A modelling study of hyporheic exchange pattern and the sequence, size, and spacing of stream bedforms in mountain stream networks, Oregon, USA

Michael N. Gooseff,[1]* Justin K. Anderson,[2] Steven M. Wondzell,[3] Justin LaNier[4] and Roy Haggerty[4]

[1] *Department of Geology and Geological Engineering, Colorado School of mines, Golden, CO 80401, USA*
[2] *Department of Forest Sciences, Oregon State University, Corvallis, OR 97331-5752, USA*
[3] *US Forest Service, Pacific Northwest Research Station, Olympia Forestry Sciences Lab, Olympia, WA 98512, USA*
[4] *Department of Geosciences, Oregon State University, Corvallis, OR 97331-5506, USA*

Abstract:

Studies of hyporheic exchange flows have identified physical features of channels that control exchange flow at the channel unit scale, namely slope breaks in the longitudinal profile of streams that generate subsurface head distributions. We recently completed a field study that suggested channel unit spacing in stream longitudinal profiles can be used to predict the spacing between zones of upwelling (flux of hyporheic water into the stream) and downwelling (flux of stream water into the hyporheic zone) in the beds of mountain streams. Here, we use two-dimensional groundwater flow and particle tracking models to simulate vertical and longitudinal hyporheic exchange along the longitudinal axis of stream flow in second-, third-, and fourth-order mountain stream reaches. Modelling allowed us to (1) represent visually the effect that the shape of the longitudinal profile has on the flow net beneath streambeds; (2) isolate channel unit sequence and spacing as individual factors controlling the depth that stream water penetrates the hyporheic zone and the length of upwelling and downwelling zones; (3) evaluate the degree to which the effects of regular patterns in bedform size and sequence are masked by irregularities in real streams. We simulated hyporheic exchange in two sets of idealized stream reaches and one set of observed stream reaches. Idealized profiles were constructed using regression equations relating channel form to basin area. The size and length of channel units (step size, pool length, etc.) increased with increasing stream order. Simulations of hyporheic exchange flows in these reaches suggested that upwelling lengths increased (from 2·7 m to 7·6 m), and downwelling lengths increased (from 2·9 m to 6·0 m) with increase in stream order from second to fourth order. Step spacing in the idealized reaches increased from 5·3 m to 13·7 m as stream size increased from second to fourth order. Simulated downwelling lengths increased from 4·3 m in second-order streams to 9·7 m in fourth-order streams with a POOL–RIFFLE–STEP channel unit sequence, and increased from 2·5 m to 6·1 m from second- to fourth-order streams with a POOL–STEP–RIFFLE channel unit sequence. Upwelling lengths also increased with stream order in these idealized channels. Our results suggest that channel unit spacing, size, and sequence are all important in determining hyporheic exchange patterns of upwelling and downwelling. Though irregularities in the size and spacing of bedforms caused flow nets to be much more complex in surveyed stream reaches than in idealized stream reaches, similar trends emerged relating the average geomorphic wavelength to the average hyporheic wavelength in both surveyed and idealized reaches. This article replaces a previously published version (*Hydrological Processes*, **19**(17), 2915–2929 (2005) [DOI:10.1002/hyp.5790]. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS   hyporheic zone; geomorphology; MODFLOW; groundwater flow modelling; spatial scaling

Received 14 October 2003; Accepted 16 April 2004

*Correspondence to: Michael N. Gooseff, Department of Geology and Geological Engineering, Colorado School of mines, Golden, CO 80401, USA. E-mail: mgooseff@mines.edu

INTRODUCTION

Hyporheic exchange processes greatly impact aquatic biogeochemical cycling (Bencala, 1984; Duff and Triska, 1990; Bencala *et al*., 1994; Jones *et al*., 1995; Mulholland *et al*., 1997; Gooseff *et al*., 2002) and aquatic habitat (Baxter and Hauer, 2000; Geist, 2000). Though the physics of hyporheic exchange are well understood (once subsurface flow becomes Darcian; e.g. Vaux, 1968), characterization of exchange requires either an abundance of wells coupled to modelling or tracer tests, or both. Well networks are expensive and difficult to install, so that installing an extensive network of wells is not feasible for many ecological applications. Alternatively, tracer tests, though less expensive, are complicated by confounding phenomena such as transient surface storage and non-conservative transport. The difficulties associated with well networks and the complications associated with tracer studies limit researchers' abilities to study long reaches of stream or to make comparisons among many reaches. The ability to incorporate hyporheic exchange processes more effectively into biogeochemical and ecological studies will require characterizing these processes more efficiently. We suggest that longitudinal patterns in fluvial geomorphology, such as channel unit spacing, can be applied to characterize the process of hyporheic exchange flow more efficiently across a broad range of stream size and gradient.

That fluvial geomorphic characteristics of stream channels and floodplains change systematically along a downstream continuum from relatively small bedforms in steep headwater streams to larger bedforms and lower longitudinal gradients in larger streams has long been established (e.g. Hack, 1957). More recently, several workers have suggested that stream channel network morphology generally develops downstream from cascade through step–pool and plane-bed to pool–riffle reach types, with decreasing reach slope and increasing pool spacing (e.g. Montgomery and Buffington, 1997). Chin (1999, 2002) documented increased step spacing and pool-to-pool wavelengths with increasing drainage area in two coastal basins in southern California. In a study of western Cascade mountain stream basins (including Lookout Creek), Grant *et al*. (1990) found that step spacing was inversely proportional to bed slope, and that pool-to-pool spacing averaged two to four channel widths. Duckson and Duckson (2001) document the occurrence of taller steps and shorter pools in steeper reaches in Soda Creek, Oregon. These studies demonstrate that geomorphic bedform size and spacing of channel units increases along the river continuum of various stream basins.

Several studies have addressed the control of fluvial geomorphology on hyporheic exchange at the stream reach scale, namely the influence of channel form on near-stream hydraulic head gradients, driving hyporheic exchange. Harvey and Bencala (1993) found upwelling zones (where hyporheic water enters the stream) and downwelling zones (where stream water enters the hyporheic zone) related to the subsurface hydraulic head patterns developed by streambed slope breaks of a pool–riffle sequence. Further work by Wondzell and Swanson (1996) and Kasahara and Wondzell (2003) identified additional influences on hyporheic exchange by other bedform features that dictate subsurface head distributions, such as bars, side channels, meander bends and steps. In a comparison of second- and fifth-order stream reaches, Kasahara and Wondzell (2003) found that longitudinal profile changes (boulder- or log-induced steps) accounted for about half of the hyporheic exchange flows in second- and fifth-order stream reaches. Lateral hyporheic exchanges are also controlled by stream channel form (Vervier *et al*., 1993; Morrice *et al*., 1997; Storey *et al*., 2003). Anderson *et al*. (2005) characterized increases in channel unit size and spacing with increasing drainage basin area, and demonstrated that the length of downwelling zones in stream reaches instrumented with piezometers also increased with drainage basin area. These field studies suggest that patterns in channel form will become useful indicators for efficiently characterizing patterns in hyporheic exchange flow.

Because channel form controls hyporheic exchange flow in mountain streams, and because bedform size and spacing between channel units increases with increasing watershed area, we hypothesize that the average flow-path length of stream water exchanging through the hyporheic zone will similarly increase with basin area—a hypothesis that is supported by field results presented by Anderson *et al*. (2005). The groundwater modelling used in this study allowed us to isolate bedform size and sequence as factors controlling hyporheic flowpaths, and to visualize how hyporheic flowpaths are driven by slope breaks in the stream longitudinal profile. We use two-dimensional (2-D) groundwater flow and particle tracking models to simulate exchange

flows in stream reaches with different-sized bedforms and different patterns in bedform configuration. We generated pairs of idealized, second-, third-, and fourth-order stream reaches that varied only by the sequence of channel slope units (POOL−RIFFLE−STEP pattern sequences versus POOL−STEP−RIFFLE sequences). We also simulated hyporheic exchange flow in three surveyed stream reaches representing different stream size in order to evaluate whether heterogeneity in channel unit size and sequence in real streams would mask the results obtained from the analysis of idealized profiles.

Site description

The 64 km^2 Lookout Creek watershed, located in central Oregon, USA, comprises the H.J. Andrews Experimental Forest (Figure 1). Previous hyporheic investigations in the Lookout Creek basin suggest a strong influence of hyporheic exchange on solute transport dynamics (Haggerty *et al*., 2002; Gooseff *et al*., 2003). This study focuses on three sets of second-, third-, and fourth-order stream reaches, one of which is a set of surveyed reaches, and two of which are idealized (as described earlier). The first surveyed reach, Reach 224, is 90·2 m of a second-order, single-thread channel draining a 1·98 km^2 stream basin. The second reach, Reach 356, is 202·3 m of a single thread channel in third-order Lookout Creek, draining 16·87 km^2. The third reach, Reach 410, is 212·2 m of a single-thread alluvial channel with step−pool and step−riffle morphology in fourth-order Lookout Creek, draining 25·9 km^2.
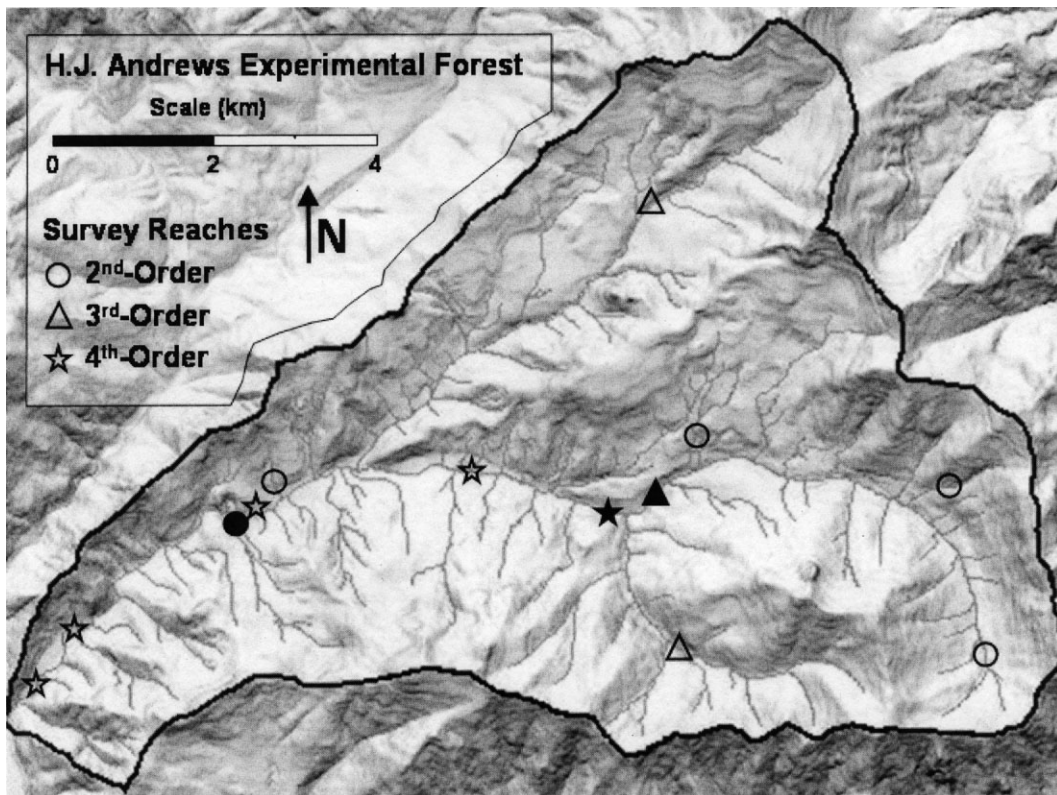

Figure 1. Location map of the H.J. Andrews Experimental Forest, USA, surveyed reaches, and experimental Reaches 224 (second order), 356 (third order), and 410 (fourth order) denoted by solid symbols. Note, Reach 410 was not one of the 12 randomly selected reaches used to generate idealized reach profiles

METHODS

Stream reach surveys and analysis

Longitudinal stream reach bed and surface water profiles were surveyed with an auto level and stadia rod during the summer of 2001. A fibreglass measuring tape was stretched between stakes driven into the streambed along the centre of the channel. Streambed and water surface elevations were surveyed at points along the measuring tape. The spacing interval between survey points varied to capture channel-spanning breaks in the slope of the bed and water surface. After surveying, longitudinal profiles were systematically broken into generalized categories of channel units defined exclusively by the slope of the water surface. Channel unit categories included POOLs (channel units with slope <0·025), RIFFLEs (channel units with 0·025 < slope < 0·13), or STEPs (channel units with slope >0·13). The source area for each reach was calculated from a 10 m digital elevation model.

Bedform size and spacing in the Lookout Creek basin are characterized by high variability; however, regression models show statistically significant increases in bedform size and spacing with increasing basin area (Anderson *et al*., 2005). Here, we investigate how observed trends in average bedform characteristics will affect patterns of hyporheic exchange flow. To do so, we created idealized longitudinal profiles for second-, third-, and fourth-order stream reaches using regression models that predict the shape of the longitudinal profile based on specified values for basin size and stream reach slope (Table I).

Idealized longitudinal profiles were created based on output from a set of regression models developed for predicting bedform configuration based on survey data for 12 randomly selected stream reaches in the H.J. Andrews Experimental Forest (Anderson, 2002). Explanatory variables in regression models included drainage basin area and stream reach gradient. The approach for creating idealized profiles was to use the predicted median distance between STEPs to set the spacing for a repeating pattern of channel units, and to use the predicted relative abundance of POOLs, RIFFLEs, and STEPs to determine the shape of the longitudinal profile between STEPs. This approach was chosen because regression models for predicting step spacing and the proportion of stream reach length and height occupied by POOLs, RIFFLEs, and STEPs in surveyed stream profiles explained more variability than models for predicting pool spacing, pool length, riffle spacing, or riffle length (Table I; Anderson *et al*., 2005). For simplicity, we constructed idealized longitudinal profiles to represent only two common sequences: POOL–RIFFLE–STEP and POOL–STEP–RIFFLE. The approach described here resulted in an oversimplification of stream reach characteristics; however, this was necessary in order to isolate bedform spacing and sequence as individual factors controlling hyporheic flowpaths.

Reach averages of the following geomorphic bedform characteristics were analysed: STEP spacing, geomorphic wavelength (Λ_G, defined as the sum of the average POOL, RIFFLE, and STEP lengths, represented by L_{POOL}, L_{RIFFLE}, and L_{STEP} respectively), slope, elevation loss per RIFFLE (E_{RIFFLE}), and elevation loss per STEP (E_{STEP}). These variables reflect the changes in vertical and longitudinal size of morphologic features we expect to control hyporheic exchange patterns, and which are efficiently measured with survey techniques.

2-D hyporheic exchange modelling

A groundwater model, MODFLOW (Harbaugh and McDonald, 1996), and a groundwater particle tracking model, MODPATH (Pollock, 1994), were used to simulate longitudinal hyporheic exchange in all nine stream reaches considered in this study. Streambed and water surface elevation along the thalweg of the stream reach were used to parameterize the groundwater models.

Lateral complexity in stream reach morphology was purposely ignored so as to isolate and test longitudinal stream bed and water surface variation as a control on hyporheic exchange. A previous study by Kasahara and Wondzell (2003) suggests that longitudinal fluvial geomorphic variability is the primary driver of hyporheic exchange in the small streams of the Lookout Creek basin. The observed reaches studied here are all single-thread channels. Furthermore, we chose to focus on longitudinal variability because bedform spacing and sequence are readily measurable morphologic characteristics that can be defined for nearly any stream reach.

Table I. Regression models used to create idealized longitudinal profiles, derived from longitudinal surveys of 12 channels (Anderson *et al*., 2005). AREA is contributing basin area; S is stream gradient

Parameter	Model	n	R^2	Two-sided p-value
(A) Median distance between STEPs	$= \exp\{2.53 + 0.29[\ln(\text{AREA})] - 6.57S - 2.46[\ln[\text{AREA} \times S)]\}$	112	0.498	<0.0001
(B) Mean proportion of POOL length	$= 44.81 + 10.16[\ln(S) - 129.81S - 112.17[\ln(\text{AREA})^*S]$	13	0.942	<0.0001
(C) Median proportion of STEP length	$= \exp[1.99 - 0.047(\text{AREA}) + 9.07S + 0.96(\text{AREA} \times S)]$	13	0.944	<0.0001
(D) Proportion of RIFFLE length	$= 1 - (B) - (C)$	na	na	na
(E) Median proportion of POOL elevation loss	$= \exp[0.71 + 0.04(\text{AREA}) - 9.32S]$	12	0.813	0.0005
(F) Mean proportion of STEP elevation loss	$= 34.30 - 6.96[\ln(\text{AREA})] + 277.40S + 113.52[\ln(\text{AREA}) \times S]$	13	0.887	0.0001
(G) Proportion of RIFFLE elevation loss	$= 1 - (E) - (F)$	na	na	na
(H) Median POOL depth maximum	$= \exp\{2.83 + 0.40[\ln(B)]\}$	183	0.283	<0.0001
(I) Median POOL depth minimum	$= \exp\{2.39 + 0.18[\ln(\text{AREA})]\}$	183	0.157	<0.0001

Hyporheic hydraulic conductivity K was parameterized as isotropic and homogeneous, and was arbitrarily set to 2×10^{-4} m s^{-1} in all models, similar to that used by Kasahara and Wondzell (2003). Boundary conditions at the upstream and downstream extents of the model domain were defined by constant-head cells, whereas the boundary conditions for the sides and the bottoms of the model domain were defined as no-flow boundaries. To reduce the influence of upstream and downstream boundary conditions on the model simulations, an additional 10 m of stream reach was added to the top and bottom of each model. Idealized and observed reaches had varying streambed slopes and depths. Average depth to bedrock (lower boundary condition) was set to 3·0 m, 4·0 m, and 5·0 m for all second-, third-, and fourth-order stream reaches respectively. The particle tracking models released 15–30 particles per metre stream length, along the top of the uppermost hyporheic cells (Table II).

From the MODFLOW output, average upwelling lengths L_{UP} and downwelling lengths L_{DN} are computed, defined as the length of stream reach along which a positive or negative (respectively) vertical flux between the hyporheic zone and the stream. Stream reaches were entirely composed of upwelling and downwelling, and no length of neutral exchange was found in any reach. We define the sum of L_{UP} and L_{DN} as the hyporheic wavelength Λ_{H} (m), which represents an average maximum longitudinal length over which water is expected to cycle through the hyporheic zone. We also calculated the mean hyporheic penetration depth for each stream reach, based on the MODPATH particle tracking output. We evaluate the relationships between L_{UP} and/or L_{DN} and reach geomorphic metrics (e.g. channel unit lengths and elevation drops); however, these results are interpreted with caution because of the small sample sizes on which the comparisons are made.

RESULTS

Geomorphic characteristics of surveyed stream reaches

Average longitudinal gradients in surveyed reaches decreased greatly from second- to third-order reaches, but changed little from third- to fourth-order reaches (Table II). The proportion of elevation loss along a reach

Table II. Observed and idealized stream reach characteristics and groundwater modelling–particle tracking parameter values for hyporheic exchange modelling, where E represents elevation loss and L represents the longitudinal length of a geomorphic feature and subscripts POOL, RIFFLE, and STEP represent flat water, steep water, and steps channel units respectively. Number of channel units represented in each observed reach denoted by n. In surveyed reaches, average values are followed by plus/minus standard deviation

Attribute	Reach 224	Idealized 2nd-order reach	Reach 356	Idealized 3rd-order reach	Reach 410	Idealized 4th-order reach
Reach geomorphic characteristics						
Reach length (m)	90.2	—	202.3	—	212.2	—
Average bed slope (m m^{-1})	0.10	0·10	0.05	0·05	0.05	0·05
Average streambed variance (m)	3.2	0·1	0.4	0·1	0.5	0·1
Amount of reach drop due to steps (%)	67.9	65·6	52.9	43·5	60.1	44·6
Average L_{STEP} (m)	1·7 ± 1·2 ($n = 14$)	1·4	1·7 ± 0·6 ($n = 14$)	1·7	1·7 ± 1·4 ($n = 14$)	1·9
Average L_{RIFFLE} (m)	3·0 ± 2·1 ($n = 12$)	3·3	3·6 ± 2·8 ($n = 20$)	5·6	7·0 ± 4·8 ($n = 10$)	5·5
Average L_{POOL} (m)	2·0 ± 1·2 ($n = 15$)	2·1	4·3 ± 2·7 ($n = 25$)	7·8	10·0 ± 6·1 ($n = 16$)	8·2
Geomorphic wavelength Λ_G (m)	6.7	6·7	9.5	15·1	18.6	15·6
Average E_{STEP} (m)	0.5	0·4	0.4	0·3	0.5	0·4
Average E_{RIFFLE} (m)	0.2	0·2	0.20	0·4	0.5	0·4
Groundwater flow modelling parameters						
Average bed depth (m)	3.0	3·0	4.0	4·0	5.0	5·0
Number of particles released per metre	30	30	15	15	15	15

due to steps decreased from 67·9% in the surveyed second-order reach to 52·9% in the surveyed third-order reach, but increased to 60·1% in the surveyed fourth-order reach. Average elevation loss per step E_{STEP} decreased from 0·5 m in Reach 224 to 0·4 m in Reach 356 and Reach 410. The distance between steps (the sum of L_{RIFFLE} and L_{POOL}) increases with increasing stream order from 5·04 m in Reach 224 to 16·97 m in Reach 410. Increases in channel unit lengths with stream order are reflected in the increase of geomorphic wavelength Λ_G with stream order, from 6·7 m to 18·6 m in surveyed reaches, and from 6·7 m to 15·6 m in idealized reaches.

2-D hyporheic exchange modelling

Groundwater flow and particle tracking models revealed complex hyporheic flow paths in the surveyed reaches (Figure 2) and regular, repeated hyporheic flow paths in the idealized reaches (Figures 3). An analysis of the streambed vertical groundwater fluxes in the surveyed stream reaches indicates that average L_{DN} increased from 2·7 m in Reach 224, to 4·0 m in Reach 356, to 7·6 m in Reach 410 (Table III). Average L_{UP} in these surveyed reaches increased from 2·9 m in Reach 224, to 3·7 m in Reach 356, to 6·0 m in Reach 410 (Table III). Most of the length of Reach 224 was dominated by upwelling, whereas most of the length of Reaches 356 and 410 was dominated by downwelling.
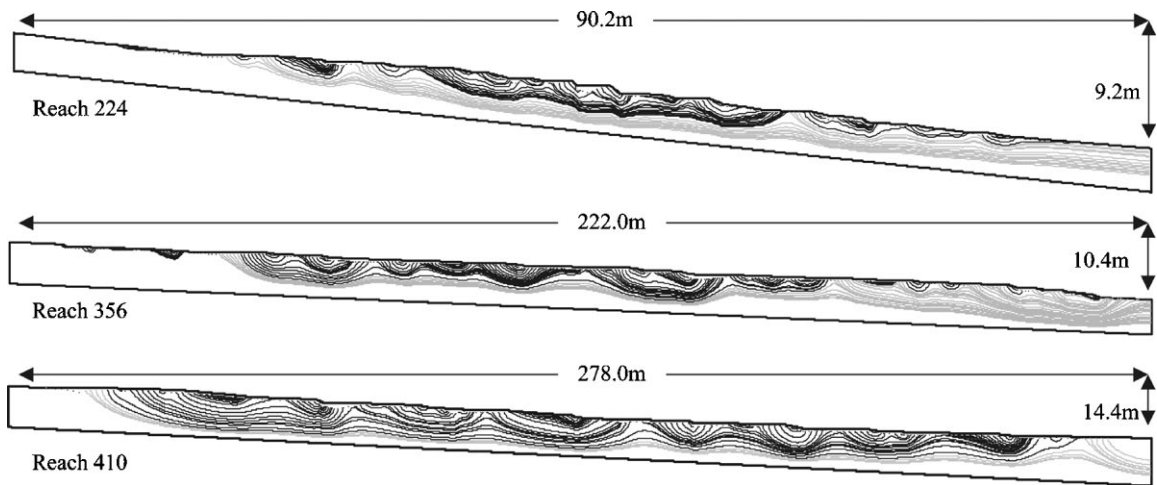
Figure 2. Hyporheic flow paths resulting from groundwater flow modelling and particle tracking for observed Reaches 224, 356, and 410
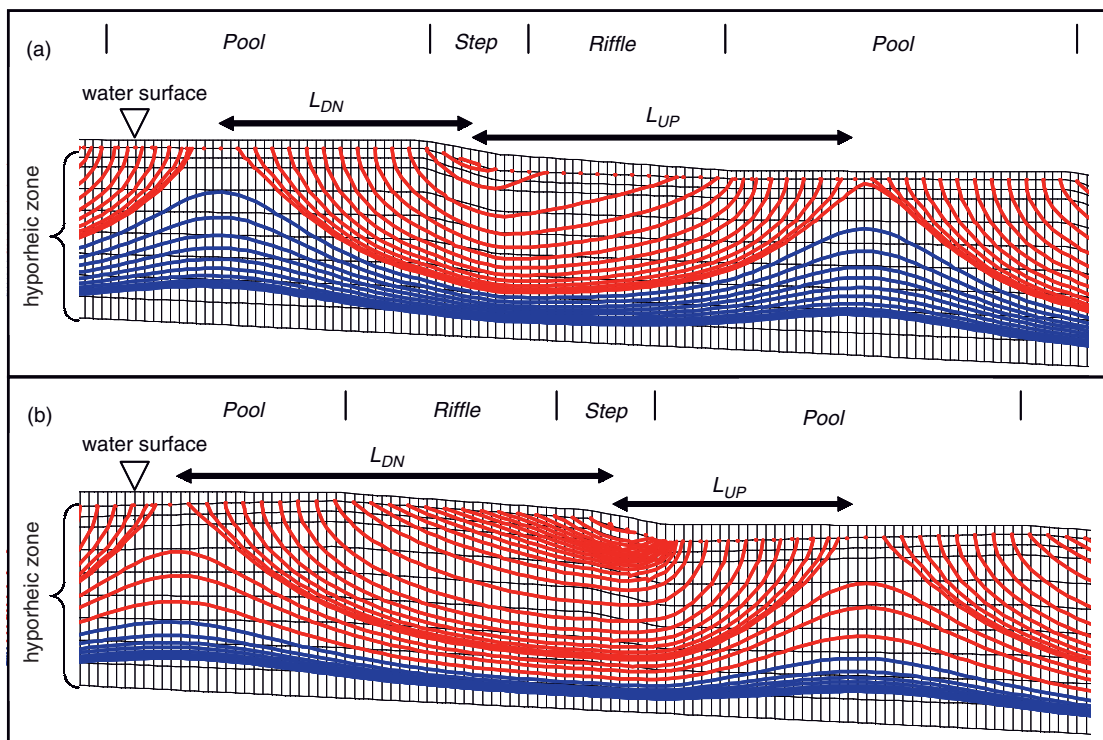

Figure 3. Hyporheic flow paths resulting from groundwater flow modelling and particle tracking for third-order idealized reaches in (a) POOL–STEP–RIFFLE (PSR), and (b) POOL–RIFFLE–STEP (PRS) configurations. Stream sections presented are both 23 m long. Second- and fourth-order profiles are similar. This figure is available in colour online at www.interscience.wiley.com/journal/hp

Table III. Average upwelling (L_{UP}) and downwelling (L_{DN}) lengths, percent of stream reach length composed of upwelling and downwelling zones, and hyporheic wavelengths (Λ_H) as determined by groundwater modeling of stream reaches within the Lookout Creek basin, Oregon USA. Standard deviations are noted in parenthesis. Number of upwelling and downwelling zones denoted by *n*

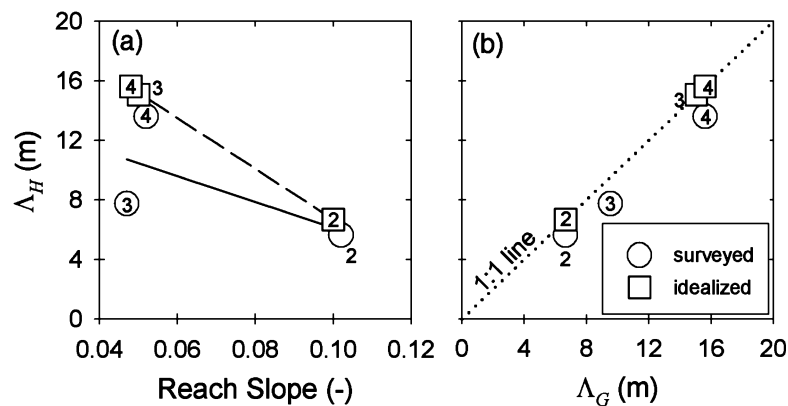| | Observed reach | | | Idealized reach | | | | | |
| | | | | POOL−RIFFLE−STEP | | | POOL−STEP−RIFFLE | | |
	224	356	410	2nd-order	3rd-order	4th-order	2nd-order	3rd-order	4th-order
n	16	25	19	na	na	na	na	na	na
L_{DN} (m)	2·7 (±1·4)	4·0 (±2·6)	7·6 (±4·5)	4·3	9·5	9·7	2·5	5·8	6·1
Stream length downwelling (%)	48	54	56	64	63	62	37	39	39
L_{UP} (m)	2·9 (±2·1)	3·7 (±2·4)	6·0 (±4·3)	2·4	5·6	6·0	4·2	9·2	9·5
Stream length upwelling (%)	52	46	44	36	37	38	63	61	61
Λ_H (m)	5·6	7·7	13·6	6·7	15·1	15·6	6·7	15·0	15·6

Figure 4. Hyporheic wavelengths Λ_H, as computed by groundwater flow modelling, related to (a) stream reach slope and (b) stream reach geomorphic wavelength Λ_G, which is equal to the sum of the average POOL (L_{POOL}), RIFFLE (L_{RIFFLE}), and STEP (L_{STEP}) lengths. Numbers in or near plot symbols represent reach stream order

In idealized reaches, L_{UP} and L_{DN} increased with stream order. However, in the reaches with the POOL−RIFFLE−STEP channel unit sequence, L_{DN} was always longer than L_{UP}, whereas this pattern was reversed in POOL−STEP−RIFFLE reaches, so that L_{DN} was always shorter than L_{UP} (Table III). Hyporheic wavelengths Λ_H increased with stream order in all reaches, increasing from 5·6 m to 13·6 m in second- to fourth-order surveyed reaches, from 6·7 m to 15·6 m in second- to fourth-order POOL−RIFFLE−STEP idealized reaches, and from 6·7 m to 15·6 m in second- to fourth-order POOL−STEP−RIFFLE idealized reaches (Table III). Hyporheic wavelengths increased greatly between second- and third-order in the idealized POOL−STEP−RIFFLE and POOL−RIFFLE−STEP reaches (>8·3 m), but only increased slightly between third- and fourth-order reaches (0·5 m in each case); and in the surveyed reach analysis, Λ_H increased only slightly between second- and third-order reaches (2·1 m), but increased greatly between third- and fourth-order reaches (5·9 m).

Further analysis of the relationships between L_{UP}, L_{DN} and geomorphic characteristics suggests that Λ_H values appear to be related to stream reach slope (Figure 4a), with a high correlation coefficient for idealized

reaches ($R^2 = 1\cdot0$, $p = 0\cdot013$) and a moderate correlation for the surveyed reaches ($R^2 = 0\cdot4$, $p = 0\cdot020$). Additionally, Λ_H and Λ_G are highly correlated (Figure 4b), with correlation coefficients above $0\cdot9$ ($p = 0\cdot99$) in each case (not shown in Figure 4 for clarity). Idealized reaches plot on a line with a slope of $1\cdot0$, but observed reaches plot on a line with a slope of $0\cdot91$. The slope of $1\cdot0$ for the idealized reaches is expected; as all stream length was either upwelling or downwelling, geomorphic units are equally represented by a repeated sequence (POOL : RIFFLE : STEP $= 1 : 1 : 1$). The deviation from a slope of $1\cdot0$ in the observed reach analysis is a result of the geomorphic wavelengths surveyed being heterogeneous. Bedforms are neither repeated sequentially, nor are all three bedforms equally represented. That is, the number of POOLs, RIFFLEs and STEPs is not equal in surveyed reaches (Table II). At the subreach scale, in both the idealized and surveyed reaches, L_{UP} and L_{DN} scale exactly with step spacing (Figure 5). The vertical size of steps E_{STEP} was poorly correlated to L_{UP} and L_{DN} (Figure 6). Finally, we expected that hyporheic penetration depths, at the deepest inflection point, would be related to E_{STEP} (Figure 7a). Our results, however, were not consistent between surveyed and idealized sets of stream reaches. In general, there was shallower hyporheic penetration with larger steps in idealized reaches, whereas in the surveyed reaches there was greater hyporheic penetration with larger steps. In idealized reaches, step length L_{STEP} appears to be related to average hyporheic penetration (Figure 7b). This relationship does not appear to be consistent for surveyed reaches, likely because of the irregularity of the channel unit sequence.

DISCUSSION

Potential ecological importance of differences in flow paths

Analysis of longitudinal hyporheic exchange dynamics in response to bedform variability may be applicable to many stream ecology studies. Chinook salmon and bull trout have been known to select downwelling streambed sites for building redds (Baxter and Hauer, 2000; Geist, 2000), and greater maximum algal biomass and diversity has been reported in upwelling zones than in downwelling zones (Valett *et al.*, 1994; Pepin and Hauer, 2002). The relative proportion of upwelling and downwelling zones may determine stream habitat constraints and aquatic ecological patterns. Similarly, hyporheic return flows to streams may have very different characteristics depending on whether the water has moved along a long or short, shallow or deep, hyporheic flow path because of the influence of residence time on many biologically active solutes (Findlay, 1995). The size of upwelling zones may also influence the relative retention of biologically available nutrients entering the stream in hyporheic return flows. Depending on nutrient uptake rates of biofilms on streambed alluvium, short upwelling zones could focus nutrient fluxes over a small area and could result in fluxes of nutrients at rates higher than can be retained by biofilms. Alternatively, nutrient concentrations might be rapidly diluted by mixing with stream water in large upwelling zones so that upwelling waters would be too dilute for biofilms to capture bioavailable nutrients from the upwelling water. This would, however, depend on the relative concentrations of nutrients and the lower concentration limit at which biofilms can effectively scavenge nutrients from stream water. Thus, there should be both physical and biological factors affecting uptake and retention of nutrients released from the hyporheic zone, and these factors could be expected to vary with the relative size of the upwelling and downwelling zones.

Comparison of reach types

The six idealized stream reaches used in this study incorporate an increase in bedform spacing between second-, third- and fourth-order streams that is characteristic of a larger sample of stream reaches within the Lookout Creek basin. The idealized profiles are not a perfect representation of real stream reaches because they lack heterogeneity in bedform size, spacing, and sequence. However, it is this simplicity that allowed stream reach characteristics to be evaluated separately for their individual roles in controlling hyporheic flow paths. Thus, the idealized profiles were useful in that they provided a basis for analysing the influence of
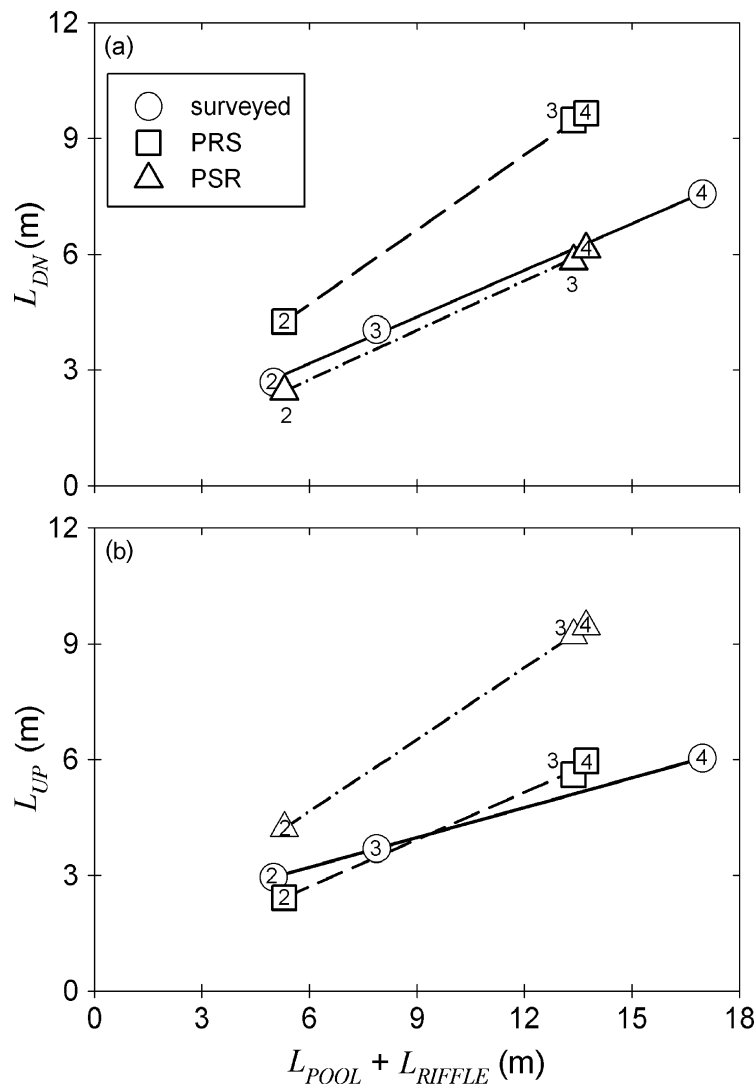
Figure 5. Relationships between average step spacing (as the sum of average POOL length L_{POOL} and RIFFLE length L_{RIFFLE}) within a stream reach and (a) downwelling lengths and (b) upwelling lengths. Numbers in or near plot symbols represent reach stream order. PRS: POOL–RIFFLE–STEP; PSR: POOL–STEP–RIFFLE

bedform spacing, channel unit sequence, and heterogeneity in spacing and sequence on hyporheic exchange flows.

In contrast to the idealized longitudinal profiles, the three surveyed reaches are characterized by the heterogeneity in bedform size, spacing, and sequence that is typical of mountain streams in the Lookout Creek basin. In general, Reaches 224 and 356 are similar to the second- and third-order idealized reaches, having a similar STEP spacing. Reach 410, however, has larger and more widely spaced steps than the idealized fourth-order reach (Table II). The order of channel unit sequences, and the size and spacing of the channel units in the surveyed reaches are variable. Therefore, relations among observed L_{UP} and L_{DN} values and bedform spacing and size are expected to be less than perfectly correlated. Because of the repeated channel unit sequence and homogeneous bedform spacing and size within each idealized reach, it is to be expected
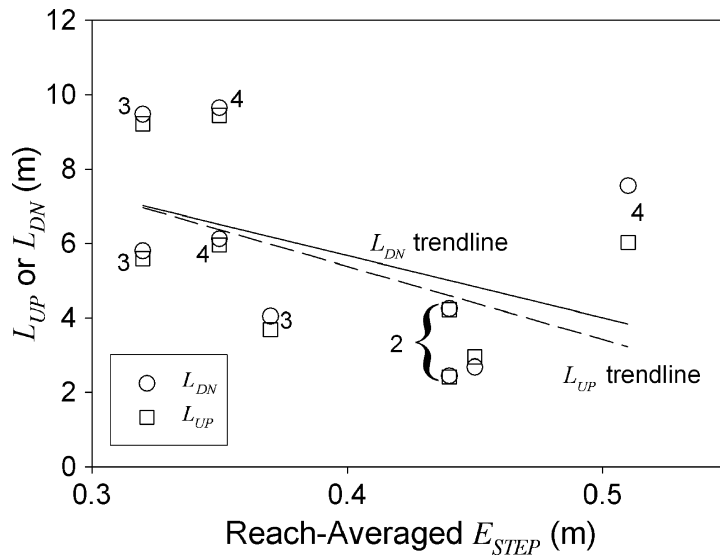
Figure 6. Relationship between upwelling and downwelling longitudinal lengths (L_{UP} and L_{DN} respectively) and average elevation loss per step E_{STEP} within idealized and observed stream reaches. Numbers in or near plot symbols represent reach stream order
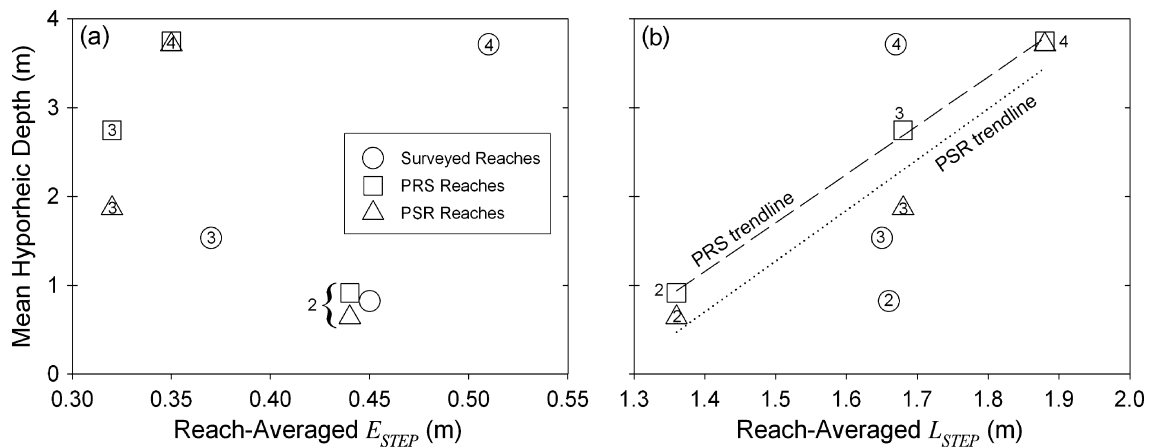

Figure 7. Relationship between mean hyporheic depth (below streambed) and (a) average step elevation loss E_{STEP} and (b) average step length L_{STEP} for surveyed, POOL–RIFFLE–STEP (PRS), and POOL–STEP–RIFFLE (PSR) reaches. Numbers in or near plot symbols represent reach stream order

that the idealized reaches would produce higher correlations among hyporheic exchange characteristics and geomorphic characteristics.

Groundwater model design

One of the objectives of this study, and related research (Kasahara and Wondzell, 2003; Anderson *et al.*, 2005) is to generate a non-invasive and efficient method of detecting potential hyporheic exchange throughout a stream basin, as called for by Bencala (2000). Our analysis of longitudinal controls of hyporheic exchange is consistent with the findings of Harvey and Bencala (1993) and Kasahara and Wondzell (2003), both of which suggest that discontinuities in the longitudinal profile of the stream are the dominant drivers of hyporheic exchange in mountain streams. Of course, lateral complexity in channel form also contributes to hyporheic

exchange flow. However, the inclusion of lateral survey information increases the demand for data-gathering activities and requires the use of more complex, three-dimensional groundwater flow models. In this paper, we have tested our hypotheses in the simplest cases available, i.e. using 2-D models of real and idealized mountain streams with single-thread channels. Future research should explore the full complexity of channel features found in mountain streams to examine the relationships between channel morphology and hyporheic exchange flows better. Our analysis is framed within the river continuum concept (Vannote *et al.*, 1980), which is focused on the downstream, longitudinal evolution of rivers.

Assumptions in our groundwater modelling design are simplifications of natural heterogeneity. For example, the hyporheic zone depth was idealized because substream bedrock profiles are unknown and difficult to characterize. We chose to set an average depth of the hyporheic zone, and set the slope of the bottom of that zone to be the average of the overlying streambed along the entire reach. This simplification may be limiting, particularly if bedrock comes close to the streambed. Shallow bedrock sills would force hyporheic flow to upwell just upstream of the sill, and to downwell just downstream. Additionally, we did not acquire specific information on streambed (hyporheic) hydraulic conductivity, which is likely to be heterogeneous and anisotropic. Our results are independent of the value of K, because changing K in a homogeneous, steady-state model only serves to change the flow rate of water and does not change spatial patterns of the flow net. However, our results would be affected by heterogeneity in the spatial distribution of K and by anisotropy. For example, heterogeneity in hydraulic conductivity with correlation lengths on the same scale as geomorphic characteristics could result in focused upwelling or downwelling, changing upwelling and downwelling lengths, the hyporheic wavelength, and adding variability to each (as suggested by Woessner (2000), Matos *et al.* (2003) and Cardenas and Zlotnik (2003)). Therefore, our results for homogeneous, isotropic hyporheic zones with effective hydraulic conductivity should be recognized as a simplification of real stream–groundwater systems, and the results interpreted qualitatively. Nonetheless, variations in reach responses are useful for comparison among reaches because they are shown to be distinct, if not exact.

Modelling results

Comparing the results of the groundwater modelling between different sets of stream reaches demonstrates the strong effect of both stream size and channel unit sequence on patterns of hyporheic exchange flow. The results of the upwelling–downwelling length analysis in surveyed stream reaches supports our hypothesis that such lengths would increase with increasing stream order and the size of bed features (Table III), also corroborating the results of Anderson *et al.* (2005). In the idealized reach analyses, L_{UP} and L_{DN} consistently increased with increasing stream order for both the POOL–RIFFLE–STEP sequence and the POOL–STEP–RIFFLE sequence (Table III, Figure 5). The increase in L_{UP} and L_{DN} with increasing stream order is proportional to the increases in distances between slope breaks. Although Λ_H in POOL–RIFFLE–STEP and in POOL–STEP–RIFFLE reaches was essentially equal within any stream order, L_{DN} was consistently greater in POOL–RIFFLE–STEP reaches and L_{UP} was consistently greater in POOL–STEP–RIFFLE reaches (Figure 5). This demonstrates that channel unit sequence can affect the relative ratio of downwelling length to upwelling length along the longitudinal profile.

Further analysis of the relationships between hyporheic exchange patterns and the size and spacing of geomorphic features suggests a strong dependence of Λ_H upon Λ_G (Figure 4b). Hyporheic exchange pattern scaling and spatial geomorphic scaling for both idealized and observed reaches are highly correlated (>0·9, Figure 5), with the exception of hyporheic exchange pattern (L_{UP} or L_{DN}) dependence upon E_{STEP} (Figure 6). The inconsistency in correlation between L_{UP} or L_{DN} and E_D is evidence of the lack of control that vertical size of features plays in the longitudinal pattern of upwelling and downwelling lengths within a stream reach. But, the consistently high correlations between Λ_H and bed slope, Λ_H and Λ_G, L_{UP} and STEP spacing, and L_{DN} and STEP spacing (as $L_{POOL} + L_{RIFFLE}$) suggests that there is a direct relationship between longitudinal geomorphic scaling and hyporheic exchange patterns. The near-perfect correlation between Λ_H and Λ_G for even the observed reaches is further evidence of the longitudinal geomorphic control on hyporheic exchange patterns.

Hyporheic exchange along the river continuum

Our simulation results suggest that under homogeneous, isotropic conditions, hyporheic exchange patterns change systematically along the length of the stream continuum. Thus, some of the variation in the size of the hyporheic zone and the length of exchange flow paths can be explained by systematic changes in the physical template of the stream (including longitudinal gradient, as well as channel unit size and spacing), which lead to systematic changes in hyporheic properties that we examined in our idealized stream reaches. This is clearly illustrated by the patterns of hyporheic exchange flows in the idealized reaches, which show consistent, repeated patterns of downwelling and upwelling, with a uniform hyporheic wavelength that increases in a downstream direction. However, the flow paths simulated in the surveyed reaches were much more complex than those simulated in the idealized reaches. The surveyed stream reaches showed multiple nested scales of downwelling and upwelling, distributed over a wide range of hyporheic wavelengths. This difference in flow path complexity demonstrates the influence that local-scale variation in the size of channel morphologic features plays in determining the longitudinal pattern of upwelling and downwelling within a stream reach. Consequently, water travelling through the hyporheic zone of real streams should exhibit a greater variance in residence time distribution and, therefore, greater variation in influence on biogeochemical cycling than would be expected from a model of the idealized reaches.

While we have emphasized the systematic changes in geomorphic features along the stream continuum in this paper, we also recognize the importance of local variation. Thus, our work finds parallels in the ecological treatment of streams in both the stream continuum (Vannote *et al.*, 1980) and patch dynamic (Townsend, 1989) concepts in stream ecology. The use of idealized stream reaches allows us to illustrate the systematic changes that might be expected in streams, whereas the survey reaches illustrate the role of local-scale variation. The role of local-scale variation in morphologic features relative to the role of systematic changes in channel morphology must be combined to understand the hyporheic zone fully at the scale of the stream network.

CONCLUSIONS

The goal of this study was to investigate hyporheic exchange patterns and the influences of fluvial geomorphic bedform spacing, size, and sequence. We utilized current non-invasive techniques, employed at the reach scale, to provide information about how patterns in hyporheic exchange flow change along the river continuum. The assumptions we used in building models to represent different stream reaches allowed us to evaluate bedform spacing and channel unit sequence separately, and to determine that both have an important influence on patterns of hyporheic exchange flow. Because of the simplicity of the models used, measurements of upwelling and downwelling in real streams are expected to be much more complex due to spatial bedform heterogeneity, heterogeneity in streambed conductivity, and irregularities in underlying bedrock topography. Despite these differences, our simulation results clearly demonstrate the influence of channel structure on hyporheic exchange patterns. The results of this modelling study are consistent with a field study conducted by Anderson *et al.* (2005).

Hyporheic upwelling and downwelling lengths were investigated using groundwater flow modelling and particle tracking based on boundary conditions obtained from longitudinal stream surveys. Observed and idealized longitudinal stream reach bedforms and surface water profiles were investigated at stream reach scales from second to fourth order in the Lookout Creek basin, Oregon. From this work, we make the following three conclusions:

1. We describe a method, based on longitudinal stream surveys, that may provide an easily applied alternative to installing well networks for the qualitative characterization of hyporheic exchange.
2. The simulated hyporheic wavelength, the average maximum distance over which water would be expected to travel in the hyporheic zone, is correlated to average geomorphic wavelength, which dictates the spacing of the longitudinal slope breaks that drive hyporheic exchange.

3. Simulated observed and idealized upwelling and downwelling lengths increase with increasing stream order in response to increasing sizes of fluvial geomorphic bedform features in three observed reaches.

Simulated downwelling lengths increased with increasing stream order in all reaches, but did not scale proportionally in the reaches observed. These results corroborate the results of Kasahara and Wondzell (2003) and Anderson *et al*. (2005), suggesting that longitudinal stream geomorphologic bedform scaling and channel unit sequence both control hyporheic exchange patterns along the river continuum.

REFERENCES

Anderson JK. 2002. *Patterns in stream geomorphology and implications for hyporheic exchange flow*. Master's thesis, Department of Forest Sciences, Oregon State University.
Anderson JK, Wondzell SM, Gooseff MN, Haggerty R. 2005. Patterns in stream longitudinal profiles and implications for hyporheic exchange flow. *Hydrological Processes* **19**: this issue.
Baxter CV, Hauer FR. 2000. Geomorphology, hyporheic exchange, and selection of spawning habitat by bull trout (*Salvelinus confluentus*). *Canadian Journal of Fisheries and Aquatic Sciences* **57**: 1470–1481.
Bencala KE. 1984. Interactions of solutes and streambed sediment 2. A dynamic analysis of coupled hydrologic and chemical processes that determine solute transport. *Water Resources Research* **20**: 1804–1814.
Bencala KE. 2000. Hyporheic zone hydrological processes. *Hydrological Processes* **14**: 2797–2798.
Cardenas MB, Zlotnik VA. 2003. Three-dimensional model of modern channel bend deposits. *Water Resources Research* **39**: 1141. DOI: 10·1029/2002WR001383.
Chin A. 1999. The morphologic structure of step–pools in mountain streams. *Geomorphology* **27**: 191–204.
Chin A. 2002. The periodic nature of step–pool mountain streams. *American Journal of Science* **302**: 144–167.
Duckson Jr DW, Duckson LJ. 2001. Channel bed steps and pool shapes along Soda Creek, Three Sisters Wilderness, Oregon. *Geomorphology* **38**: 267–279.
Duff JH, Triska FJ. 1990. Denitrification in sediments from the hyporheic zone adjacent to a small forested stream. *Canadian Journal of Fisheries and Aquatic Sciences* **47**: 1140–1147.
Findlay S. 1995. Importance of surface–subsurface exchange in stream ecosystems: the hyporheic zone. *Limnology and Oceanography* **40**: 159–164.
Geist DR. 2000. Hyporheic discharge of river water into fall Chinook salmon (*Onchorhynchus tshawytscha*) spawning areas in the Hanford Reach, Columbia River. *Canadian Journal of Fisheries and Aquatic Sciences* **57**: 1647–1656.
Gooseff MN, McKnight DM, Lyons WB, Blum AE. 2002. Weathering reactions and hyporheic exchange controls on stream water chemistry in a glacial meltwater stream in the McMurdo Dry Valleys. *Water Resources Research* **38**: 1279. DOI: 10·1029/2001WR000834.
Gooseff MN, Wondzell SM, Haggerty R, Anderson JK. 2003. Comparing transient storage modeling and residence time distribution (RTD) analysis in geomorphically varied reaches in the Lookout Creek basin, Oregon, USA. *Advances in Water Resources* **26**: 925–937.
Grant GE, Swanson FJ, Wolman MG. 1990. Pattern and origin of stepped-bed morphology in high-gradient streams, Western Cascades, Oregon. *Geological Society of America Bulletin* **102**: 340–352.
Hack JT. 1957. Studies of longitudinal stream profiles in Virginia and Maryland. *United States Geological Survey, Professional Paper* **294-B**: 45–97.
Haggerty R, Wondzell SM, Johnson MA. 2002. Power-law residence time distribution in the hyporheic zone of a 2nd-order mountain stream. *Geophysical Research Letters* **29**: DOI: 10·1029/2002GL014743.
Harbaugh AW, McDonald MG. 1996. *User's documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model*. US Geological Survey Open-File Report 96–485, US Geological Survey, Denver, CO.
Harvey JW, Bencala KE. 1993. The effect of streambed topography on surface–subsurface water exchange in mountain catchments. *Water Resources Research* **29**: 89–98.
Jones JB, Fisher SG, Grimm NB. 1995. Nitrification in the hyporheic zone of a desert stream ecosystem. *Journal of the North American Benthological Society* **14**: 249–258.
Kasahara T, Wondzell SM. 2003. Geomorphic controls on hyporheic exchange flow in mountain streams. *Water Resources Research* **39**: 1005. DOI: 1010·1029/2002wr001386.

Matos JER, Welty C, Packman AI. 2003. Stream–groundwater interactions: the influence of aquifer heterogeneity and stream meandering on 2-D and 3-D hyporheic exchange flows. In *MODFLOW and More 2003: Understanding Through Modeling Conference Proceedings*, Golden, CO; 217–220.

Montgomery DR, Buffington JM. 1997. Channel–reach morphology in mountain drainage basins. *Geological Society of America Bulletin* **109**: 596–611.

Morrice JA, Valett HM, Dahm CN, Campana ME. 1997. Alluvial characteristics, groundwater–surface water exchange and hydrological retention in headwater streams. *Hydrological Processes* **11**: 253–267.

Mulholland PJ, Marzolf ER, Webster JR, Hart DR, Hendricks SP. 1997. Evidence that hyporheic zones increase heterotrophic metabolism and phosphorous uptake in forest streams. *Limnology and Oceanography* **42**: 443–451.

Pepin DM, Hauer FR. 2002. Benthic responses to groundwater–surface water exchange in 2 alluvial rivers in northwestern Montana. *Journal of the North American Benthological Society* **21**: 370–383.

Pollock DW. 1994. *User's guide for MODPATH/MODPATH-PLOT, version 3: a particle tracking post-processing package for MODFLOW, the U.S. Geological Survey finite-difference ground-water flow model*. US Geological Survey Open-File Report 94–464, US Geological Survey, Denver, CO.

Storey RG, Howard KWF, Williams DD. 2003. Factors controlling riffle-scale hyporheic exchange flows and their seasonal changes in a gaining stream: a three-dimensional groundwater flow model. *Water Resources Research* **39**: 1034. DOI: 1010·1029/2002wr001367.

Townsend CR. 1989. The patch dynamics concept of stream community ecology. *Journal of the North American Benthological Society* **8**: 36–50.

Valett HM, Fisher SG, Grimm NB, Camill P. 1994. Vertical hydrologic exchange and ecological stability of a desert stream ecosystem. *Ecology* **75**: 548–560.

Vannote RL, Minshall GW, Cummins KW, Sedell JR, Cushing CE. 1980. The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences* **37**: 130–137.

Vaux WG. 1968. Intragravel flow and interchange of water in a streambed. *Fishery Bulletin* **66**: 479–489.

Vervier P, Dobson M, Pinay G. 1993. Role of interaction zones between surface and ground waters in DOC transport and processing: considerations for river restoration. *Freshwater Biology* **29**: 275–284.

Woessner WW. 2000. Stream and fluvial plain ground water interactions: rescaling hydrogeologic thought. *Ground Water* **38**: 423–429.

Wondzell SM, Swanson FJ. 1996. Seasonal and storm dynamics of the hyporheic zone of a 4th-order mountain stream I: hydrologic processes. *Journal of the North American Benthological Society* **15**: 3–19.