HYPORHEIC FLOW ENHANCEMENT

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Abstract

This paper explores and evaluates the possible use of hyporheic flow enhancement to mitigate elevated water temperatures affecting aquatic species in the upper Chehalis River Basin. The Chehalis Flood Control Zone District engaged the Kleinschmidt consulting team to prepare a mitigation assessment to guide planning for mitigation to address unavoidable impacts to aquatic and terrestrial resources resulting from construction and operation of flood hazard mitigation measures including a Flood Reduction Only – Expandable (FRE) facility and levee improvements. Early in the mitigation planning process, project impacts on water temperatures were identified as a high-priority project impact that would be particularly challenging to address in the context of a watershed impaired by elevated water temperature as a pre-project baseline condition. The Kleinschmidt team identified hyporheic flow enhancement as a potential innovative mitigation technique to address project impacts on water temperature. The analysis documents examples of hyporheic flow enhancement and discusses the feasibility and potential benefits of incorporating hyporheic flow enhancement as a component of a comprehensive aquatic habitat mitigation plan.

Stream temperatures in Western Washington have been increasing for decades as a result of land use activities that include forestry, agriculture, flood control, water diversions, and development. Native salmon and trout species are particularly dependent on water temperature for survival. Protecting cold-water aquatic life from existing and anticipated future thermal stress will require significant watershed management actions that include expansion and preservation of woody riparian vegetation, transfer of water rights to instream flow during low flow periods, floodplain reconnection, utilization of groundwater inflow areas, and the enhancement of hyporheic zones. The hyporheic zone is defined as the saturated interstitial areas beneath the stream bed and into the stream banks that contain some proportion of channel water or that have been altered by channel water infiltration (White 1993). In floodplain rivers with lateral hyporheic zones that are larger than the surface area of the stream channel, interstitial volume available to conduct hyporheic flow can be greater than the surface water volume (Edwards, 1998). Hyporheic flow is biogeochemically distinct from groundwater and serves many valuable functions in dynamic freshwater systems, including instream thermal regulation and nutrient cycling in support of primary biomass production. Because benefits would be realized within one year of enhancement, hyporheic flow projects as early actions could provide readily implementable thermal refuge for sensitive aquatic species while additional, more long-term, actions (such as riparian planting to increase shade) are implemented in the watershed. Enhancement of hyporheic flow

exchange has the potential to increase the migration, spawning, and rearing success of native anadromous salmonids and increase primary production that supports the aquatic food chain. Thermal mitigation can be achieved in the riverine environment by modifying and capitalizing on existing geographic locations and morphologic features that are already actively providing hyporheic flow exchange or have the capacity to improve exchange. An effective application of hyporheic flow enhancement would be to establish strategically distributed pockets of accessible cold water thermal refugia for aquatic species during times when average water temperatures are detrimental or lethal to aquatic species. Such a strategy could be applied as an early action that provides immediate and sustained benefits during the longer time required to increase the extent of forested riparian zones that shade the drainage network and provide long-term water temperature reduction. While this analysis initially focused on the water temperature benefits of hyporheic flow enhancement, research has revealed a broad and complex suite of ecological benefits provided by hyporheic flow. In conclusion, hyporheic flow enhancement could be used strategically as an integrated component of an aquatic mitigation plan providing multiple ecological benefits in addition to thermal refugia.

Introduction

Stream temperatures in Western Washington have been increasing for decades as a result of landuse activities that include forestry, agriculture, flood control, water diversions, and development. Some water bodies, including the Chehalis River, have experienced water temperature increases that have exceeded water quality criteria for aquatic species, thereby impacting the migration, spawning, and rearing of native anadromous fish species. Climate change is expected to exacerbate the warming trend primarily by decreasing late summer flows and increasing heat transfer from warmer air to stream water. In many of Washington's streams and lakes, the duration of periods that cause stress to salmon because of warmer temperatures and migration barriers is projected to at least double and perhaps quadruple by the 2080s (Mantua et al. (2010)). The expanded warm water duration is expected to have the greatest impact to late summer and early fall spawning. Increased water temperatures can be lethal for salmon and other cold-water species.

Protecting cold water aquatic life from existing and anticipated future thermal stress will require significant watershed management actions that include expansion and preservation of woody riparian vegetation, transfer of water rights to instream flow during low flow periods, floodplain reconnection, utilization of groundwater inflow areas, and the enhancement of hyporheic zones. This discussion is focused on enhancement of the hyporheic zone and hyporheic flow exchange because it is an early action that can provide readily implementable thermal refuge for sensitive aquatic species while additional, more long-term, actions can be incorporated into the watershed.

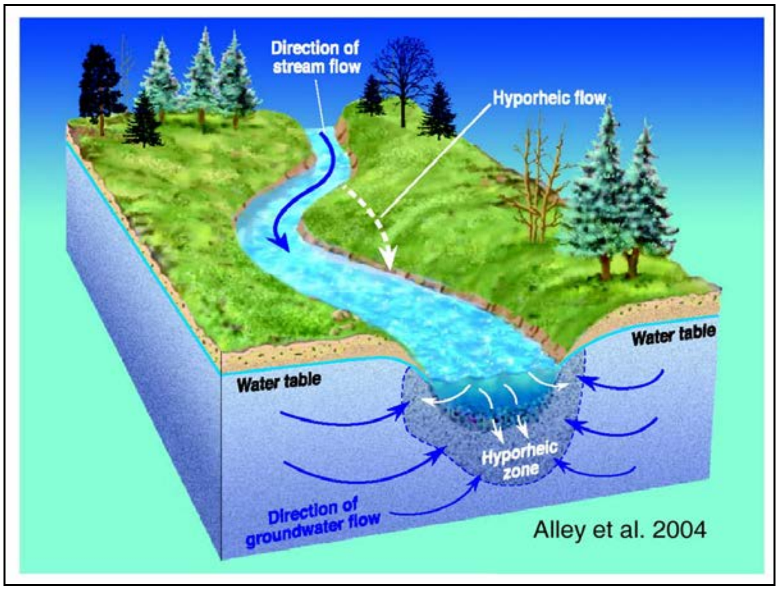
The hyporheic zone is defined as the saturated interstitial areas beneath the stream bed and into the stream banks that contain some proportion of channel water or that have been altered by channel water infiltration (White 1993). The word “hyporheic” is composed of the latin words “hypo”, meaning below, and “rheic”, meaning flow. The hyporheic zone is the volume of native porous materials, including sand and gravel, that undergoes an exchange of flow between the shallow groundwater and surface water (Figure 1). The flow of water through this zone is referred to as hyporheic flow. Hyporheic flow is biogeochemically distinct from groundwater. Hyporheic flow serves many valuable functions in dynamic freshwater systems, including instream thermal regulation and nutrient cycling in support of primary biomass production. These two primary functions will be treated separately here with an emphasis on thermal regulation. Enhancement of hyporheic flow exchange has the potential to increase migration, spawning, and rearing success of native anadromous salmonids andincrease primary production that supports the aquatic food chain.

Overview of Hyporheic Zone Functions and Processes

Definition of the Hyporheic Zone

An important and defining element of the hyporheic zone is the presence of surface water because of its influence on both thermal exchange and biogeochemical processes, or the flow of chemical elements and compounds between living organisms and the physical environment. There is an important distinction between surface water, groundwater, and hyporheic water in defining the influence of the hyporheic zone. In the context of the riverine environment, “Surface water” is water that is contained within the river channel with sources that include direct rainfall, surface runoff, and groundwater inflow. “Groundwater” is subsurface water that has not entered a channel or other surface water body. “Hyporheic water” is subsurface water within close proximity to a river channel that contains a significant proportion of surface water resulting from direct exchange between the channel and the underlying and adjacent saturated interstitial areas. Defining the hyporheic zone by surface water content within the interstitial areas associated with a stream channel provides a framework for understanding the thermal exchange and biogeochemical processes between the channel and the hyporheic zone. The hyporheic zone can also be defined in more strictly biological terms. Hyporheic fauna, known as the hyporheos, are often distinguished by life history characteristics or adaptations to life within sediment intersticies (Edwards, 1998).

Figure 1: Hyporheic Zone –

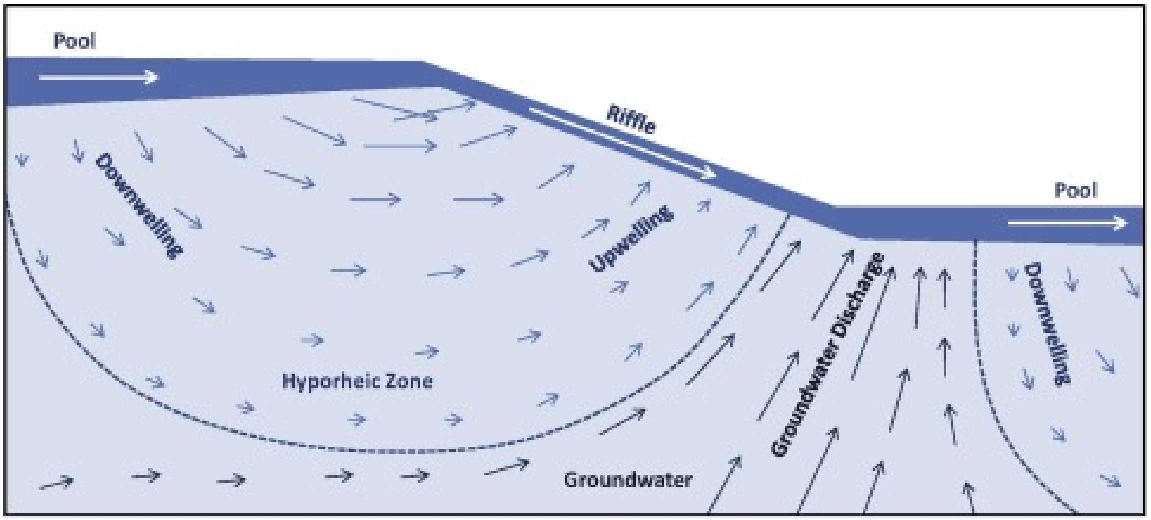


Hyporheic zones in alluvial rivers are dominant links between the riparian forest and the stream channel. The porous, hydraulically conductive sediments characteristic of alluvial rivers of the Pacific coastal ecoregion support extensive hyporheic zones. Hyporheic zones are hotspots of biological diversity that contain intensive physical and chemical gradients. Hyporheic zone processes can dominate surface water quality (Edwards, 1998). Rivers with extensive hyporheic zones retain and process nutrients with greater efficiency than rivers without. Organic matter elimination can be two times greater in rivers with intact hyporheic zones. Upwelling nutrients from hyporheic zones influence primary production within surface communities and accelerate the recovery of surface production from floods and other disturbances (Edwards, 1998).

Hydrology and Hydraulics

Understanding the hydrology and hydraulics of hyporheic flow exchange is necessary to better understand the natural formation of hyporheic zones, how human activity can impact them, and what measures can be taken to enhance them. The hydrology of the hyporheic zone, defined by the exchange of water between the stream channel and the adjacent porous materials (such as sand, gravel, and cobble), controls the rate and extent of biogeochemical processes, nutrient cycling, and thermal exchange. Depending on the extent of alluvium within a river valley and the strength of processes driving hyporheic flow, the hyporheic zone may extend vertically up to tens of meters and horizontally hundreds of meters to more than a kilometer (Stanford and Ward 1988). In floodplain rivers with lateral hyporheic zones that are larger than the surface area of the stream channel, interstitial storage volume available to conduct hyporheic flow can be greater than the surface water storage volume. Stanford and Ward (1988) estimated hyporheic flow volumes along a floodplain reach of the Flathead River in Montana to be 2,400 times greater than channel volume. Generally, downstream flow rate in the channel is much larger than the rate of flow through the hyporheic zone, but it is possible for the volume of water stored within the hyporheic zone to be much greater than the volume of water present in the channel.

Figure 2: Hyporheic Zone Hydraulics in a Pool-Riffle Stream Reach (profile view)



Flow through the hyporheic zone can be estimated using Darcy's law, described as:

Q = (K)A(∆h/∆l)

Where:

Q = Discharge of water through sediment (m^3/s)
A = Cross sectional area of flow (m^2)
K = Hydraulic conductivity of the sediment through the hyporheic zone (m/s)
∆h = Hydraulic head between two points under consideration (m)
∆l = Distance between the two points under consideration (m)

Hyporheic flow is primarily dependent on the hydraulic conductivity of the sediment and the hydraulic head on the sediment. Hydraulic conductivity is a measure of flow resistance, and is a function of sediment particle size, shape, and grading (particle size distribution). Sediment particle sizes range from boulders in the high energy reaches of mountain streams to silts and clays in the lower energy reaches and estuaries. Grading can range from well graded with greater pore space and higher hydraulic conductivity to poorly graded with lesser pore space and lower hydraulic conductivity. The high porosity of alluvium in the Pacific coastal ecoregion creates large interstitial volume and high flow velocities, which are optimal traits for hyporheic flow (Edwards, 1998).

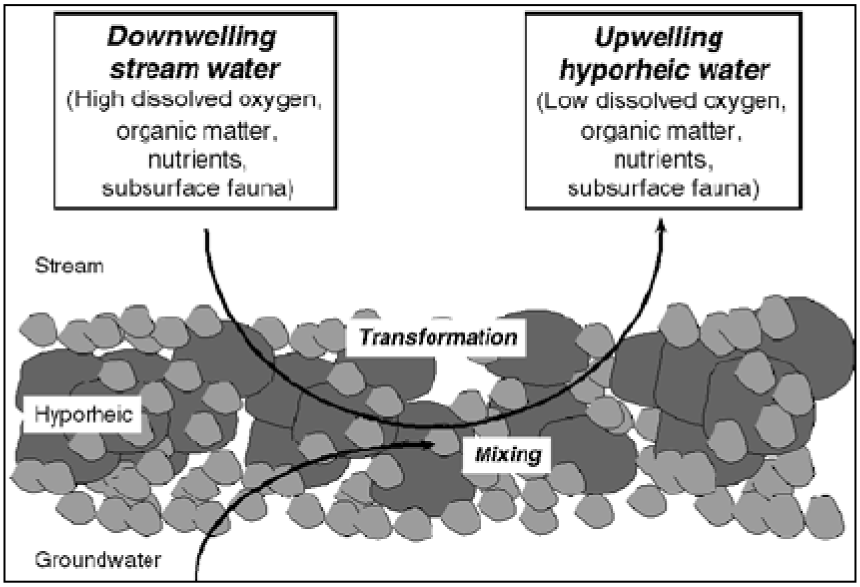
Total hydraulic head in an open channel, such as a stream, is a combination of static and dynamic head. Static head is measured as pressure created by the horizontal depth of water between two points. Dynamic head is measured as the pressure created by the momentum of water in motion. Hydraulic head is the driving force of hyporheic exchange. In the Darcy equation, division of the hydraulic head by the distance over which it is measured gives the hydraulic gradient. The greater the hydraulic gradient is the higher the hyporheic flow will be for a given hydraulic conductivity.

Hydraulic conductivity and hydraulic head are the controlling factors in the *rate* of flow through the hyporheic zone. The *volume* of flow is a function of the area of flow, with rate multiplied by area equaling flow. Efforts to increase hyporheic flow should include increasing hydraulic head on the hyporheic zone, increasing hydraulic conductivity of the sediments, and/or increasing the cross-sectional flow area.

Biogeochemical Processes

Hyporheic flow exchange is the driving force of biogeochemical processes within the hyporheic zone that have a profound effect on nutrient cycling and biological activity within streams (Figure 3). A biogeochemical cycle is a natural pathway by which essential elements of living matter are circulated. The hyporheic zone is an ecotone, or a region of transition between two biological communities, that provides a biogeochemical link between the riparian forest and the stream channel. The influence of hyporheic biogeochemical processes on water quality and primary production of organic matter stems from the combination of an enormous, highly reactive surface area and long periods of sediment and water contact (Edwards, 1998). The surface area available for biological activity within hyporheic zone sediments of alluvial rivers can be much greater than the surface area of the channel. Stanford and Ward (1988) estimated hyporheic habitat volume to be 2,400 times greater than channel habitat volume along a floodplain reach of the Flathead River, Montana.

Figure 3: Hyporheic Exchange Nutrient Cycling



Nutrient cycling in the hyporheic zone is enhanced by a process of transient storage that increases the residence time of water and expands the contact time between solutes and the hyporheos, or the collective organisms that inhabit the hyporheic zone. Essential elements of living matter that are cycled through the hyporheic zone include oxygen, nitrogen, carbon, phosphorus, carbon dioxide, and methane. Oxygen is supplied to the hyporheic zone by the downwelling of oxygenated stream water and from photosynthesis occurring in the algal communities of the hyporheos. Algal communities are more concentrated in areas of upwelling adjacent to riparian areas in the Pacific Northwest that include a red alder (*Alnus rubra*) component of the woody vegetation due to the higher concentration of dissolved nitrogen from nitrogen fixation. Primary production in the streams of Western Washington and Oregon can be limited by low nitrogen levels. In relatively undeveloped forested portions of watersheds, the primary source of nitrogen is nitrogen fixation through the symbiotic relationship between red alder trees *(Alnus rubra*) and *Frankia alni*, an actinomycete, filamentous, nitrogen-fixing bacterium. Red alder is a common riparian zone tree in the Pacific Northwest that fixes nitrogen within the hyporheic zone. Downwelling of hyporheic water from a forest containing red alder trees supplies nitrogen in support of the base of the food chain that ultimately provides food for juvenile salmonids.

Carbon is typically supplied to the stream and its hyporheic zone as inputs of organic matter from the riparian zone. This organic carbon serves as a food source for non-photosynthetic microorganisms living on the sediment surfaces known as the epilithon. Epilithic bacteria within this community rapidly take up and metabolize dissolved organic matter, thereby serving as the primary driver of carbon cycling.

Hyporheos Ecology

Bacteria and protozoans readily colonize rocks and sediments near hyporheic upwelling and downwelling in the benthic zone. The benthic zone is the ecological region within a water body that includes the sediment surface and shallow subsurface layers. Benthic microbe populations are primarily responsible for organic matter decomposition and oxygen consumption. Respiration within the hyporheic zone is a major fraction of total river metabolism (Grimm and Fisher 1984, Edwards and Myer 1987, Pusch and Schwoerbel 1994). Organic matter deposited by the stream and dissolved in hyporheic water is the food source for the community of microorganisms living on the surface of sediment particles. This community of microorganisms, known as the epilithon, is ubiquitous on surface sediments. It is composed of layers of bacteria, fungi, protozoans, and meiofauna (Karlstrom 1978). Meiofauna are small benthic invertebrates that include herbivores and omnivores that feed on the epilithon microbes and are a primary source of food for juvenile fish. Current understanding of the abundance, distribution, community structure, productivity, and trophic structure of subsurface communities is limited (Edwards, 1998).

Hyporeheos ecology and productivity is supported by the nutrient cycling that is driven by hyporheic flow exchange. The food web within the hyporheic zone is fully dependent on the supply of particulate and dissolved organic matter delivered to it from outside the zone (allochthonous material). Much of the organic matter, including from leaves and wood, delivered to the hyporheic zone is carried and deposited by higher, bank full flow events. However, in alluvial reaches of pacific coastal streams, buried wood from previous channel migrations is often abundant and lasts for centuries. Large amounts of slowly decomposing buried wood provide a continuous source of food to hyporheic fauna despite the low return frequencies of fresh inputs (Edwards, 1998). Downwelling water in the hyporheic zone delivers organic material, carbon, micronutrients and oxygen to the epilithon. The dissolved oxygen contained in downwelling surface water is necessary for the aerobic metabolism of the organic material.

Upwelling water in the hyporheic zone supplies nitrogen to the epilithon where nitrogen fixing Red alder (*Alnus rubra*) trees are a component of the riparian woody vegetation. Red alder fixes nitrogen well in excess of its needs, creating a reservoir of nitrogen adjacent to the stream and into the hyporheic zone. In upper basins of Pacific coastal ecoregion rivers, where primary production is limited by the availability of nitrogen, the input of nitrogen from hyporheic zones significantly influences primary and secondary production and invertebrate grazing in the stream. Epilithic algae are concentrated at sites of upwelling hyporheic water where standing stocks of epilithic chlorophyll in backchannels are seven times greater than in downwelling zones (Edwards, 1998).

Hyporheic Thermal Exchange

Pacific Northwest streams are critical to the migrating, spawning, and rearing life stages of native Anadromous fish, including salmon and steehead trout (*Oncorhynchus sp.*), bull trout (*Salvelinus confluentus*) smelt (*Thaleichthy pacificus*), and Pacific lamprey (*Entosphenus sp.)*. Salmon, steelhead, and Bull trout are cold water fishes with multiple life stages that are sensitive to, and greatly affected by, stream temperatures. Moreover, water temperature in Pacific Northwest mountain streams regulates virtually every biotic component of the aquatic ecosystem (Thompson, 2005).

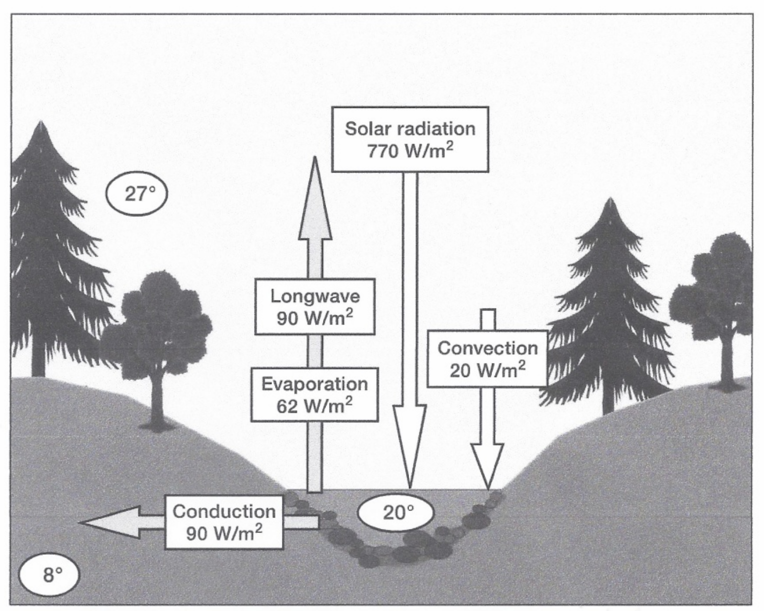
Stream water temperature is a function of multiple heat inputs and losses. A simplified heat budget of a stream is shown in Figure 4 below (Thompson, 2005). White arrows indicate heat transfer to the stream, and grey arrows indicate heat loss from the stream. Temperatures inside the ovals represent typical temperatures of the air, stream, and ground that can be experienced during late summer in the Pacific Northwest. All heat exchange figures are in units of Watts per square meter (W/m^2). Thermal inputs in order of descending magnitude include direct solar radiation, convection from air to water, and hyporheic exchange. Thermal losses in order of descending magnitude include longwave radiation, hyporheic exchange, and evaporation. In this simplified heat budget, heat lost to the hyporheic zone is 90 W/m^2, or approximately 11% of all heat inputs per square meter.

Solar radiation is the dominant source of heat input to streams, with its thermal contribution between one and two orders of magnitude greater than the contribution from convection. The simplified heat budget presented in Figure 4 is representative of the magnitude of heat inputs to a stream that lacks shade from an intact riparian forest. Due to the dominance of solar radiation as a source of thermal inputs to streams, the most effective means of reducing thermal stress for aquatic life is to decrease solar radiation inputs by increasing the level of shading. Hyporheic flow exchange can remove some, but not all, of the heat from stream water resulting from solar inputs.

When water leaves the stream channel and comes into contact with the cooler substrate, it loses heat through conduction, the process of heat transfer from warmer to cooler bodies of matter. The quantity of heat transferred is a function of the temperature difference between the stream and the substrate and the length of time of contact. High hyporheic flow rates will result in greater total heat loss for a given temperature differential between the stream and substrate. However, high flow rates will result in a lower temperature drop between downwelling stream water and upwelling hyporheic water due to the shorter contact time.

Low hyporheic flow rates will result in greater temperature drops between the stream and hyporheic flow for a given temperature differential due to the longer time of contact. However, low flow rates will result in smaller total heat loss and smaller quantities of water cooled.

Figure 4: Simplified Heat Budget of a Stream (Thompson, 2005).



The thermal reduction associated with hyporheic flow exchange is of interest in the Pacific Northwest because it has the potential to reduce stream temperatures and improve migration, spawning, and rearing habitat for salmonid fishes. Although the heat loss in the hyporheic zone may be a significant portion per unit area of the total heat added to a stream through solar radiation and convection, it is not effective over the full length of a stream because most hyporheic flow exchange occurs at very specific geomorphic features. Heat inputs can occur the full length of a stream, but the effect of solar radiation varies with changes in shade from riparian vegetation, orientation of the channel, and topography. Geomorphic features that support hyporheic exchange include pool-step systems, pool and riffle systems, sinuous and meandering channels, secondary or side channels, paleo channels (subsurface channel deposits), channel splits and island gravel bars, and meander point bars.

The results of a study of the influence of hyporheic flow on water temperature in the Clackamas River in Oregon during the summer of 2006 suggests that hyporheic exchange will cool the average temperature of larger rivers only a fraction of a degree. Hyporheic flow may only comprise a fraction of 1% of total river flow, and that fraction varies with stream flow. Hyporheic flow is most impactful and beneficial at lower river flows because it is a larger fraction of total river flow and lower river flows generally coincide with the highest water temperatures of the year. It is therefore difficult for hyporheic exchange to exert a significant effect on overall stream temperature, because any hyporheic buffering present is diluted by larger surface water discharges (Burkholder, *et al*. 2008). However, hyporheic exchange can produce small patches of cooler water that increase thermal heterogeneity within the river channel and can provide thermal refugia (up to 4°C cooler) for aquatic species that are stressed by conditions in the mainstem channel (Fernald *et al*., 2006 and Arscott *et al*., 2001). This local refuge benefit can be of critical importance to fish survival and is the focus of this paper in regards to mitigation value.

Hyporheic Zone Distribution

The distribution of hyporheic zones in a drainage basin varies with the physical processes that control sediment production, routing, and discharge. The interaction of geologic, geomorphic, and hydrologic processes determines the location, volume, and shape of sediment accumulation in the channel network, the shape and particle size distribution of the substratum, and the magnitude and location of head differentials necessary to drive water through a porous medium (Edwards, 1998). There can be great variability in the size, location, and flow exchange rates between different drainage basins and different reaches within a drainage basin.

Drainage basin factors that control hyporheic zone formation include bedrock geology, basin hydrology, and channel gradient. All of these factors have both temporal and a spatial variability within a drainage basin. Basin geology will have a strong influence on the characteristics of the sediment, including size and texture. Basin hydrology and channel gradient (hydraulics) will drive the transport, sorting, and placement of sediments.

In mountain streams, the steeper upper reaches will typically provide high hydraulic heads to drive hyporheic flow but will often have a bedrock substrate, constrained valleys, and insufficient sediment to facilitate hyporheic exchange. As stream channel gradients decrease in the downstream direction, hydraulic head decreases but sediment deposits increase. The lowest reaches of a stream may contain high volumes of sediment but very low hydraulic head. Hydraulic conductivity of sediments also generally decreases in the downstream direction, with very high conductivity in the boulder substrate of the upper basin and very low conductivity in the silt and clay substrate of the lower basin. The middle reaches of mountain streams are therefore likely to have the best combination of hydraulic head and sediment hydraulic conductivity to facilitate hyporheic exchange.

Hyporheic exchange appears to be significantly influenced by the geomorphic type of stream reach in a drainage basin. Colluvial reaches, or those with significant inputs of colluvium (unconsolidated material that accumulates at the base of slopes), are often steeper gradient reaches with significant hydraulic head, but the sediment tends to be poorly sorted with a low hydraulic conductivity. Colluvial reaches can be expected to have a lower rate of hyporheic exchange than alluvial reaches. Bedrock reaches contain a high proportion of solid rock substrate with very low hydraulic conductivity and therefore support only small areas of hyporheic exchange. Alluvial reaches contain high volumes of sediment transported and sorted by water combined with sufficient hydraulic head to produce conditions most favorable for hyporheic exchange (Edwards, 1998). Within the Chehalis River Basin, alluvial reaches are present both upstream and downstream of the proposed FRE site and likely support hyporheic exchange. Bedrock reaches are more prevalent upstream of the FRE site, and extensive alluvial reaches dominate the river morphology for tens of miles downstream with localized exceptions.

Chehalis River Basin Thermal Impacts

Within the state of Washington, water quality standards are published pursuant to Chapter 90.48 of the Revised Code of Washington (RCW). Listed streams in the Upper Chehalis River Basin are designated as Class A with a temperature criterion of 18°C. Temperature in a Class A waterbody shall not exceed 18°C due to human influences (DOE, 2001).

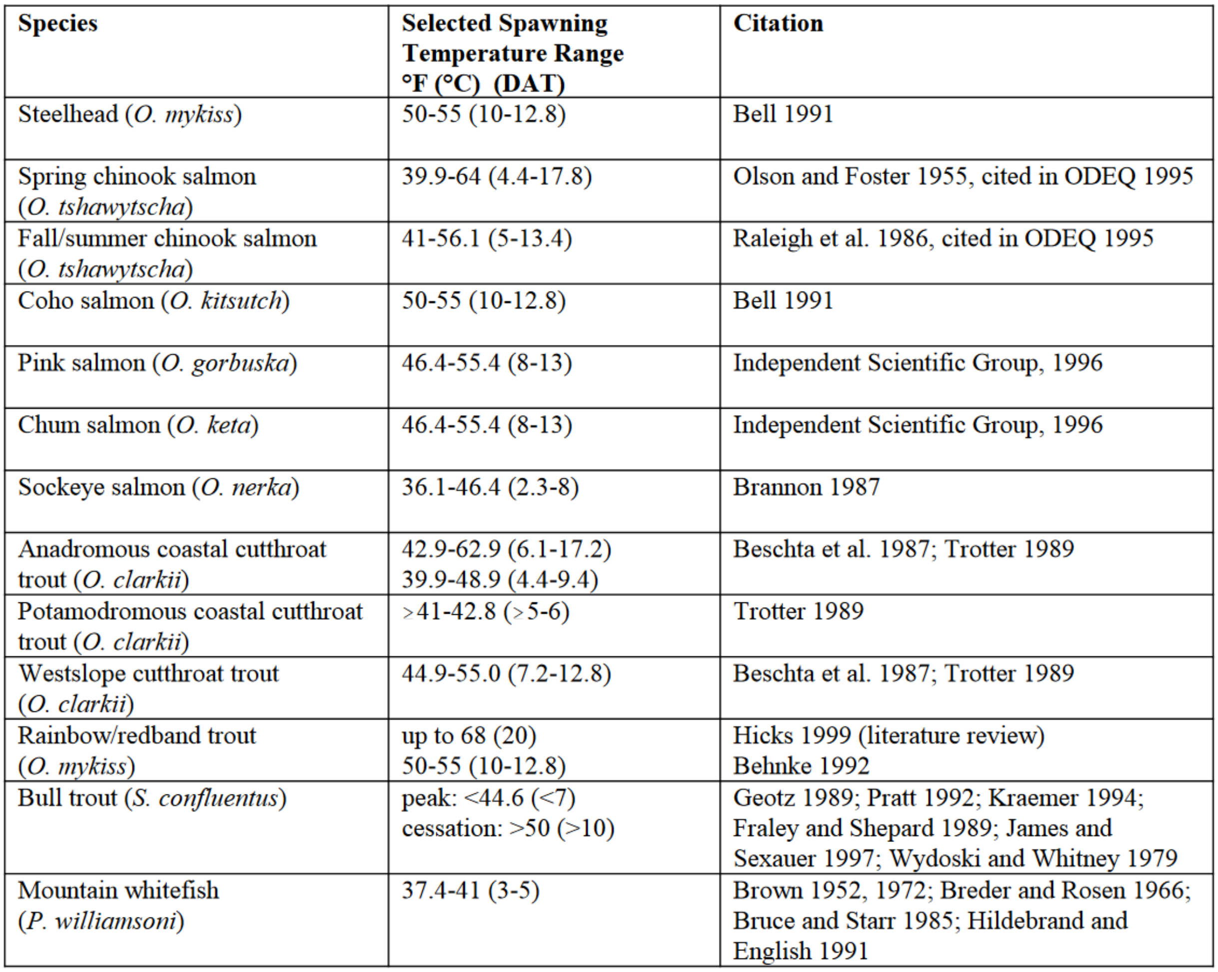
High stream temperatures are a known concern in the upper Chehalis Basin. Data collected by the Washington Department of Ecology's (Ecology) Ambient Monitoring Program at ten stations between October 1991 and September 1998 were compiled and descriptive statistics generated (Table 1). Months with exceedances of the temperature criterion are shaded pink in Table 1. Ecology has documented exceedances of temperature criteria at long-term monitoring stations in nearly all years since 2001. Chehalis Basin streams affected include Mainstem Chehalis River, Black River, South Fork Chehalis River, Dillenbaugh Creek, Lincoln Creek, Newaukum River, Salzer Creek, Scatter Creek, and Skookumchuck River (DOE, 2001).

Table1. Temperature Statistics of the Upper Chehalis River Basin (DOE, 2001).

Month	**Number of Samples**	**Mean Temperature (°C)**	**Median Temperature (°C)**	**Maximum Temperature (°C)**	**Samples over the Criteria (%)**
January	29	5.1	4.9	9.1	0
February	29	5.1	5.0	9.7	0
March	29	8.3	8.2	11.3	0
April	29	10.0	10.0	12.8	0
May	29	14.1	14.5	18.1	0.1
June	29	16.3	16.2	24.5	17
July	29	18.9	18.5	22.2	62
August	29	16.9	17.0	19.8	24
September	29	13.6	13.6	18.4	<0.1
October	29	9.4	9.4	13.1	0
November	29	7.2	7.4	10.1	0
December	29	5.4	4.9	10.5	0

Temperatures are expected to continue to rise in the Chehalis Basin due to climate change and future human activities. Historical human activities, including urban and residential development, agriculture, and logging, have degraded riparian vegetation in the Chehalis River Basin, contributing to warmer stream temperatures in some locations (DOE, 2001). Stream temperatures have tremendous influence over the adult migration, spawning, egg incubation, smolt and juvenile rearing, and adult holding of salmonids. Table 2 below provides preferred spawning temperatures by species.

Table 2. Selected water temperatures for spawning by Pacific Northwest salmonids. For the purpose of water temperature criteria protective of spawning salmonids, these references are assumed to be Daily Average Temperatures (DAT) (EPA Region 10).



Species	**Selected Spawning Temperature Range °F (°C) (DAT)**	**Citation**
Steelhead (*O. mykiss*)	50-55 (10-12.8)	Bell 1991
Spring chinook salmon (*O. tshawytscha*)	39.9-64 (4.4-17.8)	Olson and Foster 1955, cited in ODEQ 1995
Fall/summer chinook salmon (*O. tshawytscha*)	41-56.1 (5-13.4)	Raleigh et al. 1986, cited in ODEQ 1995
Coho salmon (*O. kitsutch*)	50-55 (10-12.8)	Bell 1991
Pink salmon (*O. gorbuska*)	46.4-55.4 (8-13)	Independent Scientific Group, 1996
Chum salmon (*O. keta*)	46.4-55.4 (8-13)	Independent Scientific Group, 1996
Sockeye salmon (*O. nerka*)	36.1-46.4 (2.3-8)	Brannon 1987
Anadromous coastal cutthroat trout (*O. clarkii*)	42.9-62.9 (6.1-17.2) 39.9-48.9 (4.4-9.4)	Beschta et al. 1987; Trotter 1989
Potamodromous coastal cutthroat trout (*O. clarkii*)	>41-42.8 (>5-6)	Trotter 1989
Westslope cutthroat trout (*O. clarkii*)	44.9-55.0 (7.2-12.8)	Beschta et al. 1987; Trotter 1989
Rainbow/redband trout (*O. mykiss*)	up to 68 (20) 50-55 (10-12.8)	Hicks 1999 (literature review) Behnke 1992
Bull trout (*S. confluentus*)	peak: <44.6 (<7) cessation: >50 (>10)	Geotz 1989; Pratt 1992; Kraemer 1994; Fraley and Shepard 1989; James and Sexauer 1997; Wydoski and Whitney 1979
Mountain whitefish (*P. williamsoni*)	37.4-41 (3-5)	Brown 1952, 1972; Breder and Rosen 1966; Bruce and Starr 1985; Hildebrand and English 1991

Despite the variations in observed spawning temperatures, the Independent Scientific Group (1996) states that the optimal temperature for anadromous salmonid spawning is 50°F (10°C) and that stressful conditions for anadromous salmonids begin at temperatures greater than 60.08°F (15.6°C,) with lethal effects occurring at 69.8°F (21°C) (EPA Region 10). As shown in Table 1, the water temperatures in the Upper Chehalis River Basin currently exceed preferred spawning temperatures during the time period of May through September.

Future human activity in the Basin, combined with the altered hydrology and thermal regimes resulting from climate change, is expected to cause an increase in stream temperatures. The Chehalis River Basin Flood Control Zone District is proposing to construct a flood retention facility (FRE) and associated temporary reservoir near Pe Ell, Washington, on the Chehalis River and make changes to the Chehalis-Centralia Airport levee to reduce flood damage in the Chehalis-Centralia area. Based on computer model results, river temperatures would increase both within the temporary reservoir area and downstream of the FRE facility. The combination of trees removed during construction and trees that die in response to episodic inundation during operation of the FRE would cause the river temperature to increase due to decreased shading. The increase would be as much as 5.4°F (3°C) in the reservoir area and immediately downstream and as much as 9°F (5°C) within the temporary reservoir at Crim Creek. Farther downstream, the increases in temperature would be less and are estimated to end about 20 miles downstream of the facility (DOE 1). The magnitude of the expected temperature increase is sufficient to eliminate optimal spawning temperatures in the Mainstem Chehalis River for potentially 20 miles downstream of the proposed facility for the entire year, and extend stressful spawning conditions to the months of April and October. A temperature increase of 3°C would also create lethal conditions for salmonids for 7 months of the year in the Mainstem Chehalis River reach downstream of the FRE.

Thermal and Hyporheic Flow Mitigation

Cold-water refugia protect salmonids from extreme water temperatures and also permit them to behaviorally thermoregulate to conserve energy when water temperatures are suboptimal. In stream reaches that have warmed above levels optimal for salmonids, fish persist by using cold-water refugia (Berman and Quinn 1991, Li et al. 1994, Neilson et al. 1994, McIntosh et al.1995a, Torgersen et al. 1999, King 1937, Mantelman 1958, Gibson 1966, as cited in McCullough1999) (EPA Region 10). Salmonids will migrate to cooler water when stream temperatures are less than optimal.

Thermal refugia are distinct geographic areas within a riverine system, separated from the main stream flow, with water temperatures noticeably different than the main flow and more optimal to critical life stages of aquatic organisms during periods of seasonally extreme water temperatures. Thermal refugia include warmer zones during the cold of winter and cooler zones during the heat of the summer. Warm summer stream temperatures that are suboptimal for salmonid life stages and other aquatic fauna have been trending upward for decades and are expected to be exacerbated by climate change. Stream temperatures have been increasing far more rapidly than salmonid populations can adapt, resulting in significant impact to reproduction and survival. Cold-water refugia is becoming a critical means of providing thermal mitigation for rising stream temperatures.

Based on EPA guidance, the Oregon Department of Environmental Quality developed a more specific definition: "*Cold-Water Refugia* means those portions of a water body where, at times during the diel temperature cycle, the water temperature is at least 2°C colder than the daily maximum temperature of the adjacent well-mixed flow of the water body." (OAR 340-041-0002 [10]) (EPA Region 10 2).

Alluvial valleys are more likely to have reach-scale cold-water refuges formed by hyporheic processes, whereas bedrock canyons primarily may be limited to tributary sources (EPA Region 10-2). Cold-water refugia is found near groundwater seeps, tributary confluences, and areas of hyporheic flow exchange where mixing with main channel surface water is limited (e.g. side channels, backwater areas, and pools sheltered by in-stream structure). Although hyporheic flow can be greater than surface flow, the volume of hyporheic flow exchange between the channel and its substrate is typically much less than the overlying surface flow. Once fully diluted by the surface flow, upwelling hyporheic water will have a negligible effect on average stream temperature. Limited mixing of inflowing cool water with main channel surface flow is critical for producing cool-water refugia by avoiding thermal dilution by the main flow.

Thermal mitigation can be achieved in the riverine environment primarily by modifying and capitalizing on existing geographic locations and morphologic features that are already actively providing hyporheic flow exchange or have the capacity to improve exchange. Thermal mitigation opportunities that capitalize on groundwater and cooler surface water sources may also exist at their confluence with mainstem surface water.

The fluvial geomorphic features that are most conducive to facilitating hyporheic exchange include the following:

1. Pool-step systems
2. Pool and riffle systems
3. Sinuous/meandering channels
4. Secondary or side channels
5. Paleo channels
6. Channel splits and island gravel bars
7. Meander point bars

All of these features are prevalent within the Chehalis Basin and the Willapa Hills Subbasin, however some features are more conducive to modification for the purpose of enhancing hyporheic flow for thermal mitigation. Geomorphic features that are most conducive for hyporheic flow enhancement for thermal mitigation are listed below. Pool-step systems are smaller features within the landscape that are more difficult to access, due to steeper and more rugged terrain, and should be considered a lower priority for consideration as mitigation sites. Pool and riffle systems can provide hyporheic exchange on a small scale and are more likely to be accessible for modification than pool-step systems, but they should also be considered a lower priority for consideration as mitigation sites compared to other opportunities that can provide larger-scale benefits.

Thermal Mitigation Site Characteristics

The fluvial geomorphic features that can provide significant hyporheic exchange, can be readily modified for enhancement of hyporheic flow, and are more likely to be accessible for construction of enhancements include the following. All of these sites are also readily discernible on aerial imagery. Larger sites should be prioritized over smaller sites.

1. Gravel bars with side channels
2. Channel splits with gravel islands
3. Large degree (> 90°) meander bends with long cross-peninsula flow paths
4. Sinuous reaches with point bars
5. Paleo channels
6. Straightened channel reaches that can be re-meandered

Nutrient Mitigation Site Characteristics

Primary production in the streams of Western Washington and Oregon can be limited by low nitrogen levels. In relatively undeveloped forested portions of watersheds, the primary source of nitrogen is nitrogen fixation through the symbiotic relationship between red alder trees (Alnus rubra) and Frankia alni, an actinomycete, filamentous, nitrogen-fixing bacterium. Red alder is a common riparian zone tree in the Pacific Northwest that fixes nitrogen within the hyporheic zone. Downwelling of hyporheic water from a forest containing red alder trees supplies nitrogen in support of the base of the food chain that ultimately provides food for juvenile salmonids. Wherever the riparian zone and its red alder component has been reduced within the watershed, the base of the aquatic food chain has been reduced, thereby diminishing secondary production. The primary site characteristic that can provide nutrients to the stream, can be readily modified for enhancement (red alder tree planting), and is likely to be accessible for modification is listed below.

1. Riparian areas adjacent to the ordinary high water line and lacking woody vegetation

Floodplain Mitigation Site Characteristics

Stream channel incision reduces, and in some cases eliminates, frequent interaction between the stream and its floodplain. Regular activation of the floodplain is one of the means by which the hyporheic zone is recharged with stream water for later release as cooler and more nutrient rich hyporheic water back into the channel. Restoring the floodplain connection can enhance the hyporheic flow and its associated thermal and nutritional benefits. Examples of actions that help to restore the floodplain reconnection include the addition of step structures to the channel using native wood and rock materials, lowering the floodplain elevation, or both. Another floodplain enhancement that could increase hyporheic zone recharge and create additional aquatic thermal refuge is the excavation of channels and alcoves into the floodplain. The primary site characteristics that can provide mitigation through floodplain reconnection are listed below. Incised channels may be difficult to identify through examination of aerial imagery.

1. Floodplains that are lacking flood vulnerable structures and any significant woody vegetation (to avoid removing riparian forest)
2. Incised channels with adjacent disconnected floodplain
3. Paleo channels that can be reconnected to the mainstem.

Other Thermal Mitigation Site Characteristics

Groundwater and surface water can also provide thermal refugia at their confluence with mainstem surface water. Site characteristics that are likely to be potential thermal refugia mitigation opportunities are listed below.

1. Surface water tributaries with mean water temperatures at least 2°C lower than main stem surface water temperatures. Surface water tributaries are often mapped and easily identifiable from aerial imagery and field investigations. Temperature differentials are readily measurable with inexpensive data loggers.
2. Groundwater seeps, springs, and upwelling areas with mean water temperatures at least 2°C lower than main stem surface water temperatures. Groundwater sources of inflow to surface water can be estimated based on geomorphological assessments at the basin, subbasin, and segment level. More detailed analysis using remote sensing techniques, such as aerial photography, LiDAR, and thermal infrared imaging combined with ground truthing may be necessary to more accurately delineate and define potential groundwater supported thermal refugia.

Hyporheic Flow Exchange Enhancement Measures

Hyporheic flow exchange can be enhanced to improve thermal diversity and refugia, nutrient cycling, and primary production to mitigate degradation caused by human activities and climate change. Potential enhancement actions listed below are presented as specific to fluvial site characteristics but are very generic in nature. Design and implementation of hyporheic flow enhancement projects will be site specific.

1. **Gravel bars with side channels**: Install engineered log jams, log weirs, rock weirs, or beaver dam analogs to increase the hydraulic head at the upstream end. Decrease mainstem flow through the side channel through restrictions or plugs at the upper end of the channel. Excavate deeper channel or pool at the lower end of the side channel. Beaver dam analogs may not be applicable on larger streams.
2. **Channel splits with gravel islands**: Install engineered log jams, log weirs, rock weirs, or beaver dam analogs to increase the hydraulic head at the upstream end. Decrease mainstem flow through the side channel through restrictions or plugs at the upper end of the channel. Excavate deeper channel or pool at the lower end of the side channel. Beaver dam analogs may not be applicable on larger streams.
3. **Large degree (> 90°) meander bends with long cross-peninsula flow paths**: Install engineered log jams, log weirs, or rock weirs to increase the hydraulic head at the upstream end of the bend.
4. **Sinuous reaches with point bars:** Enhance floodplain connection and provide gravel augmentation to increase the hyporheic zone if sediment supply has been limited.
5. **Paleo channels:** Reconnect paleo channels at the downstream end to provide fish access for refugia. Create alcove near downstream end.
6. **Straightened channel reaches that can be re-meandered:** Re-meander channel appropriate to geomorphic setting and provide gravel augmentation if needed to increase the hyporheic zone.
7. **Riparian areas adjacent to the ordinary high water line and lacking woody vegetation:** Replant riparian zone with diverse assemblage of native woody species to include red alder (Alnus rubra).
8. **Floodplains:** Restore floodplain activation frequency and extent by installing in-channel hydraulic roughness and/or lowering the floodplain within the hyporheic zone through excavation and grading.
9. **Incised channels with adjacent disconnected floodplain:** Restore floodplain activation frequency and extent by installing in-channel hydraulic roughness and/or lowering the floodplain within the hyporheic zone through excavation and grading. Install grade control structures to reduce further incision.
10. **Cold water tributaries, seeps, and springs:** Excavate pools between the cold water source and the mainstem channel that minimize dilution with mainstem surface water to provide holding areas for fish.

Figure 5: Example Chehalis River Hyporheic Flow Exchange Mitigation Downstream of Pe Ell, Washington.

Hyporheic Flow Project Examples

Five example projects were identified and described to illustrate applications of hyporheic flow enhancement in rivers and streams in the Pacific Northwest region. The following project descriptions are taken directly and unedited from the abstracts of the reports prepared by the technical contributors for each of these projects.

<u>Floodplain Restoration Increases Hyporheic Flow in the Yakima River Watershed, Washington</u>

> A parameterized groundwater model was used to study the effects of floodplain restoration on hyporheic flow in Gap to Gap region of Yakima Basin, Washington during steady and transient states. The attributes of hyporheic flow pathlines generated from the particles adjacent to Yakima River were compared for pre- and post-restoration periods. It was noticed that at two transects along the Yakima River where levee setback occurred, there was change in the directions of hyporheic pathlines. The change in the directions of the pathlines resulted in wider area of coverage and likely surface water and groundwater interactions. Statistical tests conducted to compare the lengths of the hyporheic pathlines for pre- and post-restoration conditions, showed that restoration in the form of levee setback resulted in increase in the length of pathlines after floodplain restoration. Model simulations during transient state showed that the longest pathlines during both pre- and post-restoration (pre: 398.19 m and post: 460.57 m) occurred in relatively drier periods. Overall, this study supported the hypothesis that flood plain restoration efforts in the form of levee setback should improve the hyporheic

flow in the floodplain regions. The improved hyporheic flow and river reconnection to greater floodplain area should improve the ecosystems conditions that support more opportunities for enhanced biogeochemical processing, improved water quality, and restoration of habitat to occur (Harsh et al. 2018).

Key Applications to Chehalis Basin Mitigation:

- Removing artificial constraints (in this example, levee setback) and floodplain reconnection can increase the extent of hyporheic exchange.
- Largest increases occurred during drier periods.

Thornton Creek Hyporheic Process Restoration: Design and Performance of an Engineered Streambed

Stream restoration designed specifically to enhance hyporheic processes has seldom been contemplated. To gain experience with hyporheic restoration, an engineered streambed was built using a gravel mixture formulated to mimic natural streambed composition, filling an over-excavated channel of Thornton Creek in Seattle, Washington to a minimum depth of 90 cm. Specially designed plunge-pool structures, built with subsurface gravel extending down to 2.4 m, promoted greatly enhanced hyporheic circulation, path length, and residence time. Hyporheic process enhancement was verified using intra-gravel temperature mapping to document the distribution and strength of upwelling and downwelling zones, computation of vertical water flux using diurnal streambed temperature patterns, estimation of hyporheic zone cross section using sodium chloride tracer studies, and repeat measurements of streambed sand content to document evolution of the engineered streambed over time. Results showed that vertical water flux in the vicinity of plunge-pool structures was quite large, averaging 89 times the pre-construction rate, and 17 times larger than maximum rates measured in a pristine stream in Idaho. Upwelling and downwelling strengths in the constructed channel were larger and more spatially diverse than in the control. Streambed sand content showed a variety of response over time, indicating that rapid return to an embedded, impermeable state is not occurring.

Key Applications to Chehalis Basin Mitigation:

- This project demonstrated on a small scale that hyporheic flow conditions could be engineered effectively into a stream restoration project
- Hyporheic flow enhancements were persistent over time and did not degrade as a result of fine sediment accumulation or embeddedness.

Bird Track Springs Fish Habitat Enhancement Project Environmental Assessment

To address limited habitat conditions for native fish within the project area, the US Forest Service and the Bonneville Power Administration have proposed actions for the Bird Track Springs reach of the Grand Ronde River in Oregon that would re-establish natural river-floodplain connections and processes. Natural processes within this reach of the Grande Ronde River (GRR) include multiple channel networks created through forcing mechanisms of large wood, ice, beaver, and rock. To meet the purpose and need described above, the following types of activities are proposed within the Bird Track Springs project area (USFS et al., 2018):

•Improve channel geometry to reduce width-to-depth ratios through large wood placement, channel fill, and bar construction.
•Place large wood structures throughout the mainstem channel to provide habitat and channel control. •Place floodplain wood and plant native shrubs to reduce overland velocities and trap ice.
•Increase channel/floodplain interactions by removing topographical features that inhibit overland flows (historical railroad grade).
•Increase connectivity of existing channel scars (swales) and enhance fish cover.
•Re-meander channel in appropriate locations to reconnect to floodplains and existing swale networks while improving channel form and function.
•Improve alcove connectivity to mainstem and enhance fish cover.
•Enhance and protect existing functional juvenile fish-rearing habitats.
•Improve connectivity of spring-fed side channels, wetlands, and alcoves to provide additional summer and winter rearing habitats.
•Plant native vegetation to improve riparian and floodplain conditions and to shade the stream.
•Reduce risk of erosion to highway embankments and ice damage through strategic placement of log structure treatments, rock, and graded features.

Key Applications to Chehalis Basin Mitigation:

- This is a large-scale project example that will restore complex physical and ecological interactions between the river and its floodplain. This is a good project to monitor for insights regarding multiple benefits of restoration actions that affect hyporheic exchange.

Opportunities and Limitation of Hyporheic Restoration in a 4th Order Semi-Arid Floodplain: A Case Study of Meacham Creek, Oregon

Persistent societal interest in improving water quality and recovering imperiled, native, aquatic species has expanded the scope of stream restoration to include the hyporheic zone as a focus. Despite the lack of detailed studies, hyporheic restoration is often invoked as a means to achieve multiple objectives including moderation of water temperature, delay of seasonal flows and increasing the localized volume of floodplain water. The ongoing Meacham Creek case study monitors changes as a result of stream restoration of the hyporheic zone of a 4th order, alluvial floodplain in northeast Oregon. Active and passive restoration of 2.5 km of Meacham Creek has altered the creek from a single-threaded, incised and bedrock-dominated channel to a perched, alluvial channel that seasonally exchanges overbank flows with the surrounding floodplain. Our results suggest that the stream restoration effort on Meacham Creek has increased the volume of annual hyporheic storage and created a more diverse distribution of flowpath lengths within the restoration site. Furthermore, our monitoring indicates that hyporheic process response to stream restoration, analogous to other geomorphic processes, conforms to a systematic hierarchy where nested flow paths range in length and residence time from meters and hours at the habitat scale to tens of meters and months at the floodplain scale. We assert that scale-explicit and measurement-focused restoration planning has a greater likelihood of meeting the

> stated objectives and result in improved water quality and encourage recovery of many native aquatic species (O'Daniel et al., 2014).

Key Applications to Chehalis Basin Mitigation:

- Demonstrated success enhancing hyporheic exchange on a 2.5-mile river reach
- Example of effectively integrating hyporheic enhancement into a multi-faceted, multi-objective ecological restoration effort
- The longer hyporheic flow paths that have residence times of months will store colder water entering the hyporheic zone in the winter and spring that is then released to the stream during the summer hotter months.

<u>Influence of hyporheic flow and geomorphology on temperature of a large, gravel-bed river, Clackamas River, Oregon</u>

> The hyporheic zone influences the thermal regime of rivers, buffering temperature by storing and releasing heat over a range of time scales. We examined the relationship between hyporheic exchange and temperature along a 24-km reach of the lower Clackamas River, a large gravel-bed river in northwestern Oregon (median discharge = 75·7 m^3/s; minimum mean monthly discharge = 22·7 m^3/s in August 2006). With a simple mixing model, we estimated how much hyporheic exchange cools the river during hot summer months. Hyporheic exchange was primarily identified by temperature anomalies, which are patches of water that demonstrate at least a 1°C temperature difference from the main channel. Forty hyporheic temperature anomalies were identified through field investigations and thermal-infrared radiometry (TIR) in summer 2006. The location of anomalies was associated with specific geomorphic features, primarily bar channels and bar heads that act as preferential pathways for hyporheic flow. Detailed field characterization and groundwater modelling on three Clackamas gravel bars indicate residence times of hyporheic water can vary from hours to weeks and months. This was largely determined by hydraulic conductivity, which is affected by how recently the gravel bar formed or was reworked. Upscaling of modelled discharges and hydrologic parameters from these bars to other anomalies on the Clackamas network shows that hyporheic discharge from anomalies comprises a small fraction (<<1 %) of mainstem discharge, resulting in small river-cooling effects (0·012°C). However, the presence of cooler patches of water within rivers can act as thermal refugia for fish and other aquatic organisms, making the creation or enhancement of hyporheic exchange an attractive method in restoring the thermal regime of rivers (Burkholder et al., 2008).

Key Applications to Chehalis Basin Mitigation:

- During warm summer months, hyporheic exchange contributes to formation and persistence of thermal refugia.
- Hyporheic exchange makes little difference in the overall temperature of the main river flow.

- Hyporheic flow and associated thermal refugia zones were linked to identifiable geomorphic features.

Summary

Recent research clearly demonstrates that the hyporheic zone plays a central role in controlling instream thermal diversity, nutrient cycling, and primary production. In addition to beneficial effects on water temperature, enhancement of hyporheic flow exchange has the potential to increase the migration, spawning, and rearing success of native anadromous salmonids and enhance the aquatic food chain. Hyporheic flow enhancement, using a suite of techniques, provides viable options for aquatic habitat mitigation measures to increase thermal diversity and refugia, enhance nutrient cycling, and support the aquatic food chain. Fluvial geomorphic features that can provide significant hyporheic exchange, can be readily modified for enhancement of hyporheic flow, and are more likely to be accessible for construction of enhancements include the following:

- Gravel bars with side channels
- Channel splits with gravel islands
- Large degree (> 90°) meander bends with long cross-peninsula flow paths
- Sinuous reaches with point bars
- Straightened channel reaches that can be re-meandered
- Riparian areas adjacent to the ordinary high water line and lacking woody vegetation
- Floodplains that are lacking flood vulnerable structures and any significant woody vegetation (to avoid removing riparian forest)
- Incised channels with adjacent disconnected floodplain
- Paleo channels that can be reconnected to the mainstem.

Project examples demonstrate the effectiveness of successful hyporheic enhancement efforts. Key observations from those examples include:

- Hyporheic enhancement works best when it is an integrated component of a comprehensive restoration strategy. Specific restoration sites integrate multiple physical and ecological processes and components.
- Large-scale hyporheic enhancement is possible with levee setbacks and floodplain reconnection efforts.
- Engineered and constructed hyporheic zones can be effective at a small scale.

Hyporheic flow enhancement may be applied most effectively as a strategic component of a comprehensive aquatic habitat mitigation plan. For mitigation of temperature impacts, hyporheic enhancement would be most effective for providing thermal refugia. Due to the small ratio of hyporheic flow to surface water flow, this approach would not produce a meaningful reduction in the overall temperature of the water body. But for salmonids in warm rivers, thermal refugia can greatly increase their probability of survival. By providing thermal refugia, hyporheic enhancement provides immediate benefits to aquatic species during the time it would take for riparian reforestation to mature and provide long-term temperature mitigation.

Other potential opportunities to enhance thermal refugia in the Chehalis Basin include modification of groundwater sources that contribute flow directly to the river and its tributaries. Groundwater sources that may produce water that is significantly cooler than mainstem surface water include cold water tributaries, seeps, and springs. These features can be modified to improve their function as thermal refugia through the excavation of pools between the cold water source and the stream channel to minimize the dilution of the cooler water by the warmer surface water and to provide holding areas for fish.

Hyporheic Video

Please see the video at this link for an overview of the value of the hyporheic zone:

https://www.youtube.com/watch?v=cGEXjbEP0YA&feature=youtu.be

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