# RECLAMATION
*Managing Water in the West*

# The potential for restoring thermal refuges in rivers for cold-water fishes

## Research and Development Office
## Science and Technology Program
## Final Report ST-2019-212-01

U.S. Department of the Interior
Bureau of Reclamation
Research and Development Office

September, 2019

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This report is the first piece of a larger research effort to study how river restoration practices can bring about thermal restoration and create thermal refugia from the reach, meander wavelength, and geomorphic unit scales. This report summarizes the research question, introduces the study site, and analyzes existing data. We conclude by outline future work necessary to evaluate how water and temperature fluxes within the hyporheic zone are mediated by channel and floodplain restoration at three spatial scales.


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## Final Report ST-2019-212-01

# The potential for restoring thermal refuges in rivers for cold-water fishes

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# Executive Summary

This report is the first document of a larger research effort to study how river restoration practices can bring about thermal restoration and create thermal refuge on geomorphic unit, meander bed, and reach scales. In this report, we:

1. provide background information,
2. define the research question,
3. introduce the study site,
4. analyze existing pre-construction data, and
5. provide a research plan for future work.

Background information includes a definition of hyporheic flow (mixing of surface water and shallow groundwater) and introduces how hyporheic flow can influence surface water temperatures. Stream water temperature follows a sinusoidal pattern on a daily and annual scale (Hatch et al., 2006). Hyporheic flow can influence that pattern by cooling, buffering, and lagging temperature patterns (Arrigoni et al., 2008). The extent of the influence depends on the length of the hyporheic flow path. The lengths discussed in this report have been separated into three categories. Short flow paths (1-100 feet) are associated with geomorphic unit scale restoration efforts (riffle/pool sequences). Medium flow paths (100+ ft) can be associated with a planform-scale feature such as a sharp meander bend (Wroblicky et al., 1998). Finally, long flow paths (1000+ m) are created by long side channels, slope breaks, and coarse substrate (Hester and Gooseff, 2010).

Based on the knowledge of how hyporheic flow lags, buffers, and cools surface water temperatures, can we design restoration features to enhance hyporheic exchange and provide thermal refuge for target fish species at the three previously defined spatial scales? We focus on how restoration can mediate hyporheic flow, which can decrease and buffer temperatures in the main and side channels.

To investigate our research question, we are studying a channel and floodplain restoration project where temperature of surface and subsurface water along with groundwater level are being monitored before and after project construction. Bird Track Springs restoration project is located on the upper Grande Ronde River in north eastern Oregon. Project goals include modifying the channel planform to include side channels to increase geomorphic complexity, add sinuosity, and restore hyporheic flow connectivity by creating short, medium, and long flow paths.

Temperature and water level monitoring equipment were deployed by the Confederated Tribes of the Umatilla Indian Reservation across the study area between 2003 and 2018 to monitor hourly surface and groundwater level and temperature. These data inform diel (24-hour time period) and annual surface and groundwater temperature trends before and after restoration. Analysis of pre-project conditions shows that effective mixing of the groundwater and surface water flow has a high potential of buffering, lagging, and cooling surface water temperatures on a local scale. In other words, cooling throughout the project scale is unlikely, but restoration may increase the number of upwelling locations, creating local pockets of cool/warm water and thermal refuge.

A conducting proposal to continue this research was submitted to Reclamation's Science and Technology Program in June of 2019. The proposal identifies several project partners and outlines a clear plan to answer the above research questions. We divide our research question in subsets to define future tasks: 1) If the hyporheic exchange is occurring, are water temperatures effectively lagged or buffered to provide cooler temperatures during the summer and warmer temperatures during the winter? We propose a large data collection effort which will include streamflow, surface water temperature monitoring, and forward-looking infrared data to define the temperature regime throughout the site. 2) Can we refine our restoration techniques to optimize hyporheic flow path lengths to provide thermal refuge? Potential employment of a two-dimensional groundwater model could inform how hyporheic flow paths have changed with certain restoration measures. 3) Finally, are these measures creating thermal refuges in a manner that benefits target species at pertinent seasons and life stages? Snorkel surveys will inform fish use. We will also compare measured flow temperature and presence with literature on life stages by season.

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# Introduction

By altering the landscape, humans have influenced river water temperatures. While channelizing and removing riparian vegetation have increased water temperatures, large dams often release artificially cold water to the downstream ecosystem (Caissie, 2006; Justice et al., 2016; Olden & Naiman, 2010). Warmer water threatens cold-water aquatic species, such as salmonids, and reduces their viability by influencing fitness and fecundity (Konecki et al., 1995, Schindler, 1998). This can result in localized extirpation of certain species and overall reduction in available habitat and fish production basin wide (Battin et al., 2007; Ruesch et al., 2012). Many cold-water aquatic species recovery programs need to consider mitigating the impacts of warming waters with “thermal restoration” and creation of thermal refuges. Thermal refuges are defined as discrete patches of habitat within a river corridor where temperatures are different (warmer in winter, cooler in summer) relative to surrounding water (Torgersen et al., 2012). Thermal restoration has two primary mechanisms: (1) reducing solar insolation by reducing channel width-to-depth ratios and increasing shading by riparian vegetation, and (2) enhancing exchange of surface-subsurface water (i.e., hyporheic flow) within the channel bed, banks, and floodplain. We focus on the latter mechanism studying how restoration can mediate hyporheic flow, which can decrease and buffer temperatures in main and side channels. Currently, there is little documentation of the ability of and degree to which physical channel and floodplain restoration can mitigate the impacts of warming at different scales.

This report is the first piece of a larger research effort to study how river restoration practices can bring about thermal restoration and create thermal refuge from the geomorphic unit, meander bed, and reach scales.  Pre-restoration stream temperature and groundwater data suggest that restoration efforts could improve meander and geomorphic unit scale thermal refuge. However, reach-scale temperature buffering may be difficult to demonstrate. This report summarizes the research question, introduces the study site, and analyzes existing data. The restoration site is currently under construction, to be completed in October of 2019. We conclude by outlining future work necessary to evaluate how water and temperature fluxes within the hyporheic zone are mediated by channel and floodplain restoration at these three scales.

# Background

Hyporheic exchange is the mixing of surface water in the channel and shallow groundwater in the hyporheic zone across the streambed (Kasahara and Wondzell, 2003; Arrigoni et al., 2008; Tonina and Buffington, 2009). Research has documented thermal flux between water in the hyporheic zone and river channel (i.e., Poole et al., 2008). To understand the influence hyporheic exchange has on surface water temperatures as well as how restoration measures might influence this, we must understand temperature cycles of both channel and hyporheic water. Second, we must understand how these two reservoirs are hydrologically connected.

Temperature in stream surface water follows a sinusoidal pattern on a daily time period (Hatch et al., 2006). Arrigoni et al. (2008) describe the influence of hyporheic exchange on stream surface water in terms of cooling, buffering, and lagging this temperature pattern at various time scales (Figure 1). Cooling indicates a difference in mean temperature between hyporheic outflow and surface water. Buffered cycles demonstrate an attenuation in the temperature range (dampened peaks and troughs) but no change to mean temperature. Finally, lagging indicates a change in timing or phase of the temperature pattern. Studies have shown that hyporheic exchange at reach scales (1-5 km) effectively buffers and lags diel and annual temperature cycles. A net cooling effect is rarely observed outside of local groundwater or hyporheic outflow zones where reach-scale hyporheic flow paths may exist (Poole et al., 2008) or where regional groundwater may be mixing with the alluvial aquifer (Arrigoni et al., 2008). Along a reach, there may be numerous short and medium hyporheic flow paths in which buffering and lagging occurs and but only a relative small number of longer flows paths where cooling might occur. Therefore, from a thermal flux standpoint, only a small amount of water might be cooled resulting in negligible changes to the temperature of the main channel flow.

The magnitude of temperature lagging is dependent on the length of the flow path connecting surface water with the hyporheic zone (examples provided in Figure 2). The flow path length directly correlates to the residence time within the alluvial or floodplain aquifer. Short flow paths (1 m to 10 m) are typically created by changes in longitudinal gradient such as along the longitudinal profile of a pool-riffle stream (Harvey and Bencala, 1993; Hester and Gooseff, 2010).

Hyporheic flow entering the channel bed from a short flow path (feet to tens of feet) may alter the daily temperature range and phase compared to the main channel. These patterns are most evident in spring channels, compared to side channels or the main channel (Arrigoni et al., 2008). Therefore, cooler water may re-emerge during the hottest time of day, while warmer water surfaces at night if the lagging offsets the phase of the diurnal temperature pattern at the appropriate time scale.

Medium (tens of feet to hundreds of feet) and long flow (1000 ft) paths are created by the channel planform and groundwater flow paths (i.e., meander bends, braiding/anastomosing, abandoned channels, and channel avulsion; Restoration techniques to create medium and long flow paths include planform re-alignment, side channel construction, and coarsening of subsurface material (Hester and Gooseff, 2010). Longer flow paths buffer and lag temperature cycles at longer time periods such as weeks and months. Water re-emerging from long flow paths can cool summer surface water temperatures or provide warm refuge in the winter. Any associated mean temperature changes will be localized for long flow paths given the relatively small contribution they represent to flow in the main channel(s) (Poole, et al., 2008).

Evidence of buffered, lagged, and cooled water temperatures has been documented on a channel and floodplain restoration site on Catherine Creek, a tributary to the Grande Ronde River. Hourly temperature data monitored in surface water in the main channel and in an “alcove” adjoining the main channel show all these elements (Figure 3). An alcove may serve as an outlet for a side channel rejoining the main channel. It may also be a deeper feature excavated into the floodplain with a surface connection to the main channel. This may indicate that the alcove receives hyporheic flow from longer flow paths originating further upstream at this site.

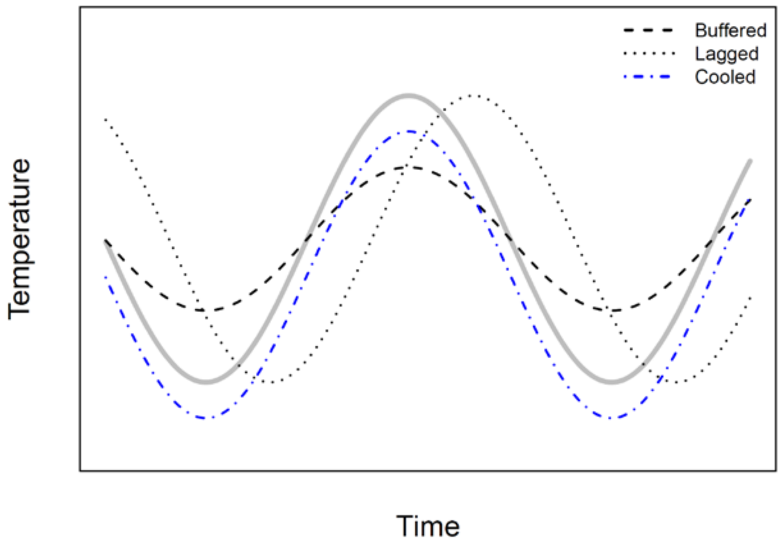


**Figure 1. Representation of buffering (black dashed lines), lagging (black dotted line), and cooling (blue dash-dot line) of diurnal surface water temperature pattern compared to a standard (thick grey) after Arrigoni et al. (2008).**


**Figure 2. Example of short (geomorphic unit scale), medium (planform scale), and long (long planform scale) flow paths at the Bird Track Springs study site. The study restoration effort includes modifying the channel planform to restore hyporheic flow connectivity. The existing planform is in blue and proposed constructed planform in yellow for a low flow event.**

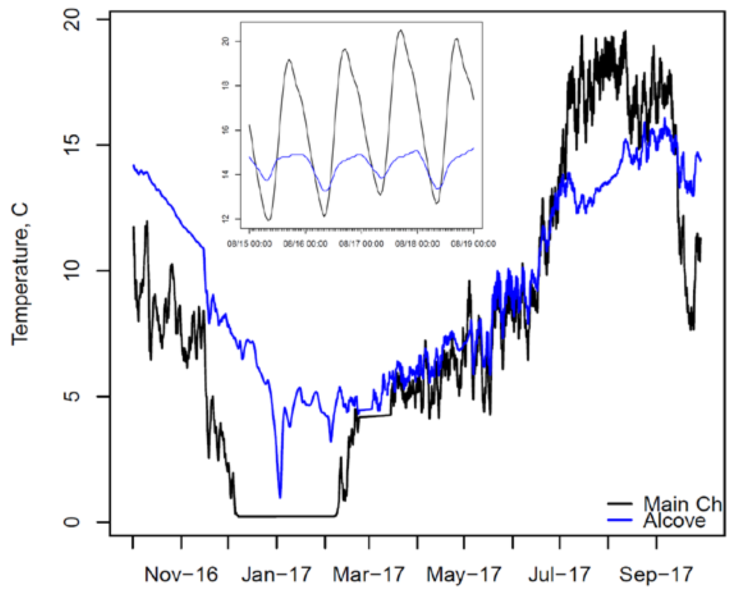


**Figure 3. Plot of annual- and daily-scale surface water temperature patterns from a constructed restoration site on Catherine Creek, a tributary to the Grande Ronde River. Main Channel surface temperatures plotted in black and alcove (off-channel feature with surface connection) in blue. Annual time series averaged over a centered 30-day window. Lower average temperature and buffered and lagged pattern indicate potentially longer flow paths sourcing the flow in this alcove. Data from the Confederate Tribes of the Umatilla Indian Reservation: [http://gis.ctuir.org/](http://gis.ctuir.org/).**

# Problem Statement

Based on the knowledge of how hyporheic flow lags, buffers, and cools surface water temperatures, are we able to design restoration features that enhance hyporheic exchange and provide thermal refuge for target fish species at three spatial scales? First, we must understand how current restoration techniques influence hyporheic exchange. For example, are sharp meander bends coupled with large wood structures facilitating subsurface flow? If the hyporheic exchange is occurring, are water temperatures effectively lagged to provide cooler temperatures during the hottest months of the year? Second, can we refine our stream rehabilitation techniques to optimize hyporheic flow path lengths to provide thermal refuge? Finally, are these measures creating thermal refuges in a manner that benefits target species at pertinent seasons and life stages?

# Study Area

Our study area, the Bird Track Springs restoration project is located on the upper Grande Ronde River in north eastern Oregon (Figure 4). The project reach's hydrology is primarily snow melt driven, having an average annual peak discharge of 900 cubic feet per second (cfs). It is located at approximately 3,100 ft in elevation where it experiences extreme swings in seasonal temperature. Average summer high temperatures are approximately 30°C, and winter low temperatures are typically -4°C. The existing planform is straight (sinuosity = 1.2) and average high flows are contained in the main channel, which has a high width to depth ratio and limited riparian vegetation. Low flow in the late summer and winter seasons coupled with these seasonal temperature swings result in high water temperatures in the summer and limited ice-free areas in the winter. These conditions, especially during the summertime, are harmful to salmonid productivity (Torgersen et al., 2012; Justice 2017).

Project goals include an overall increase in the geomorphic complexity of the reach including an increase in sinuosity along the mainstem and the generation of multiple perennial and intermittent side channel flow paths (Figure 5). These constructed flow paths will distribute flow across a broader expanse of the floodplain with the objective of increasing the potential for hyporheic flow as well as a greater variety of habitat conditions for the target species. Smaller-scale features such as alcoves and enhanced longitudinal profile complexity (pools and riffles) may also serve to enhance hyporheic exchange at the geomorphic unit scale. Inclusion of hundreds of large wood structures across the study area add to the complexity of the system. Finally, a riparian revegetation effort will establish shading and provide new sources of large wood to recruit over the long term.

This restoration project is part of a greater effort in the Upper Columbia River Basin to restore habitat for threatened and endangered salmonid species across their life cycles under commitments of the Bonneville Power Authority, the Bureau of Reclamation, and the Army Corps of Engineers outlined in the 2008 Federal Columbia River Power System Biological Opinion (NOAA Fisheries 2008) and subsequent Supplemental Biological Opinions in 2010 and 2014 (NOAA Fisheries, 2014). The primary project sponsor is the Confederated Tribes of the Umatilla Indian Reservation (CTUIR) and the lead design team is the Bureau of Reclamation, Pacific Northwest Regional Office who developed the design in coordination with the project sponsor, the consulting engineer Cardno Inc., and a host of stakeholders (Cardno, Inc., 2017).

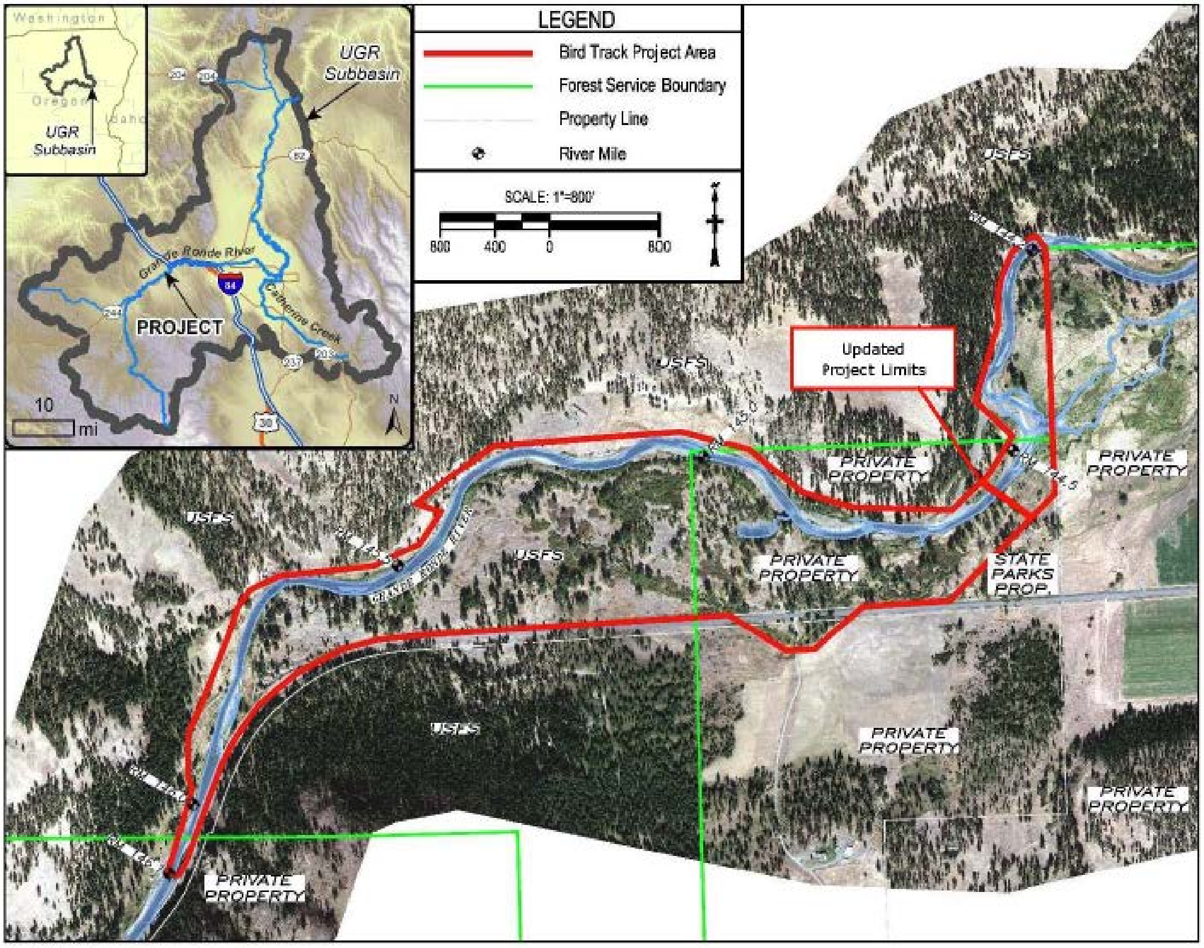


**Figure 4. Overview map of study area project. From the Bird Track Springs Basis of Design Report (2017).**

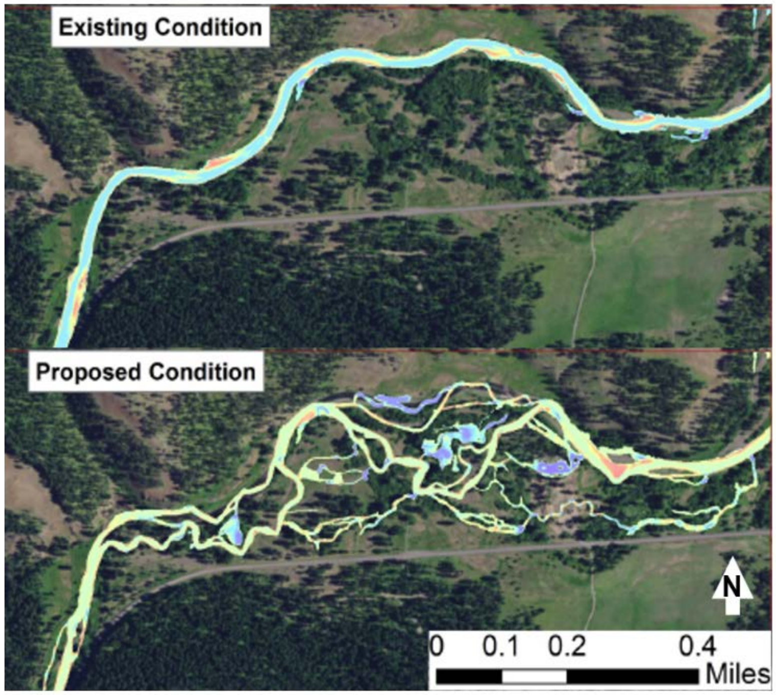


**Figure 5. Bird Track Springs project reach showing modeled summer and winter high flow (900 cfs) for existing (top) and proposed (bottom) topographies (Cardno Inc., 2017).**

# Data and Methods for Scoping Study

Temperature and water level monitoring equipment were deployed by CTUIR across the study area to monitor hourly surface and groundwater level and temperature (Figure 5). These data document existing surface and groundwater temperature trends. We present an analysis of existing main stem and groundwater temperature patterns. Future work will include deploying additional temperature and pressure loggers to analyze geomorphic unit hyporheic flow paths (Wondzell, 2006). Loggers will be placed at predicted groundwater resurfacing locations, which will be informed by constructed design features (i.e., alcoves and side channels) and hydraulic modeling results. Spot measurements of surface water temperatures made with a hand-held temperature probe will also be used to identify potential outflow locations.

Groundwater monitoring wells with 1-inch diameters were installed in 11 locations across the study area (Figure 5). Onset HOBO© temperature (Pendant 64k or TidbiT v2) and pressure loggers (U20L-04) were deployed in the study area to log hourly temperature and water level data. One temperature logger was installed within a human-made pond intersecting the alluvial aquifer, referred to as Jordan Cr. Ranch. Each year prior to deployment temperature probes are tested in an ice bath and verified with an NIST certified thermometer.

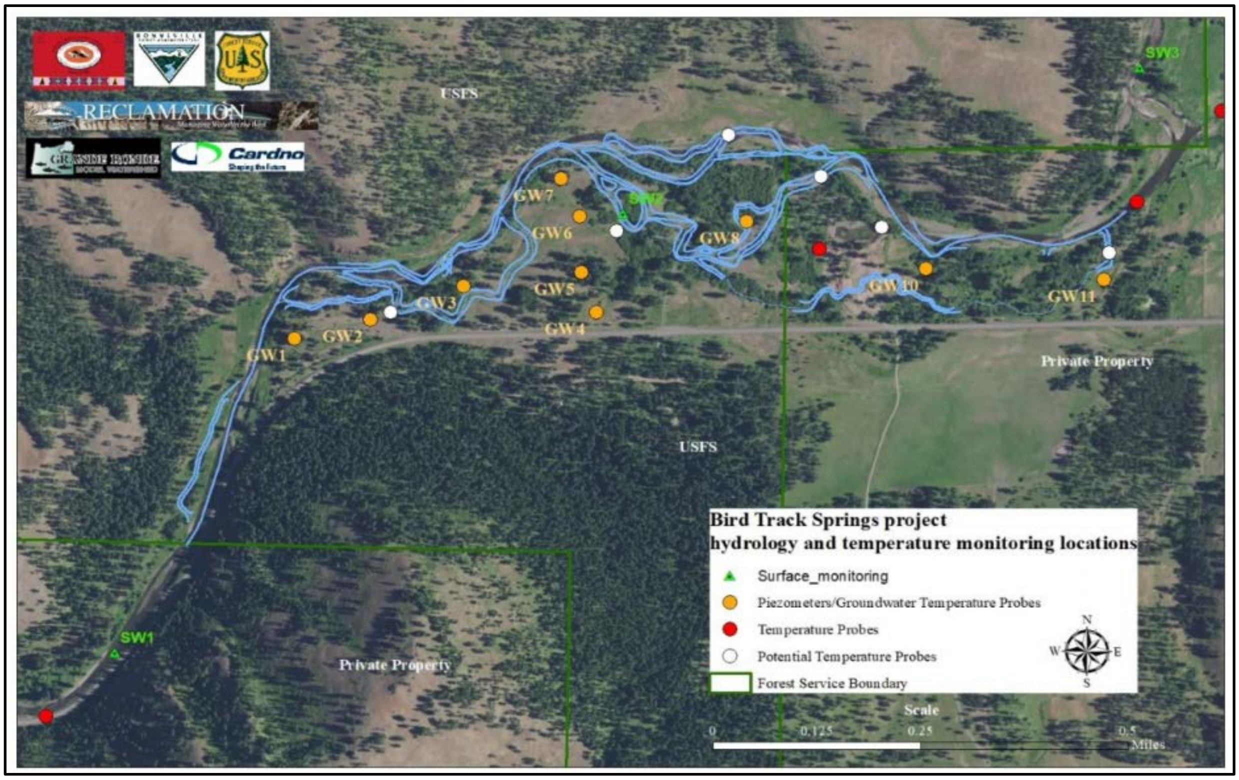


**Figure 6. Groundwater level and temperature and surface water level and temperature monitoring locations on the study area. Map from the Confederated Tribes of the Umatilla Indian Reservation (2019).**

# Existing Surface-Groundwater Temperature Analysis

## Annual Temperature Trends

Ground water temperature values are buffered and lagged compared to main channel water temperature values from November 2017 through December 2018 (Figure 7). During the summer, main channel water temperature is much warmer than all measured groundwater temperatures. Main channel temperature peaks during July and August with values as high as 23°C, far exceeding the preferred temperature range of juvenile Chinook salmon (10°C to 15.6°C, Yanke et al., 2004). Temperature values exceed the 15.6°C upper extent of the preferred temperature range approximately 80 days within the period of record. The DEQ standard of 17.8°C (ODEQ, 2000) was exceeded over 50 days. In contrast, winter main channel water temperature values are lower than groundwater temperature values from October through April. From November to January, stream water temperature values hover around 0°C, occasionally dipping below freezing.

During the summer, groundwater temperature values are consistently lower than stream temperatures, peaking between 10°C and 16°C, within the DEQ standard threshold of 17.8°C. Peak groundwater temperature occurs in September, lagged from main channel temperatures by nearly two months. During July and August, ground water temperature is at least 10°C lower than stream temperature. Conversely, ground water temperature values range from 7 to 13° between November and January. We can conclude that increased hyporheic flow has the potential to cool water in the main channel during the summer and warm surface water temperature during the winter if hyporheic exchange can be enhanced by restoration treatments.

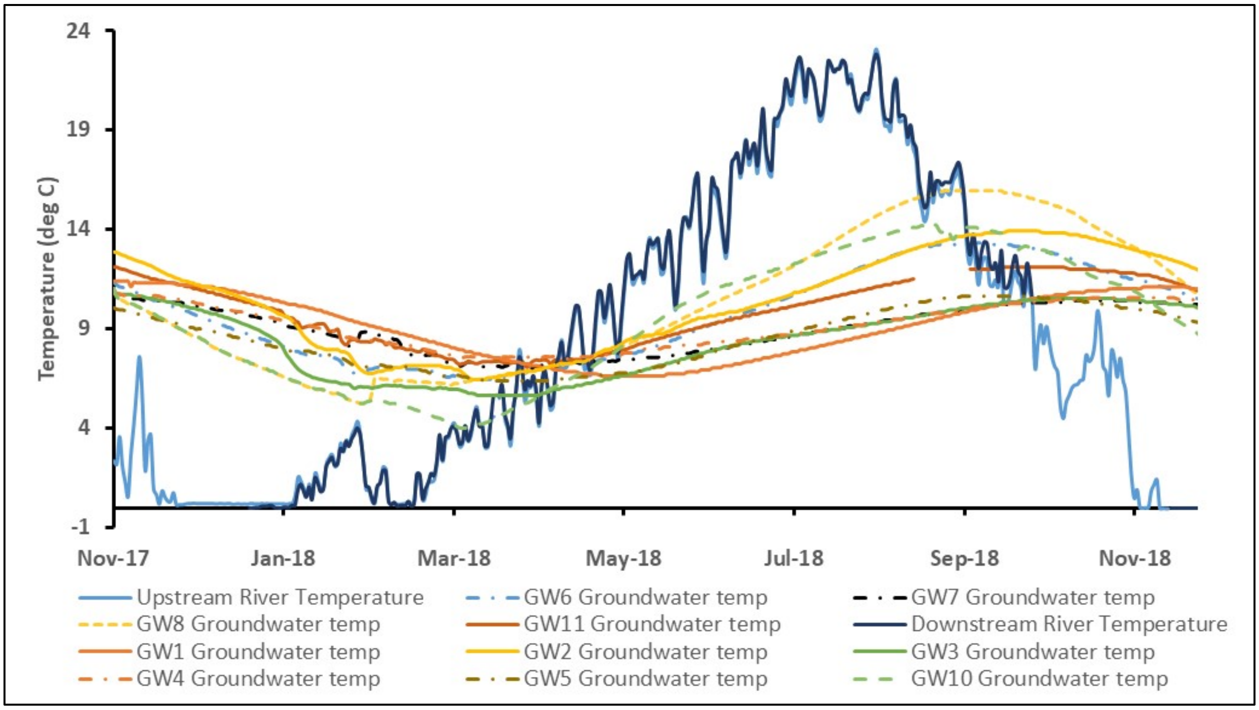


**Figure 7. Annual stream water and ground water temperature trends (data provided by CTUIR).**

## Diel Temperature Trends

Stream temperature data indicates strong diel patterns during the summer months (Figures 8 and 9). Main channel diel temperature can fluctuate by more than 10°C. The peak temperature occurs between 16:00 and 18:00 while the coolest time is between 7:00 and 9:00. As seasonal temperatures cool, the variation throughout the day decreases until it is less than 1°C during the coldest months (December and January).

In general, warmer water temperatures are observed downstream of the project site during the summer. On average, water temperatures recorded at the logger downstream of the site were 0.4°C higher during the study period. This is likely due to absorption of solar radiation throughout the broad, shallow, minimally shaded channel. The temperature differential between the two gages is evident during peak daily temperature, where the downstream water temperature values are almost 2°C higher. During cooler parts of the day, the difference in temperature is much lower (<1°C).

Groundwater temperature loggers and piezometers record hourly data were installed in November of 2017. These data show a strong annual trend (Figure 7), but no diel trend (Figure 9). If restoration efforts can increase interaction between surface and groundwater, daily stream temperature values may be buffered or lagged, at least at the local scale where hyporheic outflow occurs. This effect has been observed at other restoration sites in the area (Figure 3) as well as the study site. Data show temperature buffering in the Jordan Cr. Ranch pond. In September 2017 (Figure 8), daily temperature values fluctuate within 2°C each day. Temperature values ranged from 9°C to 18°C in the pond as opposed to the main channel, where temperature ranged from 6°C to 25°C during the same timeframe. A cooling effect is noticeable during the summer of 2018 at this site (Figure 9). Water within the pond maintains a temperature within 14°C to 17°C whereas the main river channel ranges from 15°C to 29°C, temperatures that can be lethal to fish (Becker, 1973). The restoration design will include side channel and pond habitat whose goal is to connect to and interact with the buffered and lagged temperatures of the alluvial aquifer as is observed in this pond.

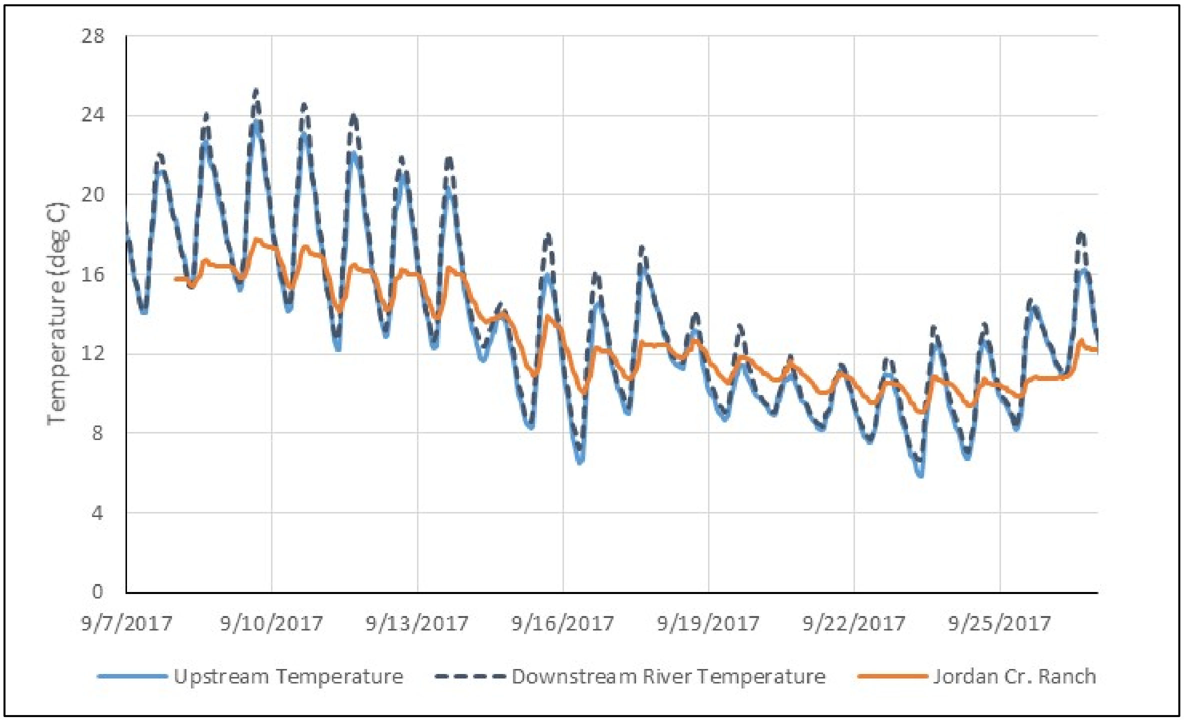


**Figure 8. Diel stream temperature patterns (data provided by CTUIR). Downstream temperatures are slightly higher than those observed upstream, confirming that warming is occurring within the project reach. Buffering occurs within a pond fed by the alluvial aquifer (Jordan Cr Ranch).**

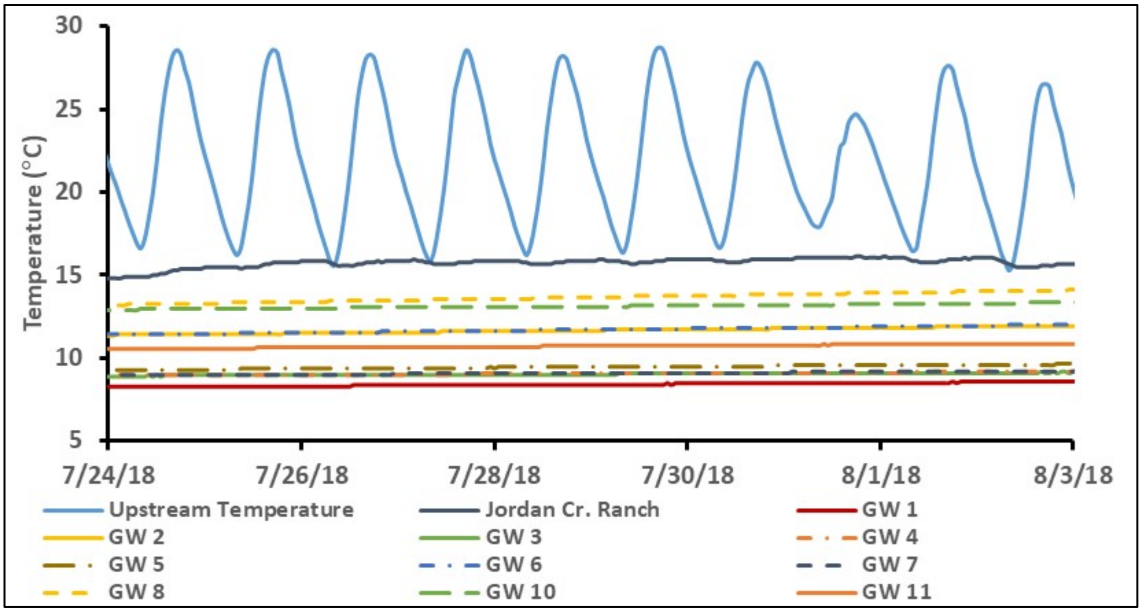


**Figure 9. Diel temperature trends within the Bird Track Springs project area during the summer of 2018 (Data provided by CTUIR).**

## Well Depth Trends

Data suggests that well depth influences the extent of which groundwater temperatures are buffered compared to river water. The influence of well depth could be a result of longer flow path lengths, which provide longer residence time. Average groundwater temperatures do not show a strong pattern; thus, well depths are too shallow for cooling. Temperature ranges decrease as well depth increases (Table 1 and Figure 10). Smaller range values are due to better buffering of water temperature as well depth increases.

**Table 1. Groundwater well depth sorted from smallest to largest, compared to surface water measurements upstream of the project site.**

| Temperature Gage | Well depth (ft) | Well Bottom Elevation (ft) | Average (°C) | Range (°C) |
|---|---|---|---|---|
| Upstream Temperature | Surface water | | 8.5 | 23.1 |
| GW 10 | 10.0 | 3104.3 | 9.3 | 10.2 |
| GW 8 | 10.0 | 3111.4 | 10.3 | 10.7 |
| GW 6 | 11.0 | 3116.8 | 9.8 | 7.1 |
| GW 2 | 11.1 | 3123.6 | 10.5 | 7.5 |
| GW 1 | 11.1 | 3127.6 | 9.2 | 4.8 |
| GW 5 | 12.0 | 3117.0 | 8.6 | 4.3 |
| GW 3 | 14.3 | 3117.8 | 8.5 | 5.2 |
| GW 4 | 14.4 | 3111.4 | 9.2 | 3.3 |
| GW 7 | 15.1 | 3112.3 | 9.0 | 3.5 |
| GW 11 | 15.3 | 3095.0 | 9.9 | 5.0 |

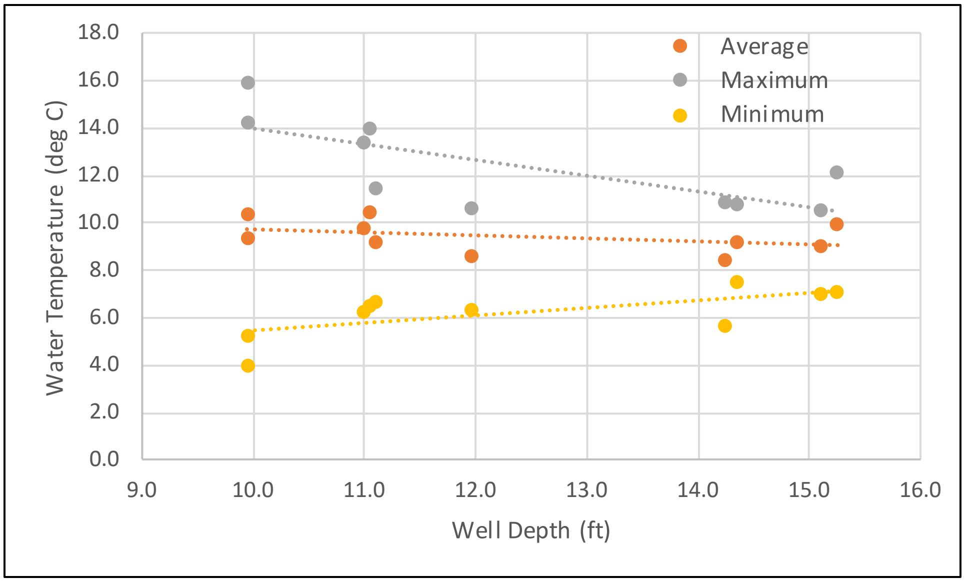


**Figure 10. Daily groundwater temperature trends as a function of well depth.**

## Spatial Trends

Groundwater wells 4, 5, 6, and 7 were aligned to measure the change in groundwater temperature as a function of distance from the river to provide insight into the influence of flow path length (Figure 6). GW 4 is located the furthest from the river (approximately 1,160 ft), while GW 7 is located the closest (140 ft). The original hypothesis predicted that temperature buffering would be the most evident in GW 4, the well furthest from the river with the longest hyporheic flow path, and less noticeable in GW 7, the closest well with the shortest flow path. Unfortunately, results do not confirm that hypothesis for the 2018 water year.

Results show the greatest temperature buffering occurs at the two wells closest and furthest from the river, GW 7 and 4 respectively (Figure 11). Temperature values are higher in the winter and lower during the summer. They both follow very similar trends, peaking at approximately 10.7°C in November and reaching a low between 7°C and 7.5°C in April. While these two wells occupy both the closest and furthest location from the river, they are also the deepest wells based on well depth and bottom of well elevation (Table 2). It is possible that the well depth influences the range of temperature observed at these sites. Based on data from these wells within the 2018 water year, we can conclude that distance from the river is not the primary process dictating the magnitude of temperature buffering at these groundwater wells.

GW 5 and 6 are located 820 and 480 ft from the river, respectively. These wells are 11 to 12 feet deep, located at approximately the same well bottom elevation (Table 2). The groundwater temperature within these two wells are noticeably different. Peak temperature values in GW 6 are almost 3°C higher than GW 5 while the minimum temperature values are comparable. As GW 6 is approximately 340 ft closer to the river, it is possible the differing temperatures can be attributed a longer flow path associated with being further away from the main channel.

Results are inconclusive based on the available data. Future work will install wells and optimal locations and consistent well depths to better understand the influence of hyporheic flow path length.

**Table 2 . Well information from GW 4 – 7.**

| Well # | Well depth (ft) | Well Bottom Elevation (ft) | Distance from the River (ft) |
|---|---|---|---|
| GW 4 | 14.4 | 3111.4 | 1,160 |
| GW 5 | 12.0 | 3117.0 | 820 |
| GW 6 | 11.0 | 3116.8 | 480 |
| GW 7 | 15.1 | 3112.3 | 140 |

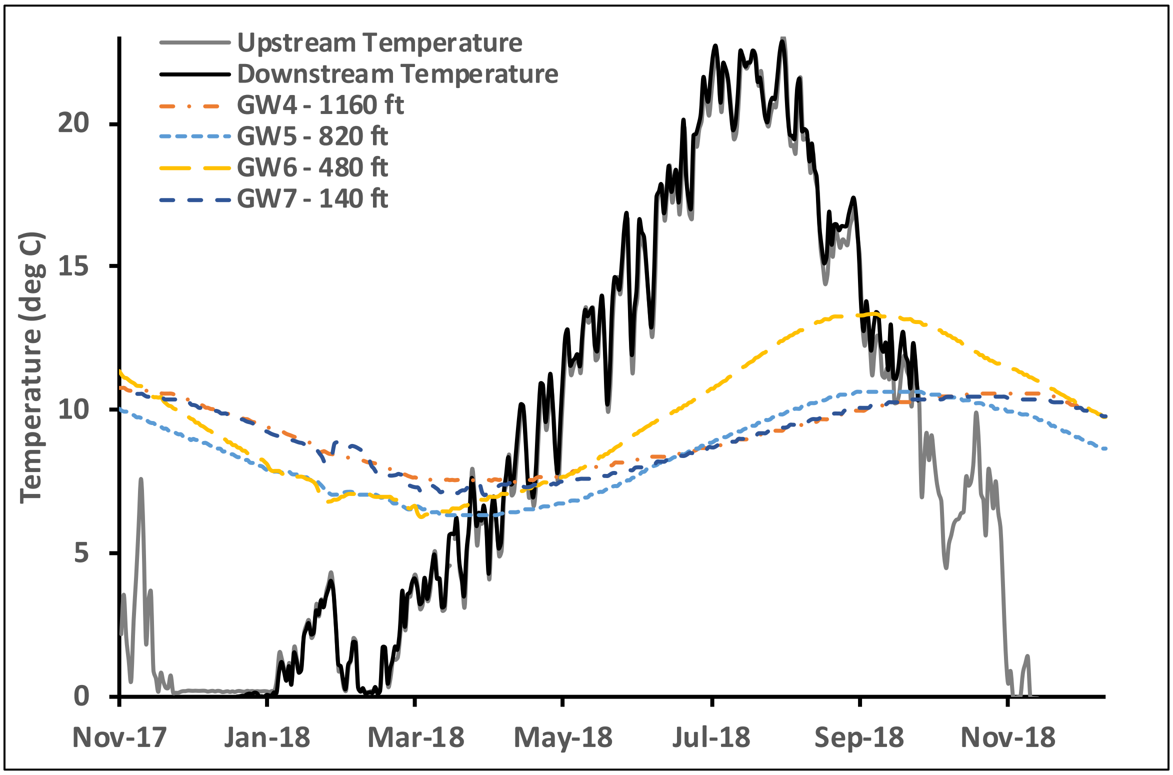


**Figure 11. Average daily groundwater temperature trends comparing distance from the river (Data provided by CTUIR).**

# Future Work

A conducting proposal was submitted to the Bureau of Reclamation's Science and Technology Program for fiscal year 2020. The proposal is in partnership with Reclamation's Pacific Northwest Region, the Confederated Tribes of the Umatilla Indian Reservation, Oregon Department of Fish and Wildlife, the University of Idaho, and the University of Colorado, Boulder. The following five tasks were proposed to be completed by September of 2022:

1. Light Literature Review,
2. Data Collection,
3. Hydraulic surface and groundwater modeling
4. Data analysis
5. Reporting and distribution of results.

Data collection includes several subtasks to better understand effect of restoration features on hyporheic flow paths and the extent of temperature buffering and lagging. A stage gage will be moved to the upstream end of the project to record incoming streamflow. Manual discharge measurements will be required at the gage to develop a relationship between discharge and stage (discharge rating curve). Manual discharge measurements will also be made at one point in time throughout the project area to quantify surface water gains and losses. Additional level and temperature data loggers will be installed throughout the site to monitor surface and groundwater temperatures. Solute sampling and/or forward-looking infrared data can be used to identify upwelling locations. Finally, snorkel surveys will be conducted within the project reach three times each year for the duration of three years. These surveys will inform fish use to determine if restoration efforts are benefiting cold-water fishes.

Using time series analysis, we will compare buffer (amplitude), lag (phase), and average temperature parameters at the following types of locations (

Figure 2):

1. expected hyporheic inflow locations (surface);
2. floodplain groundwater at along a transect through a meander bend (Figure 6, GW4 to GW7) (subsurface); and,
3. expected hyporheic outflow locations associated with constructed features such as alcoves and side channels (surface).

Time series analysis will allow for statistical comparison of diurnal temperature patterns to discern whether an ecologically significant change has occurred as a result of the restoration project.

Data from surface water stage loggers deployed in the main and side channels will be compared to groundwater stage to understand the hydraulic gradient and flow rates within the floodplain aquifer. We will evaluate the difference in temperature and elevation of surface and groundwater patterns at daily to seasonal time scales to characterize the influence of restoration at the reach to geomorphic unit scales. Employment of a two-dimensional groundwater model will be considered to aid in comparing potential hyporheic flow paths prior to and after restoration (Poole et al., 2008). The model could be parameterized with existing subsurface seismic surveys, a LiDAR digital elevation model, and existing 2-D surface hydraulic model-generated surfaces at key flow rates. Temperature and groundwater stage monitoring will be coordinated with planned post-restoration fish monitoring to evaluate if the observed temperature refuges are providing ecologically beneficial temperature and flow patterns. We will compare measured flow temperature and presence with literature on life stages of target species for each season.

# Conclusion

Comparative temperature time series analysis on a similar restoration project in the same basin has resulted in indirect evidence of enhanced hyporheic flow paths resulting in thermal refuge (Figure 2). Analysis of annual- and diel-scale temperature patterns at the study site indicate buffering and lagging of temperatures in the alluvial aquifer compared to the main channel. This report summarizes an analysis of pre-construction temperature and groundwater monitoring data at the Bird Track Springs study area to characterize temperature and groundwater patterns at daily to seasonal time scales. Information gained from this analysis will guide us to where additional temperature and stage monitors should be installed to study the influences of geomorphic unit to planform-scale restoration measures on temperature and hyporheic flow patterns (Figure 12).

A conducting proposal has been submitted to the Science and Technology Program to continue this research. After project construction at the end of 2019, we will continue monitoring surface and groundwater temperature and stage over the next year to compare with the prior years of pre-construction monitoring data. Biological monitoring will be mobilized during the summer of 2020 and continue through 2022. We will also explore the potential of groundwater modelling to aid in interpretation of our observations.

While thermal refuge creation is often the goal of river restoration projects throughout the United States, it has not been widely studied. This project will offer valuable insight to how effective restoration projects are for thermal refuge and lessons learned to inform future projects with similar goals.

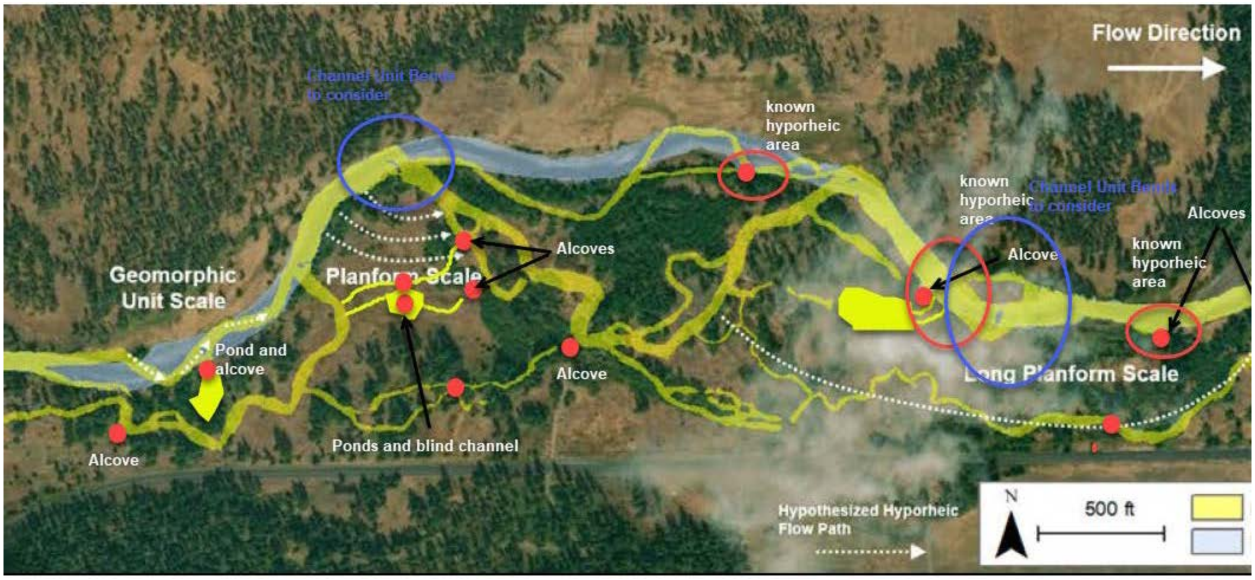


**Figure 12. Proposed locations of future temperature and level loggers to assess hyporheic flow patterns and temperature buffering to inform how and to what extent restoration practices create thermal refuge for salmonid fish species.**

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