Potential effects of gravel augmentation on temperature in the Clackamas River, Oregon

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Abstract

Reintroducing gravel to rivers whose sediment supply has been reduced or depleted by dams and reservoirs is emerging as a new approach to river restoration. Although gravel augmentation is primarily used to allow rivers to rebuild bars, riffles, and other habitat features, it may also help mitigate the thermal effects of reservoirs by increasing hyporheic exchange, thereby reducing temperature peaks and variation. This project aims to evaluate the effectiveness of gravel augmentation for providing thermal benefits through a coordinated and sequenced two-phase set of field, modeling and experimental investigations. Initial field investigations will attempt to characterize the geomorphology and temperature conditions of the current gravel bedform network located on an 18-mile river reach below the River Mill Dam on the Clackamas River. Data collected will include detailed mapping and surveys, determination of hydrogeologic data, detailed thermal profiles within and downstream of gravel deposits, and current flow volumes and residence times of water traveling through these features. This information will be input to the CE-QUAL-W2 model that will be developed to explore the expected magnitude, timing, and longitudinal trends of temperature effects from sediment volumes and 3-dimensional architectures. If results from this first phase are promising, a second phase of experimental validation of model results will be conducted by pilot studies and potential use of the flume facilities at the National Center for Earth-Surface Dynamics in Minneapolis, MN. This could lead to progressively larger field implementations and measurements of thermal effects of gravel augmentation. Taken together, this project will provide a sound technical basis for predicting likely temperature benefits of gravel augmentation and designing optimum augmentation strategies.

Introduction

As part of the relicensing application for its Clackamas River Hydroelectric Project, Portland General Electric (PGE) is considering a gravel introduction that may involve adding thousands of cubic meters of gravel annually to the Clackamas River below River Mill Dam (hereafter "the lower river"). This augmentation is primarily intended to restore channel morphology and sediment transport interrupted by the dam complex, but may also have ancillary benefits for mitigating temperature effects of the upstream dams and reservoirs. Theoretically, gravel augmentation will increase hyporheic exchange, where surface water enters the riverbed and flows along subsurface paths before returning to the main channel. Because this exchange promotes mixing of waters of different ages and temperatures, it can potentially buffer stream temperatures, thereby reducing maximum temperatures in the lower river.

Determining the magnitude and timing of temperature changes that might result from gravel augmentation is challenging, however. To date, no models address both hyporheic flow and heat exchange in rivers, and there is little field data to guide decision makers. This proposal seeks to address this gap through a coordinated set of field studies, modeling, and experiments. Successful completion of this project will test whether increasing hyporheic flow through gravel augmentation can provide thermal benefits, as well as help design the most efficient gravel augmentation program to accomplish this objective and fulfill others, such as enhanced fish habitat.

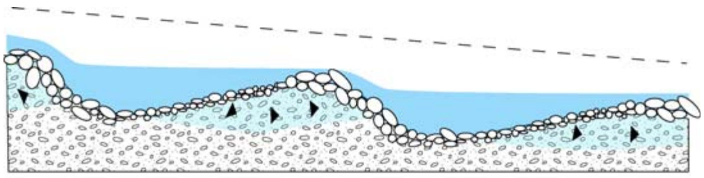
In this report we summarize the evidence, drawn from the literature, of possible thermal cooling associated with increased hyporheic flow, and describe a field study intended to explore the potential thermal benefits of gravel augmentation on the Clackamas River. The field study seeks to estimate the reduction in peak temperature likely to result from gravel augmentation in the Clackamas River (Phase 1), and test alternative designs and approaches to gravel augmentation for the purpose of maximizing thermal benefits while achieving improved fish habitat benefits (Phase 2).

Background

Hyporheic exchange occurs when surface water enters the riverbed and flows along subsurface paths before returning to the main channel. Because this exchange promotes mixing of waters of different ages and temperatures, the rate of hyporheic exchange exerts a first-order control on the distribution of instream heat exchange, making it a dominant mechanism for buffering stream temperature (*Poole and Berman, 2001).*

Hyporheic exchange occurs at different spatial and temporal scales. At the finest scale (streambed scale), hyporheic flow is driven by local hydraulic pressure gradients due to local variations in hydraulic slope, i.e., at the heads and tails of riffles or steps (Fig. 1). Water enters the channel bed, travels through it, and exits at rates determined by the character of the hyporheic flow paths, hydraulic gradient, and bed sediment characteristics that determine hydraulic conductivity. At the scale of larger alluvial rivers, where the hyporheic zone is an area of mixing between moving surface and ground water as well as standing water, the hyporheic zone is much more complex.

While external drivers (i.e. solar radiation, air temperature, and windspeed) determine total heat exchange of a river (*Sullivan and Adams, 1991*), internal buffers including the hyporheic zone determine the temporal and spatial distribution of heat energy within the stream. Hyporheic exchange removes heat/water from the channel when temperature/discharge is high and releases heat/water to the channel when temperature/discharge is low (*Poole and Berman, 2001*). Therefore, although hyporheic exchange may not affect the mean temperature of water in a reach, it may dampen diel or seasonal fluctuations, decrease maximum temperatures, and increase minimum temperatures. Figure 2 shows how this works in an idealized system.



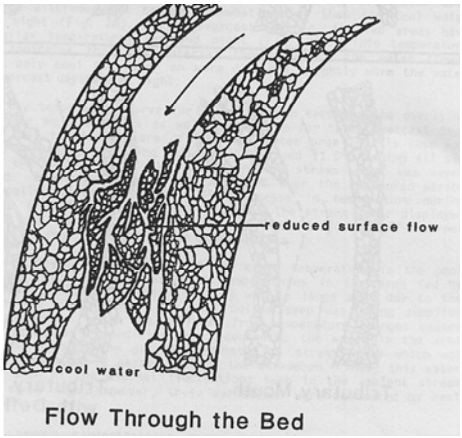


Figure 1: Schematic views of hyporheic flow through gravel a) cross-section (after *Stewart, 2004*) b) map view (from *Bilby, 1984*)

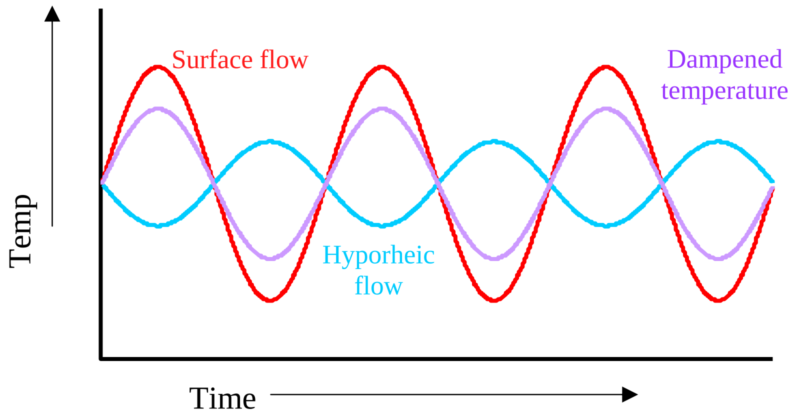


Figure 2: Idealized schematic demonstrating how out-of-phase diurnal temperature peaks and troughs of hyporheic and surface flow combine to buffer temperature extrema. Hyporheic flow that is 12 hours out of phase will lower peak temperature the most, but any phase lag will result in a peak temperature decrease.

Stream temperature in the absence of hyporheic exchange is shown in **red**. Average stream temperature is determined by the inputs and outputs of heat, and diurnal maxima and minima are determined by the daily timing of these inputs and outputs as well as by temporary exchanges of heat between the channel and subsurface (hyporheic exchange) and in-channel mixing (dispersion). The temperature of hyporheic water as it returns to the channel is shown in **blue**. The temperature of hyporheic water is out of phase with water in the stream channel due to slower transport and heat exchange of the water in the hyporheic zone. The net effect of hyporheic exchange is to buffer stream temperature extrema – the maxima (peaks) are lowered and the minima are raised, but the average remains the same. The net stream temperature in the presence of hyporheic exchange is shown in **purple**

Literature Review

Temperature field studies over a wide range of stream sizes, scales, and geographies support the finding that increasing hyporheic exchange through gravel can affect stream temperatures. We identified field 16 studies that discuss the effects of hyporheic flow through gravel on stream temperature (Table 1). These studies fall into two general categories: those that looked at surface and hyporheic temperature effects associated with specific *bedforms* (i.e., gravel bars and riffles) (11 studies), and those that examined *reach* longitudinal trends in surface temperature as a function of channel morphology (i.e., bedrock vs. alluvial reaches) (4 studies). One study (Arscott et. al., 2001) examined both scales. Only two of these studies (Merz & Setka, 2004; Stewart, 2004) actually compared stream temperatures before and after gravel emplacement or deposition, either by artificial or natural processes.

For each reference, we identify the river location and give a brief description of what the study measured relevant to our inquiry (Table 1). This description includes whether the study reports the temperature of the surface river water or the hyporheic (or intergravel) temperature within a bedform, and how temperature was measured over what spatial and temporal scales. The right hand columns of the table present the details of the observed temperature effect and summarize its direction and magnitude.

Bedform scale

At the bedform scale, an early study compared cool areas to ambient river stream temperatures and attributed 10 of the 29 cool areas to hyporheic flow through gravel (*Bilby, 1984*). Five of these sites were described as “flow through gravel” (shown in Figure 1b); the other five were described as “pool bottom seeps.” Five more recent studies conducted on relatively small catchments (3rd- to 4th-order) measured temperature at the heads and tails of gravel riffles, and four report cooling of hyporheic water (*White et al., 1987; Evans & Petts, 1997; Hancock & Boulton 2005; Sliva & Williams, 2005). Fowler & Scarsbrook (2002)* report cooling of surface water above and below riffles in two of the rivers they studied, and slight warming in the third. *Moore et al. (2005)* measured temperature variations within a step-pool unit and also demonstrates that on average, upwelling temperatures are cooler than downwelling temperatures.

A study within the Taillon-Gabietous catchment, France measured cooler temperatures within the hyporheic zone, as well as showed field evidence of the phase shift of temperature in the hyporheic zone (*Brown et al., 2005*). The smallest phase shift is seen in shallow gravels, while the largest phase shift is seen in deep gravel (Fig. 3).

The study focusing on the largest river (Willamette River, OR) measured hyporheic flow rates and surface water temperatures through gravel bars and into off-channel areas, termed “alcoves”, and found an inverse relationship between rate of hyporheic flow and alcove water temperature (*Fernald et al., 2000*). Half of the alcoves were colder than the main river by an average of 4.5 °C, although there was considerable site-to-site variation. This study reports that the greatest effects of hyporheic flow on surface water temperatures were found at sites with recently reworked, highly porous gravels.

Another large river study on the Tagliamento River in northern Italy documented daily and seasonal fluctuations in surface water temperature for 22 “habitats” extending from narrow constrained headwaters to wide alluvial floodplains, and related a range of temperature metrics to environmental factors (*Arscott et. al., 2001*). Although elevation and aspect were the dominant controls on daily temperature patterns within habitats, the influence of surface-groundwater

Table 1: Summary of Studies

	Reference	River	Order	Study	Measures	Spatial Scale	Temporal Scale	Method	Description of Temperature Change	average direction and
bedform scale	Arscott et al., 2001	Tagliamento River [ITALY]	2nd-7th	compares different "habitats"	surface	22 sites within 5 reaches	hourly for 1 year (May 1998 to June 1999)	continuous - VEMCO Minilog	surface-groundwater interaction dampens variation in stream temperature	↓ no data
	Hunt et al., 2006	Allequash, North & Stevenson Creeks, WI	1st-2nd	compares sites of groundwater discharge and recharge	surface & hyporheic	1 site per stream	every 3-15 hours for 1.5 yr	continuous - Onset Hobo tidbits & thermocouples	Hyporheic temperatures cooler than surface water	↓ -6 ↓ -3.4 ↓ -4.8
	Moore et al., 2005	Malcolm Knapp Research Forest, BC [CANADA]	1st-2nd	measures variations within step-pool unit	surface	24 locations over 325m long reach	10 minute intervals for summer 2001	continuous - Onset Hobo tidbits	upwelling cooler than downwelling on average	↓ -2
	Fowler & Scarsbrook, 2002	Makaretu, Tukituki and Waipawa Rivers [NZ]	3rd-4th	compares head and tail of riffles	surface	3 riffles per river (9 sites total)	once during 24-27 March 1999	point - Orion portable meter	Makaretu sites increased up to 1.7C Tukituki sites decreased up to 0.9C Waipawa sites decreased up to 3.5C	↑ +1 ↓ -0.5 ↓ -3.2
	White et al., 1987	Maple River, MI	3rd-4th	compares head and tail of riffles (below reservoir)	hyporheic	3 pool-riffle-pool sections	1-3 times (July, Oct, March)	point - YSI probe	at 2 sites tail cooler than head 1 site no change	↓ -4.5 - no data
	Sliva & Williams, 2005	Speed River, Ontario	not specified	compares pool-riffle-pool	surface & hyporheic	1 segment ~11 km long	3 times over summer & fall 2001	continuous - Hydrolab Scout Multiprobe	upwelling cooler than downwelling	↓ no data
	Brown et al., 2005	Taillon-Gabietous catchment [FRANCE}	not specified	compares surface and hyporheic temperatures	surface & hyporheic	8 sites over 5 reaches	15 min intervals, summer 2002	continuous - Campbell scientific thermistors	Hyporheic temperatures cooler than surface (also exhibits lag in diurnal fluctuations)	↓ -3.4
	Bilby, 1984	Thrash Creek, WA	5th	classifies "cool areas" by morphology/ hydrology	surface & hyporheic	10 sites over 3.5 km	once during summer 1982	point - handheld probe	5 undergravel flow sites (riffles, bars & side channels, landslide deposits) 5 pool-bottom seep sites (not fully mixed with overlying water)	↓ -3.9 ↓ -4.9
	Hancock & Boulton, 2005	Hunter River, NSW [AUSTRAILIA]	not specified	compares heads and tails of riffles	surface	3 sites over 105 km	3, 2-day sampling periods Fall 2001	point - YSI handheld probe	upwelling cooler than downwelling	↓ no data
	Evans & Petts, 1997	River Blithe [UK]	not specified	compares head and tail of riffles (below reservoir)	hyporheic	2 riffles	for 5 days (July 1994).	continuous - Orion Tinytalk-Temp logger	at both sites tail cooler than head	↓ -2.2
	Fernald et al., 2000	Willamette River, OR	8th	compares "alcoves" separated by gravel bars to main channel	surface	6 sites within 60km	twice during August low flow, 1999	point - YSI probe	3 sites temps in alcoves decreased with respect to river water in main channel 2 sites no change 1 site increase	↓ -4.5 - 0 ↑ +2
	*Merz & Setka, 2004	Mokelumne River, CA - augmented with 976m^3 of gravel below dam		compares enhanced gravels to unenhanced gravels	surface & hyporheic	45m reach	4 times over 30 months (2000-2002)	point - YSI probe	enhanced hyporheic water temps statistically cooler than unenhanced no change in ambient river temp	↓ -1.9 - 0
reach scale	Johnson, 2004	Watershed 3, Lookout Creek, OR	2nd	compares bedrock and alluvial reaches	surface	each reach 200 - 300m long	1 month during summer 1997	continuous - Onset stowaway logger	Max temps decrease as much as 8.7C mean temps unchanged	↓ -6.3 - +0.4
	Cozzetto et al., 2006	Von Guerard Stream, Taylor Valley [ANTARCTICA]	not specified	measured longitudinal profile of stream temp	surface & hyporheic	7 sites along 5 km	January 2004	continuous -Optic Stowaway Probes	hyporheic temperatures cooler than stream temperatures	↓ -8.4
	Torgersen et al., 1999	Upper Middle and North Forks, John Day River, OR	not specified	measured longitudinal profile of stream temp	surface	each reach 60-70km long	first week of August 1994	FLIR imaging, continuous loggers and point probes	distinctly cooler reaches attributed to low gradient alluvial valleys	↓ -0.8
	*Stewart, 2004	Dinner Creek, OR (1st-2nd order) - sediment release due to dam removal		compares reach below dam before and after gravel deposition	surface	125m reach	1 year (2003-2004)	continuous - Onset Hobo logger	diurnal fluctuations in temp below dam moderated (mostly by reduction of max temp) after deposition of reservoir sediment	↓ -0.5

* gravel enhancement/deposition study

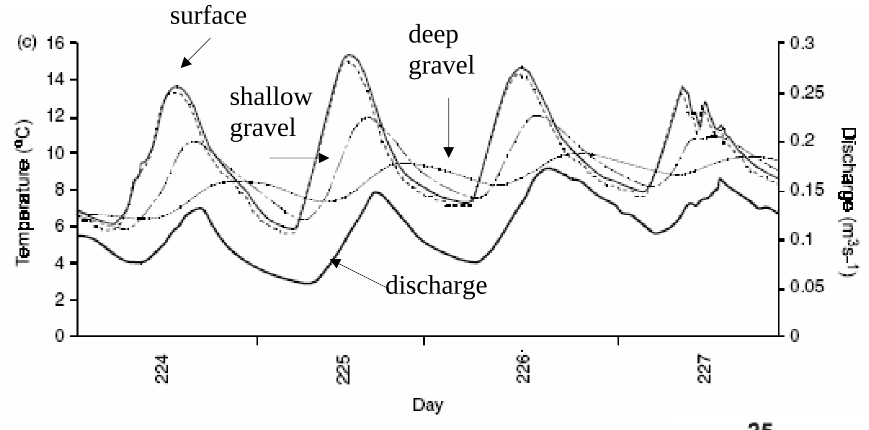
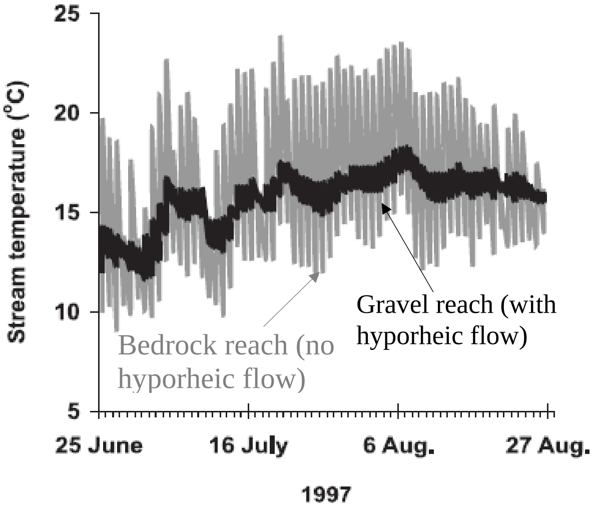


Figure 3: Temperature in the hyporheic zone (shallow gravel and deep gravel) of a small stream (7.7 km^2 catchment) in the French Pyrénées. Note the phase shift in temperature from the surface water to shallow to deep gravel. Modified from *Brown et al.*, 2005.

Figure 4: Stream temperature in two adjacent reaches of a stream (WS03, 1 km^2 catchment) in the HJ Andrews Experimental Forest, Oregon. The stream with large diurnal temperature fluctuations (gray) runs over bedrock and has no hyporheic zone. The stream with small diurnal fluctuations (black) has a gravel bed with a large hyporheic zone. Modified from *Johnson*, 2004.



interaction (as inferred from geomorphic features) on dampening variation in stream temperature was pronounced in both upland and alluvial habitats. Low-gradient habitats displayed more spatial and temporal heterogeneity with respect to temperature than upland habitats, and floodplain habitats displayed a greater temperature variation than the mainstem river. The specificity of the habitat-level definitions used in this study limited comparison with other studies.

Reach scale

Johnson (2004) found that maximum stream temperature decreased by as much as 8.7°C, and diurnal temperature fluctuations were moderated over a 300 m alluvial reach in contrast to a 250 m bedrock reach for a small, 2nd-order headwater stream (Fig. 4). Average water velocities and residence times in the hyporheic zone were slower and longer in this alluvial reach than an adjacent bedrock reach where temperatures increased downstream. Mean daily temperatures in the two reaches were similar.

Torgersen et al. (1999) used FLIR (Forward-Looking InfraRed) imaging to profile longitudinal stream temperature and demonstrate general downstream increases in temperature, punctuated by peaks and troughs. Some peaks were associated with bedrock reaches, and some troughs with flow through low gradient alluvial reaches. Although neither study report specific data, additional work by *Torgersen et al. (2001)* and *Arscott et. al. (2001)* provides drainage basin scale perspectives and comparisons, and argues that different mechanisms are responsible for longitudinal effects on stream temperature as a function of scale.

Cozzetto et al., 2006 measured a longitudinal profile of surface and hyporheic temperatures along a 5-km reach of the Von Guerard stream in Taylor Valley, Antarctica. Two tracer experiments demonstrated cooler temperatures within the hyporheic zone throughout the reach. The addition of snow during one of those experiments greatly enhanced the discharge of the stream, enlarging the hyporheic zone up to three times of its non-perturbed cross-sectional area. This augmented the cooling effect of the hyporheic zone, so that maximum hyporheic temperatures in this experiment were 0.6-1.4°C cooler than those measured in the non-perturbed tracer experiment.

Gravel emplacement/deposition studies

As part of a salmon spawning habitat enhancement experiment, 976m^3 of gravel (25-150mm) was placed in berm and bar configurations in a 45m reach below Comanche Dam on the Mokelumne River, CA. The gravel features were 30 to 100m long, channel spanning, and 0.1 to 2.1m deep. In order to evaluate the primary goals of improving existing and increasing total available spawning habitat, numerous morphologic, hydrologic, and biologic variables were monitored. Surface water and hyporheic temperatures were measured in three enhanced (placed) gravel bars and three un-enhanced (original) gravel bars before, immediately after, and 12 and 24 months after gravel emplacement. Although minimal data was reported, hyporheic temperatures in enhanced bars were cooler than in unenhanced bars, and surface water temperatures were not affected. They suggest that gravel enhancement helped equalize temperatures between hyporheic and surface waters.

Stewart (2004) monitored temperature and geomorphic changes due to removal of a small (4 m high) dam on Dinner Creek, a tributary of the Row River in western Oregon. Temperatures were continuously monitored for a year in the reach below a sediment-filled dam before and after the dam's removal. Prior to and immediately following dam removal, temperatures in the reach increased downstream. After a series of storm events that mobilized the sediment and deposited it in the experimental reach, maximum temperatures decreased downstream, and diurnal fluctuations were moderated.

Discussion of Literature

Overall average and range of change in temperature reported by the 16 studies clearly demonstrates that, on balance, increasing flow through gravel decreases maximum stream temperatures for all studies and at all scales for both surface and hyporheic water (Fig. 5). The average reported temperatures decreased or remained constant at virtually all sites, with average decreases ranging from 0 to > 6°C. Differences in study methods and site characteristics limit more rigorous comparison among this population of studies, however.

Hyporheic Exchange on the Clackamas River

While the literature demonstrates that hyporheic exchange has the capacity to lower peak temperatures in streams, few studies have been completed on large rivers. Furthermore, no one has yet quantified the change in peak temperatures to be expected from gravel augmentation or other associated geomorphic modifications of a river. Therefore, given our current knowledge,

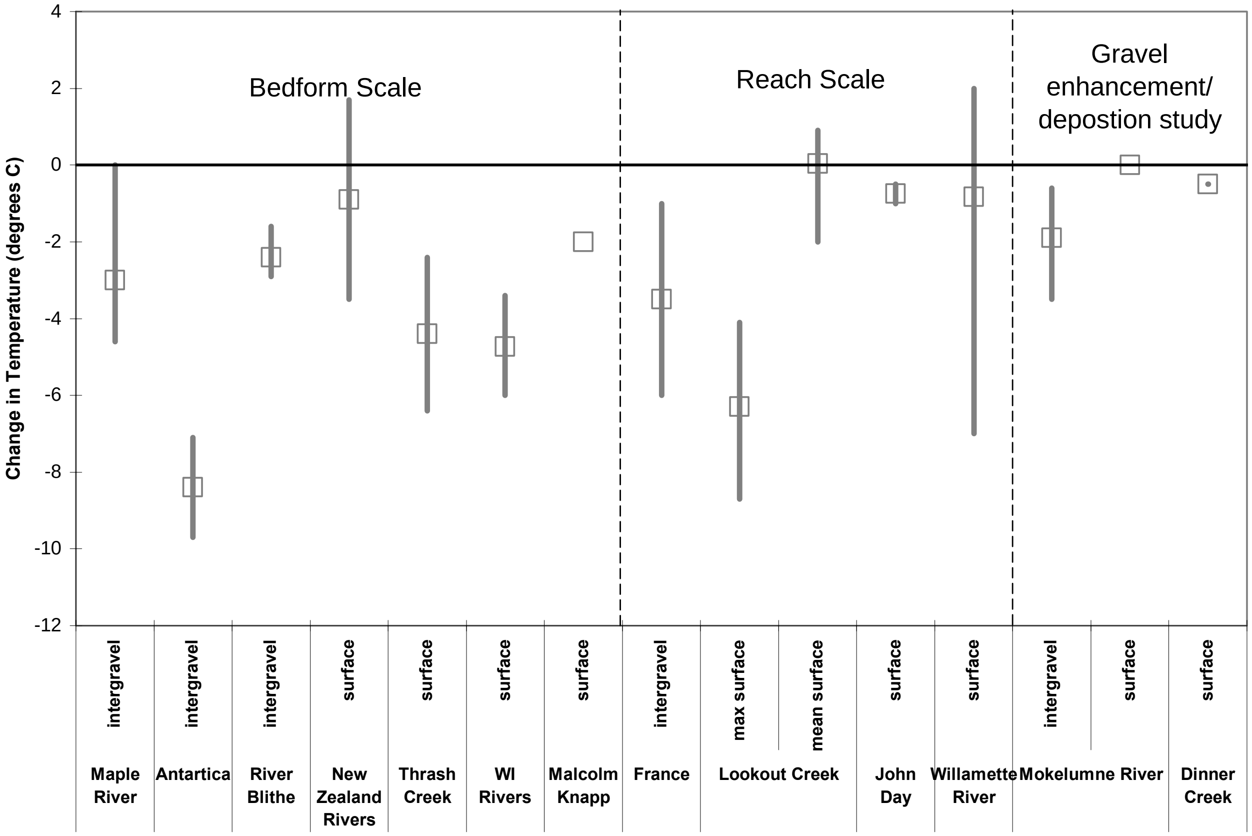


Figure 5: Average (box) and range (line) change in stream temperature for the 16 studies reported in Table 1. Note that studies vary in terms of location and type of measurement.

gravel augmentation in the Clackamas River will cause an unknown amount of decrease in the peak temperature. The changes in peak temperature may be spatially complex due to harmonics formed by mixing of phase-shifted hyporheic water with variable residence times. The overall effect of this complexity may be to increase the diversity and number of temperature refuges for fish.

Bibliography

Arscott, D. B., K. Tockner, J.V. Ward, Thermal heterogeneity along a braided floodplain river (Tagliamento River, northeastern Italy). *Canadian Journal of Fisheries and Aquatic Sciences 58*: 2359-2373, 2001..

Bilby, R.E., Characteristics and Frequency of Cool-water Areas in a Western Washington Stream. *Journal of Freshwater Ecology 2(6*): 593-602, 1984.

Brown, L.E., D.M. Hannah, and A.M. Milner, Spatial and temporal water column and streambed temperature dynamics within an alpine catchment: implications for benthic communities, *Hydrological Processes*, *19*, 1585–1610, 2005.

Cozzetto, K., D. McKnight, T. Nylen, and A. Fountain, Experimental investigations into processes controlling stream and hyporheic temperatures, Fryxell Basin, Antarctica, Advances in Water Resources 29(2): 130-153, 2006.

Evans E.C., and G.E. Petts, Hyporheic temperature patters within riffles. *Hydrological Sciences 42(2)*: 199-213, 1997

Fernald, A., D. Landers, P.J. Wigington.. Water quality effects of hyporheic processing in a large river. *International Conference on Riparian Ecology and Management in Multi-Land Use Watersheds*, American Water Resources Association, 2000.

Fowler, R. T. and M. R. Scarsbrook, Influence of hydrologic exchange patterns on water chemistry and hyporheic invertebrate communities in three gravel-bed rivers. *New Zealand Journal of Marine and Freshwater Research 36 Part 3*: 471-482, 2002.

Gooseff, M.N., J. LaNier, R. Haggerty, and K. Kokkeler, Determining in-channel (dead zone) transient storage by comparing solute transport in a bedrock channel–alluvial channel sequence, Oregon, *Water Resources Research*, *41*, W06014, doi:10.1029/2004WR003513, 2005.

Hancock, P.J., and A.J. Boulton, The effects of an environmental flow release on water quality in the hyporheic zone of the Hunter River, Australia, Hydrobiologia, 552: 75-85, 2005.

Harbaugh, A.W., E.R. Banta, M.C. Hill, and M.G. McDonald, 2000, *MODFLOW-2000, the U.S. Geological Survey modular ground-water model -- User guide to modularization concepts and the Ground-Water Flow Process*, U.S. Geological Survey Open-File Report 00-92, 121 p. Online summary at http://water.usgs.gov/nrp/gwsoftware/modflow2000/modflow2000.html last accessed June 1, 2006.

Hunt, R.J., M. Strand, and J.F.Walker, Measuring groundwater-surface water interaction and its effect on wetland stream benthic producivity, Trout Lake watershed, northern Wisconsin, USA, Journal of Hydrology, 320(3-4): 370-384, 2006.

Johnson, S.L., Factors influencing stream temperatures in small streams: substrate effects and a shading experiment, *Canadian Journal of Fisheries and Aquatic Sciences*, *61*, doi: 10.1139/F04-040, 913-923, 2004.

Merz, J. E. and J. D. Setka, Evaluation of a spawning habitat enhancement site for Chinook salmon in a regulated California river. *North American Journal of Fisheries Management* 24: 397-407, 2004.

Moore, R.D., P. Sutherland, T. Gomi, and A. Dhakal, Thermal regime of a headwater stream within a clear-cut, coastal British Columbia, Canada, Hydrological Processes, 19(13): 2591-2608, 2005.

Poole, G. C. and C.H. Berman. An ecological perspective on in-stream temperature: natural heat dynamics and mechanisms of human-caused thermal degradation. *Environmental Management*. 27: 787-8022001.

Sliva, L., and D.D. Williams, Exploration of riffle-scale interactions between abiotic variables and microbial assemblages in the hyporheic zone, Canadian Journal of Fisheries and Aquatic Sciences, 62(2): 276-290, 2005.

Stewart, Gregory, 2004. Personal Communication

Sullivan, K., and T. N. Adams. The physics of stream heating: 2) An analysis of temperature patterns in stream environments based on physical principles and field data. Weyerhaeuser Company Technical Report 044-5002/89/2, 1991.

Torgersen, C.E., R.N. Faux, B.A. McIntosh, N.J. Poage, and D.J. Norton, Airborne thermal remote sensing for water temperature assessment in rivers and streams. *Remote Sensing of Environment* 76:386-398, 2001.

Torgersen, C. E., D. M. Price, H. W. Li, and B. A. McIntosh.. Multiscale thermal refugia and stream habitat associations of Chinook salmon in northeastern Oregon. *Ecological Applications* 9:301-319, 1999.

Wampler, P. J., *Contrasting geomorphic responses to climatic, anthropogenic, and fluvial change across modern to millennial time scales, Clackamas River, Oregon*, PhD dissertation, Oregon State University, 398 p., 2004.

White, D.S, C.H. Elzinga, and S.P. Hendricks. Temperature patterns within the hyporheic zone of a northern Michigan river. *Journal of North American Benthological Society* 6(2):85-91, 1987.

Wondzell , S.M. and S.L. Johnson. Influence of hyporheic exchange flow on the temperature of a small mountain stream. *NABS Annual meeting*, Vancouver, British Columbia, 2004.