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The Potential for Restoring Thermal Refuge in Rivers for Cold-Water Salmonids

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14. ABSTRACT

River restoration targeted at promoting thermal refuge for cold-water salmonids is often critical for encouraging fish recruitment and success in channels that are too warm for fish survival. One method of promoting thermal refuge is to increase the exchange of surface-subsurface flow (hyporheic flow) through creating geomorphic diversity. Previous studies have not explored the impacts of these types of features on reach-scale thermal buffering. This study combines field work, two-dimensional hydraulic modeling, and three-dimensional groundwater modeling to address the question of if river restoration can increase hyporheic exchange at the Bird Track Springs restoration site of the Grande Ronde River, Oregon. The model results showed that restoration did increase the overall hyporheic exchange in the channel. However, the magnitudes of upwelling and downwelling were relatively small due to the low hydraulic conductivity of the alluvial material. In spite of this, the reach showed an overall reduction in the maximum summer water surface temperatures and thermal buffering that reduced the temperature variations from 12 °C to 4.5 °C between pre- and post-restoration. Pool stratification can account for the observed reduction in temperatures and thermal buffering. These effects are flow-dependent, and only come into play at very low flows. Field observations showed that thermal refuge was localized to morphologic features that could retain the low magnitude hyporheic discharges.

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Executive Summary

Anthropogenic activities may alter the natural landscape and influence water temperatures to levels outside of historical trends. Channelizing and removing riparian vegetation can result in warmer water temperatures, whereas dam releases can input cool water to rivers (Caissie 2006; Justice et al., 2017; Olden & Naiman, 2010). Cold-water aquatic species, like salmonids, require a narrow range of temperature conditions to ensure their survival and support their life history (Konecki et al. 1995; Schindler 1997). High water temperatures can cause localized mortality of cold-water species and basin-wide reduction in viable habitat and spawning (Battin et al., 2007; Ruesch et al. 2012). Many cold-water aquatic species recovery programs, therefore, need to consider water temperatures in their restoration efforts by creating thermal refuges. Thermal refuges are areas of a river that buffer, lag, and cool/warm stream temperatures at biologically relevant scales and times. This water is often warmer in the winter and cooler in the summer (Arrigoni et al. 2008; Torgerson et al. 2012). To address acute summer water temperatures, we define thermal refuge as discrete patches of surface water that are cooler than 1 degree Celsius (°C) from the reference water temperature. Thermal refuge is typically created by two 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 exchange) within the channel bed, banks, and floodplain. For this study, we focus on the second mechanism by studying how restoration can alter hyporheic flow, which can in turn, affect water temperatures in the main and side channels. Currently, there is little documentation on the ability and degree to which physical channel and floodplain restoration can influence hyporheic exchange and associated stream ecosystem function (Hester and Gooseff 2010). To improve river and floodplain restoration outcomes, we must develop a better understanding of what mechanisms are capable of generating thermal refuge.

The U.S. Bureau of Reclamation (Reclamation) has been working on habitat restoration in the Grande Ronde basin in Oregon since 2011. Over this period, nearly a dozen river restoration projects were constructed or are currently in planning phases. Many of these projects have thermal restoration as one of their main objectives, and thus highlight the need for a better understanding of how physical aspects of restoration directly influence in-channel water temperatures. Many researchers have studied the physical conditions that lead to hyporheic flow, its influence on surface water temperature, and the hydrological processes associated with the hyporheic zone (e.g. Poole et al. 2008; Arrigoni et al. 2008; Hester and Gooseff 2010). To date, studies related to the potential of river restoration to enhance hyporheic exchange have focused on specific structures rather than reach-scale restoration effects on hyporheic and thermal conditions in a river (Hester et al. 2009; Hester and Gooseff 2010; Crispell and Endreny 2009; Torgersen et al. 2012). This study closes that knowledge gap by applying the connection between hyporheic exchange and thermal refuge to study the efficacy of reach-scale thermal restoration at a designed restoration site.

The Bird Track Springs Restoration Project is located on the upper Grande Ronde River in north-eastern Oregon. The basin hydrology is snowmelt-driven, with annual peak flows of around 900 cubic feet per second (ft^3/s) occurring in April and May and low flows from July through

October. Temperatures in the summer reach a typical high of around 30 °C and winter lows are typically around -4 °C. Low flows in the summer coupled with the seasonal temperature swings result in warm water in the summer and little ice-free area in the winter, which are a concern for salmonid productivity. This reach was therefore targeted for restoration to remediate the poor habitat quality and encourage an increase in the native fish population.

The pre-restoration river planform was historically straightened (sinuosity of 1.2) for splash-dam logging, and the average annual high flows were contained in the main channel. The main channel had a high width to depth ratio and limited riparian vegetation with fewer than 0.25 miles (mi) of side channels. The restoration design defined one large pool in the study reach, but this pool was less than 2 ft deep during low flow and was not considered in this study. Only 60 acres of floodplain were connected to the channel. This resulted in high water temperatures in the summer and limited ice-free areas in the winter that created thermally stressful conditions for Chinook salmon during summer months (Cardno, 2017).

Because of the warm water temperature conditions, Reclamation restored the channel from 2017 to December of 2019. The goals of the restoration effort were to increase surface-groundwater exchange between the channel and floodplain and provide thermal refuge for migratory and resident Chinook salmon during critical summer months. During restoration, engineers excavated 5,000 linear feet (ft) of new main channel and 9,500 ft of side channel to increase the sinuosity to 1.4, an additional 135 acres of floodplain were reconnected to the active channel with 439 pieces of large woody material placed per mi, and over 15,000 plants were installed as part of the riparian restoration effort. Additionally, alcoves, riffles, point bars, glides, and 19 large pools were added within the main channel (Childs et al., 2020).

The post-restoration channel exhibits much greater morphologic heterogeneity and diversity than the pre-restoration channel. Unit scale and planform geomorphic features were incorporated throughout the reach and provide an opportunity to study morphologically induced hyporheic exchange.

This study aims to answer two key questions:

1. How do stream and floodplain rehabilitation practices create or enhance thermal refuge at different spatial scales?
2. Can thermal refuge restoration be accomplished in a manner that is ecologically relevant to target species?

To answer these questions, this study requires looking at mechanisms of buffering, lagging, and cooling of water temperature provided by hydrologic connections between surface and subsurface hydrologic connectivity. We test the hypothesis that hyporheic flow paths can be enhanced by restoration measures at geomorphic unit and planform scales. The design expectation is that unit-scale geomorphic features are expected to buffer or lag surface water temperatures at hourly timescales while planform-scale restoration work has the potential to buffer or lag water temperatures at longer timescales (days to months) due to the different flowpath lengths. Specifically, longer hyporheic flowpaths that result from planform-scale features provide a longer duration of subsurface interactions. The inputs from these flowpaths to the channel tend to be cooler during the summer because they trend toward the groundwater temperature. This will result in an increase in thermal refuge with localized small fluxes of cooled water, but net cooling is not expected in the reach.

This study combined field data collection efforts, two-dimensional surface water modeling using the Sedimentation and River Hydraulics Two-Dimensional model (SRH-2D), and three-dimensional groundwater modeling using MODFLOW to assess the extent of hydraulic exchange within the hyporheic zone. We compare results between pre- and post-restoration scenarios to assess the performance of specific constructed morphologic features in inducing hyporheic exchange. The hypothesis is that by increasing subsurface connectivity and hyporheic exchange, the channel exhibits greater thermal refuge. The field work and modeling efforts were a collaboration between the Confederated Tribes of the Umatilla Indian Reservation (CTUIR), the Reclamation's Pacific Northwest Regional Office, Snake River Area Office (SRAO), and Technical Service Center (TSC), the Oregon Department of Fish and Wildlife (ODFW), the University of Idaho, and Colorado Mesa University.

To evaluate spatial temperature trends and establish boundary conditions for the groundwater model, we collected surface-water discharge, groundwater levels and temperatures in observation wells, and surface-water temperatures during the timeframe used in the modeling efforts. The SRAO Geology group assessed the range of hydraulic conductivities present in the floodplain through field slug tests in a subset of wells in August 2021 to help constrain the groundwater model parameters. Collaborators from the University of Idaho designed and installed 40 hyporheic flux probes, 1 atmospheric sensor, and 3 piezometers throughout the channel and floodplain to monitor groundwater conditions and hydraulic fluxes along the stream bed and near prominent morphology. They also developed a way to assess spatial variations in water temperatures within the channel by affixing temperature and pressure sensors to Real Time Kinematic Global Positioning Units. They used these units to conduct longitudinal thermal surveys in early August 2021 to measure near-bed water temperatures and identify areas of potential thermal refuge within the main and side channels. CTUIR deployed HOBO temperature TidbiTs every year to assess water temperatures in the river during ice-free periods (spring through fall). Due to vandalism, only 14 of the hyporheic flux probes were recovered.

The MODFLOW groundwater model was coupled with SRH-2D to calculate groundwater flow and track flowpaths through the floodplain and alluvium using MODPATH. The model consisted of six subsurface layers that were informed by the available geophysical survey and well log data. Boundary conditions for the pre- and post-restoration channels were informed by the well and piezometer water table elevation data. Surface water elevations from SRH-2D during a characteristic summer low-flow condition provided the static head condition within the river channel for the model. Model calibration was conducted using the well and piezometer data from the floodplain and the hyporheic flux probes in the riverbed, as well as visual comparison between standing water in the floodplain from aerial imagery and numerical model results. After calibration, the model reproduced both water levels and hyporheic exchange within the river with a mean error of 0.477 ft.

Groundwater modeling results were assessed by comparing the pre- and post-restoration results. The results show that channel realignment post-restoration distributes the surface water over a wider area in the valley. This resulted in water table elevations increasing by almost 2.5 ft in the middle section of the channel. It also changed the local gradient of subsurface flows and the direction of flowpaths through the valley. Pre-restoration flowpaths largely ran parallel to the channel in the down-valley direction (East) and bypassed most of the river domain, while post-restoration flowpaths were more sinuous and skewed to the South. This resulted in more intersection of the channel with the flowpaths, which increased lateral influxes of upwelling in parts of the river. Flowpath lengths were also on average 2.5 times longer post-restoration, resulting in longer residence times of water in the hyporheic zone, increasing the possibility for thermal buffering of instream water temperatures. Average subsurface residence times were 300 days (~10 months) pre-restoration and 750 days (~2 years) post-restoration. Residence times less than 20 days were about the same pre- and post-restoration, and the upper end of the distribution (residence times >5,000 days or ~13.5 years) were longer pre-restoration.

The model further showed that morphologic features and valley-scale influences (bedrock/geologic constraints) can affect upwelling and downwelling. Valley-scale influences force groundwater upwelling at the upstream end of the valley where bedrock underlies the channel, and at the downstream end where the channel abuts the canyon wall. These valley-scale influences persist in pre- and post-restoration conditions. Within these valley-scale influences, hyporheic exchange changes after restoration due to constructed morphologic features (pools and riffles) during restoration. Pool-riffle sequences generate a structured distribution of downwelling at pool tails and riffles and upwelling at pool heads. Plane bed features have random distributions of upwelling and downwelling and accounted for most of the pre-restoration channel. The position of the feature relative to the valley-scale groundwater gradient dictates the spatial distribution of hyporheic exchange. Depending on the orientation of the river channel relative to the valley groundwater gradient, hyporheic exchange can shift away from pool heads and tails to cross-channel pool margins. This effect is present but less notable in riffles and can limit the efficacy of morphologic-driven hyporheic exchange. Further, if the feature is located in a losing reach (water table below the channel water surface elevation), less upwelling and greater downwelling occurs and vice versa if in a gaining reach (water table above the water surface elevation in the channel). Therefore, the construction of morphologic features can generate predictable hyporheic exchange in the channel, but the hyporheic response in each feature will depend on both the valley-scale groundwater direction and adjacent water table elevation.

Comparing sections of the channel that maintained the same water surface slope pre- and post-restoration indicate that pool-riffle morphologies are able to generate net hyporheic discharge magnitudes 300 percent greater than those in the pre-restoration channel's weirs and riffles. In lower slope channel sections, pool-riffle sequences were able to generate similar magnitudes of hyporheic discharge as the steep pre-restoration channel. Further, restoration increased total downwelling by 19percent and upwelling by 16percent relative to the pre-restoration channel, indicating overall greater hyporheic exchange in the post-restoration channel. Net gains and losses were similar between the two channels over the length of the reach.

For thermal habitat conditions, water temperatures in excess of 25 °C are lethal to many salmonids. Restoration increased the total upwelling discharge to the channel from 1.10 percent (percent) (0.24 ft^3/s) to 1.27percent (0.27 f^{t3}/s) of the typical late summer discharge in the Grande Ronde River restoration reach. Accounting for this percentage, hyporheic discharge has the capacity to reduce mean water temperature in the channel by only 0.12 °C. However, no change in mean water temperature was observed through the reach after restoration. In comparison, maximum daily water temperatures were affected. In both the pre-restoration and post-restoration channel during summer low-flow conditions, the peak temperatures entering the upstream end of the reach often exceed 25 °C. In the pre-restoration channel, water temperatures warmed 2-3 °C over the length of the reach, with the typical maximum daily water temperature exceeding 25 °C (figure 1). The cumulative time spent over the 25 °C threshold was reduced by 75percent between the upstream and downstream boundary after restoration. This reach-scale buffering that reduced maximum daily temperatures is unlikely to be from hyporheic exchange because the hyporheic fluxes in the channel are of low magnitude and have limited potential to significantly affect the bulk temperatures in the channel. Examination of hyporheic discharge to the channel with specific ranges of residence times shows that the mean water temperatures of upwelling flows with a week-timescale flowpath is 21.4 °C, which is not low enough to reduce the river temperature but could provide a thermally constant input to moderate minimum and maximum daily temperatures if fluxes were high enough. Hyporheic discharges with month-timescale flowpaths have a mean temperature of 11 °C, which is capable of cooling the stream water because it is less than the minimum daily summer temperature. However, hyporheic discharges in this category decreased by 19percent after restoration. Flowpaths with an annual timescale have a mean water temperature of 9 °C and were increased by 16percent after restoration. However, measured hyporheic discharge entering the river channel was limited owing to the low hydraulic conductivity of the valley sediments. The low magnitude of hyporheic discharge and its limited post-restoration cooling potential indicates that some other mechanism must be responsible for the reach-scale thermal buffering seen at Bird Track Springs.

Thermal pool stratification can explain the reach-scale thermal buffering in the Bird Track Springs reach. Nighttime pool filling with cool water from upstream creates cool pool temperatures at the beginning of each day. As surface waters warm from solar insolation during the day, shearing of the stratified thermal boundary of each pool serves to export cool water from the pool bottoms downstream. This phenomenon can reduce the duration of lethal conditions at the bottoms of individual pools and cumulatively at the reach scale, but cannot reverse the lethal conditions entering at the upstream boundary over the reach analyzed here. Further, pool stratification is flow-dependent and only has the capability to impact thermal buffering at low discharges (<30 ft^3/s at Bird Track Springs). To link the concepts of pool volume and streamflow, we show that when the cumulative hydraulic residence time of all the pools in the reach is greater than 3 hours, thermal buffering becomes influential within the study site. This suggests that pool stratification only affects reach-scale water temperatures at very low-flow conditions in the Grande Ronde River.

Field observations tested for the presence of thermal refuge in the Bird Track Springs restoration reach. The observations showed mean daily surface water temperatures vary seasonally and sometimes exceed the 25 °C threshold in summer. On average, temperatures remain well above 18 °C stress threshold for Chinook from June to late August, and then late June to early August can exceed the migration barrier and mortality. Refuge was measured in discrete patches within morphologic features and depended on their location within the channel. Pools had the greatest number of thermal refuge measurements, followed by riffles, spring channels, the pool downstream of the backfilled channel, alcoves, and plane bed features. Low magnitude hyporheic fluxes during summer conditions had limited impact on water temperatures in the channel and thermal refuge, but some features could retain those fluxes to facilitate refuge. Further, specific morphologic features generated longitudinal changes in water temperature over their spatial extent. On average, pools cooled water by 0.5 °C, riffles increased temperatures by 0.48 °C, and plane bed features increased temperatures by 0.4 °C. Without riparian vegetation to shade the channel, spring channels had limited ability to cool the temperatures in the main channel. Cool groundwater inputs to spring channels were warmed by the time they joined the main channel, thereby making them ineffective for thermal buffering.

Future restoration projects targeting increased hyporheic flow for thermal benefits should evaluate the hydraulic conductivity of floodplain sediments and existing hyporheic fluxes in the channel during the design phase to assess the potential for using channel morphology to increase subsurface flows. The limited hyporheic discharge proved insufficient to generate cool-water patches in the channel without a morphologic feature to retain those cool inputs. For example, measured upwelling fluxes where the channel had a plane bed or riffle morphology resulted in no observed thermal refuge, irrespective of the flux magnitude. In contrast, pool features with lower magnitude fluxes often had thermal refuge present. Thus, the low-magnitude hyporheic discharge may constitute only a limited part of the mechanics generating thermal refuge in these features, and other physical mechanisms like cool nighttime filling and thermal daytime stratification in pools provide the primary driver of thermal refuge. In smaller morphologic features like alcoves and spring channels, riparian shading and increased flow depth would improve potential for generating thermal refuge.

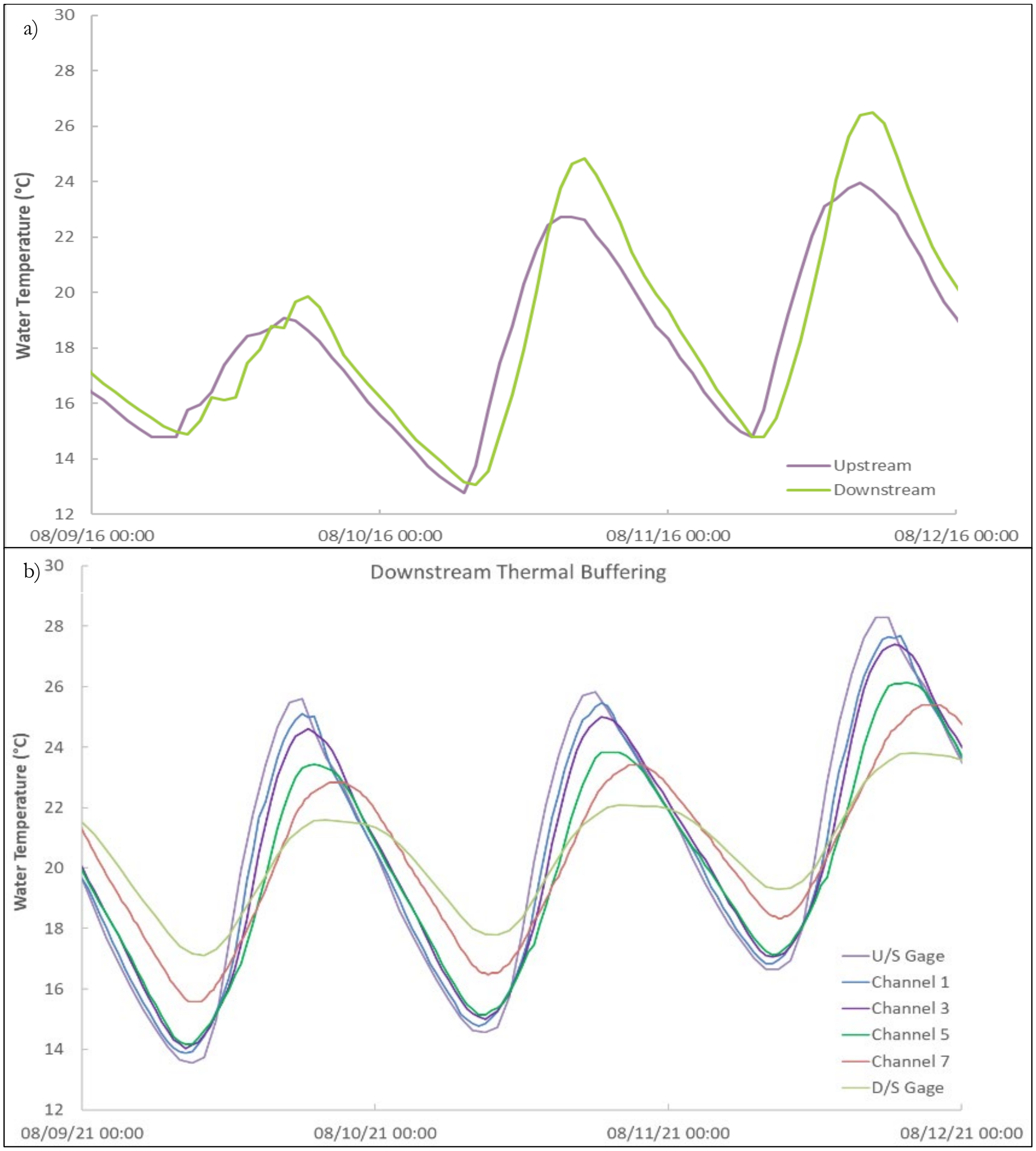

Figure ES-1.—Hourly surface water temperatures from a) tidbits from upstream and downstream of the pre-restoration reach in 2016 and b) tidbits and temperature probes between the upstream and downstream gages in the post-restoration channel in 2021. Post-restoration water temperatures exhibit thermal buffering from upstream and downstream. Increasing channel numbers represent increased longitudinal distance in the channel.

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