

Patterns in stream longitudinal profiles and implications for hyporheic exchange flow at the H.J. Andrews Experimental Forest, Oregon, USA

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Abstract:

There is a need to identify measurable characteristics of stream channel morphology that vary predictably throughout stream networks and that influence patterns of hyporheic exchange flow in mountain streams. In this paper we characterize stream longitudinal profiles according to channel unit spacing and the concavity of the water surface profile. We demonstrate that: (1) the spacing between zones of upwelling and downwelling in the beds of mountain streams is closely related to channel unit spacing; (2) the magnitude of the vertical hydraulic gradients (VHG) driving hyporheic exchange flow increase with increasing water surface concavity, measured at specific points along the longitudinal profile; (3) channel unit spacing and water surface concavity are useful metrics for predicting how patterns in hyporheic exchange vary amongst headwater and mid-order streams. We use regression models to describe changes in channel unit spacing and concavity in longitudinal profiles for 12 randomly selected stream reaches spanning 62 km² in the H.J. Andrews Experimental Forest in Oregon. Channel unit spacing increased significantly, whereas average water surface concavity (AWSC) decreased significantly with increasing basin area. Piezometer transects installed longitudinally in a subset of stream reaches were used to measure VHG in the hyporheic zone, and to determine the location of upwelling and downwelling zones. Predictions for median pool length and median distance between steps in piezometer reaches bracketed the median distance separating zones of upwelling in the stream bed. VHG in individual piezometers increased with increasing water surface concavity at individual points in the longitudinal profile along piezometer transects. Absolute values of VHG, averaged throughout piezometer transects, increased with increasing AWSC, indicating increased potential for hyporheic exchange flow. These findings suggest that average hyporheic flow path lengths increase—and the potential for hyporheic exchange flow in stream reaches decreases—along the continuum from headwater to mid-order mountain streams. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS hyporheic zone; stream reach morphology; concavity; channel unit spacing; river continuum; longitudinal profiles

INTRODUCTION

Recently, there has been a call for a better characterization of the important physical and hydrometric properties of stream–catchment systems that determine the characteristics of transport within a hyporheic zone and that can be routinely measured or mapped along greater distances of streams (Bencala, 2000). Geomorphic control of the physical processes driving hyporheic exchange flow at the channel-unit- or stream-reach-scale has been well documented (Vaux, 1968; Savant *et al.*, 1987; White *et al.*, 1987; Harvey and Bencala, 1993; Morrice *et al.*, 1997; Hill *et al.*, 1998; Wroblicky *et al.*, 1998; Kasahara and Wondzell, 2003). Physical

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modelling of hyporheic exchange flow has identified several mechanisms that drive hyporheic exchange flow. Vaux (1968) explained how stream profile shape, bed permeability, and bed depth influence the flow of water through stream beds. This work showed that downwelling occurs where the stream profile is convex, where permeability increases in the downstream direction, or where bed depth increases in the downstream direction, and that upwelling occurs where the stream profile is concave, where permeability decreases in the downstream direction, or where bed depth decreases in the downstream direction. More recent research has focused on advective flow into and out of the stream bed that is controlled by dynamic pressure variation over bedforms (Thibodeaux and Boyle, 1987; Elliot and Brooks, 1997; Packman *et al.*, 2000; Packman and Brooks, 2001). This model, termed the pumping model, accounts for pressure variations that are induced by velocity distributions on the upstream and downstream faces of dune-like bedforms. The pumping model and the model developed by Vaux (1968) represent different channel morphologies: the pumping model assumes a constant water surface slope, whereas the model developed by Vaux (1968) accounted for convex and concave longitudinal profiles that represented slope breaks associated with pool–riffle sequences. Both models likely have application in natural streams, depending on which model more closely approximates the morphology of the stream. Although the previous studies have been largely successful in demonstrating geomorphic control on the process of hyporheic exchange flow within stream reaches, with the exception of the hyporheic corridor concept (HCC; Stanford and Ward, 1993), there has been little attempt to use systematic patterns in stream geomorphology to predict how patterns of hyporheic exchange flow will change between stream reaches in headwater and larger streams.

Geomorphologists have long been interested in systematic changes in channel morphologic properties along stream networks, and the factors that control these changes. Early work by Leopold and Maddock (1953) and Hack (1957) examined variations in drainage area, discharge, longitudinal gradients, and size of bed materials. These and other authors (e.g. Schumm, 1960) also examined the effect of differing parent lithology on these morphologic patterns. Knighton (1984) observed that systematic changes in bed configuration are expected along the longitudinal continuum of a river, from headwater channels with pool–step sequences or poorly developed pools and riffles to better-defined riffle–pool sequences and finally to ripples and dunes in larger order sand-bed streams. Similarly, Montgomery and Buffington (1997) conceptualized a continuum of channel types in mountain catchments ranging in the down-valley direction from cascade to step–pool to plane bed to pool–riffle to dune–ripple. Research has also identified empirical relationships between channel width and bedform spacing (Keller and Melhorn, 1973; Keller and Melhorn, 1978). Efforts to identify systematic changes in channel properties with increasing drainage area continue today (McCandless and Everett, 2002), and have been expanded to explore spacing between features in the channel longitudinal profile of step–pool stream reaches (Grant *et al.*, 1990; Lenzi, 2001; Chin, 2002). This geomorphologic view of rivers having predictable and systematic change in basic channel morphology and sediment size set the foundation for the river continuum theory of biological processes in stream ecosystems (Vannote *et al.*, 1980). The organizing influence of systematic and predictable changes in channel morphologic features cannot be ignored. Characterizing relationships between drainage area and channel characteristics is appealing because it may support models for predicting reach characteristics based on information easily obtained from maps.

Stanford and Ward (1993) proposed a conceptual framework, the hyporheic corridor, that incorporates channel–aquifer interactions into the river continuum. The HCC focuses on valley characteristics at different locations along the river continuum, and connectivity between rivers and floodplain aquifers at the reach scale. The HCC likens alternating bedrock-constrained and unconstrained alluvial reaches typical of river systems draining glaciated mountainous catchments to ‘beads on a string’ along the river continuum. This is a useful analogy for describing stream networks in the northern Rocky Mountains, where broad, glaciated valleys were aggraded by postglacial fluvial outwash that left expansive deposits of cobble and gravel tens of metres thick. Research leading to the development of the HCC (Stanford and Ward, 1988, 1993), and other studies on hyporheic exchange in the Flathead Lake basin, Montana, USA (Baxter and Hauer, 2000), has focused on broad alluvial reaches and has documented the occurrence of hyporheic exchange flows up to the kilometre scale. However, the HCC does not make use of research suggesting systematic changes in channel unit

size, spacing, and bedform roughness within stream reaches—patterns that may prove useful for describing systematic changes in patterns of hyporheic exchange amongst stream reaches along the river continuum. Furthermore, the application of the HCC to other terrains may be tenuous in stream networks where broad alluvial valleys are rare, such as in many headwater and mid-order streams draining the western Cascade Mountains of Oregon, USA. The HCC is a useful conceptual model for making qualitative comparisons about the characteristics of hyporheic zones in stream reaches with varying valley constraint; however, the conceptual model may be improved by accounting for systematic changes in stream channel characteristics that occur both in unconstrained and constrained stream reaches. This study relates patterns in hyporheic exchange flow to patterns in stream morphology that reflect internal channel-forming mechanisms and, therefore, may be applicable to a wide range of headwater and mid-order streams, regardless of the degree of valley constraint.

The overall goal of this study is to identify patterns in stream geomorphology that can be used to predict patterns of hyporheic exchange flow in high-gradient headwater and mid-order mountain streams where step–pool and pool–riffle morphologies are present. We focus our investigation on the size and spacing of channel-unit-scale morphologic features, and concavity in the water surface profile. With the exception of a few studies (Thibodeaux and Boyle, 1987; Savant *et al.*, 1987), there has been little attempt to relate the size and spacing of channel-unit-scale morphologic features to hyporheic flowpath lengths and residence times. Although the influence of stream bed concavity on patterns of upwelling and downwelling originally explained by Vaux (1968) has received considerable attention in hyporheic literature, there has been little attempt to evaluate the reliability of concavity as an indicator for upwelling and downwelling in high-gradient mountain streams. We develop and evaluate the usefulness of a simple index, water surface concavity, in explaining patterns of upwelling and downwelling in step–pool and pool–riffle stream reaches. In addition, we investigate two specific hypotheses relating hyporheic exchange flow to stream geomorphology: (1) average near-surface hyporheic flow-path lengths increase predictably across the river continuum in association with predictable increases in channel unit size and spacing; (2) the potential for gravity-driven hyporheic exchange flow in high-gradient mountain stream reaches increases as the average magnitude of concavities in the water surface profile increases.

STUDY AREA AND METHODS

Study area and stream reach selection

This study was conducted in the Lookout Creek Basin within the H.J. Andrews Experimental Forest in the western Cascade Mountains of Oregon, USA (Figure 1). Elevation within the Lookout Creek basin ranges from 420 to 1615 m. The area receives approximately 2300 mm of precipitation annually near the mouth of Lookout Creek, primarily as rain, whereas higher elevations receive enough snow to develop a seasonal snowpack. Major floods result from a combination of rain and snowmelt (Harr, 1981). The basin is underlain by rocks of volcanic origin, including lava and ash flows, tuffs, cinder beds, and water-worked tuffaceous sediments (Swanson and James, 1975), and has been sculpted over the last 3 million years by glacial, mass movement, fluvial, geochemical, and other processes (Swanson and Jones, 2002). Although glacial landforms such as cirques and U-shaped valleys dominate the southeastern quadrant of the area, much of the basin is dominated by steep, straight slopes and valley floors produced by stream erosion and rapid debris slides and debris flows (Swanson and Jones, 2002). Stream environments range from steep, narrow, bedrock chutes, to wide alluvial reaches; however, gravel- and cobble-bedded, moderate- or high-gradient streams in narrow, V-shaped valleys are typical. Wide alluvial reaches are few, and occur primarily in a single valley segment approximately 3 km in length located near the centre of the basin. A preliminary study to determine the depth of valley fill using seismic techniques indicated a depth of approximately 5 m in a wide alluvial reach (Trehu, unpublished data, 2001). Bedrock outcroppings are not uncommon in the streams within the study area, suggesting that valley fill is typically shallow, and ranges between 1 and 5 m in most stream reaches. Very high bed roughness is a distinctive characteristic of Lookout Creek and its tributaries (Grant *et al.*, 1990).

Stream reach types within the study area include cascade, step–pool, plane bed, and pool–riffle reaches, but steps occur in nearly all stream reaches due to an abundance of wood and large boulders in stream beds.

Twelve stream reaches within the Lookout Creek basin (Figure 1; Table I) were randomly selected from a population of possible reach locations delineated using a 10 m digital elevation model (DEM). Stream reaches were numbered to facilitate random sampling, beginning with 200 for second-order reaches (Strahler, 1964), 300 for third-order reaches, and 400 for fourth-order reaches. Four each of the second-, third-, and fourth-order stream reaches were selected, and then located in the field by using a hand-held global positioning system unit to locate UTM coordinates obtained from the digital map of the study area. Selected locations were treated as the upstream end of a study reach and the downstream ends of reaches were set equal to a distance

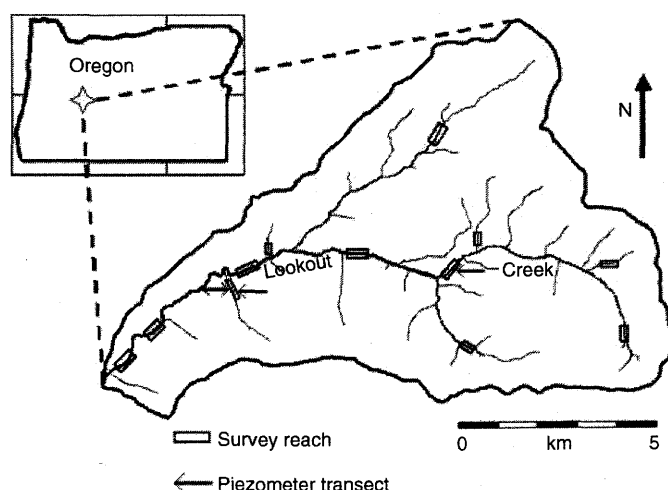


Figure 1. The Lookout Creek basin in the H.J. Andrews Experimental Forest near Blue River, Oregon, USA. Study sites included 12 randomly selected survey reaches, two of which were instrumented with piezometers installed longitudinally along transects in the thalweg of the stream. Two piezometer transects were installed in a second-order tributary of Lookout Creek and a third transect was installed in a third-order reach of main-stem Lookout Creek

Table I. Stream reach characteristics in study reaches. Stream reaches were numbered to facilitate random sampling, beginning with 200 for second-order streams, 300 for third-order streams and 400 for fourth-order streams

Stream reach	Drainage basin area (km ²)	Average gradient	Valley segment type	Stream reach type
282	0.62	0.202	Alluvial	Cascade
241	1.04	0.078	Alluvial	Step–pool
214	1.12	0.218	Alluvial	Cascade/step–pool
224	1.98	0.102	Alluvial	Step–pool
395	1.34	0.102	Alluvial	Step–pool
348	3.85	0.102	Alluvial	Step–pool
333	5.21	0.079	Alluvial	Step–pool
356	16.87	0.048	Alluvial	Step–pool
428	31.29	0.027	Alluvial	Step–pool/plane bed
416	53.86	0.023	Alluvial	Step–pool/plane bed
407	60.46	0.018	Alluvial/bedrock	Step–pool
403	62.35	0.015	Bedrock/alluvial	Bedrock/step–pool

of 20 active channel widths from the head of the reach. Watershed area at the head of each reach was also calculated from the DEM.

Stream survey

Stream reaches were surveyed with an auto level and a levelling rod between June and August of 2000 and 2001. A fibreglass measuring tape was stretched between stakes driven into the streambed along the thalweg. Streambed elevations and water surface elevations, relative to an arbitrary benchmark, were surveyed at points along the measuring tape. Elevations were recorded in millimetres. Survey points were spaced between 0.5 and 8 m according to the size of stream features, to measure the influence of all channel-spanning slope breaks on the water surface profile.

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 $<2.5\%$), RIFFLES (channel units with $2.5 \leq \text{slope} \leq 13\%$), or STEPs (channel units with slope $>13\%$). Using these slope-break criteria, average slopes were 0.35% for POOLS, 6.56% for RIFFLES, and 37.71% for STEPs. POOLS included what are commonly referred to as pools, runs, and glides; RIFFLES included what are commonly referred to as riffles and rapids; and STEPs included what are commonly referred to as steps and cascades. Lengths of channel units and the distances between STEPs were calculated.

Statistical analysis of morphologic patterns

Morphologic characteristics of stream reaches, including bedform size, spacing, and abundance, and average water surface concavity (described below), were characterized using simple linear regression. Basin area was selected as the explanatory variable so that the results could be reported in the context of a longitudinal continuum from headwater to mid-order streams. Model selection included a visual inspection of plotted data to ensure a good linear fit. In many cases the data needed to be transformed with the natural logarithm in order to satisfy the assumption of linearity and equal spread implicit in the linear regression analysis.

Piezometer installation and monitoring

Two of 12 randomly selected stream reaches were instrumented with piezometers. Piezometer reaches were chosen based on their accessibility, because all equipment had to be carried to the work site. Piezometers were installed in the winter of 2001–02 in a second-order and a third-order stream reach, draining watershed areas of 1.98 km² and 16.87 km² (Table II). Piezometers were also installed in a fourth-order stream reach, but a winter spate destroyed the piezometers before observations could be made at the desired flow conditions. Piezometers were installed in longitudinal transects along the thalweg of the stream. Transect numbers correspond to stream reaches. Two separate piezometer transects (P224.0 and P224.1) were installed in two different subreaches within a single second-order reach (reach 224). Transect P224.0 had 22 piezometers covering a weakly developed step–pool morphology. Just downstream, transect P224.1 had 18 piezometers covering a well-developed step–pool morphology. A single transect of 35 piezometers (P356.0), was installed in a third-order reach (reach 356), also with a step–pool morphology.

Table II. Stream reach characteristics within piezometer transects. Substrates in all transects include gravels, cobbles and small boulders

Piezometer transect	Number of piezometers	Stream order	Drainage basin area (km ²)	Average gradient over transect (%)	Active channel width (m)
P224.0	22	2	1.98	5.7	3.9
P224.1	18	2	1.98	13	3.9
P356.0	35	3	16.87	4.8	9.4

Piezometers were constructed from 1.875 cm inside diameter, aluminium tubing cut to 90, 120, and 150 cm lengths. Piezometers were screened by drilling 0.24 cm diameter holes spaced 1 cm apart over an interval between 2 and 4 cm from the bottom end. The bottom end was crimped to facilitate driving with a sledge hammer and prevent clogging by sediment. Piezometers were installed vertically, 34 cm into the bed (deeper installation was impractical with this design and these methods). Piezometers were spaced at 1 m intervals, in transects that followed the thalweg of the stream. A 1 m spacing interval was chosen so that measurements would occur at a scale finer than the scale of individual channel units; previous research in streams at the H.J. Andrews indicated that patterns in hyporheic exchange flow responded to morphologic features at the channel unit-scale (Kasahara and Wondzell, 2003). Depth and spacing were not exact where boulders hindered installation. The relative elevations of the top of each piezometer were surveyed using an auto level and levelling rod. Stream water elevations were calculated as the elevation at the top of the piezometer minus the length of the portion of piezometer protruding above the water surface. Water height in piezometers was measured with a graduated electrical contact meter. Vertical hydraulic gradients (VHG) were calculated as

$$\text{VHG} = \Delta h / \Delta l \quad (1)$$

where Δh is the elevation of water in the piezometer minus the elevation of the stream water surface, and Δl is the distance between the top of the screened interval to the surface of the stream bed. VHG is positive when hydraulic gradients create a potential for flows from the bed toward the channel (upwelling), and negative when the potential for flow is oriented from the channel into the bed (downwelling).

Downwelling zone lengths were defined as the longitudinal distance from the last upwelling piezometer in a series to the last downwelling piezometer in a series of consecutive piezometers. Simple linear regression was used to test for an increase in downwelling zone lengths with increasing basin area. A two-sided p -value of 0.1 was used to determine significance.

Water elevations in piezometer transect P356.0 were measured on 22 February 2002, at flow conditions that approximated steady winter baseflow. Piezometer transects P224.0 and P224.1 were measured on 7 April 2002, also at flow conditions near steady winter baseflow. All piezometers were installed at least a week before measuring water elevations. After measuring water elevations, qualitative tests were performed on piezometers to ensure hydrologic connectivity with the hyporheic zone. Piezometers were filled with water and allowed to re-equilibrate. Five piezometers showed no response over a 2 h period and were not used in this analysis.

Concavity and groundwater hydraulics

Under conditions of steady flow, the Laplace equation

$$\nabla(K\nabla H) = 0 \quad (2)$$

where K is the hydraulic conductivity, describes the total hydraulic head H at all points within a flow field, for a given set of boundary conditions.

The control of hyporheic exchange flow by the shape of the longitudinal profile, longitudinal gradients of permeability, and the depth of the gravel bed is expressed by the approximation

$$v_z \cong \frac{\rho g}{\mu} b k \frac{d^2 z_1}{dx^2} \quad (3)$$

where v_z is the vertical component of interchange of water between the stream and the bed, ρ is the density of water, g is the acceleration due to gravity, μ is the liquid viscosity, k is the permeability of the bed sediments, b is the depth of the permeable stream bed, z_1 is the elevation of the stream bed as a function of x , and x is the distance in the downstream direction (Vaux, 1968). Equation (3) shows that, for constant water properties,

g, bed depth and permeability, the concavity of the stream profile, expressed by the term d^2z_1/dx^2 , controls the vertical exchange of water between the stream and the bed sediments.

A consequence of Equation (3) is that, where bed depth and permeability are constant, VHGs will be negative for negative values of concavity and positive for positive values of concavity in the stream profile. Furthermore, the magnitude of VHG at a point along the longitudinal profile will increase with increasing magnitude of concavity. In this study we compared water surface concavity with VHG at specific points along the longitudinal profile of instrumented stream reaches and evaluated whether concavity alone could be used to predict the direction of hydrologic exchange between streams and their hyporheic zones. We also used simple linear regression to evaluate the amount of variability in VHG that can be explained by concavity alone, and to test the significance of the positive relationship between VHG and concavity. A two-sided p -value of 0.1 was used to determine significance. Our second hypothesis, that the potential for gravity-driven hyporheic exchange flow in high-gradient mountain stream reaches increases as the average magnitude of concavities in the water surface profile increase, is evaluated on the reliability of concavity as a predictor for the direction and magnitude of VHG.

Concavity at successive points along the water surface profile was calculated as the second derivative of water surface elevation z_2 as a function of distance downstream x . We measured concavity in the water surface profile, as opposed to the bed surface profile, because it provides a more consistent metric in small streams, where cobbles and boulders cause a highly irregular bed shape. First derivatives for $z_2(x)$ were calculated as

$$\frac{d}{dx}(z_2) = z_2(x_{i-1}) \frac{(2x - x_i - x_{i+1})}{(x_{i-1} - x_i)(x_{i-1} - x_{i+1})} + z_2(x_i) \frac{(2x - x_{i-1} - x_{i+1})}{(x_i - x_{i-1})(x_i - x_{i+1})} + z_2(x_{i+1}) \frac{(2x - x_{i-1} - x_i)}{(x_{i+1} - x_{i-1})(x_{i+1} - x_i)} \quad (4)$$

Second derivatives were calculated by substituting first derivatives for z_2 in Equation (4). Equations for estimating second derivatives of evenly spaced data are simpler, and can be found in many textbooks (e.g. Chapra and Canale, 1988). In this study it was necessary to use Equation (4), rather than a simpler one, because piezometers could not be spaced in exactly even intervals.

Average water surface concavity

Building on the relationship between concavity and VHG, we introduce a metric for comparing the potential for hyporheic exchange flow in different stream reaches, i.e. the average water surface concavity (AWSC), calculated as

$$AWSC = \left(\frac{1}{n} \right) \left(\sum_{i=1}^n \left| \frac{d^2z_2}{dx_i^2} \right| \right) \quad (5)$$

AWSC is calculated by averaging the absolute values of the concavity measured at every survey point within the longitudinal water surface profile and has units of length per unit length squared. In order to evaluate the usefulness of AWSC as a metric for comparing the potential for hyporheic exchange in streams at different locations along the river continuum, we used simple linear regression to test for a trend in AWSC with increasing drainage basin area.

RESULTS

Patterns in the size and spacing of channel slope units

The first step towards testing the first hypothesis (that average near-surface hyporheic flow path lengths increase predictably across the river continuum in association with predictable increases in channel unit size and spacing) was characterizing patterns in the size and spacing of channel units that are expressed across a gradient of drainage basin area. The differences in how the observed trends are reported result from differences

Table III. Regression models for predicting stream reach characteristics

Parameter	Model	<i>n</i>	<i>R</i> ²	Two-sided <i>p</i> -value	SE for β_1
Median length of POOLS	$\exp(0.795 + 0.022 \times \text{AREA})$	181	0.300	<0.0001	0.003
Median length of RIFFLES	$\exp(0.979 + 0.007 \times \text{AREA})$	165	0.037	0.0130	0.003
Median distance between STEPs	$\exp(1.461 + 0.444 \times \ln(\text{AREA}))$	112	0.450	<0.0001	0.046
Median distance between POOLS	$\exp(1.858 + 0.012 \times \text{AREA})$	168	0.160	<0.0001	0.002
Median downwelling zone length	$\exp(0.741 + 0.067 \times \text{AREA})$	12	0.255	0.094	0.036
AWSC	$0.084 - 0.019 \times \ln(\text{AREA})$	10	0.850	<0.0001	0.003

Table IV. Summary of changes in channel unit spacing, downwelling zone lengths, and AWSC with increasing drainage basin area. Differences in how the observed trends are reported result from differences in data transformations in the regression models

Geomorphic variable	Change with increasing drainage basin area	95% confidence bounds for estimated effect
POOL length	Increases by 2.3% for every increase in basin area of 1 km ²	1.8% to 2.8%
RIFFLE length	Increases by 0.65% for every increase in basin area of 1 km ²	0.60% to 0.70%
Distance between STEPs	Increases by 36% for every doubling in basin area	28% to a 45%
Distance between POOLS	Increases by 1.25% for every increase in basin area of 1 km ²	0.80% to 1.68%
Downwelling zone lengths	Increases by 7.0% for every increase in basin area of 1 km ²	-1.4% to 16.0%
AWSC	Decreases by 0.013 m m ⁻² for every doubling in basin area	0.010 to 0.016

in data transformations in the regression models. In some cases the natural logarithm transformation was performed on the explanatory variable, sometimes on the response variable, and sometimes on both.

The absolute length of POOLS and RIFFLES increased significantly with basin area (Table III); however, no significant increase in STEP length was detected. Both the distance between STEPs and the distance between POOLS also increased significantly with basin area. Though significant, the models describing increases in RIFFLE lengths and distances between POOLS described very little of the observed variability, and observed trends were subtle (Tables III and IV). The model for predicting the distance between STEPs explained the greatest amount of variability, followed by the model for predicting the length of POOLS (Table III).

The model for predicting STEP spacing suggested that, as watershed area increases with distance down the stream network, a doubling in AREA would result in a 36% increase in the distance between STEPs (Table IV, Figure 2a). The model predicting the length of POOLS suggested that an increase in basin area of 1 km² would result in an increase of 2.3% in median POOL length (Table IV, Figure 2b).

Upwelling and downwelling in piezometer transects

Six downwelling zones were identified in P224.0, three were identified in P224.1, and five were identified in P356 (Figures 3–5). Two downwelling zones were omitted from the data set because they occurred in only one or two piezometers at an end of a piezometer transect, and the entire length of the downwelling zone may not have been captured. Evidence suggested that the median longitudinal length of downwelling zones increased with increasing basin area (Tables III and IV, Figure 6). It is estimated that an increase in basin area of 1 km² is associated with an increase in downwelling zone length of 7.0% (Table IV). Upwelling zones were short, with none spanning more than approximately 3 m (Figures 3–5) and no significant trend was detected in their length in association with drainage basin area.

Drainage basin area in the piezometer transects ranged from 1.98 to 16.87 km². Over this range, the estimated average downwelling zone lengths were bracketed by estimates for POOL lengths and the distance

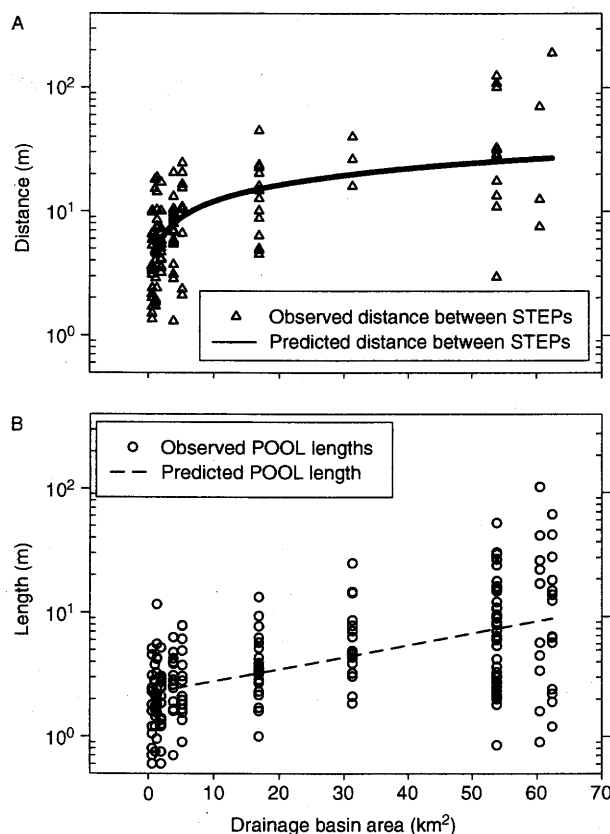


Figure 2. (a) Observed and predicted relationships between drainage basin area and the distance between STEPs in randomly selected stream reaches; (b) observed and predicted relationships between drainage basin area and the length of POOLs in randomly selected stream reaches

between STEPs (Figure 6). POOL lengths are predicted to increase from 2.31 m to 3.22 m, downwelling zone lengths are predicted to increase from 2.40 m to 6.54 m, and the distance between STEPs is expected to increase from 5.84 m to 15.16 m. This provides evidence to support the hypothesis that average near-surface hyporheic flow-path lengths increase predictably across the continuum from headwater to mid-order streams in association with predictable increases in channel unit size and spacing.

Water surface concavity and VHG

Values for water surface concavity at piezometer locations ranged from -0.26 to 0.39 m m^{-2} (Figures 3–5). Large values of concavity were associated with abrupt slope breaks in the water surface profiles. The most extreme values in water surface concavity were associated with transitions between POOLs and STEPs in piezometer transect P224.1 (Figure 4), where the step–pool morphology is very pronounced. Comparatively, the step–pool morphology is poorly expressed in transects P224.0 and P356.0. Transitions between POOLs and RIFFLES and between RIFFLES and STEPs in P224.0 and P356.0 were less abrupt than transitions between POOLs and STEPs in P224.1. Consequently, AWSC was greatest in P224.1 (Table V).

Individual values of concavity, calculated for each point along the longitudinal water surface profile, were either positive or negative (i.e. concave or convex). Success in using the sign (negative or positive)

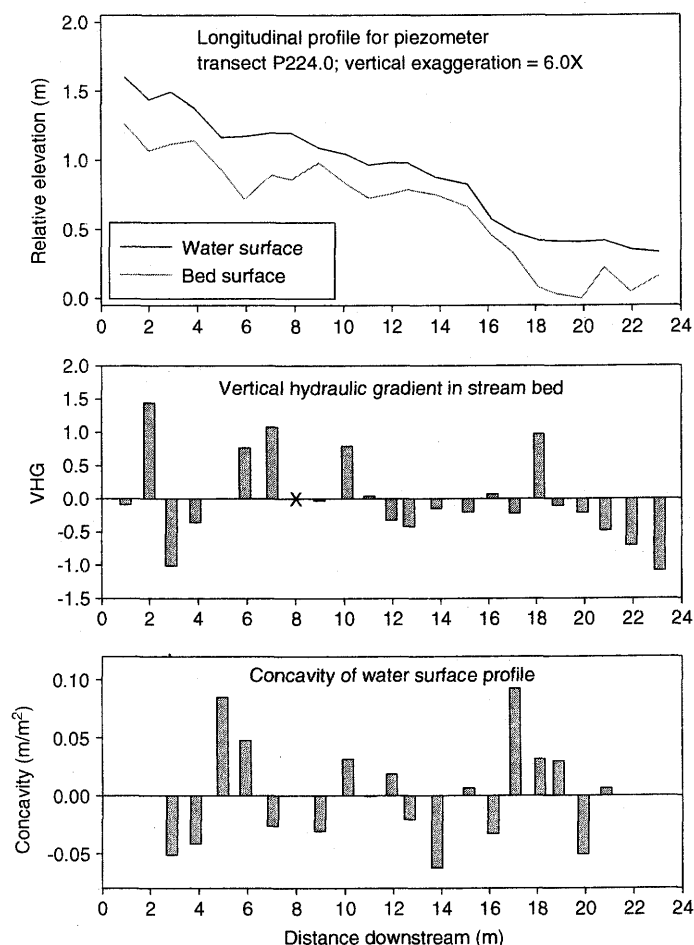


Figure 3. Observed longitudinal profile, vertical hydraulic gradients, and water surface concavity for piezometer transect P224.0. 'x' indicates missing data

of concavity values to predict whether a piezometer would be upwelling or downwelling varied between piezometer transects. Concavity correctly predicted upwelling or downwelling locations 56% of the time in P224.0 (Figure 3), 71% of the time in P224.1 (Figure 4), and 63% of the time in P356.0 (Figure 5). Overall, predictions were correct in 63% of the cases.

Vertical hydraulic gradients, calculated at each piezometer location within longitudinal transects, varied from -1.30 to 1.07 (Figures 3–5). The degree to which VHGs were predictable varied amongst the three piezometer transects. From simple linear regression, the slope describing the observed relationship between VHG and water surface concavity at specific points along the longitudinal profile varied between 1.7 and 7.5 (Figure 7). The amount of variability described by the regression models varied between 8 and 38% in individual piezometer transects (Table V). The best model fits came from piezometer transect P224.1 in the reach with the well-developed step–pool morphology. The poorest model fit came from P224.0, where the pool–step morphology is poorly defined. Variability not explained by the simple linear regression model

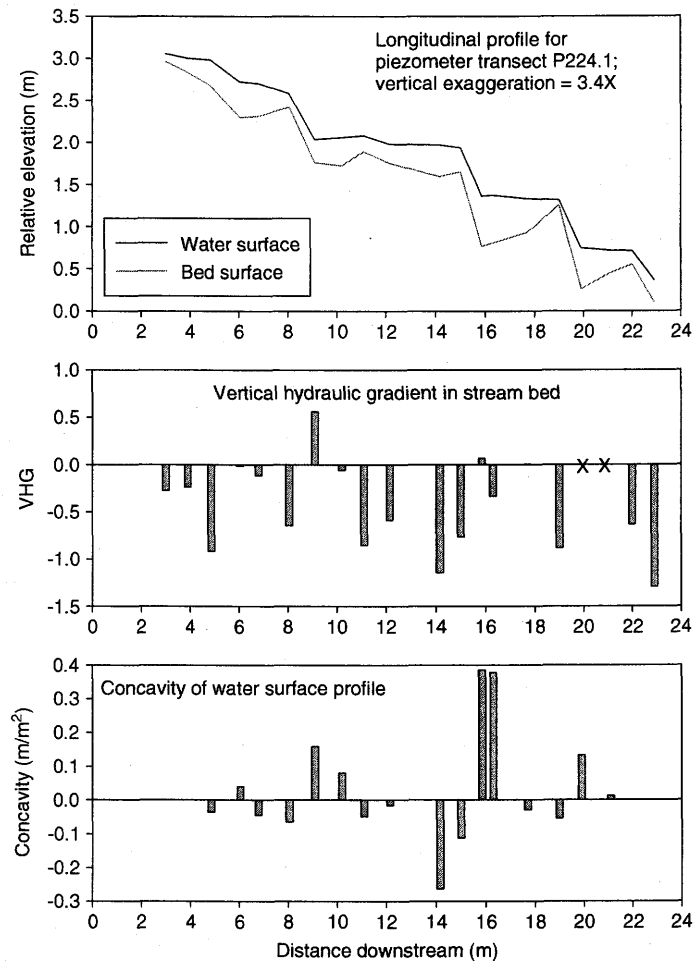


Figure 4. Observed longitudinal profile, vertical hydraulic gradients, and water surface concavity for piezometer transect P224.1. 'x' indicates missing data

indicates that VHG is responding to factors not explained by concavity alone. Likely factors include varying depth of alluvium, heterogeneities in hydraulic conductivity, and cross-valley hydraulic gradients.

In all cases the regression models predicted a positive trend relating VHG to water surface concavity (Figure 7). The models predicted that an increase of in concavity of 0.01 m m^{-2} would be associated with an increase in VHG of 0.35 for P224.0, 0.017 for P224.1, and 0.075 for P356.0. The regression for VHG in P224.0 as not statistically significant; however, the other regression models were significant (Table V). The positive trends characterized by the regression models demonstrate that the magnitude of VHG at a point along the longitudinal profile tends to be greater at points where the magnitude of concavity in the water surface is greater.

AWSC

AWSC in piezometer reaches varied from 0.021 to 0.122 m m^{-2} with the largest value occurring in a well-developed step-pool reach with abrupt slope breaks in the water surface profile (Table V). Survey data

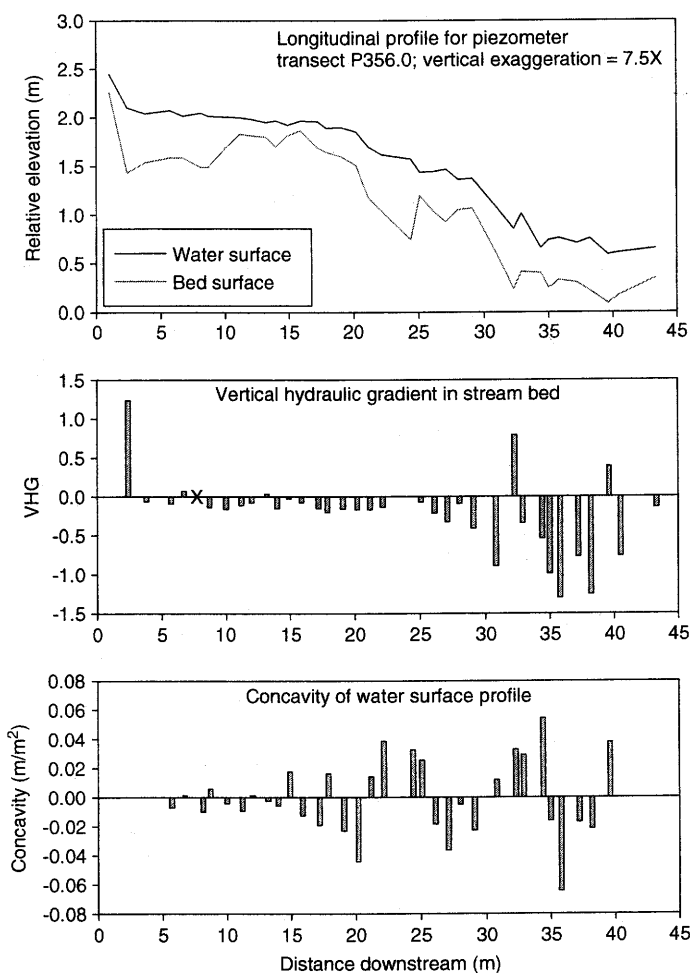


Figure 5. Observed longitudinal profile, vertical hydraulic gradients, and water surface concavity for piezometer transect P356.0. 'x' indicates missing data

from all 12 randomly selected reaches showed that AWSC decreased as basin area increased (Figure 8). It is estimated that AWSC decreases by 0.013 m m^{-2} for every doubling in drainage basin area within the observed range of data (Table IV). The model characterizing the relationship between basin area and AWSC explained 85% of the observed variability—much more than models for predicting the spacing between morphologic features (Table III).

The average of the absolute values of VHG calculated for each piezometer transect varied between 0.34 and 0.50 m m^{-1} and was greatest in P224.1, where AWSC was greatest. A comparison of data from all three piezometer transects shows that the average of the absolute values of VHG for a piezometer transect increased with increasing AWSC (Figure 9). This is consistent with the positive relationship observed by comparing VHG with concavity in individual piezometers (Figure 7). The positive relationship between VHG and water surface concavity provides strong evidence in support of the hypothesis that the potential for gravity-driven

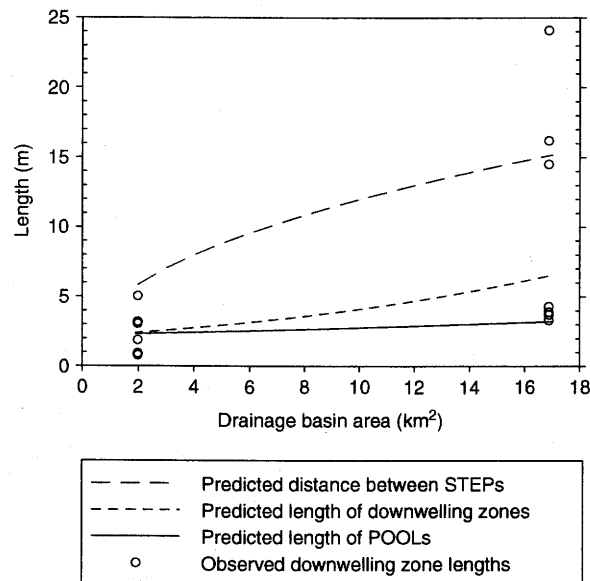


Figure 6. Predicted relationships between drainage basin area and the distance between STEPs, the length of POOLs, and the length of downwelling zones over the range of basin area represented by the piezometer transects. Observed lengths of downwelling zones are also shown here. The observed distances between STEPs and the POOL lengths are shown in Figure 2a and b

Table V. Results from regression models for predicting VHJ using water surface concavity in piezometer transects. AWSC values are included for comparison

Piezometer transect	<i>n</i>	β_1 (slope)	SE β_1	R^2	<i>p</i> -value	AWSC (m m ⁻²)
P224.0	18	3.5	2.9	0.08	0.24	0.037
P224.1	14	1.7	0.63	0.38	0.02	0.122
P356.0	30	7.5	2.9	0.21	0.01	0.021

hyporheic exchange flow in high-gradient mountain stream reaches increases as the average magnitude of concavity in the water surface profile increases.

DISCUSSION

Spacing between upwelling and downwelling zones

The relationships between basin area and the size and spacing of channel units was characterized by high variability, but increases in the size and spacing of channel units were predictable. Downwelling zone lengths in piezometer reaches also increased with basin area, and median downwelling zone lengths were bracketed by predictions for median POOL length and median distance between STEPs. These results support the hypothesis that average near-surface hyporheic flow-path lengths increase predictably between headwater and mid-order streams in association with predictable increases in channel unit size and spacing. Where slope breaks are frequent, such as in headwater streams, we expect that water will cycle through the hyporheic zone frequently, along short flow paths. In mid-order streams, where slope breaks are less frequent, we predict that water will

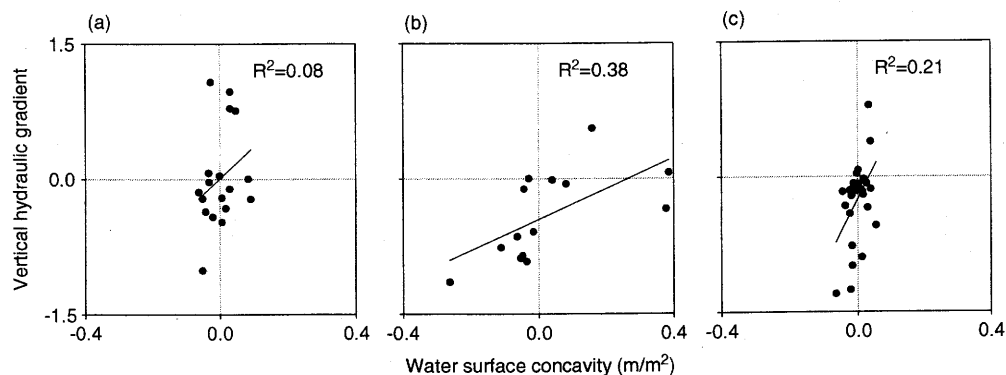


Figure 7. Observed relationship between VHG and water surface concavity at specific points along piezometer transects: (a) P224.0; (b) P224.1; (c) P356.0

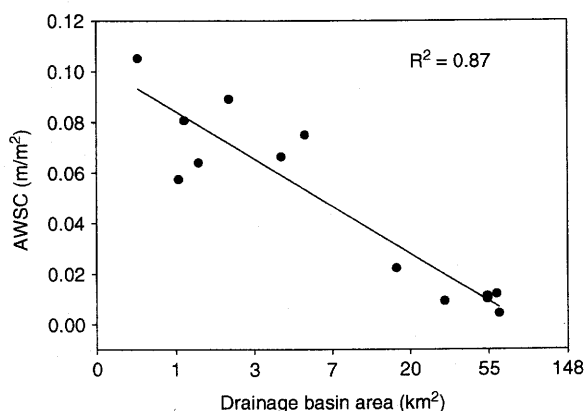


Figure 8. Observed and predicted relationship between basin area and AWSC in randomly selected stream reaches in the H.J. Andrews Experimental Forest

exchange less frequently, along longer flowpaths. Results of two-dimensional groundwater flow simulations presented in a companion paper (Gooseff *et al.*, 2005) support this prediction. Frequent hyporheic exchange in headwater streams should increase the uptake of soluble nutrients transported in stream water (Triska *et al.*, 1989; Findlay, 1995; Mulholland and DeAngelis, 2000). And because repeated interchange increases the amount of stream water in contact with geochemically and microbially active biofilms on sediment (Harvey and Wagner, 2000), more frequent exchange should increase processing of organic matter and nutrients. Frequent hydrologic exchange is also expected to increase the exchange of heat between the stream and the hyporheic zone, and increase the retention of water, effectively moderating temperatures and discharge rates.

Water surface concavity

The factors controlling the spatial patterns of upwelling and downwelling along a stream bed, and the rate of vertical hydrologic exchange, include: the concavity of the stream at points along its longitudinal profile; the depth and permeability of bed sediments; variations in permeability; and variations in hydraulic gradients adjacent to the stream. Of these factors, only concavity is easily characterized. In this study we show that

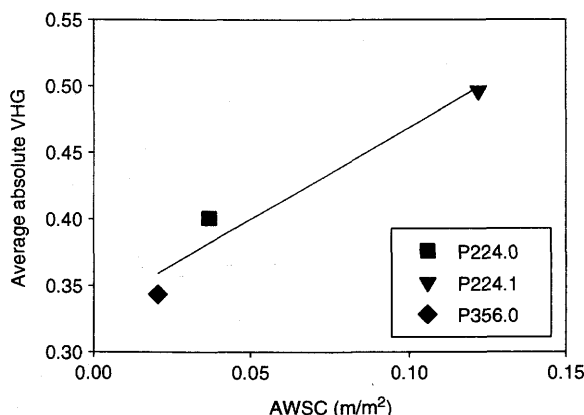


Figure 9. Relationship between the average absolute value of VHG and the AWSC in the three piezometer transects

concavity can explain between 8 and 38% of the observed variability in VHG, which suggests that VHG at any given location is also influenced by other factors. Despite the low to moderate amounts of variability in VHG explained by concavity, this study demonstrates a consistently positive relationship between VHG and water surface concavity in the reaches instrumented with piezometers (Figure 7). This relationship provides the basis for using water surface concavity as a metric for predicting the relative magnitude of VHG at different points along a stream profile, and for using AWSC to compare the relative potential for hyporheic exchange flow in different stream reaches. Stream reaches characterized by low AWSC are expected to have narrow fluctuations in VHG along the longitudinal profile, whereas reaches characterized by high AWSC are expected to have broader fluctuations in VHG and, therefore, a greater potential for hyporheic exchange flow. We also observed a tight, negative relationship between AWSC and basin area (Figure 8), which suggests that cycling of stream water through the hyporheic zone will involve a smaller proportion of the total stream discharge as stream size increases. Combined, these factors make AWSC an appealing metric for describing how channel morphology affects hyporheic exchange flow along the continuum from headwater to mid-order streams.

We expect that the water surface in the longitudinal profile of mountain streams varies with varying stream discharge. An increase in stream stage should decrease water surface concavity, as smaller slope breaks in the water surface profile are flooded. Our results suggest that the decrease in water surface concavity should decrease vertical hydraulic gradients through the streambed. Consequently, the effect of concavity on patterns of upwelling and downwelling should be most strongly expressed during low flow periods. However, because slope breaks in the longitudinal profiles of headwater and mid-order streams are very pronounced, we expect that concavities in the water surface profiles of these streams will exist during all but the most extreme flow events.

The influence of hydraulic conductivity and bed depth on VHG

In this study, we related patterns in the longitudinal profile of mountain streams to hyporheic exchange flows. Saturated hydraulic conductivity K and depth of bed sediments are also widely recognized as important controls on hyporheic exchange and may also change systematically across the stream network. In general, downstream fining in the mean diameter of streambed sediments suggests that K should decrease as watershed size increases. However, at the reach scale, the size of sediment deposited on the valley floor is controlled by a variety of factors, including sediment supply and hydraulic roughness (Buffington and Montgomery, 1999a,b). Although longitudinal trends in K of valley-floor sediment in the streams of the Lookout Creek network have

been little studied, the few available observations suggest that K does not follow a simple pattern related to downstream fining. Kasahara and Wondzell's (2003) observations, based on slug tests from many wells and from tracer tests, showed that average saturated hydraulic conductivities were higher in mid-order reaches than in headwater reaches. The results presented here show that AWSC decreases with increasing basin area and suggest that hyporheic exchange flow will also decrease with drainage basin area. However, the apparent trend toward increasing hydraulic conductivity with increasing basin area may offset decreases in AWSC, and maintain large amounts of hyporheic exchange flow in mid-order reaches.

The variability in K within the piezometer reaches and the degree to which this influences patterns of upwelling and downwelling in this study are not known. Kasahara (2000) reported that K in streams at the H.J. Andrews Experimental Forest varied by four orders of magnitude within stream reaches. Though this is expected to influence patterns of upwelling and downwelling in stream reaches, the relative importance of variability in K and variability in water surface concavity as influences on vertical exchange is not known. Although we did not attempt to compare the influence of concavity and K in this study, our results suggest that the strength of the association between VHG and concavity will increase with the steepness of the slope breaks in the water surface profile. Thus, in steep, well-developed step-pool reaches the water surface concavity may be a stronger influence on patterns of upwelling and downwelling than K , whereas the opposite may be true in low-gradient reaches with relatively constant water surface slopes.

The depth of saturated alluvium under the stream was not measured in any of the 12 stream reaches examined in this study; however, we do not expect bed depth to change systematically across the stream network. Nonetheless, reach- and subreach-scale variations in bed depth may either strengthen or weaken the association between water surface concavity and VHG, depending on whether or not the change in bed depth is expressed in the shape of the water surface profile. For instance, underlying irregularities in bedrock topography may not be expressed in the water surface profile. However, sediment deposits upstream from STEPs often are expressed in the water surface profile, and variations in bed depth and water surface concavity may have complementary effects on patterns of upwelling and downwelling. Bed depth measurements taken longitudinally in stream reaches would likely improve the predictability of VHG; however, these measurements would be difficult to obtain in most streams.

Hierarchy in stream systems and hyporheic exchange flow

Stream systems are often viewed as being hierarchically structured and having characteristics that vary across spatial scales ranging from individual particles, subunits (less than one channel width), channel units, stream reaches, and valley segments (Allen, 1968; Jackson, 1975; Grant *et al.*, 1990). Features such as geologic contacts, glacial deposits, and immobile debris flow and landslide deposits influence stream channel characteristics at the reach scale. However, geomorphologists have emphasized channel units and subunits as particularly important scales of variation that express internal channel-forming mechanisms (Grant *et al.*, 1990; Chin, 2002). In light of this, we chose to focus on channel-unit- and subunit-scale variations in stream gradient in the hope of identifying stream reach characteristics that would be predictable in stream reaches of varying size, regardless of external influences such as valley constraint. Our results are consistent with work by Chin (2002), which suggests that underlying periodicity in step-pool spacing is not obscured by external influences. Furthermore, our results suggest that the underlying spacing in step-pool reaches is expressed in the spacing between zones of upwelling and downwelling in the stream bed and is, therefore, a useful scale at which to evaluate hyporheic exchange flow in high-gradient streams.

Hyporheic exchange flow has also been described at scales defined by the size of individual particles, bedforms, stream reaches, valley segments, and catchments (Brunke and Gonser, 1997; Boulton *et al.*, 1998; Baxter and Hauer, 2000). The morphologic features driving exchange flow also vary across these scales, resulting in a distribution of flow paths of widely varying length and residence time that can be nested in space, as described by Haggerty *et al.* (2002). Alternatively, interactions between morphologic features at different scales can be superimposed, resulting in high rates of hyporheic exchange, as described by Kasahara

and Wondzell (2003). Biological processes in streams can be sensitive to exchange flows at multiple scales. For example, Baxter and Hauer (2000) showed that bull trout (*Salvelinus confluentus*) responded to channel-unit-scale patterns in downwelling superimposed upon reach-scale patterns of upwelling when selecting spawning sites in glaciated alluvial valleys in the Swan River system in Montana, USA. The complex flow paths created by a variety of channel morphologic features operating at a variety of spatial scales in mountain streams makes it difficult to characterize the full distribution of flow-path lengths and residence times in any given stream reach. However, sensitivity analysis of groundwater flow models simulating hyporheic exchange in headwater and mid-order mountain streams suggests that channel-unit-scale features, such as steps and riffles, were dominant features driving hyporheic exchange flow (Kasahara and Wondzell, 2003). The focus on channel-unit-scale morphologic features in this study addressed the need to identify morphologic indicators of patterns in hyporheic exchange flow that would be useful in a wide range of headwater and mid-order streams, including reaches constrained by narrow valleys and unconstrained reaches. We recognize that both larger and smaller scale flow paths are present in the stream reaches we studied. However, the relative importance of local channel-unit-scale flow systems, compared with larger reach-scale flow systems, will be greatest where topographic relief within the stream profile is greatest, as predicted by groundwater flow theory (Toth, 1963) and empirical evidence (Kasahara and Wondzell, 2003). In light of this, we expect that channel-unit-scale patterns in upwelling and downwelling will be most important in headwater streams where AWSC is highest, and that subreach- or reach-scale patterns in upwelling and downwelling are likely to become more important as AWSC decreases with increasing basin area. Thus, increases in hyporheic flow-path lengths with increasing basin area result not only from increased spacing and size of channel-unit features, but also from the increased importance of reach-scale morphologic features in driving hyporheic exchange flow.

CONCLUSIONS

The overall goal of this study was to identify patterns in stream geomorphology that could be used to predict patterns of hyporheic exchange flow in high-gradient headwater and mid-order mountain streams. This study demonstrated that stream longitudinal profiles provide useful indicators for estimating the spacing between upwelling and downwelling zones, and for predicting the variability in the magnitude of the vertical hydraulic gradients driving hyporheic exchange flow. Specifically, we showed that the size and spacing of channel slope units increased predictably with basin area. Although these relationships were highly variable, regression models characterized significant trends allowing increases in channel unit size and spacing to be predicted on basin area alone. Estimates for the length of POOL units and the distance between STEPs bracketed the predicted length of downwelling zones in instrumented stream reaches. This suggests that the length of flow paths along which water travels through the hyporheic zone can be estimated as a range defined by the average POOL length and the average distance between STEPs in mountain stream reaches. These estimates are expected to be most accurate in headwater stream reaches, where slope breaks in stream longitudinal profiles are most pronounced. Flow-path lengths may be less influenced by channel unit spacing in larger stream systems, where slope breaks are less pronounced and valley morphology is more varied.

We developed AWSC as a metric for predicting the relative magnitude of vertical hydraulic gradients driving upwelling and downwelling in mountain stream reaches. The factors controlling the spatial patterns of upwelling and downwelling along a stream bed, and the rate of vertical hydrologic exchange, include: the concavity of the stream along its longitudinal profile; the depth and permeability of bed sediments; variations in permeability; and variations in hydraulic gradients adjacent to the stream. Of these factors, only concavity is easily characterized. Predicting the exact location of upwelling and downwelling zones proved difficult, but we demonstrated that concavity was useful for predicting the relative magnitude of fluctuations in VHGs—and, hence, the potential for hyporheic exchange flow—within the beds of different stream reaches. AWSC is an appealing morphologic metric for comparing the potential for hyporheic exchange flow in headwater and mid-order stream reaches, because it is easily quantified for stream reaches of any length and because it is

highly correlated to drainage basin area. The combined effects of increasing spacing between channel units and decreasing water surface concavity with increasing stream size suggest that the potential for hyporheic exchange flow decreases along the continuum from headwater to mid-order streams, and also suggests that the distribution of flow-path lengths and residence times should increase with increasing basin area.

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REFERENCES

- Allen JRL. 1968. The nature and origin of bed-form hierarchies. *Sedimentology* **10**: 161–182.
- Baxter CV, Hauer FR. 2000. Geomorphology, hyporheic exchange, and selection of spawning habitat by bull trout (*Salvelinus confluentus*). *Canadian Journal of Fisheries and Aquatic Science* **57**: 1470–1481.
- Bencala KE. 2000. Hyporheic zone hydrological processes. *Hydrological Processes* **14**: 2797–2798.
- Boulton AJ, Findlay S, Marmonier P, Stanley EH, Valett HM. 1998. The functional significance of the hyporheic zone in streams and rivers. *Annual Review of Ecology and Systematics* **29**: 59–81.
- Brunke M, Gonser T. 1997. The ecological significance of exchange processes between rivers and groundwater. *Freshwater Biology* **37**: 1–33.
- Buffington JM, Montgomery DR. 1999a. Effects of sediment supply on surface textures of gravel-bedded rivers. *Water Resources Research* **35**: 3523–3530.
- Buffington JM, Montgomery DR. 1999b. Effects of hydraulic roughness on surface textures of gravel-bed rivers. *Water Resources Research* **35**: 3507–3521.
- Chapra SC, Canale RP. 1988. *Numerical Methods for Engineers*, 2nd edition. McGraw-Hill: USA.
- Chin A. 2002. The periodic nature of step–pool mountain streams. *American Journal of Science* **302**: 144–167.
- Elliott AH, Brooks NH. 1997. Transfer of nonsorbing solutes to a streambed with bed forms: theory. *Water Resources Research* **33**: 123–136.
- Findlay S. 1995. Importance of surface–subsurface exchange in stream ecosystems: the hyporheic zone. *Limnology and Oceanography* **40**: 159–164.
- Goosseff MN, Anderson JK, Wondzell SM, LaNier J, Haggerty R. 2005. A modelling study of hyporheic exchange pattern and the sequence, size, and spacing of stream bedforms in mountain stream networks, Oregon, USA. *Hydrological Processes* **19**: this issue.
- Grant GE, Swanson FJ, Wolman MG. 1990. Pattern and origin of stepped-bed morphology in high-gradient streams, Western Cascades, Oregon. *Bulletin of the Geological Society of America* **102**: 340–352.
- Hack JT. 1957. Studies of longitudinal stream profiles in Virginia and Maryland. *United States, Geological Survey, Professional Paper* **294-B**.
- 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**(13): 18.1–18.4.
- Harr RD. 1981. Some characteristics and consequences of snowmelt during rainfall in western Oregon. *Journal of Hydrology* **53**: 277–304.
- Harvey JW, Bencala KE. 1993. The effect of streambed topography on surface–subsurface water exchange in mountain catchments. *Water Resources Research* **29**: 89–98.
- Harvey JW, Wagner BJ. 2000. Quantifying hydrologic interactions between streams and their subsurface hyporheic zones. In *Streams and Ground Waters*, Jones JA, Mulholland PJ (eds). Academic Press: San Diego; 3–44.
- Hill AR, Labadie CF, Sanmugas K. 1998. Hyporheic zone hydrology and nitrate dynamics in relation to the streambed topography of a N-rich stream. *Biogeochemistry* **42**: 285–310.
- Jackson R. 1975. Hierarchical attributes and a unifying model of bed forms composed of cohesionless material and produced by shearing flow. *Bulletin of the Geological Society of America* **86**: 1523–1533.
- Kasahara T. 2000. *Geomorphic controls on hyporheic exchange flow in mountain streams*. MS thesis, Oregon State University.
- Kasahara T, Wondzell SM. 2003. Geomorphic controls on hyporheic exchange flow in mountain streams. *Water Resources Research* **39**: 3–14.
- Keller EA, Melhorn WN. 1973. Bedforms and fluvial processes in alluvial stream channels: selected observations. In *Fluvial Geomorphology*, Morisawa M (ed.). New York State University Publications in Geomorphology: Binghamton; 253–283.
- Keller EA, Melhorn WN. 1978. Rhythmic spacing and origin of pools and riffles. *Bulletin of the Geological Society of America* **89**: 723–730.
- Knighton D. 1984. *Fluvial Forms and Processes*. Edward Arnold: London.
- Leopold LB, Maddock T Jr. 1953. The hydraulic geometry of stream channels and some physiographic implications. *United States, Geological Survey, Professional Paper* **252**.
- Lenzi MA. 2001. Step–pool evolution in the Rio Cordon, northeastern Italy. *Earth Surface Processes and Landforms* **26**: 991–1008.

- McCandless TL, Everett RA. 2002. Maryland stream survey: bankfull discharge and channel characteristics of streams in the piedmont hydrologic region. U.S. Fish and Wildlife Service, Chesapeake Bay Field Office, CBFO-S02-01. <http://www.fws.gov/r5cbfo/Piedmont.pdf>.
- Montgomery DR, Buffington JM. 1997. Channel–reach morphology in mountain drainage basins. *Bulletin of the Geological Society of America* **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, DeAngelis DL. 2000. Surface–subsurface exchange and nutrient spiraling. In *Streams and Ground Waters*, Jones JA, Mulholland PJ (eds). Academic Press: San Diego; 149–166.
- Packman AI, Brooks NH. 2001. Hyporheic exchange of solutes and colloids with moving bed forms. *Water Resources Research* **37**: 2591–2605.
- Packman AI, Brooks NH, Morgan JJ. 2000. Kaolinite exchange between a stream and streambed: laboratory experiments and validation of a colloid transport model. *Water Resources Research* **36**: 2363–2372.
- Savant SA, Reible DD, Thibodeaux LJ. 1987. Convective transport within stable river sediments. *Water Resources Research* **23**: 1763–1768.
- Schumm SA. 1960. The shape of alluvial channels in relation to sediment type. *United States, Geologic Survey, Professional Papers* **352-B**: 17–30.
- Stanford JA, Ward JV. 1988. The hyporheic habitat of river ecosystems. *Nature* **335**: 64–66.
- Stanford JA, Ward JV. 1993. An ecosystem perspective of alluvial rivers: connectivity and the hyporheic corridor. *Journal of the North American Benthological Society* **12**: 48–60.
- Strahler AN. 1964. Quantitative geomorphology of drainage basins and channel networks. In *Handbook of Applied Hydrology*, Ven te Chow (ed.). McGraw-Hill: New York.
- Swanson FJ, James ME. 1975. *Geology and geomorphology of the H.J. Andrews Experimental Forest, western Cascades, Oregon*. US Forest Service, Pacific Northwest Forest and Range Experiment Station. Research Paper PNW-188.
- Swanson FJ, Jones JA. 2002. Geomorphology and hydrology of the H.J. Andrews Experimental Forest, Blue River, Oregon. In *Field Guide to Geologic Processes in Cascadia*. Oregon Department of Geology and Mineral Industries Special Paper 36; 289–313.
- Thibodeaux LJ, Boyle JD. 1987. Bedform-generated convective transport in bottom sediment. *Nature* **325**: 341–343.
- Toth J. 1963. A theoretical analysis of groundwater flow in small drainage basins. *Journal of Geophysical Research* **68**: 4795–4812.
- Triska FJ, Kennedy VC, Avanzio RJ, Zellweger GW, Bencala KE. 1989. Retention and transport of nutrients in a third-order stream in northwestern California: hyporheic processes. *Ecology* **70**: 1893–1905.
- 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. *USDI, US Fish and Wildlife Service, Fishery Bulletin* **66**: 479–489.
- White DS, Elzinga CH, Hendricks SP. 1987. Temperature patterns within the hyporheic zone of a northern Michigan river. *Journal of the North American Benthological Society* **6**: 85–91.
- Wroblicky GJ, Campana ME, Valett HM, Dahm CN. 1998. Seasonal variation in surface–subsurface water exchange and lateral hyporheic area of two stream–aquifer systems. *Water Resources Research* **34**: 317–328.