Interactions Between Streamflow and Air Temperature Drive Spatial and Temporal Stream Temperature Patterns

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CLARK FORK COALITION

IWRRI Idaho Water Resources Research Institute

USDA

BOISE STATE UNIVERSITY

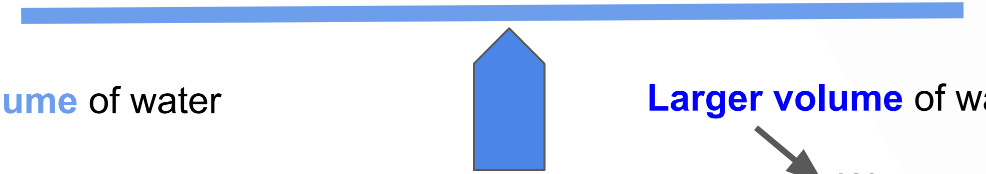
MONTANA STATE UNIVERSITY

Ecosystem Sciences Foundation

Low Flows and High Temperatures are Common

Streamflow and Stream Temperature*

Less flow | **More flow**



Less flow

Smaller volume of water

Water warms up **faster**

Water moves slower

Warming occurs over a **shorter distance**

More flow

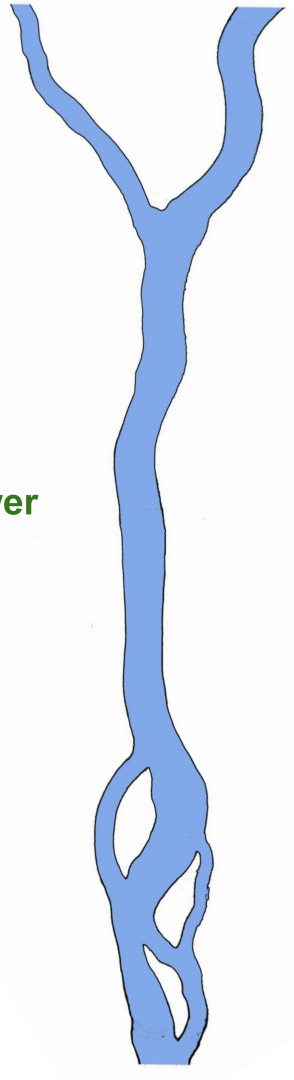
Larger volume of water

Water warms up **slower**

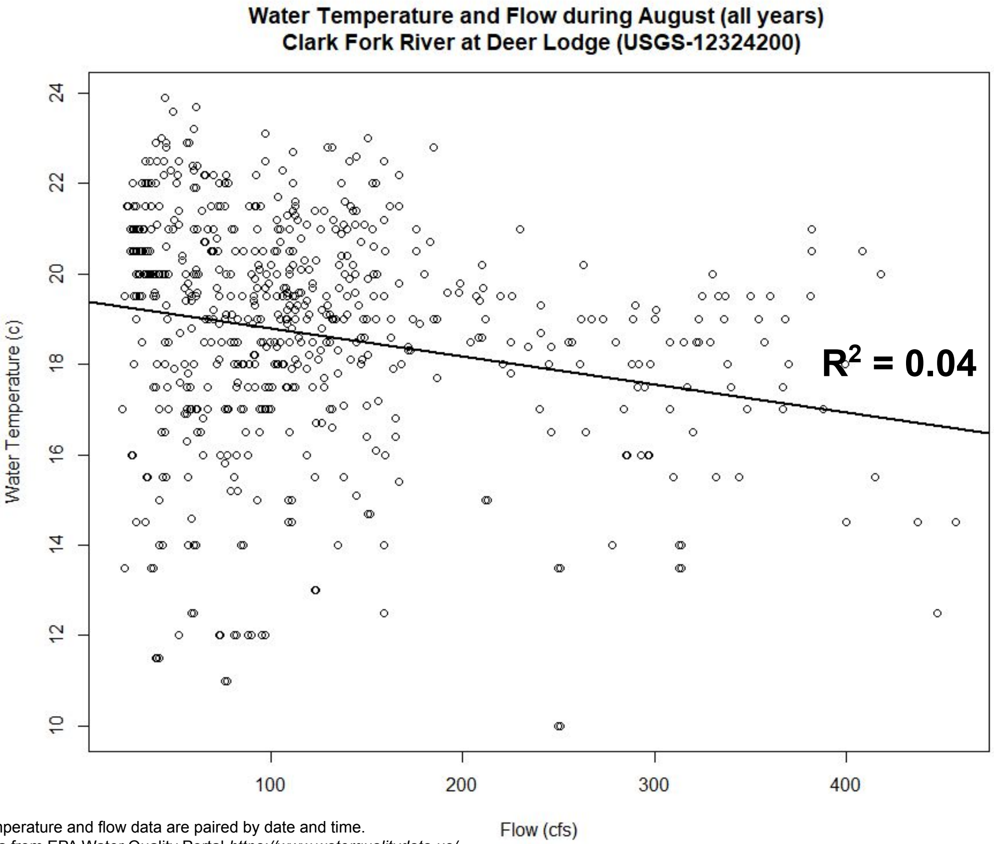
Water moves faster

Warming takes a **longer distance**

** Summertime context, where colder, upwelling groundwater warms with exposure to surface conditions*

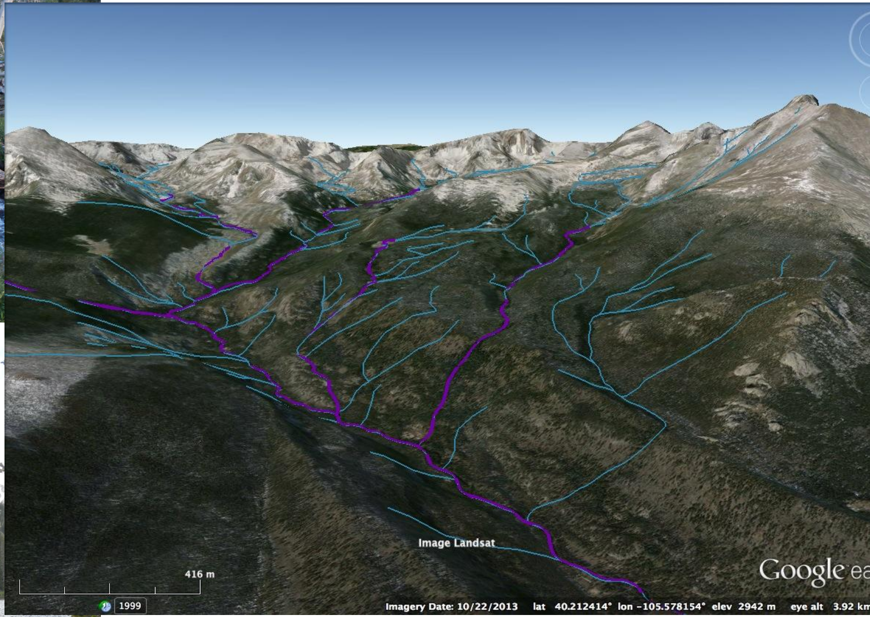


Relationship Between Flow and Temperature?



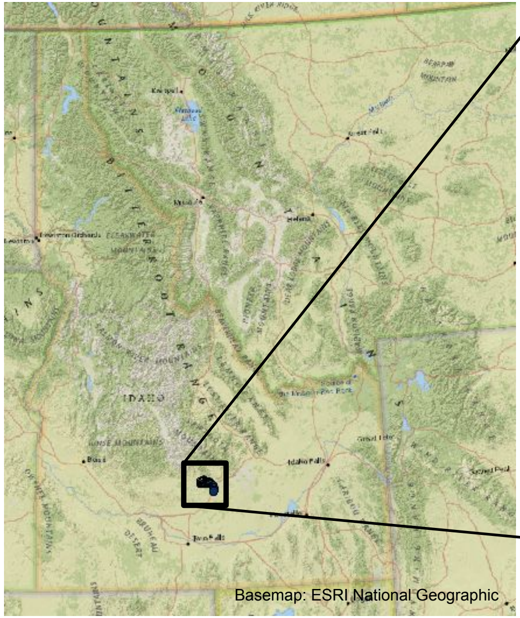
Temperature and flow data are paired by date and time.
Data from EPA Water Quality Portal *https://www.waterqualitydata.us/*

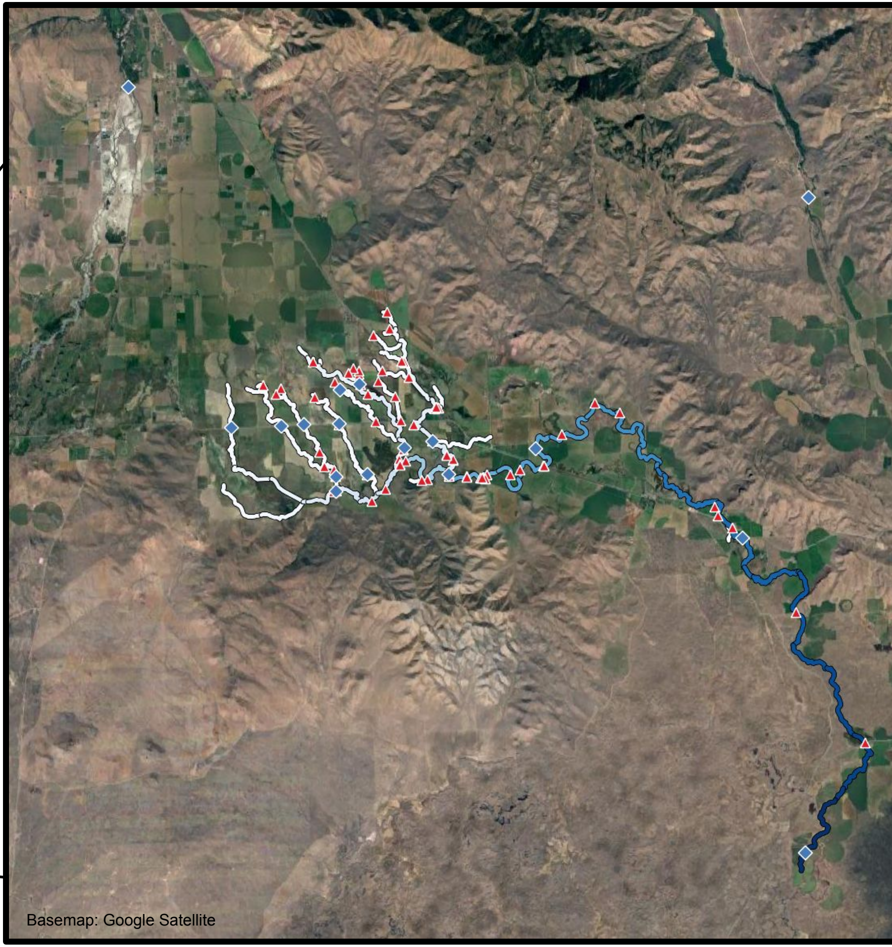
Why Does This Simple Model Fail?



Silver Creek, Idaho

- Lots of temperature and flow data!
- Summer hydrology dominated by headwater springs

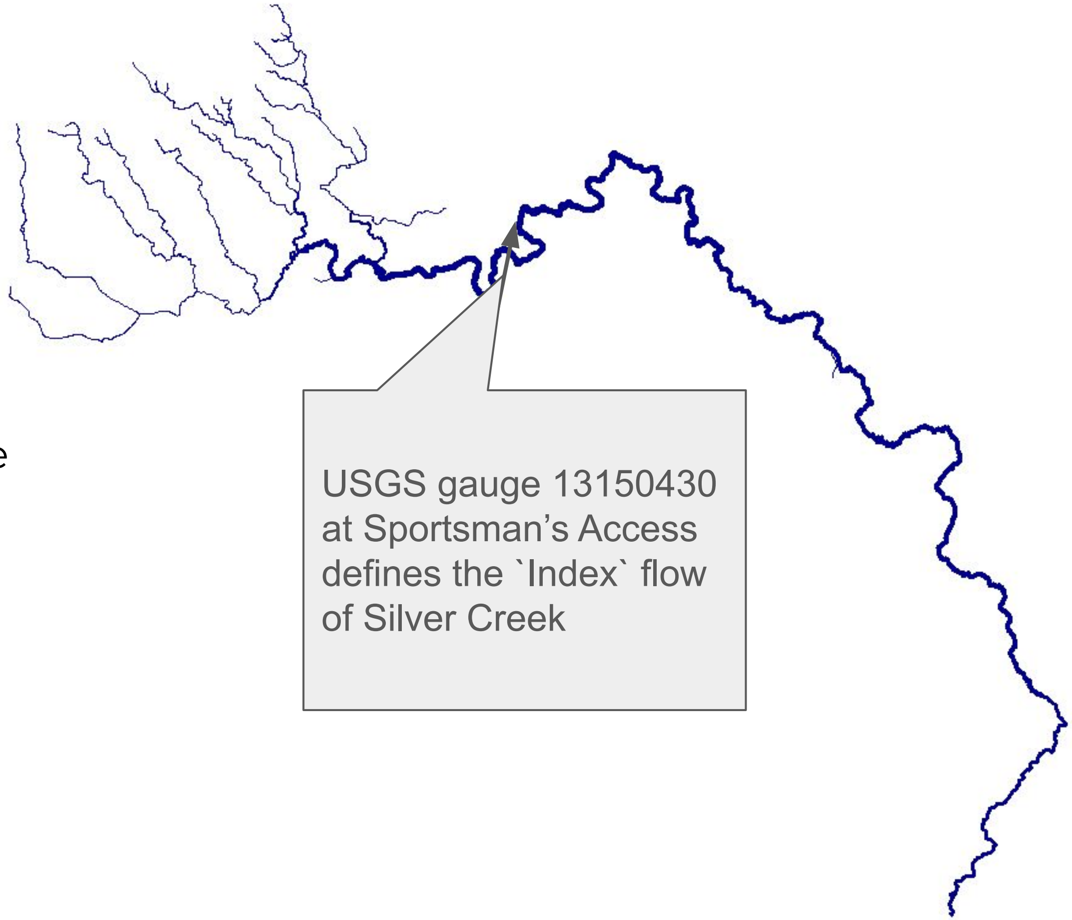




Modeling Streamflow Across Silver Creek

- Flow for each segment of Silver Creek segment is modeled with:
  - Number of tributaries (headwater springs)
  - Drainage area
  - Index flow at USGS gauge

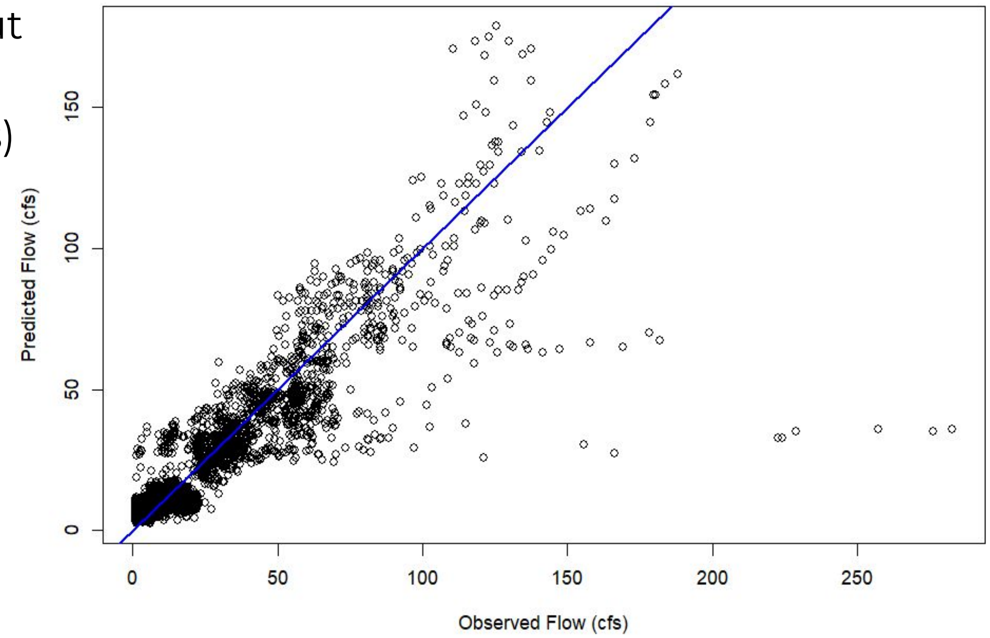
- The distribution of flow across Silver Creek varies with the index flow
  - During lower index flows, the water is skewed higher in the network



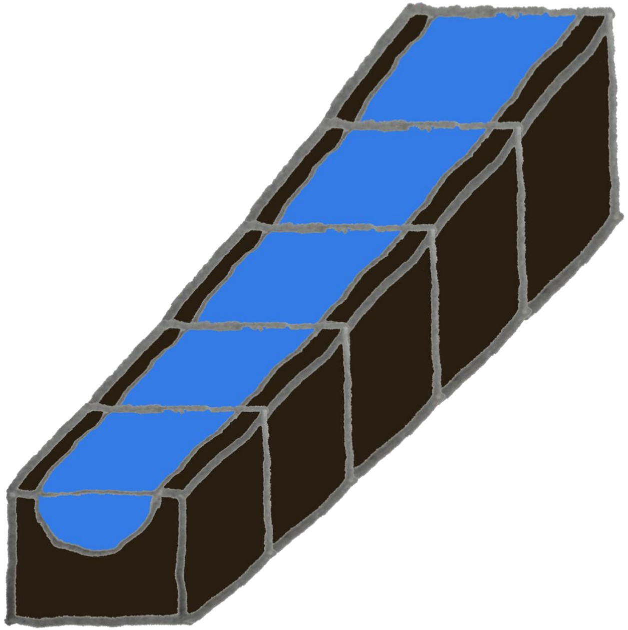
Modeling Streamflow Across Silver Creek

- The streamflow model explains about 82% of the observed variation in summer flow (~6000 measurements)

- These results are affected by irrigation withdrawals, which are an important manipulation of the system, but are not an explicit component of this model.



Flow and Temperature Across Space and Time



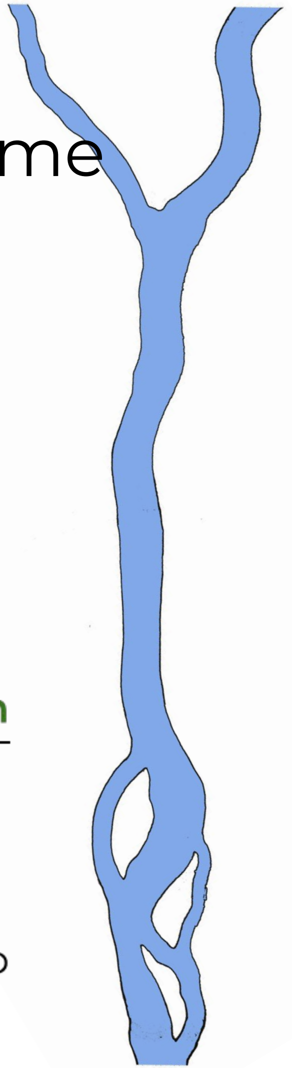
- Longer **distance** = more potential for warming

- Higher **flow** = higher water velocity, stretching warming across space, **and** greater volume, distributing warming across more water

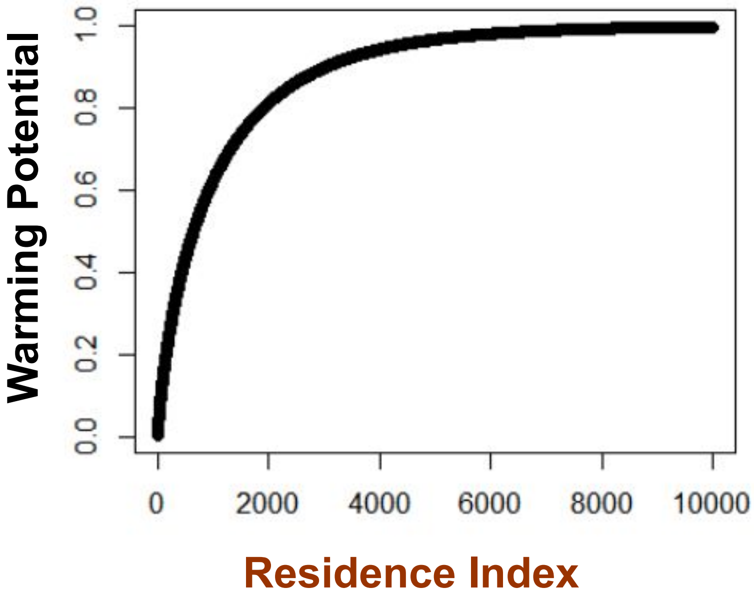
- We represent these effects as:

$$\textbf{Residence Index (RI)} = \frac{\textbf{Segment Length}}{\textbf{Segment Flow}}$$

- **Residence Index** accumulates in a downstream direction, with upstream segments contributing in proportion to

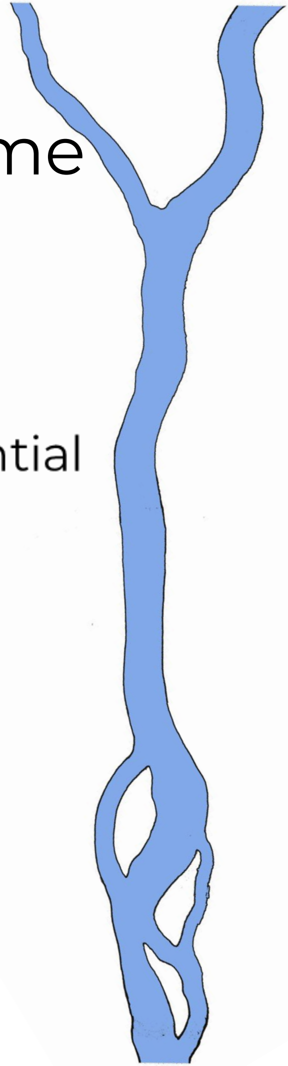


Stream Temperature Across Space and Time



The residence index is used in a fitted saturation function to approximate the warming potential due to surface exposure:

$$1 - e^{a * RI^{b}}$$



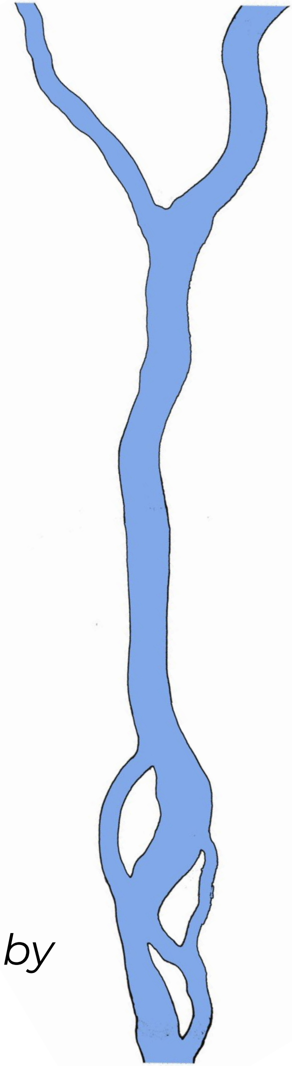
Stream Temperature Model

$$\text{Maximum Stream Temperature} = T_{gw} + \left(1 - e^{a * RI\, b}\right) * c * E_{sun} * T_{air}$$

Warming Potential

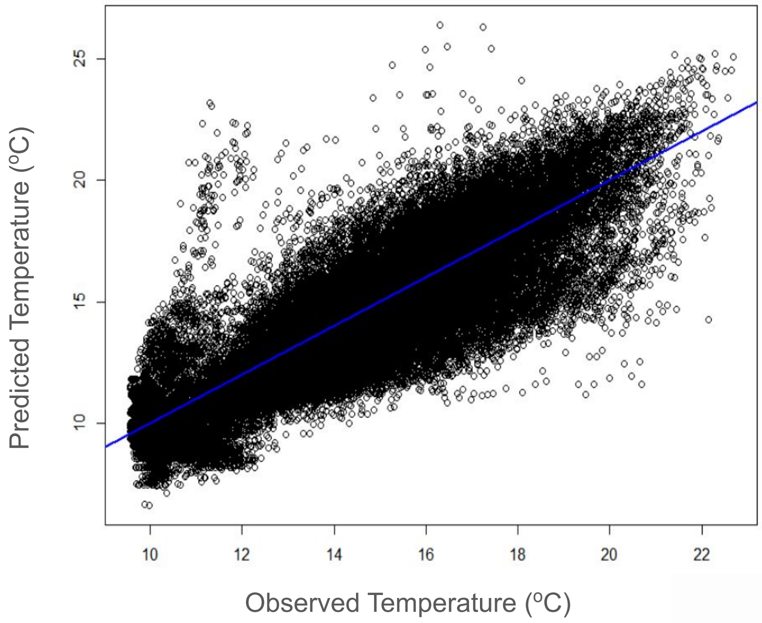
- T_{gw} is the fitted intercept representing groundwater temperature
- E_{sun} is the maximum sun elevation (indicates day length)
- T_{air} is the air temperature
- **RI** is the residence index (used to determine the warming potential)
- a, b, and c are fitted terms

This model describes the warming from T_{gw} towards T_{air} as mediated by RI and day length



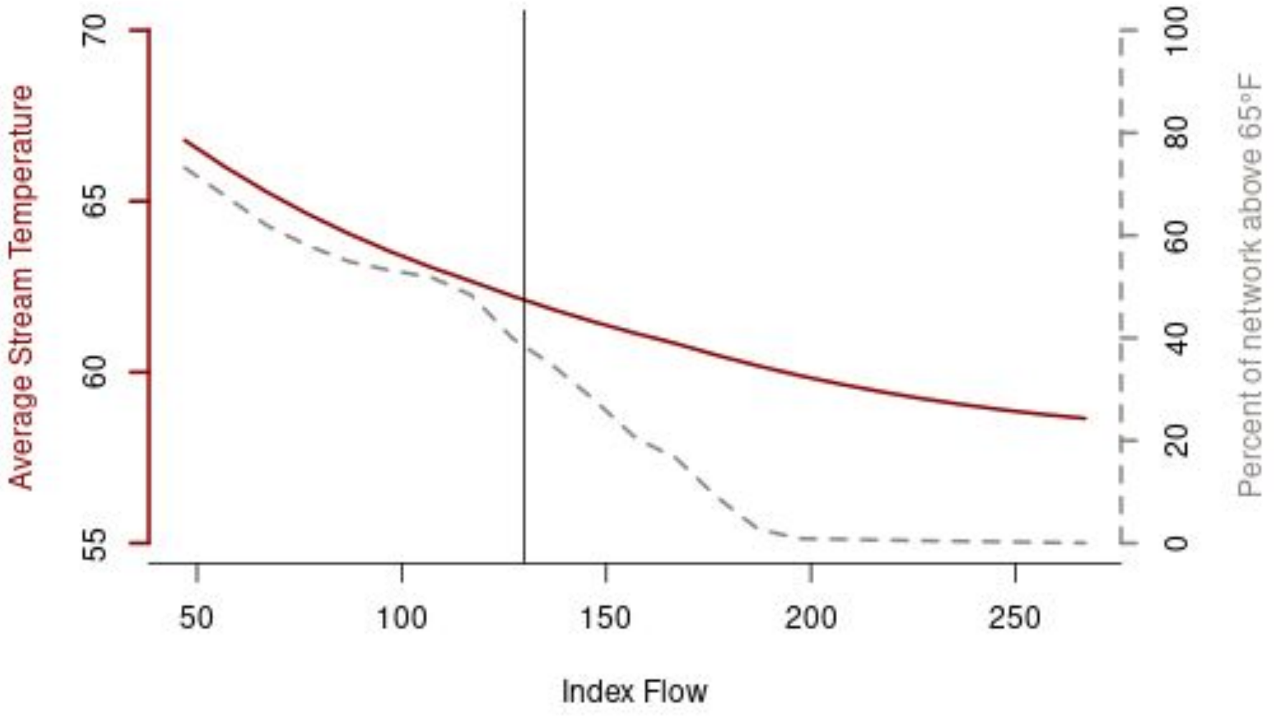
Stream Temperature Model Performance

This model explains 76% of the observed variation in summertime maximum Silver Creek stream temperatures across ~50,000 measurements



Stream Temperature Model Results

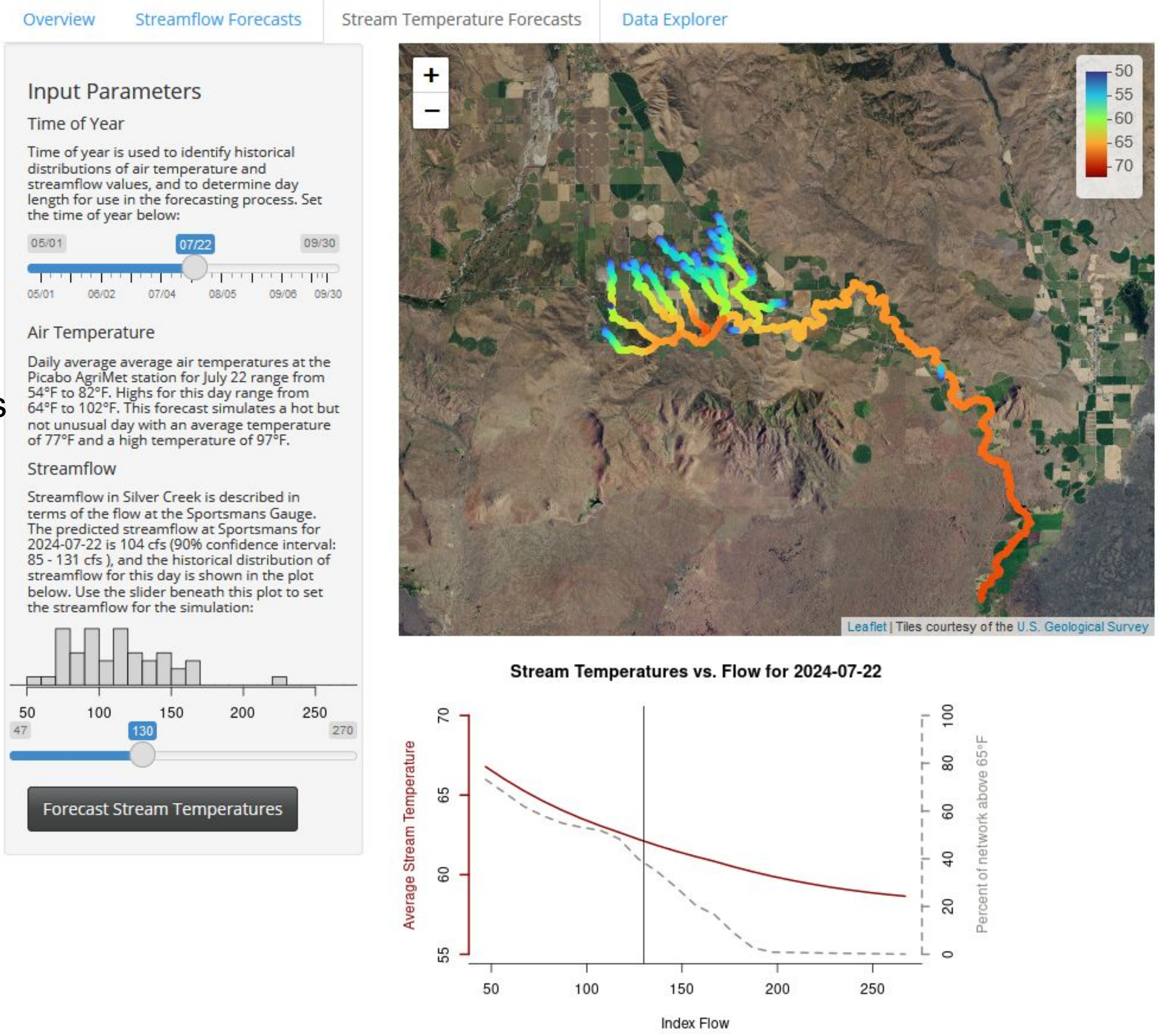
In an exploratory capacity, this model can be used to consider the effects of streamflow on the patterns of stream temperature

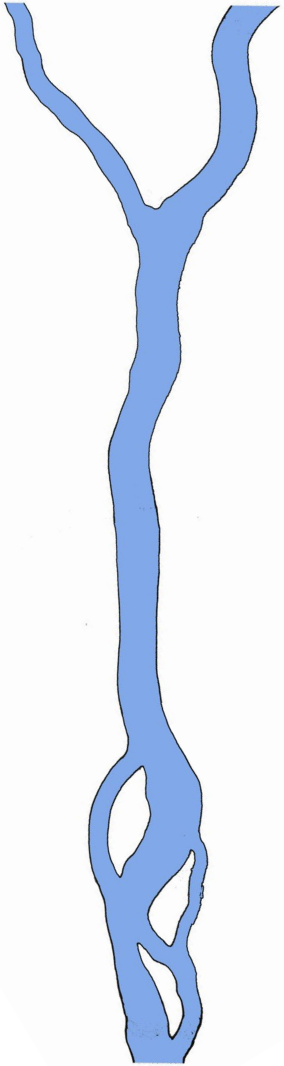


High Flow Scenario (130 cfs)

Avg Temperature: 62°F

38% of the network is above 65°F





Medium Flow Scenario (104 cfs)

Avg Temperature: 63.5°F

52% of the network is above 65°F

Overview | Streamflow Forecasts | Stream Temperature Forecasts | Data Explorer

Input Parameters

Time of Year

Time of year is used to identify historical distributions of air temperature and streamflow values, and to determine day length for use in the forecasting process. Set the time of year below:

05/01 — 07/22 — 09/30

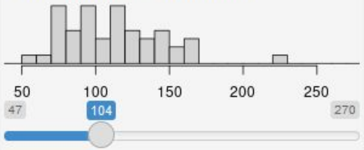
05/01 06/02 07/04 08/05 09/06 09/30

Air Temperature

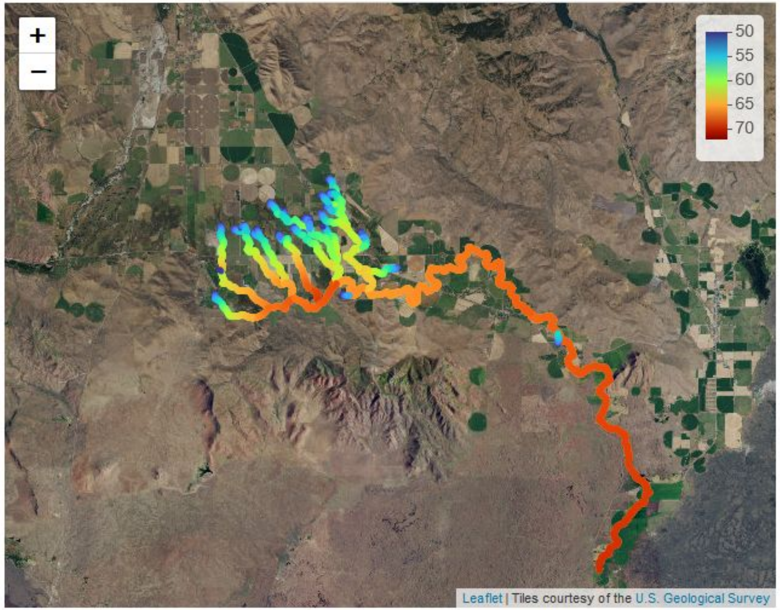
Daily average average air temperatures at the Picabo AgriMet station for July 22 range from 54°F to 82°F. Highs for this day range from 64°F to 102°F. This forecast simulates a hot but not unusual day with an average temperature of 77°F and a high temperature of 97°F.

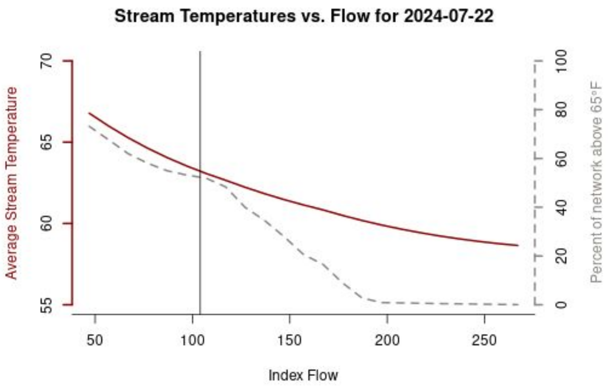
Streamflow

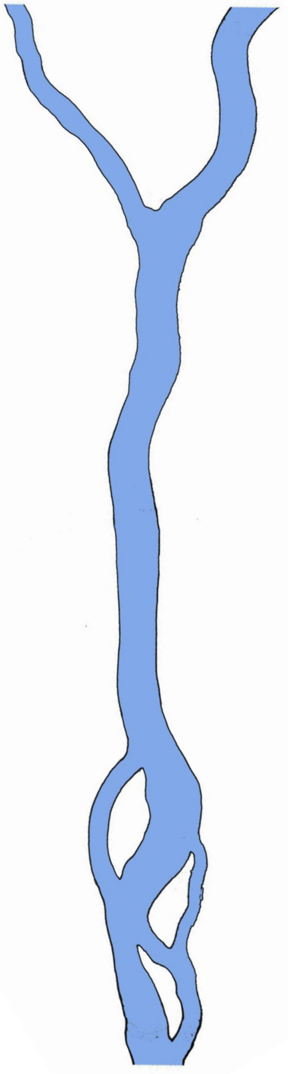
Streamflow in Silver Creek is described in terms of the flow at the Sportsmans Gauge. The predicted streamflow at Sportsmans for 2024-07-22 is 104 cfs (90% confidence interval: 85 - 131 cfs), and the historical distribution of streamflow for this day is shown in the plot below. Use the slider beneath this plot to set the streamflow for the simulation:



Forecast Stream Temperatures







Overview | Streamflow Forecasts | Stream Temperature Forecasts | Data Explorer

Low Flow Scenario (80 cfs)

Avg Temperature: 64.5°F

56% of the network is above 65°F

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05/01 — 07/22 — 09/30

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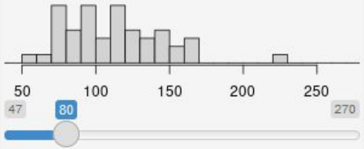

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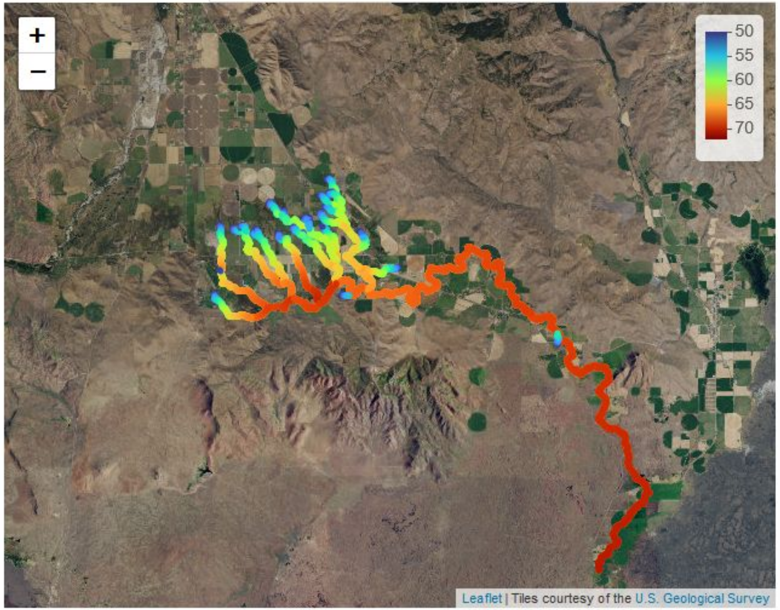
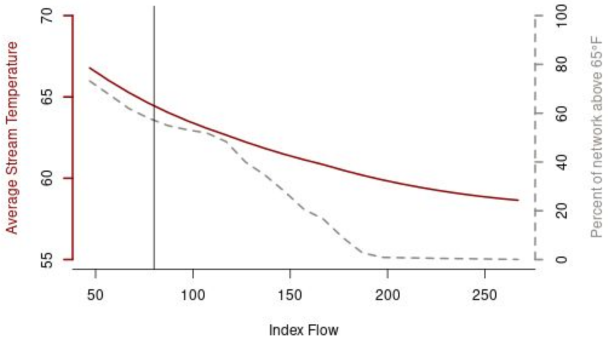
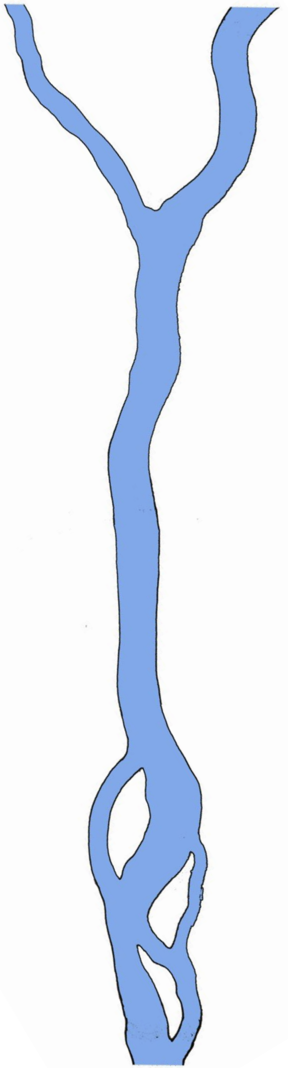
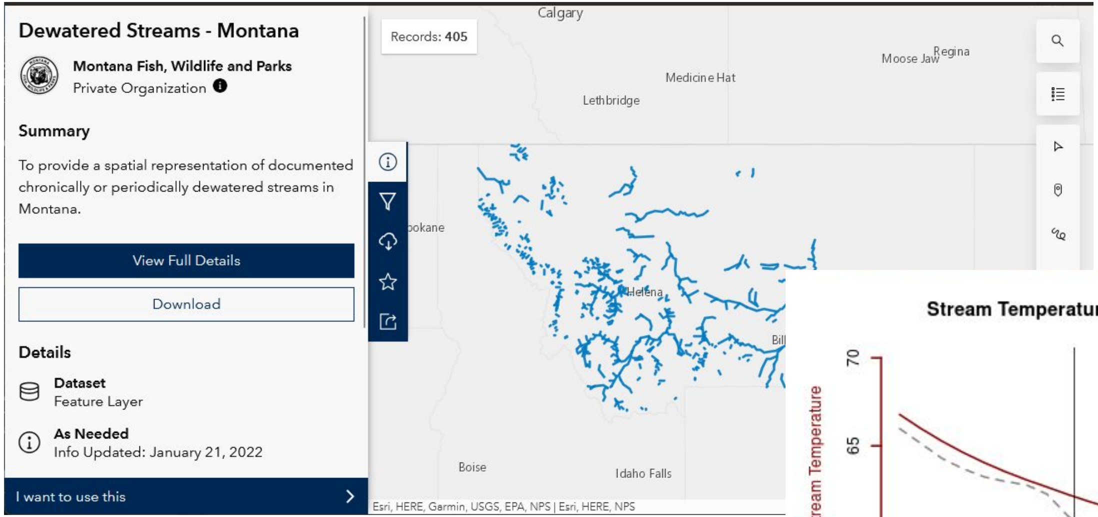
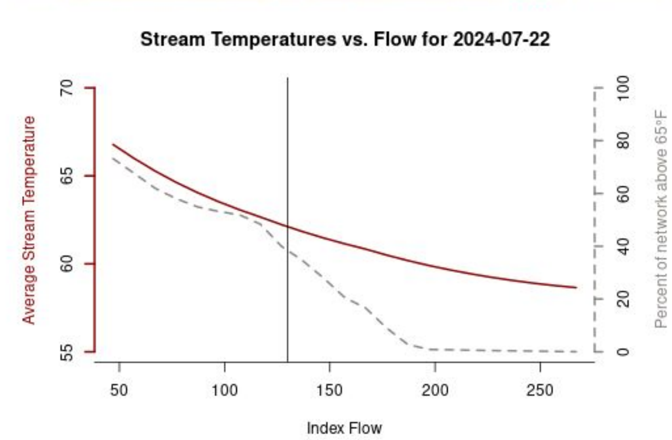


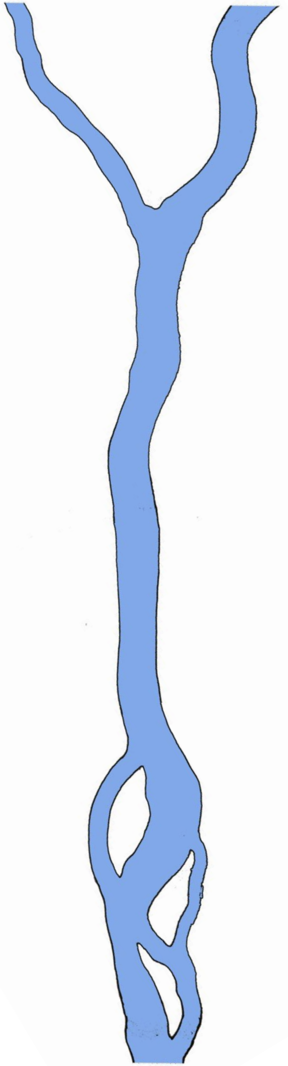




Implications for Montana’s Dewatered Streams?







Thanks!

Contact: scarlson@clarkfork.org

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Flow Model Details

We model the distribution of flow across Silver Creek relative to the measured flow at the Sportsmans Access gauge, which we term the 'index flow' (Q_{index}). The fraction of Q_{index} associated with each reach r can then calculated as the ratio of the flow of that reach (Q_r) to Q_{index}:

$$QF_r = \frac{Q_r}{Q_{index}}. \tag{1}$$

For each day of flow data, a QF_r is calculated for each measured reach from the daily average Q_{index} and Q_r. We then model the calculated QF_r values as:

$$\begin{aligned} QF_r = &-0.37 + 0.074 \cdot n_{trib} + 0.0023 \cdot Q_{index} - 0.00025 \cdot n_{trib} \cdot Q_{index} \\ &-0.5 \cdot W_r - 3.8 \cdot W_r^2 + 0.26 \cdot W_r \cdot Q_{index} - 0.018 \cdot W_r^2 \cdot Q_{index} . \end{aligned} \tag{2}$$

Equation 2 describes QF_r as a function of the number of tributaries draining to reach r (n_{trib}), the area of the watershed draining to reach r (W_r, km^2), and the streamflow at the Sportsmans Access gauge (Q_{index}, cfs), and explains 82% of the observed variation in QF_r across 6195 observations of flow spanning the summer months (June - September) of 2015 to 2022 at 14 locations within the Silver Creek Network. As fitted, this equation indicates each tributary contributes a constant portion of the Q_{index}, cfs flow to the network, that watershed area has a non-linear relationship with QF_r, and that this non-linear relationship changes with the Q_{index} value. At low Q_{index} values, this equation suggests that increases in watershed area correspond with increases in flow for small watershed areas (i.e., smaller reaches tend to be gaining reaches), but that this relationship reverses for larger watershed areas (i.e., larger reaches tend to be losing reaches). However this pattern moderates at higher Q_{index} values, where all reaches tend to become gaining reaches.

Temperature Model Details

The distribution of flow across Silver Creek is used to calculate the 'Specific Residence' of each reach r at any Q_{index} as:

$$SR_r = \frac{L_r}{QF_r \cdot Q_{index}}, \quad (3)$$

where L_r is the length of reach r (feet), and $QF_r \cdot Q_{index}$ determines the flow of reach r. This 'Specific Residence' describes the length of channel per unit flow in each reach, and can therefore be used as a relative indicator of the amount of atmospheric exposure experienced by each unit of water. The cumulative SR_r (SR_c) for any location on Silver Creek is calculated from the headwaters down by accumulating individual upstream reaches SR values, and taking a flow-weighted average of upstream SR values at tributary junctions. Because SR_r values are influenced by Q_{index} and QF_r values, SR_c varies with flow conditions.

Consistent with the idea that stream temperatures begin at groundwater temperature and warm toward the air temperature with increasing exposure to the atmosphere, daily mean stream temperatures are modeled as:

$$T_{mean} = 9.5 + 0.0079 \cdot E_{sun} \cdot airT_{mean} \cdot \left(1 - e^{-0.0048 \cdot SR_c^{0.77}}\right), \quad (4)$$

where T_{mean} is the daily mean stream temperature, E_{sun} is the maximum angle of the sun above the horizon, $airT_{mean}$ is the daily mean air temperature, and SR_c indicates the degree of atmospheric exposure experienced by each unit of water. The parenthetical portion of equation 4 describes a saturation of the SR_c effect. As SR_c increases, the value of this portion of the equation approaches (but does not exceed) 1. Thus, this equation describes an asymptotic increase from a constant temperature at the headwaters (9.5°C, roughly 50°F) towards an equilibrium temperature that is influenced by air temperature and modified by seasonal changes in day length (E_{sun}) and air temperature ($airT_{mean}$). The rate of increase towards this equilibrium temperature is determined by the downstream increase in SR_c, which is positively correlated with downstream distance and inversely correlated with flow.

Overview | Streamflow Forecasts | Stream Temperature Forecasts | Data Explorer

Input Parameters

Time of Year

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05/01 06/01 09/30

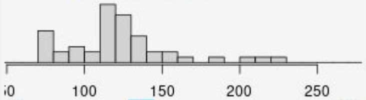
05/01 06/02 07/04 08/05 09/06 09/30

Air Temperature

Daily average average air temperatures at the Picabo AgriMet station for June 1 range from 44°F to 72°F. Highs for this day range from 59°F to 90°F. This forecast simulates a hot but not unusual day with an average temperature of 65°F and a high temperature of 84°F.

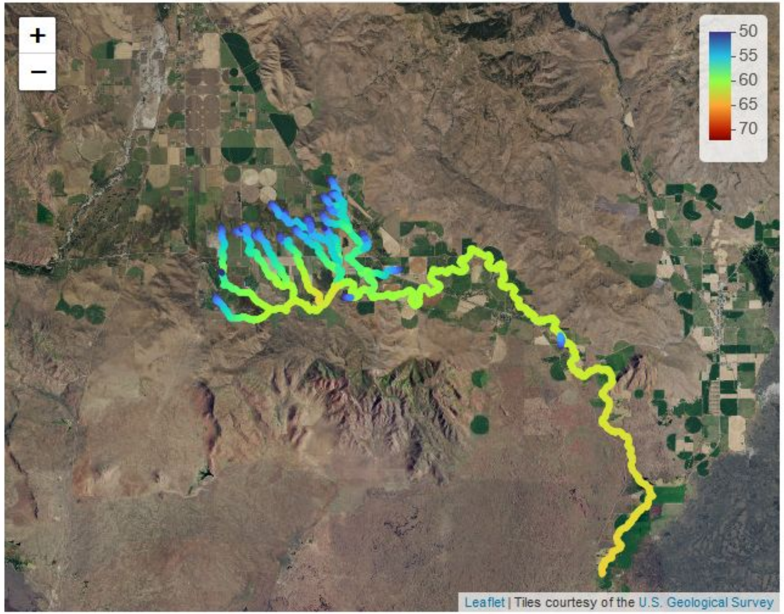
Streamflow

Streamflow in Silver Creek is described in terms of the flow at the Sportsmans Gauge. The predicted streamflow at Sportsmans for 2024-06-01 is 136 cfs (90% confidence interval: 91 - 169 cfs), and the historical distribution of streamflow for this day is shown in the plot below. Use the slider beneath this plot to set the streamflow for the simulation:



57 136 270

Forecast Stream Temperatures



Stream Temperatures vs. Flow for 2024-06-01