WATER RESOURCES RESEARCH, VOL. 45, W05406, doi:10.1029/2008WR007214, 2009

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Changes in hyporheic exchange flow following experimental wood removal in a small, low-gradient stream

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Received 11 June 2008; revised 26 November 2008; accepted 20 February 2009; published 7 May 2009.

[1] We investigated the response of hyporheic exchange flow (HEF) to wood removal in a small, low-gradient, gravel bed stream in southeast Alaska using a series of groundwater models built to simulate HEF for the initial conditions immediately after wood removal and 1 month, 2 years, 4 years, and 16 years following wood removal. The models were based on topographic surveys of the stream channel and surrounding floodplain, and surveyed water surface elevations (WSEs) were used to assign stream boundary conditions. Using the groundwater flow model, MODFLOW, and the particle tracking model, MODPATH, we calculated hyporheic exchange fluxes, their residence time distributions, and both longitudinal and plan view spatial patterns of downwelling and upwelling zones. In the first few years, streambed scour and sediment deposition smoothed the streambed and WSE profile, reducing HEF. Also, large contiguous patches of downwelling or upwelling were fragmented, nearly doubling the total number of patches present on the streambed. As the stream continued to adjust to the loss of wood, those trends began to reverse. Accretion of sediment onto alternating bars resulted in better developed pool-riffle morphology, enhanced HEF, and increased residence times and also resulted in downwelling and upwelling zones coalescing into elongated patches along bar margins. This study showed that the hyporheic zone is sensitive to changes in wood loading and that initial changes in HEF resulting from the direct effects of wood removal were contrary to longer-term channel adjustments to changes in wood loading.

Citation: Wondzell, S. M., J. LaNier, R. Haggerty, R. D. Woodsmith, and R. T. Edwards (2009), Changes in hyporheic exchange flow following experimental wood removal in a small, low-gradient stream, *Water Resour. Res.*, *45*, W05406, doi:10.1029/2008WR007214.

1. Introduction

[2] Hyporheic exchange denotes the exchange of water between the stream and shallow streamside aquifer. These exchange flows are controlled by head gradients between the stream and aquifer, which in turn, are controlled by channel geomorphologic features at a variety of spatial scales [*Harvey and Bencala*, 1993; *Kasahara and Wondzell*, 2003; *Cardenas et al.*, 2004; *Wondzell*, 2006]. Because of this close link between channel geomorphology and hyporheic exchange, changes in stream geomorphology often result in changes in the spatial patterns and/or amounts of hyporheic exchange flow [*Wondzell and Swanson*, 1999; *Kasahara and Wondzell*, 2003].

[3] Large wood is important in shaping stream channels [*Keller and Swanson*, 1979; *Triska*, 1984; *Montgomery et al.*, 1996] and has been a focus of much research as land management in many forested areas has substantially reduced large wood in streams [*Bilby*, 1984; *Ralph et al.*, 1994; *Faustini and Jones*, 2003]. Most concern focuses on changes in channel morphology and attendant changes in stream habitat quality for species of concern [*House and Boehne*, 1987; *Hauer et al.*, 1999]. The importance of the hyporheic zone to stream ecosystems is widely recognized, but the potential effects of land management practices on the hyporheic zone, as mediated by the role of large wood, have received relatively little attention.

[4] The geomorphologic response of a stream channel to changes in large wood may dramatically change the spatial extent of hyporheic zones and the amount of stream water flowing through them. In higher-gradient streams (>2%), large pieces of in-stream wood often buttress sediment wedges [*Montgomery et al.*, 2003] and create local head gradients that drive hyporheic flow [*Wondzell*, 2006]. Wood removal from high-gradient channels should cause sediment

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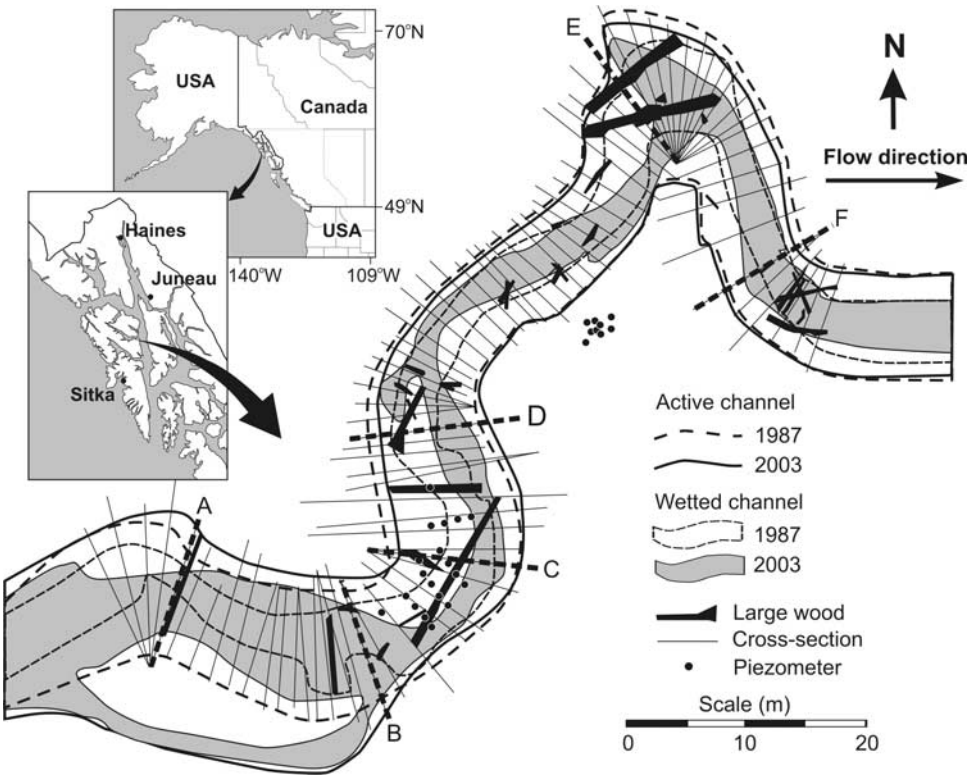

Figure 1. Study site. Insets show the location of the study site in SE Alaska, United States. The plan view map of the active and wetted stream channels generated from the 1987 cross-sectional surveys is overlain with the map of the stream from the 2003 channel survey. Large wood removed from the stream channel in May 1987 is shown, as are the locations of the original cross sections established in 1987 and the two piezometer networks established in 2003. Areas between adjacent cross-sectional surveys are called "stream segments," and the locations of six cross sections (A–F) used as reference points in subsequent graphs are highlighted with thick dashed lines.

degradation [*Faustini and Jones*, 2003] and decreased hyporheic flow [*Kasahara and Wondzell*, 2003]. In lower-gradient streams (<2%), the effects of large wood on channel geomorphology are more complex, potentially causing both sediment storage and scour [*Smith et al.*, 1993a] which in turn can cause highly variable channel morphological responses [*Smith et al.*, 1993b]. Given the wide range in potential stream responses to large wood removal, it is unclear how wood removal and subsequent changes in channel geomorphology would influence hyporheic zones in lower-gradient streams.

[5] This study builds on the work of *Smith et al.* [1993a, 1993b], who studied changes in bed load transport and channel morphology following wood removal from a small, low-gradient (~1%) stream in southeast Alaska. Prior to wood removal, channel form and sediment storage were influenced by in-channel wood in complex ways. In some places large wood embedded in the channel stored sediment via buttressing but in other places it formed pools where sediment was scoured around large wood pieces. *Smith et al.* [1993b] documented net sediment loss from the channel over the first year after wood removal. In subsequent years, after the channel was released from the morphologic control imposed by large wood, the development of alternating bars increased sediment storage, and ultimately, more gravel was stored within the active channel than before wood removal.

[6] Here, we assess changes in hyporheic exchange flows (HEF) following the experimental removal of wood. We use groundwater flow models, built from detailed channel morphologic surveys conducted immediately after wood removal and 1 month, 2 years, 4 years, and 16 years after wood removal. Using the parameterized models we examine the long-term changes in the amount of hyporheic exchange flows (Q_{HEF}) and the residence time of stream water in the hyporheic zone (HEF_{RT}). We also examine changes in both the longitudinal and planform patterns of upwelling or downwelling zones on the streambed.

2. Methods

2.1. Study Site Description

[7] Bambi Creek, a second-order stream draining a 1.55 km^2 basin undisturbed by land management, is located in the coastal lowlands on Chichagof Island, southeast Alaska, United States (N57°44′29″, W135°01′30″; Figure 1). Annual precipitation at this temperate rain forest site averages 1600 mm/a. Bankfull discharge in the study reach is approximately 1,700 L/s and annual base flows range between 50 and 100 L/s (R. D. Woodsmith, unpublished data, 2005). The reach is low gradient (slope ~ 1.2%) and meandering (sinuosity ~ 1.7). Prior to treatment the channel had a wood-forced pool-riffle morphology, as defined by *Montgomery and Buffington* [1997].

[8] In May 1987, all wood larger than 1 cm diameter was removed from the bankfull channel within the 95.7-m-long study reach to an elevation well above bankfull height (Figure 1, with largest wood prior to removal drawn to scale). Large wood (>10 cm diameter and >100 cm length) comprised 93% of the wood removed. Wood pieces buried in stream banks were cut flush with the bank and all pieces were removed by hand to minimize disturbance of the streambed. During the 16-year study, the reach remained free of large wood. The channel was not surveyed prior to wood removal. Instead, the initial survey was completed immediately after wood removal to ensure that measured channel changes resulted from fluvial processes rather than disturbances from treatment. Therefore, it is possible that large wood modified the water surface elevation (WSE) in ways not captured in the first postremoval channel survey. Large wood may have generated head gradients creating hyporheic exchange that we did not capture in our simulation of the initial conditions.

[9] Changes in channel morphology over the first 4 years are well described by *Smith et al.* [1993a, 1993b]. Bank full discharges sufficient to mobilize the streambed occurred in each of those years, with annual peak discharge ranging between 1800 and 4400 L/s. A major flood occurred in 1990 during which discharge greatly exceeded bankfull (12,000 L/s). Discharge data are not available for later dates. We assume that these peak discharges played a significant role in channel adjustments to wood removal.

[10] Changes in channel morphology were quantified by repeated topographic surveys made after each large storm in 1987 and at least once a year until 1991. These surveys used an engineering level and stadia rod to survey 84 cross sections spaced, on average, 1.14 m apart (Figure 1). The elevations were measured to the nearest 0.005 m; see *Smith et al.* [1993b] for additional information. We surveyed the study reach in August 2003 (16 years postremoval) using a Topcon GTS 223 total station and prism rod with a horizontal accuracy of 0.03 m and a vertical accuracy of 0.002 m. (The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.) We relocated and resurveyed original bench marks and many of the end stakes from the original cross sections so that our 2003 survey could be tied back to surveys conducted between 1987 and 1991. In 2003, channel elevations were surveyed approximately every meter with smaller spacing where more detail was necessary to capture abrupt changes in topography. We surveyed the elevation of the streambed down the center of the channel, recording water depth at each survey point. We also surveyed the right and left water edge. Finally, the surrounding floodplain elevations were surveyed to characterize the topography and valley margings of the study area, which were not measured in previous surveys.

[11] The detailed 2003 survey was used to create a base map of our study site. Common reference points (elevational bench marks and end stakes from the cross-sectional transects) were used to remap the locations and elevation of the edge of stream water from a subset of the earlier surveys onto our 2003 base map. This time series of maps, starting with the initial channel immediately after wood removal, showed changes in channel morphology and stream water elevation after 1 month, 2 years, 4 years, and 16 years following wood removal.

[12] Two piezometer networks were established in August 2003 to characterize the hydraulic properties of two distinct sediment types in the study area (Figure 1). Piezometers were constructed from PVC pipe, with inside diameter of 2.5 cm. Each piezometer was 1.0 m long and screened over the lower 35 cm. One network was located on an unvegetated point bar composed of fine gravel and sand. The second network was located on the floodplain, in fine textured (silt and clay) soils with a thick overlying organic layer. Falling head slug tests [*Bouwer and Rice*, 1976; *Dawson and Istok*, 1991] were conducted in all piezometers. The slug test–based estimates of saturated hydraulic conductivity (K) were 1.9×10^{-4} m/s for the gravel bar and 2.7×10^{-5} m/s for the floodplain. Tracer tests were also conducted in both piezometer networks using pulse injections of saline water with tracer detection by measuring electrical conductivity (EC). The gravel bar tracer tests yielded six useable breakthrough curves from which K was estimated at 4.7×10^{-3} m/s. We did not get usable breakthrough curves from the tracer test in the floodplain piezometer network. The measurements of K by tracer tests were significantly larger than the K measured by slug test, a result similar to that of *Kim et al.* [2005]. This is probably due to the different scales of measurement of the two methods.

2.2. Groundwater Flow Modeling

[13] Hyporheic flow in the study reach was quantified for each observation period using a steady state groundwater flow model using MODFLOW [*Harbaugh et al.*, 2000]. Brief details are given here; see *LaNier* [2006, pp. 14–24, 72–76, 79–82] for additional model information. We first developed a standard base model defining the overall model domain using data from the 2003 site survey to define the floodplain topography. There were no natural features (such as bedrock outcrops) in the study area that would create flow boundaries so we assumed that the groundwater flow system was not naturally bounded at the margin of our model domain. Therefore, to minimize the effects of boundary conditions on the model results, the model boundaries were located approximately 65 m away (upstream/downstream) and 40 m away (laterally) from the study reach. The vertical sides of the model domain were modeled as specified head cells. The reach-averaged slope of the WSEs and additional water levels measured throughout the study site were used to define longitudinal and lateral groundwater gradients from which we extrapolated head values along the boundary of the model domain. These boundary conditions were kept unchanged for all models so that comparisons over time would not be confounded by changing boundary conditions. While this approach is somewhat arbitrary, we do not expect substantial changes in boundary conditions over the period of study because wood was only removed from the active channel within the 95-m-long study reach. Although the extent of the model domain extends beyond the 95-m length of our surveyed study reach, as described above, all calculations (Q_{HEF}, etc.) are based only on that portion of the model domain containing the study reach.

[14] We used a 12-layer, spatially refined finite difference grid, with 201,096 cells and cell sizes ranging from 0.5 ×

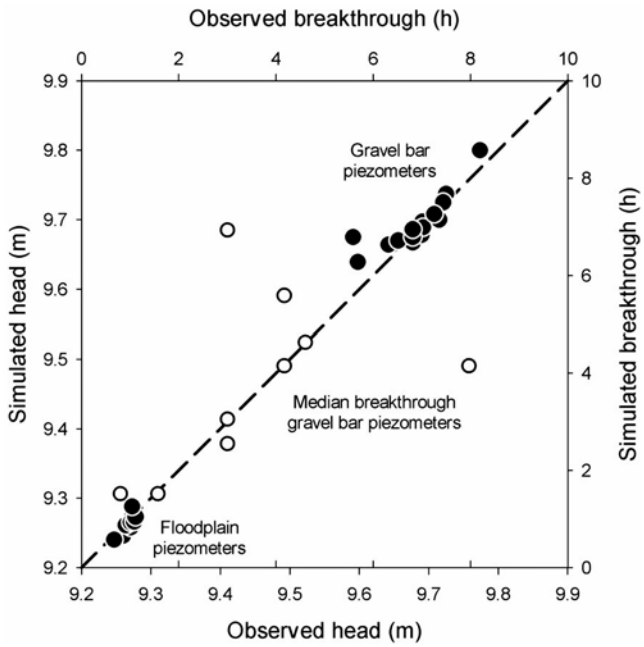

Figure 2. Comparison of model fits to observed data for the 16-year post wood removal simulation. The RMSE of the residuals (modeled versus observed heads) was 0.02 m, whereas the total change in surface water elevations over the study reach is approximately 1.10 m. The RMSE in the smaller floodplain piezometer network was 0.031 m on a maximum in-network head difference of 0.089 m. The RMSE in the larger gravel bar piezometer network was 0.026 m on a maximum in-network head difference of 0.135 m.

0.5 m in the center of the study area around the active stream channel to a maximum cell size of 2.0 × 2.0 m at the edges of the model domain. The top model layer was 10 cm thick and each lower layer increased in thickness by 45.86%, for a total model depth of 20 m. We did a model sensitivity analysis to ensure that HEF was not sensitive to grid cell size (small enough), model domain size (large enough), or model depth (deep enough). The sediment of the bed of the active channel was composed of fine gravel and sand, similar to that found in the location of our gravel bar piezometer network. Since the focus of this work is to assess the effect of geomorphic changes (i.e., boundary changes) on hyporheic exchange, we judged that a homogeneous model K within the active channel would be adequate. Therefore, the first five layers of model cells underlying the active channel were assigned a K of 9.5×10^{-4} m/s, the geometric mean of the combined slug and tracer test estimates of K. The tracer tests had a zone of influence of 1–3 m, the distance between the piezometers, whereas the slug tests had a zone of influence of 10–15 cm (on the basis of an assumed storativity of 0.20 and the methods of *Beckie and Harvey* [2002, Figure 6]). Since much of the HEF is on the scale of meters, we used the geometric mean of the two K measurements. Using this average, simulation of travel times discussed in section 4 showed factor-of-2 agreement to observations. The total depth of the high-conductivity streambed was 1.22 m. Because the slug tests suggested that the K of the floodplain was approximately 1/10 that of the gravel bar, all other model cells were assigned a K of 9.5×10^{-5} m/s.

[15] The stream was modeled as a series of specified-head cells, which we refer to as "stream cells," located in the uppermost model layer and covering the extent of the wetted channel. The surveyed elevations of the stream water and channel topography were determined from the cross-sectional surveys conducted from 1987 to 1991, and from the August 2003 channel survey. The outline of the wetted stream channel was then determined from the locations of the water edge as noted in the original surveys. Finally, the surveyed WSEs were linearly interpolated to all model cells comprising the wetted channel (see *LaNier* [2006] for further details).

[16] Model results showed good agreement between modeled and observed heads (Figure 2). Agreement between modeled and observed median breakthrough times are somewhat worse, but most lie close to the 1:1 line.

2.3. Analyzing Changes in HEF

[17] A particle tracking routine, MODPATH [*Pollock*, 1994], was used to differentiate components of exchange flow between the surface and subsurface. Stream cells in which a particle terminated were identified as upwelling, whereas stream cells whose particles traveled to another cell were identified as downwelling. We calculated the total downwelling and upwelling components of gross streambed flux within each "stream segment" (area between adjacent cross-sectional transects (see Figure 1) established by *Smith et al.* [1993b]). These stream segments averaged 1.14 m in length. We further separated the streambed fluxes into hyporheic and nonhyporheic components. HEF includes only those subsurface flows of water that both originated in and terminated in the stream cells within the model domain. Any flow that terminated at the constant head boundaries at the side of the model was not counted as HEF. The total amount of hyporheic flow occurring within a stream segment and over the entire study reach was calculated by summing the streambed fluxes at downwelling and upwelling cells and dividing by 2. We also quantified the net change in stream discharge over the study reach, including gains and losses of both hyporheic and nonhyporheic fluxes through stream cells. The MODPATH simulations also quantified the residence times of hyporheic water for each model scenario. Porosity was assumed 20%. MODPATH tracked virtual particle locations and the cumulative travel time through the model domain for each particle. Individual particle residence times were combined, normalized by the number of particles released in each simulation, and the cumulative distribution function (cdf) of hyporheic residence times were calculated.

[18] Finally, we also calculated the reach-averaged hyporheic turnover length of stream water, L_s, following [*Wondzell and Swanson*, 1996]

$$L_s = \frac{Q_{stream}}{Q_{HEF}} * L_{reach} \tag{1}$$

where Q_{stream} is the stream discharge, Q_{HEF} is total hyporheic flow over a reach of length, L_{reach}, giving the

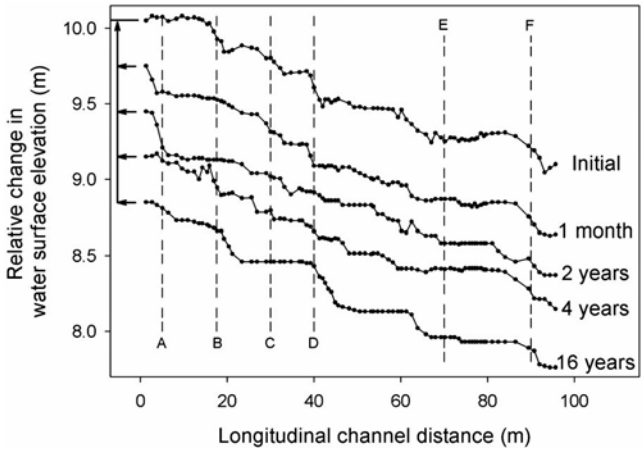

Figure 3. Longitudinal (channel) profile of stream water surface elevations (WSEs) starting from initial conditions immediately after wood removal in May 1987 through August 2003, 16 years after wood removal. The raw data overlap, making individual years impossible to distinguish. Therefore, the starting points were all set to a uniform relative elevation (10.05 m), and then 0.3 m were subtracted from each subsequent date to separate the lines. The locations of cross sections A–F are indicated with dashed lines.

average channel distance traveled by water before entering the hyporheic zone.

3. Results

3.1. Changes in Channel Morphology

[19] The changes in channel morphology and bed load transport in the 4 years following wood removal have been described in detail by *Smith et al.* [1993a, 1993b]. In general they found that large changes in channel morphology were noticeable in locations where wood had previously obstructed the channel, creating buttresses behind which sediment was stored. Wood removal led to rapid scour of this sediment. Over the longer term, removal of wood led to more free-formed development of several point and alternate bars and large net increases in the amount of sediment stored within the active channel. Because wood buried in the floodplain but projecting into the active channel was cut flush with stream banks, the lateral migration of the channel was limited in many locations by the remaining pieces of buried wood. Deflection of flow from these wood-defended banks forced thalweg crossovers and the development of alternating bars. The presence of wood-defended banks also stabilized the channel planform over the 16 years of the study.

[20] Changes in channel morphology, especially changes in the longitudinal profile of stream water elevations not quantified by *Smith et al.* [1993a, 1993b] may influence HEF. Therefore, we describe these in detail here. Prior to wood removal, there were five clearly defined riffles (steepest parts of the reach) in the longitudinal profile of the WSEs (Figure 3). Channel adjustments began immediately after wood removal. Especially notable was the scour in the first 20+ m of the study reach, between cross sections A and B. During the same period sediment accumulated between cross sections B and E, which greatly smoothed the longitudinal profile of the reach 1 month and 2 years post treatment. Sediment deposition was pervasive by 1991, 4 years after wood removal (Figure 3), creating a relatively smooth longitudinal gradient from 0 to 60 m, interrupted by numerous small riffles. By 2003, the longitudinal gradient contained 4 large riffles separated by 10- to 20-m-long flat stretches (pools) (Figure 3). In plan view, widening of the wetted channel was especially notable above cross section B (Figure 1). In contrast, the channel between 45 m and 65 m changed relatively little through time, but this portion of the reach contained little large wood at the start of the experiment.

[21] The channel between 70 m and 97 m changed little in the first several years of the experiment. The large accumulation of wood just downstream of cross section F (Figure 1) was suspended above the streambed, so its removal had negligible influence on channel morphology. By 1991 substantial deposition had occurred in the lower end of the reach, below cross section E (Figure 3). By 2003, this sediment had been scoured from the lower end of the reach, and both the longitudinal profile and plan view outlines of this portion of the study reach looked much as they did at the beginning of the experiment (Figures 1 and 3).

3.2. Influence of Large Wood on HEF

[22] We used several metrics to evaluate the influence of wood removal on HEF. At the scale of the study reach, estimates of amount of hyporheic exchange (Q_{HEF}) and its residence time distribution (HEF_{RT}) both show that changes in channel morphology following wood removal substantially impacted the hyporheic zone. Under initial conditions at the start of the experiment, our simulations suggest that Q_{HEF} equaled 0.96 l/s (Table 1). Little change in Q_{HEF} was simulated in the first month (Table 1), as the channel adjusted to wood removal by scouring sediment from small portions of the channel. By 2 years posttreatment, the simulation suggests that Q_{HEF} was reduced by about 15%, as scour and fill greatly smoothed the longitudinal profile of the channel (Figure 3). By 1991, alternating bar sequences and better defined pool-riffle sequences were well developed as signified by substantial increases in the amount of sediment stored in the active channel. Our simulations suggest that these channel adjustments increased Q_{HEF} to 1.22 l/s. By 2003, the longitudinal profile showed well developed alternating pool-riffle sequences and Q_{HEF} had nearly doubled, relative to the conditions immediately after wood removal (Table 1).

[23] The median residence times of hyporheic exchange flow (HEF_{RT}) increased as the stream channel adjusted to wood removal (Table 1). The median HEF_{RT} within the study reach, as simulated with MODPATH, increased from approximately 8 h under the initial conditions to 11.1 h by 1991. By 2003 the median HEF_{RT} had further increased to 14.6 h (Table 1). In the first month after wood removal, simulations showed substantial loss of very short (<1 and 1–6 h) exchange flow paths (Figure 4). Thereafter, the absolute abundance of short flow paths increased, albeit more slowly than did long residence time flow paths so that their relative abundance remained low in all post wood removal simulations. The simulations showed that very long residence time flow paths increased as the channel morphology adjusted to wood removal (Figure 4). For example,

Table 1. Basic Descriptive Metrics From Simulations of the Study Reach on the Five Study Dates[a]

	Initial Condition	1 month	2 years	4 years	16 years
Survey date	27 May 1987	23 Jun 1987	23 May 1989	16 May 1991	18 Aug 2003
Wetted channel area (m^2)	313	293	324	326	355
Hyporheic area (m^2)	137	136	158	173	229
Percent hyporheic	44	47	49	53	64
Number upwelling patches	7	14	12	14	7
Number downwelling patches	6	11	11	13	8
Total number of patches	13	25	23	27	15
Hyporheic exchange Q_{HEF} (L/s)	0.96	0.96	0.82	1.22	1.90
Nonhyporheic exchange (L/s)	0.86	1.28	0.52	0.64	0.70
Total exchange (L/s)	1.81	1.97	1.32	1.83	2.44
Net change in discharge (L/s)	0.64	1.11	0.81	0.27	−0.11
HEF per segment					
Max upwelling ($L/m^2/h$)	141	240	146	436	178
Max downwelling ($L/m^2/h$)	89	91	61	75	141
Average upwelling and downwelling ($L/m^2/h$)	25	25	19	25	30
Median residence time (h)	8.2	8.8	10.5	11.1	14.6
Mean residence time (h)	53.0	32.1	35.1	146.4	190.4
Standard deviation	151.3	98.4	136.9	302.0	379.2
Shapiro-Wilk W	0.9801	0.9792	0.9925	0.9157	0.9435
Probability < W	<0.0001	0.0002	0.0274	<0.0001	<0.0001
Turnover length L_s (km)	5.0	5.0	5.8	3.9	2.5

[a]The Shapiro-Wilk is a test of normality [*Shapiro and Wilk*, 1965].The W value indicates that the distributions are highly correlated to lognormal, but the probability is extremely low that they are truly lognormal.

MODPATH simulations showed that percentage of particles still in the hyporheic zone after 6 weeks was less than 1% under the initial conditions, 1 month, and 2 years post wood removal. By 1991, 1.3% of the flow paths had residence times exceeding 6 weeks, and this increased to 7.9% by 2003. This was not just a shift in the relative proportion of long versus short residence time flow paths. The MODFLOW simulations of hyporheic exchange after 4 and 16 years post wood removal showed greater total Q_{HEF} and the MODPATH simulations showed more particles entrained into long residence time flow paths. Overall, our simulations showed that the residence times of hyporheic water were quasi-lognormal, especially on the first three dates (Table 1 and Figure 4). The increase in long residence time flow paths 4 and 16 years post wood removal, however, resulted in highly skewed distributions and a substantially worse fit to a lognormal distribution.

[24] The WSE profile was a major determinant of both the amount and location of Q_{HEF}. Steep head gradients were present wherever the slope of the WSE changed abruptly and these head gradients drove hyporheic exchange. Under conditions immediately after wood removal, large wood oriented perpendicular to streamflow obstructed the channel near cross section B (Figure 1), creating a zone of hyporheic exchange, with downwelling dominant over the upstream half of the slope break and upwelling dominant downstream of the slope break (Figure 5a). Also note that hyporheic exchange where wood was oriented perpendicular to the channel may have been larger than in our model because it is possible that large wood may have generated head gradients not captured in the first postremoval channel survey. Similar patterns of hyporheic exchange were present under initial conditions at cross sections C and F; however, slope breaks in these locations were not buttressed with large wood but instead resulted from free-formed pool-riffle sequences. Hyporheic exchange flow decreased substantially in most locations 2 years after large wood removal (Figure 5b). A notable exception occurred near cross section A, where wood removal promoted streambed scour leading to devel-

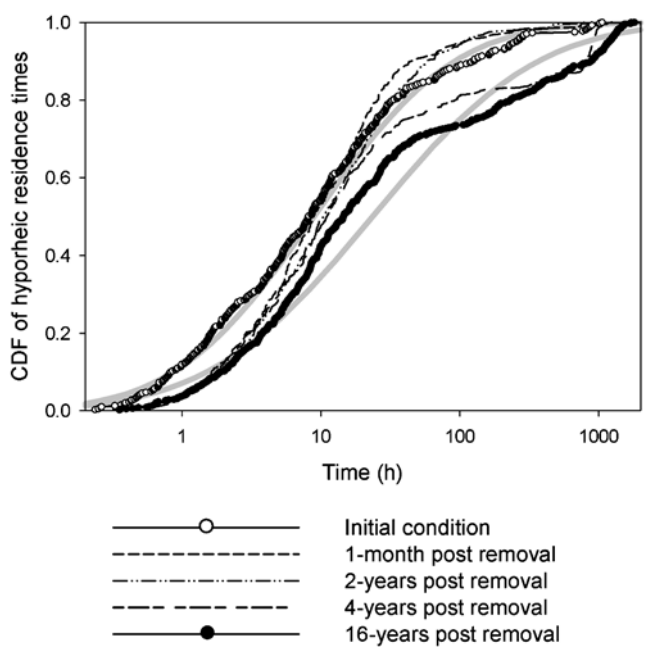

Figure 4. Cumulative distribution functions (cdfs) of the residence time of hyporheic water in the subsurface as simulated using MODFLOW and MODPATH. Thick gray lines show lognormal cdfs generated using the mean and standard deviations of the residence time distributions for the initial and 16-year post wood removal simulations.

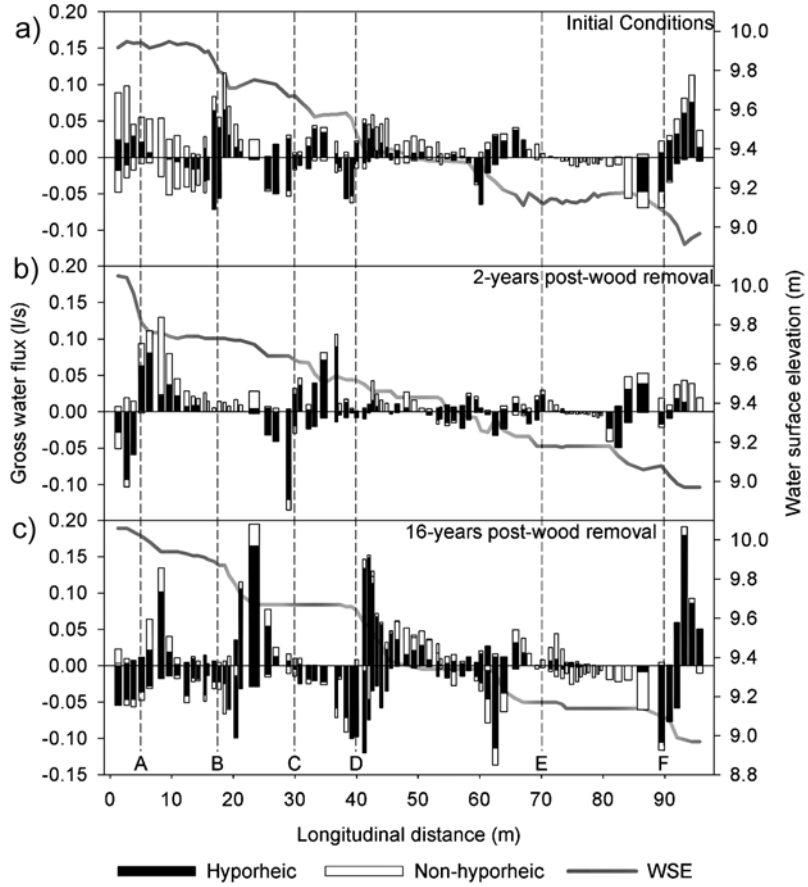

Figure 5. Longitudinal patterns of hyporheic and nonhyporheic exchange flows (bars) and the WSE profile (thick line) from three of the five simulation dates (May 1987 at initial conditions; May 1989, 2 years following wood removal; and August 2003, 16 years following wood removal). The locations of cross sections A–F are indicated with dashed lines. Bar widths are proportional to the length of stream between each pair of cross-sectional transects (stream segments).

opment of a major slope break and a large zone of HEF. By 16 years after wood removal (Figure 5c), distinct pool-riffle sequences had developed in association with the alternating bar morphology of the channel. The riffles marked major slope breaks between pools that resulted in alternating zones of downwelling and upwelling along the channel. Bar formation also caused substantially more hyporheic flow along cross-meander flow paths.

[25] The spatial patterns of HEF over the streambed were quite complex. The refined-grid approach used in our models ($\Delta X = \Delta Y = 0.5$ m) allowed a fine-scale examination of these patterns. We used MODPATH and defined the hyporheic exchange flow paths as only those that both originated and terminated in stream cells. Water upwelling into the stream originating from other locations within the model domain, or water downwelling from the stream and exiting the model domain through other boundaries was not considered hyporheic. Examining stream segments between adjacent cross-sectional transects (Figure 1) shows that downwelling and upwelling both occurred over very short reach lengths and usually included both hyporheic and nonhyporheic water (note the distance between cross-sectional transects averaged only 1.14 m) (Figures 5a–5c). The cross-sectional transects were not always aligned perpendicular to stream flow, so some of the complexity likely results from the methods we used to divide the stream reach into distinct segments. Even so, the maps (Figures 6a–6c) clearly show great spatial heterogeneity.

[26] The spatial patterns of downwelling and upwelling did tend to alternate with distance along the channel (Figures 6a–6c). Where slope breaks were controlled by log obstructions oriented perpendicular to flow (e.g., Figure 6a, log immediately upstream of cross section B), boundaries between downwelling and upwelling zones were quite sharp and also tended to be oriented perpendicular to the channel. In contrast, cross-meander flows tended to elongate the zones of HEF along the stream bank on the inside of a meander bend. The best example is shown for the initial conditions, downstream of cross section D, where a long finger of hyporheic upwelling extends downstream along the stream bank, capturing flow through that large meander (Figure 6a).

[27] Scour and fill in the first month following wood removal fragmented previously continuous zones of HEF (Table 1 and Figures 6a–6c), nearly doubling the number of downwelling and upwelling patches present on the streambed, although neither the total wetted channel area nor the area of HEF changed substantially over this time period. As the channel continued to adjust to wood removal, the size, shape, and location of the HEF patches continued to change. The total number of patches remained high 2 and 4 years after wood removal (Table 1 and Figure 6b), with the

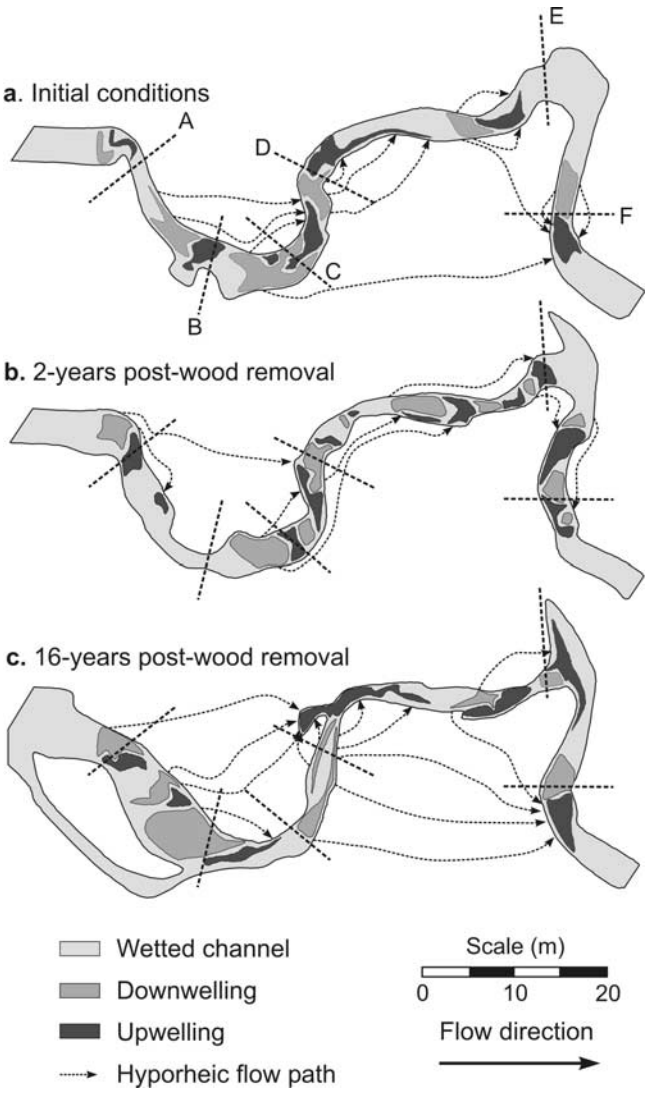

Figure 6. Plan view maps of the wetted channel from (a) May 1987 at initial conditions; (b) May 1989, 2 years following wood removal; and (c) August 2003, 16 years following wood removal. The locations of cross sections A–F are indicated with dashed lines. The locations of long, cross-meander flow paths generated in the model simulations are shown with dashed arrows.

complexity in size and shape often mirroring the complexity of the wetted channel. By 2003, 16 years after the wood removal experiment, the number of HEF patches was again similar to that at the beginning of the experiment (Table 1). Patches tended to be elongated, reflecting the alternating bar/pool-riffle structure of the channel and the dominance of cross-meander flow paths (Figure 6c). A small alcove, formed behind the tail end of the point bar near cross section D, was a zone of convergent flow. A riffle just upstream of the alcove drove flow from the channel toward the alcove, along the lower edge of the gravel bar. The alcove also collected flows from numerous cross-meander flow paths originating further upstream (Figure 6c).

[28] Model simulations showed that changes in channel morphology following wood removal substantially impacted both the area of the wetted stream channel and the amount of the streambed through which hyporheic exchange occurred. Under initial conditions at the start of the experiment, hyporheic exchange (either upwelling or downwelling) occurred over 137 m^2 (or 44%) of the total streambed area (Table 1). Little change occurred over the first month. By 2 years, however, the area of the wetted streambed had increased, and hyporheic exchange occurred over 49% of the streambed area. Although the total area of HEF increased, the hydraulic gradients driving hyporheic flow must have decreased because Q_{HEF} reached a minimum 2 years after wood removal, when scour and fill had greatly smoothed the longitudinal profile of the channel (Figure 3). The area of HEF continued to increase as the channel adjusted to wood removal. By 2003, the longitudinal profile showed very well developed alternating pool-riffle sequences and the area of the wetted channel had substantially increased. The MODFLOW simulations showed that area of the streambed through which hyporheic flow occurred had increased to 229 m^2 (or 64%) of the streambed (Table 1).

4. Discussion

4.1. Applicability of Groundwater Flow Models in Hyporheic Studies

[29] Our use of MODFLOW in this study follows that of several previous studies [*Kasahara and Wondzell*, 2003; *Storey et al.*, 2003; *Cardenas et al.*, 2004; *Lautz and Siegel*, 2006] that used models in a "sensitivity analysis" to explore different factors influencing HEF. As is common in applying groundwater flow models to hyporheic studies, we did not have sufficient information to rigorously test our model predictions. This was especially true between the initial conditions and 4 years, for which we only had stream water elevations at the cross-sectional transects. Because we lacked water table elevations for these dates, calibration of our models was impossible. Therefore, we used "uncalibrated" models in this analysis.

4.1.1. Model Performance

[30] We assumed that sediment properties and basic boundary conditions did not change during the 16-year study period. Therefore, we measured K in 2003, extrapolated these to the model domain, and used those data for all model runs. We tested the fit of the model for the 2003 simulation to the piezometric head observed in the small piezometer networks installed in 2003 (Figure 1). The root-mean-square error (RMSE) of the residuals (simulated versus observed heads) was 0.02 m, whereas the total change in surface water elevations over the study reach is approximately 1.10 m (see Figure 2 for more information). However, as *Wondzell et al.* [2009] have shown, close agreement between observed and simulated heads is to be expected when observation points are located close to specified head boundaries. Because stream water elevations can be very accurately surveyed, and because the water table elevations in near stream piezometers are tightly controlled by stream water elevations, the flow lines are likely quite accurate. However, the close agreement between the observed and simulated values should not be accepted as a rigorous test of the model's ability to simulate the magnitude of hyporheic fluxes nor hyporheic residence times.

[31] Independent measures (tracer test or other data) of flux through the model domain provide a much better test of a hyporheic simulation [*Wondzell et al.*, 2009]. Therefore, we also tested model performance by comparing observed median travel times between piezometers located on the gravel bar (described in section 2.1) with simulated median travel times from MT3D [*Zheng*, 1990]. Simulated median residence times were within a factor of 2 of observed residence time for eight out of nine piezometers, indicating the model estimates of flow through the gravel bar were reasonable (Figure 2). We did not recover usable tracer breakthrough curves from the floodplain piezometers and were therefore unable to test the model simulations from the larger model domain.

4.1.2. Effects of Uncertainties and Model Simplifications

[32] We acknowledge that our use of uncalibrated models with uncertain, homogeneous hydraulic conductivity and uncertain boundary conditions increased the overall uncertainty of our simulations and may limit the interpretation of the absolute values of model predictions. However, the modeling uncertainty does not invalidate our efforts to examine the effect of large wood on HEF. Instead, we consider our efforts to be consistent with a sensitivity analysis approach. We kept boundary conditions and the spatial distribution of K unchanged, thus allowing us to isolate the changes in HEF resulting from changes in channel morphology following wood removal.

[33] The constant head boundaries at the side and the no-flow boundaries at the bottom of the model are uncertain and may have slightly truncated the end of the residence time cdf. It is possible that a very small fraction of the flow that exited the side model should have returned to the stream and been counted as HEF with a long residence time. Similarly, flow is forced to return to the surface by the bottom no-flow boundary. Together, these boundaries may have generated a smaller number of very long and very slow flow paths than in reality. We did a sensitivity analysis on the HEF to bottom boundary depth and found no significant changes after 20 m. We did not do a sensitivity analysis to the side boundaries, but these are a minimum of 20 m from the stream and involve a negligible amount of flow originating in the stream reach. These results are reported by *LaNier* [2006]. For a further analysis of the effects of boundary conditions on long-time hyporheic flow, see *Wörman et al.* [2007], *Cardenas* [2007, 2008], and *Cardenas et al.* [2008b].

4.2. Changes in Hyporheic Exchange

[34] Previous work by *Smith et al.* [1993b] clearly showed that wood limited the development of gravel bars in this small, low-gradient stream. Once wood was removed, the channel began adjusting toward a more free-formed pool-riffle morphology. Our simulations suggest that these changes were accompanied by increased hyporheic exchange flow and increased residence times of stream water in the hyporheic zone. Because wood buried in the floodplain was cut flush with the stream banks and only the portion projecting into the active channel was removed, the degree of bar development observed since wood removal was not entirely "free form." The residual wood defends stream banks against erosion, deflects flows, and tends to fix the preexisting configuration of alternating bars in place. If both the active channel and floodplain sediments were wood free, further bar development might occur, in which case a fully free-formed channel might have still greater sinuosity, more or larger point bars, and better developed pool-riffle sequences which could further increase the amount of hyporheic exchange.

4.2.1. Spatial Patterns of Downwelling and Upwelling

[35] The spatial patterns of simulated exchange fluxes are quite complex within our study reach. There is a tendency for a net increase in nonhyporheic exchange (upwelling of nonhyporheic water) toward the top of the reach and a net loss of nonhyporheic exchange (downwelling) toward the tail of the reach (Figure 5). Much of this spatial trend is likely an artifact of our methods. We defined HEF as water that originated in stream cells, flowed into the subsurface, and subsequently flowed back into a stream cell within the study reach. Much of the nonhyporheic water upwelling through the streambed near the head of the reach, or downwelling near the tail of the reach, represents "bypass flow" that would have originated in, or returned to the stream, if we had modeled a longer reach. Certainly, some of the water flowing into the stream cells would have originated from adjacent hillslopes. We cannot distinguish among the ultimate sources or sinks of this water in our modeling approach. Therefore we refer to this water as "nonhyporheic water," and our estimation of HEF is therefore conservative.

[36] Although the spatial pattern of downwelling and upwelling is quite complex, it is clear that head gradients imposed by changes in the WSE profile along the reach are one of the dominant drivers of hyporheic exchange (Figure 5). Alternating zones of downwelling and upwelling occur in all simulations. Further, the transition between downwelling and upwelling usually occurs midway along each riffle. Under conditions immediately prior to wood removal, there was one wood-forced step controlled by a channel spanning log just upstream of cross section B. A wedge of sediment had accumulated above this log, with a steep riffle downstream of the log. Removal of the log initiated erosion and channel incision, and by 2 years post wood removal, a sharp knickpoint had migrated upstream to cross section A. The zones of downwelling and upwelling also migrated upstream, so that 2 years after wood removal, little exchange flux occurred at cross section B. Sediment was scoured from the channel near the head of the reach while deposition occurred downstream, smoothing the longitudinal profile and reducing hyporheic exchange. Continued adjustment of the channel over the next 14 years created a number of low-gradient zones separated by riffles, with substantial hyporheic exchange.

[37] Another potentially important driver of hyporheic exchange which we did not include in our models is heterogeneity in K. For an analysis of this effect, refer to *Cardenas et al.* [2004], *Salehin et al.* [2004], *Ryan and Boufadel* [2006], and *Marion et al.* [2008]. Interestingly, the deep pool scoured into the streambed just downstream of cross section E had little effect on HEF. Two large logs were removed from the channel in this location, but these logs were oriented parallel to flow and thus had relatively little influence on sediment or the WSE profile. Lateral channel migration is limited in this location by the edge of a high terrace. Removal of the wood apparently allowed additional

scour and enlargement of the pool, with relatively little effect on HEF.

[38] Calculations of gross exchange fluxes suggested that downwelling and upwelling of both hyporheic and nonhyporheic water occurred within the short stream segments between adjacent cross-sectional transects (Figure 5). The spatial patterns of exchange flow on the streambed show how such complex patterns in gross exchange can occur at such small scales (Figures 6a–6c). Although the simple pattern of alternating zones of downwelling and upwelling can be discerned, these zones are often quite elongated, especially around meander bends. For example, consider the zone from cross section C to the point bar downstream of cross section D under initial conditions (Figure 6a). Upwelling occurs on the left side of the channel (facing downstream), downstream of C where cross-meander flow paths rejoin the stream. The right side of the channel, however, is a zone of downwelling, feeding stream water into cross-meander flow paths through the next point bar. These flow paths rejoin the stream in a very elongate zone of upwelling, all along the downstream face of this point bar. Zones of downwelling and upwelling are not immediately contiguous but are separated by zones of relatively neutral exchange flux. Also, exchange fluxes of nonhyporheic water occur over large portions of the streambed.

[39] By 2 years after wood removal, the WSE profile was smoothed, with large distinct breaks in the longitudinal gradient replaced by a much finer, small-scale pattern (Figure 5). This is also reflected by the increase in number (Table 1) and the decrease in size (Figure 6b) of downwelling and upwelling patches on the streambed. By 16 years post wood removal, with the alternating bar and pool-riffle morphology well developed, the patches had coalesced, forming numerous elongate zones of downwelling and upwelling.

[40] Model-based estimates of hyporheic exchange through the streambed, averaged over the study reach, ranged between 19 and 30 L m^2/h. Estimates for individual segments of the streambed, however, can exceed 400 L m^2/h, with even higher rates simulated from individual stream cells. Significant spatial variability in streambed flux has been observed in the field [*Burkholder et al.*, 2008]. Aquatic organisms can be sensitive to these fluxes. For example, many cold water–dependent fishes seek cooler upwelling locations during summer low flows when the bulk stream temperatures exceed the species temperature preferences [*Berman and Quinn*, 1991; *Ebersole et al.*, 2001]. Similarly, patches of upwelling or downwelling water may influence spawning site selection of cold water fishes [*Baxter and Hauer*, 2000; *Geist et al.*, 2002].

[41] *Kasahara and Wondzell* [2003] argued that expressing hyporheic upwelling rates relative to the streambed area may better reflect the importance of HEF to stream ecosystem processes than the ratio of exchange flow to stream discharge (Q_{HEF}:Q_{stream}) because biological activity tends to be concentrated on benthic surfaces. The presence and importance of fine-scale environmental patchiness on streambeds generated by groundwater inflows and hyporheic return flows are increasingly recognized [*Burkholder et al.*, 2008, *Cardenas et al.*, 2008a; *Poole et al.*, 2008]. Here, we have shown that there is substantial spatial and temporal variability in the amount of water downwelling or upwelling through these patches and variability in the size, shape, and location of these patches. Patches with high rates of HEF may be hot spots of biological activity [*McClain et al.*, 2003] and may provide distinct microhabitats critical to the success of stream dwelling organisms. Our results also suggest that human land use activities that influence channel morphology may strongly affect downwelling and upwelling patches.

4.2.2. Interactions Between Wood, Channel Morphology, and HEF

[42] The general trends observed in this stream contrast with the role of large wood in higher-gradient mountain streams [*Kasahara and Wondzell*, 2003; *Wondzell*, 2006]. *Kasahara and Wondzell* [2003] used MODFLOW and conducted a sensitivity analysis of the effect of wood-buttressed sediment wedges on HEF in a stream. HEF increased with the abundance of wood-forced steps in the WSE profile, and the larger the steps, the greater the increase in HEF. *Wondzell* [2006] found similar results when examining naturally formed stream channels with the stream tracer approach. In the case of these two high-gradient streams (~13%), free-formed channels would have either been scoured to bedrock [*Montgomery et al.*, 1996] or would have formed some boulder-buttressed steps [*Faustini and Jones*, 2003]. Large logs significantly increased sediment storage in these channels [*Nakamura and Swanson*, 1993], and similar relationships between large wood and sediment storage and channel morphology have been reported for other high-gradient channels [*Beschta*, 1979; *Mosley*, 1981; *Díez et al.*, 2000; *Faustini and Jones*, 2003]. Thus, all available lines of evidence suggest that the removal or loss of large wood changes channel morphology and reduces the extent of the hyporheic zone in steep mountain streams.

[43] The interactions between in-stream large wood, channel morphology, and HEF appear to be more complex in low-gradient streams. Several authors have shown that in-stream wood promotes HEF at the scale of individual bed forms [*Mutz et al.*, 2007; *Hester and Doyle*, 2008], the channel unit scale [*Kasahara and Hill*, 2006], and whole reach scales [*Lautz et al.*, 2006].

[44] *Mutz et al.* [2007] examined a low-gradient, sand bed channel in a flume and demonstrated that the addition of large wood significantly increased bed form irregularities, leading to increases in hyporheic exchange and the depth to which stream water penetrated into the streambed sediment. This flume study, however, used a straight, plane bed channel entirely lacking bed forms as the control condition. They did not contrast channels with free-formed bed forms lacking wood with those formed in the presence of wood. Further, the flume walls tightly bounded the stream, preventing lateral adjustments in the channel planform under either wood-loaded or wood-free conditions. As our simulations of the Bambi Creek study site showed, loss of wood resulted in reduced hyporheic exchange 2 years after wood removal because scour and deposition smoothed the WSE profile. To that extent, our results from the first few years after wood removal are consistent with those of *Mutz et al.* [2007] in that HEF was positively correlated to bed form irregularity. However, our longer-term results contrast sharply with these previous studies, as wood removal eventually increased HEF. It took 4 years of channel adjust-

ments in Bambi Creek before our simulations showed increased hyporheic exchange.

[45] Both riffles [*Storey et al.*, 2003; *Kasahara and Hill*, 2006] and meander bends [*Boano et al.*, 2006] have been shown to be important locations of hyporheic exchange in low-gradient streams. *Lautz and Siegel* [2006] examined the relative importance of these features in a low-gradient, meandering stream, Red Canyon Creek. Using a groundwater flow modeling analysis, they demonstrated that exchange fluxes driven by head gradients imposed by beaver dams were much larger than exchange fluxes through meander bends. Of course, these hyporheic exchange flows would be lost if the obstructions were removed from the channel. A critical question, then, is how does that channel adjust to the loss of wood or other obstructions over the long term?

[46] Small stream studies have shown that active channels in forested reaches are wider than equivalent channels in meadows or pasture because of the combined effects of decreased bank cohesion where forest canopy shades out stream bank vegetation and bank scour caused by large wood [*Trimble*, 1997; *Davies-Colley*, 1997; *Sweeney et al.*, 2004; *Allmendinger et al.*, 2005]. In contrasting Bambi Creek (this study) to Red Canyon Creek [*Lautz and Siegel*, 2006], we suggest that the relatively wide channel at Bambi Creek allowed sufficient room for the development of alternating bars within the active channel following wood removal. At low flow, the wetted channel meandered around these unvegetated gravel bars. The development of the associated pool-riffle morphology resulted in a stepped longitudinal profile (Figure 3) that enhanced HEF. In contrast, cohesive stream banks resulting from dense herbaceous vegetation would promote a narrow active channel and limit gravel bar development within the channel of Red Canyon Creek. Because of relatively fine textured floodplain sediment at both Bambi Creek. and Red Canyon Creek, hyporheic exchange is dominated by short exchange flow paths in the near stream zone. Thus, it seems reasonable that development of gravel bars within the active channel would lead to increased hyporheic exchange at Bambi Creek, whereas the narrower channel at Red Canyon Creek would limit bar development such that steps in the energy profile of the stream created by beaver dams would dominate HEF.

[47] Overall, the Bambi Creek wood removal experiment [*Smith et al.*, 1993a, 1993b] (also this study) is different than previous studies on higher-gradient streams in that wood removal increased both sediment storage and HEF. Studies on lower-gradient streams or flumes mostly report in situ conditions or those immediately following changes in wood loading (removal or addition experiments), thereby highlighting the direct effects of wood on sediment storage, channel morphology, and hyporheic exchange. To resolve the apparent contradictions between these studies, we must consider more than just the direct effects of wood removal. We must consider the long-term channel adjustments set in motion through changes in wood. Clearly, not all channels have equal potential to adjust their planform in response to changes in wood loading. Some low-gradient natural channels are tightly constrained and others are incised, often from human land use impacts. We expect these would respond more like the flume study of *Mutz et al.* [2007]. Channel adjustments may be very slow in meadow streams where grassy vegetation maintains narrow active channels so that woody obstructions, if present, are likely to be the most important contributors to HEF. Finally, channels that are sediment supply limited are likely to incise following wood removal resulting in reduced HEF. The Bambi Creek study is relatively unique. It is a 16-year-long study of a small, low-gradient stream in a near-pristine environment. The channel is not incised, and the long record of study provided time for secondary effects of wood removal to become evident; that is, the major planform adjustments resulting from sediment redistribution into a more fully developed alternating bar channel with well developed pool-riffle morphology. Further study in other low-gradient streams will be needed to know if the pattern observed at Bambi Creek is repeated elsewhere.

5. Conclusions

[48] This study found that the hyporheic zone of a small, low-gradient stream is sensitive to changes in wood loading. However, the initial decrease in HEF resulting from the direct effects of wood removal were reversed by an unexpected longer-term increase in HEF resulting from larger-scale channel adjustments to wood removal. Soon after wood removal, scour and deposition smoothed the WSE profile, reducing HEF. Over a longer time (4+ years), the relatively wide channel at Bambi Creek allowed for the development of alternating bars within the active channel. This, in turn, led to increased hyporheic exchange.

[49] In addition to overall trends in gross HEF, different spatial patterns of HEF were observed as the system responded to wood removal. Immediately after wood removal, large distinct breaks in the longitudinal gradient focused HEF in a few patches. Within 2 years, the smoother longitudinal profile generated a much finer, small-scale pattern of local, weaker HEF. By 16 years post wood removal, with the alternating bar and pool-riffle morphology well developed, the HEF patches had coalesced, forming numerous elongate zones of downwelling and upwelling. However, at all times, the longitudinal pattern of alternating upwelling and downwelling belied a significant amount of transverse HEF, where one side of the channel experienced downwelling and the other side experienced upwelling. It is also possible that the transverse pattern of HEF would be enhanced by heterogeneity, which our study largely ignored.

[50] Residence times of HEF were in all cases quasi-lognormal, with mean residence times of tens to hundreds of hours, and standard deviations of hundreds of hours. In the long term, wood removal resulted in longer mean residence times, which could have an impact on hyporheic temperature, nutrient retention, and oxygen concentration.

[51] **Acknowledgments.** We thank Justin Anderson and Eric Norberg for help with field work in 2003. This research was funded by the Aquatic and Lands Interaction Program of the USDA Forest Service's Pacific Northwest Research Station.

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