WATER QUALITY EFFECTS OF HYPORHEIC PROCESSING

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ABSTRACT: Water quality changes along hyporheic flow paths may have important effects on river water quality and aquatic habitat. Previous studies on the Willamette River, Oregon, showed that river water follows hyporheic flow paths through highly porous deposits created by river channel meandering. To determine water quality changes associated with hyporheic flow, we studied six bar deposits positioned between the river and closed lentic side-channel alcoves. At each site we measured water levels and water quality in river, hyporheic, and alcove water. At all sites we found hyporheic flow paths from the river through the bar deposits to the alcove surface water. At a majority of the sites hyporheic dissolved oxygen and ammonium decreased relative to river water, while hyporheic specific conductance, nitrate, and soluble reactive phosphorous increased compared to the river. At three sites with fast hyporheic flow rates, hyporheic temperature decreased relative to river water, and there was little change in temperature at the other three sites. Hyporheic changes most affected receiving alcove water quality at sites with fast hyporheic flow rates. Strategies to promote ecosystem functions provided by hyporheic flow should focus on restoring natural hydrogeopmorphic river channel processes to create high porosity deposits conducive to hyporheic flow.

KEY TERMS: Hyporheic flow, water quality, aquatic habitat.

INTRODUCTION

Hyporheic flow may have important effects on water quality and aquatic habitat in the Willamette River, Oregon. Hyporheic flow occurs where river water enters the channel bed and banks to follow subsurface flow paths before reemerging to main channel or off-channel surface water. Both main channel and off-channel sites are important aquatic habitat on the upper Willamette River. Alcoves, which are high-water side channels closed by sediment plugs at the upstream end during lower flow, have been shown to be important breeding and rearing areas for native fish including threatened salmonids (C. Andrus, unpublished data). Biochemical reactions and physical changes in hyporheic flow affect water quality through processes such as microbially-mediated denitrification (Duff and Triska, 1990) and metal oxidation (Harvey and Fuller, 1998). Hyporheic flow affects aquatic ecosystem functions by providing, for example, habitat for aquatic macroinvertebrates (Stanford and Ward, 1993) and increased periphyton growth (Mulholland et al., 1997) at hyporheic upwelling zones which occur in low gradient pools (Harvey and Bencala, 1993).

If a large percentage of total river flow passes through hyporheic flow paths, water quality changes within hyporheic flow may affect main channel water quality. Tracer studies on the Willamette River in 1998 showed that hyporheic flow occurs most where the river is able to move within the active floodplain, reworking and depositing highly porous gravel deposits (A. Fernald, unpublished data). Detailed discharge measurements showed that over a 26 km-long study area, at least 70 % of total river discharge exchanged with hyporheic flow paths at in-stream riffle and pool complexes. To identify effects of hyporheic flow on water quality and aquatic habitat, this study sought to identify physical and chemical water quality changes along hyporheic flow paths. By studying alcove sites, we also sought to improve our understanding of hyporheic flow effects on these important rearing and breeding habitats. We addressed two questions in this study: 1) Do water quality characteristics change in hyporheic flow relative to river source water? and 2) Do receiving alcove surface waters show the effects of hyporheic flow inputs?

METHODS

Our study took place during summer low-flow in 1999 along 60 kilometers of the upper Willamette River between Eugene and Corvallis, Oregon. We selected six sites for detailed analysis of hyporheic flow paths and water quality (Fig. 1).

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These sites all had off-channel alcoves separated from the main river channel by a bar deposit. This type of site is excellent for studying hyporheic flow for three reasons: 1) hyporheic flow from the river into the bar deposit is created by hydraulic gradients from the river through the bar to the alcove surface water, 2) hyporheic flow can be accessed from land by driving wells into the bar deposit, and 3) the absence of river flow through the alcoves facilitates identification of the effects on alcove surface water of emerging hyporheic flow.

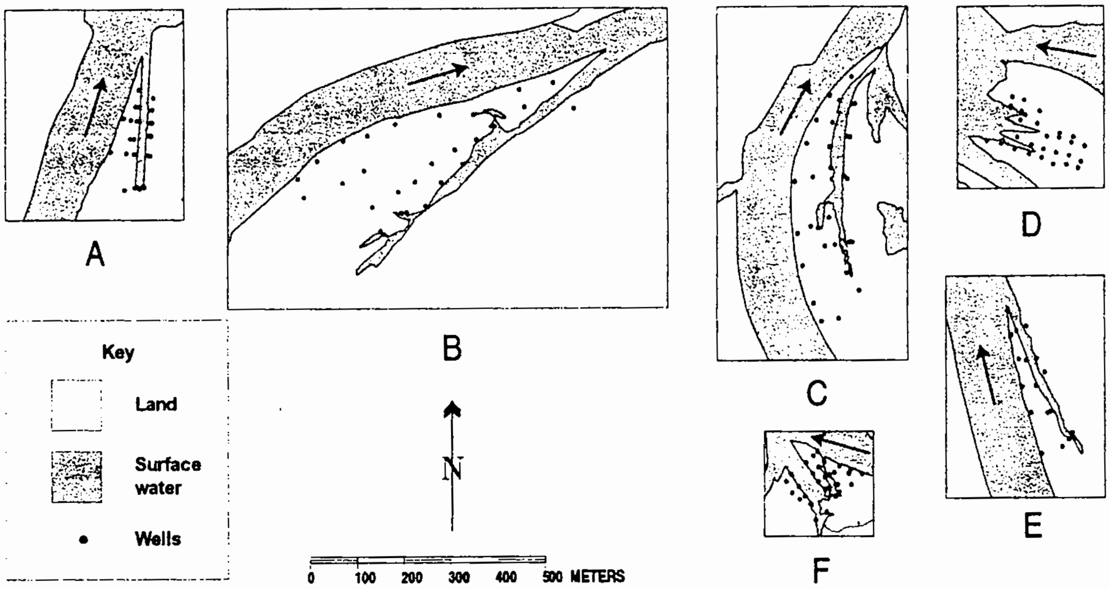

Figure 1. Hyporheic study sites on the Willamette River, Oregon

At each of the six sites we installed 20-30 wells made of 1" PVC pipe driven to a depth of about 0.5 m below summer low-flow water tables. We sampled water levels and water quality at each site twice, in early and late August. We measured groundwater elevation in each well and surface water elevations along the river and alcoves. We used kreiged areal averaging of the point water level measurements to determine a continuous water level surface. From this surface we determined hyporheic flow path directions, and we measured distance from the river bank to each well along the hyporheic flow path direction. We estimated hyporheic flow rate, q_H, using Darcy's law, $q=-K(dh/dl)$ where q is one-dimensional discharge (m/s), K is hydraulic conductivity (m/s), and dh/dl is the hydraulic gradient (Darcy, 1856).

In each of the two sampling periods, we used calibrated YSI™ probes to measure river, hyporheic, and alcove physical water characteristics including dissolved oxygen (DO), temperature (T), and specific conductance (SC). We continuously purged each well until SC readings stabilized before recording the data values. We also took samples for laboratory analysis from one or two transects per site that included river, hyporheic, and alcove sample locations. We used standard methods to analyze the samples for nitrate (NO_3^-), ammonium (NH_4^+), and soluble reactive phosphorus (SRP). At Site A, we installed recording YSI™ probes in river, hyporheic, and alcove water to obtain hourly values for T, DO, and SC.

RESULTS

Water level measurements show that at all of the six study sites, river water flowed out of the main channel and followed hyporheic flow paths through the bar deposits before emerging into receiving alcoves. The hyporheic flow path gradients of 0.0030 to 0.0045 m/m into the upstream heads of the alcoves compared to an average river surface slope of 0.0008 m/m. Mature Site F with fine substrate had the slowest q_H, while recently reworked Sites C and B with coarse alluvium had the fastest q_H values (Table 1).

Hyporheic water quality changes relative to river source water

For the three parameters DO, SC, and T, we had measurements from all hyporheic wells at each study site. This enabled us to plot the changes in hyporheic water with distance from the river along the hyporheic flow paths (Fig. 2). The patterns discussed here for the August 23-25 sampling effort were very similar to those of the August 3-6 sampling period. At all sites we found that DO rapidly decreased from near saturation in the river to much lower 5-45% saturation in hyporheic flow. At all the sites SC increased from 60-75 μS/cm in the river to 90-120 μS/cm in hyporheic flow. We found that T followed two different patterns. At three sites, T decreased along the hyporheic flow paths by 1-7°C compared to the river. At the other three sites T did not change or increased by up to 2°C relative to the river.

Table 1 : Substrate, hydraulic conductivity, gradient, and hyporheic flow rate at six Willamette River hyporheic study sites.

Site	River km	Substrate type	Saturated hydraulic conductivity (m/s)	River to alcove gradient (m/m)	Hyporheic flow rate, q_H (m/s)	Relative q_H
F	275.2	Silt, sand, clay	1.0E-03	0.0030	3.0E-06	Slow
E	271.4	Gravel, sand, silt	1.0E-02	0.0031	3.1E-05	Intermediate
A	216.4	Gravel, sand, silt	1.0E-02	0.0045	4.5E-05	Intermediate
D	262.6	Gravel, sand	1.0E-01	0.0037	3.7E-04	Intermediate
C	256.1	Gravel, sand	5.0E-01	0.0035	1.8E-03	Fast
B	247.0	Gravel, sand	5.0E-01	0.0040	2.0E-03	Fast

For our analysis of the remaining parameters, we grouped measurements of SRP, NH_4^+, and NO_3^- by river, hyporheic, and alcove location. For each study site, we plotted the single river value, the median of the hyporheic values, and the farthest upstream (head of) alcove value (Fig. 3). SRP increased in hyporheic water compared to river water at all sites but Site B, which had the fastest q_H. At all sites NH_4^+ decreased relative to river water. Hyporheic NO_3^- increased compared to river water at all sites but Site F, which had the slowest q_H.

Receiving alcove water quality relative to hyporheic and river water

For the physical characteristics of DO, SC, and T, alcove surface water appeared to show the influence of emerging hyporheic water. DO in receiving alcoves was similar to hyporheic flow, which had lower DO than in the river. Alcove SC was similar to the hyporheic water in wells closest to the alcove, following the increase in SC with distance from the river. Alcove T was also similar to hyporheic T at wells near the alcove, and alcove T showed the same changes as hyporheic T relative to the river.

In comparing SRP, NH_4^+, and NO_3^- between alcove, hyporheic, and river water, we found that alcove water reflected hyporheic changes in NH_4^+, but did not consistently follow hyporheic changes in NO_3^- and SRP (Fig. 3). At five of six sites, NH_4^+ in alcove water was lower than in river water, and at all of these sites hyporheic NH_4^+ was lower than river NH_4^+. Alcove NO_3^- was elevated compared to river water only at Site B, although five of the six sites had hyporheic NO_3^- higher than river NO_3^-. Alcove SRP was unchanged or lower than river SRP at five sites, yet four of these had hyporheic water that was elevated in SRP compared to the river.

DISCUSSION

Water quality changes related to hyporheic flow rate

The changes along hyporheic flow paths and resulting effects on receiving alcove surface water appear to be related to q_H. The greatest cooling effect on alcove water compared to river water occurred at the two sites with the fastest q_H and probably the largest volumes of hyporheic inflow. Hourly data from the recording probes at Site A showed that hyporheic and alcove T responded gradually over many days to hourly changes in river T. This suggests that gravel deposits act to dampen T fluctuations in hyporheic water compared to changes in river source water. When river stage rose at Site A and created a steeper gradient from river to alcove, we found that hyporheic and alcove SC decreased. This is consistent with our interpretation that the increases in SC along hyporheic flow paths are a result of contact with interstitial material. With faster q_H during rising river stages, there is less contact time with interstitial material and the SC in hyporheic water drops. Our measurements of T and SC were particularly important for identifying alcove changes caused by hyporheic inflows, because these characteristics were not as strongly affected by the bio-chemical reactions that affect water nutrient concentrations.

Although we did not directly measure microbially-mediated chemical transformations, they appear have an important

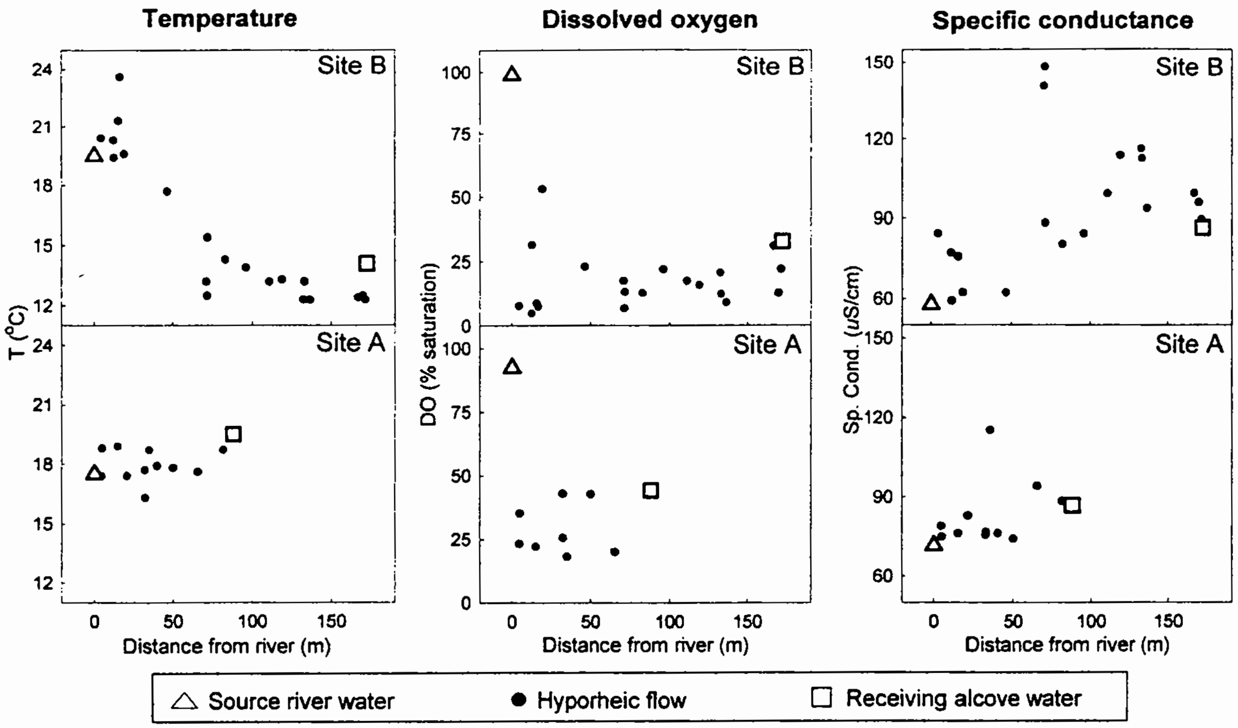

Figure 2. Water physical characteristics at two example Willamette River study sites showing two different patterns for temperature and consistent patterns for dissolved oxygen and specific conductance. Temperature decreased at three sites as at Site B and was unchanged or increased slightly as at site A. At all six sites in the study, dissolved oxygen decreased and specific conductance increased.

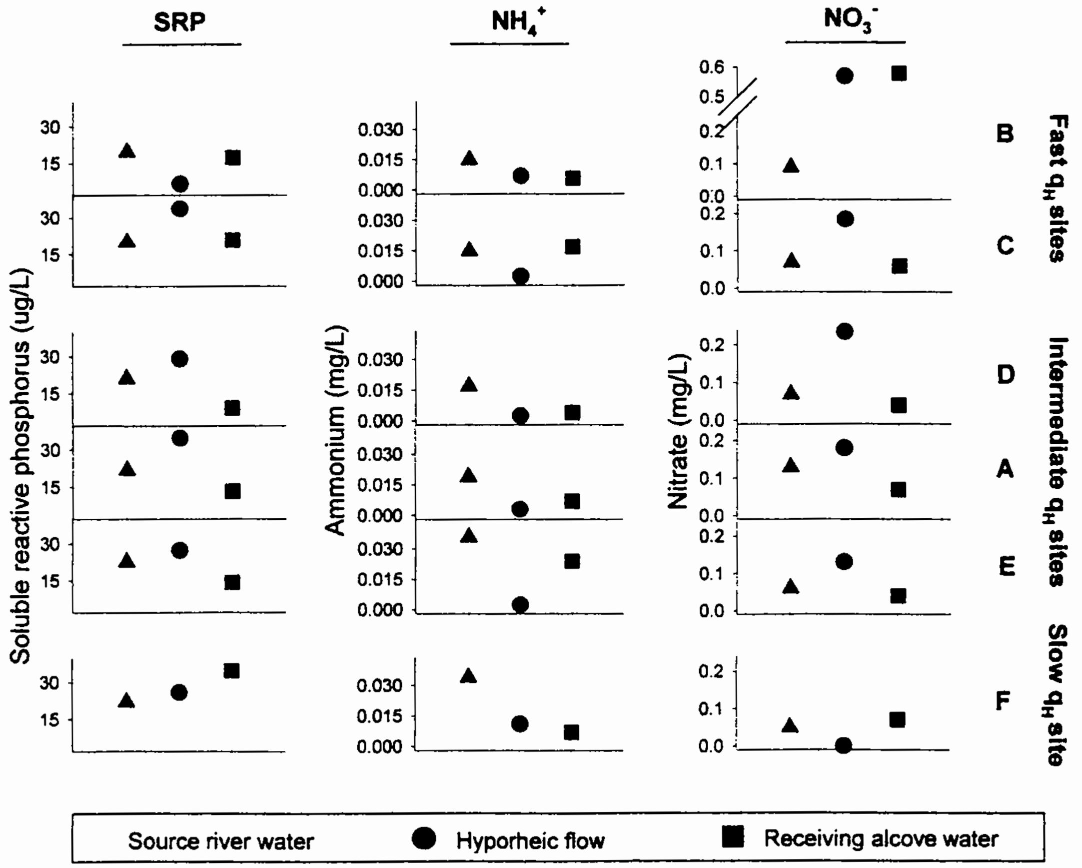

Figure 3. Nutrients in river source water, hyporheic flow (median of hyporheic values), and alcove receiving water from measurements taken August 23-25, 1999 at six Willamette River study sites (A-F) arranged in order of hyporheic flow rate, q_H.

effect on water quality changes. At site F, which had the slowest q_H, low DO and long hyporheic residence time in fine sediments may promote hyporheic denitrification as documented elsewhere (Sjodin et al., 1997). Site F hyporheic NO_3^- and NH_4^+ were lower than in river water. With lower NO_3^- and NH_4^+, surface water primary productivity may be N limited, which could explain why site F is the only site where we saw an increase in SRP. The increases in hyporheic NO_3^- at all but site F could be from nitrification of NH_4^+, since all sites showed a decrease in hyporheic NH_4^+. At Site B with the fastest q_H, we found the largest increase in hyporheic and alcove NO_3^-. At this site we found the only example of a decrease in hyporheic SRP and this could be from microbial uptake aided by high NO_3^- availability. While complete understanding of nutrient transformations in hyporheic flow would require a more extensive analysis of soil, vegetation, and microbial activity, our water quality data suggest that hyporheic flow exerts important controls on water quality in receiving alcoves.

Implications of hyporheic water quality changes for river function and management

Our study shows the importance of sampling a range of sites to better understand patterns of hyporheic water quality changes and the effects of these changes on receiving surface water. Studies at other sites have produced different conceptual models of hyporheic flow effects on water quality. In a generalized model of hyporheic flow paths at sites with rapid q_H, nitrification led to increased nitrate concentrations along hyporheic flow paths (Edwards, 1998). On a large river with fine substrates and slow q_H, ammonium was reduced and nitrate denitrified in hyporheic flow, causing reductions in river dissolved nitrogen (McMahon and Bohlke, 1996). On a river with active exchange between river water and groundwater in a glacial floodplain, exchange between groundwater and surface water minimized downstream changes in surface water quality (Ward et al., 1999). All of these processes may occur along the Willamette River. At sites with fine substrates, nitrate may be lost to denitrification, while at other sites with coarser substrates, nitrate may increase from nitrification. Hyporheic cooling may provide an important ecosystem benefit for fish. Ecosystem productivity may be enhanced at hyporheic upwelling zones downstream of riffle complexes and in off-channel alcove habitats. Movement of river water in and out of hyporheic flow paths along the entire channel may stabilize fluctuations in river water characteristics such as temperature and SRP. In general, hyporheic exchange may promote overall river system water quality stability while providing site-to-site aquatic habitat diversity.

Ecological functions provided by hyporheic flow can be promoted by managing the amount of river channel meandering. The most hyporheic flow occurs at sites where the river is free to rework large gravel deposits. In this study, we found the greatest effects of hyporheic flow on receiving surface water at recently reworked sites with highly porous gravels. Willamette River meandering has been limited by construction of bank-hardening structures like revetments, and there has been a historic loss of gravel bars on the Willamette River (Benner and Sedell, 1986). Removal of revetments as a management strategy to promote river channel movement would increase the numbers of gravel bar features and would create high porosity sites for active hyporheic flow.

CONCLUSIONS

In this study we found that water quality of hyporheic flow changed relative to river source water, and for some parameters the nature of these changes was related to hyporheic flow rate. Hyporheic specific conductance increased and hyporheic dissolved oxygen decreased relative to river water at all study sites. Hyporheic temperature decreased relative to river water at sites with relatively fast hyporheic flow rates. At sites with intermediate to fast hyporheic flow rates, hyporheic ammonium decreased, possibly from nitrification, and there was a corresponding increased in hyporheic nitrate. At the site with the slowest hyporheic flow rate, hyporheic nitrate decreased, possibly due to denitrification. At all sites but the one with the fastest hyporheic flow rate, hyporheic soluble reactive phosphorus increased relative to river water. The extent to which water quality changes were seen in receiving alcove surface waters was greatest at sites with the fastest hyporheic flow rates.

These results show that hyporheic flow has important effects on alcove aquatic habitats and has the potential to impact overall river water quality. Alcoves provide an environment with high macrophyte food availability in a low stress environment of quiescent surface water, and increased bio-available N and P contributed to some alcoves from hyporheic flow may help explain why these habitats are important for fish rearing and breeding. Along the main channel, hyporheic flow processes a large percentage of the total volume of river flow. The water quality changes we documented at the alcove sites are likely occurring at in-stream and off-channel locations along the entire main river channel. Management efforts to promote the ecological functions provided by hyporheic flow may be best targeted at increasing river channel meandering within the active channel thereby creating additional sites with a range of hyporheic flow rates. Valuable future studies could combine analyses of hyporheic water quality effects at representative sites with analyses of hyporheic flow rates over long river reaches to better estimate the net effects of hyporheic flow on river ecosystem function.

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