.0	17.9	17.8	17.7	17.5	17.3	17.2	17.1	16.8	16.4
105	20.1	19.9	19.8	19.8	19.7	19.7	19.7	19.8	19.7	19.5	19.4	19.3	19.2	19.1	19.0	18.9	18.8	18.8	18.7	18.6	18.3	18.1	18.0	17.9	17.8	17.6	17.4	17.4	17.2	16.9	16.5
100	20.2	20.0	19.9	19.9	19.8	19.8	19.8	19.9	19.8	19.6	19.6	19.4	19.3	19.2	19.1	19.0	19.0	18.9	18.8	18.7	18.4	18.2	18.1	18.0	17.9	17.7	17.6	17.5	17.3	17.0	16.6
95	20.3	20.1	20.1	20.0	20.0	19.9	19.9	20.0	20.0	19.7	19.7	19.5	19.4	19.4	19.2	19.1	19.1	19.0	18.9	18.8	18.5	18.3	18.2	18.1	18.0	17.9	17.7	17.6	17.4	17.2	16.8
90	20.4	20.3	20.2	20.1	20.1	20.0	20.1	20.2	20.1	19.8	19.8	19.7	19.5	19.5	19.3	19.3	19.2	19.1	19.1	18.9	18.6	18.5	18.4	18.2	18.2	18.0	17.8	17.7	17.6	17.3	16.9
85	20.6	20.4	20.3	20.2	20.2	20.2	20.2	20.3	20.2	20.0	19.9	19.8	19.7	19.6	19.5	19.4	19.3	19.3	19.2	19.0	18.7	18.6	18.5	18.4	18.3	18.1	17.9	17.8	17.7	17.4	17.0
80	20.7	20.5	20.4	20.4	20.3	20.3	20.3	20.4	20.3	20.1	20.1	19.9	19.8	19.7	19.6	19.5	19.5	19.4	19.3	19.2	18.9	18.7	18.6	18.5	18.4	18.3	18.1	18.0	17.8	17.5	17.2
75	20.9	20.7	20.6	20.5	20.5	20.5	20.5	20.6	20.5	20.3	20.2	20.1	20.0	19.9	19.7	19.7	19.6	19.5	19.5	19.3	19.0	18.9	18.8	18.7	18.6	18.4	18.2	18.1	18.0	17.7	17.3
70	21.0	20.8	20.8	20.7	20.7	20.6	20.6	20.7	20.6	20.4	20.4	20.2	20.1	20.1	19.9	19.8	19.8	19.7	19.6	19.5	19.2	19.0	18.9	18.8	18.7	18.6	18.4	18.3	18.1	17.8	17.5
65	21.2	21.0	20.9	20.9	20.8	20.8	20.8	20.9	20.8	20.6	20.5	20.4	20.3	20.2	20.1	20.0	19.9	19.9	19.8	19.6	19.3	19.2	19.1	19.0	18.9	18.7	18.5	18.4	18.3	18.0	17.6
60	21.4	21.2	21.1	21.0	21.0	21.0	21.0	21.1	21.0	20.8	20.7	20.6	20.5	20.4	20.2	20.2	20.1	20.0	20.0	19.8	19.5	19.4	19.3	19.2	19.1	18.9	18.7	18.6	18.5	18.2	17.8
55	21.6	21.4	21.3	21.2	21.2	21.2	21.2	21.3	21.2	21.0	20.9	20.8	20.7	20.6	20.4	20.4	20.3	20.2	20.2	20.0	19.7	19.6	19.5	19.4	19.3	19.1	18.9	18.8	18.7	18.4	18.0
50	21.8	21.6	21.5	21.5	21.4	21.4	21.4	21.5	21.4	21.2	21.1	21.0	20.9	20.8	20.7	20.6	20.5	20.5	20.4	20.2	19.9	19.8	19.7	19.6	19.5	19.3	19.1	19.0	18.9	18.6	18.2

Unfortunately, this investigation did not identify a panacea for controlling water temperatures in the way desired by local stakeholders. However, this assessment does implicate other management objectives identified by stakeholders. Specifically, results raise important questions about the appropriateness of existing water quality standards for water temperature on this section of the Yampa River and may be useful in future discussions and regulatory hearings with the Water Quality Control Division/Commission. Modeling outcomes also suggest that the most cost-effective approaches to managing ecological conditions to benefit the local fishery may involve increases in habitat/network connectivity and invasive species control. Ultimately, longer data records of water temperature at locations monitored historically by CPW and the City of Steamboat Springs and additional thermal and topographic data for Lake Catamount may help refine the predictive models presented here and may help identify unique opportunities for reducing summer temperatures in the reach of the Yampa River above Walton Creek.

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