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ON THE IMPORTANCE OF CONSIDERING CHANNEL MICROFORMS IN GROUNDWATER MODELS OF HYPORHEIC EXCHANGE

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ABSTRACT

The infiltration of stream water in the sediment and its return to the stream—a process known here as hyporheic exchange flows (HEF)—is a critical control of the structure and functions of the stream ecosystem. River restoration programmes will increasingly require quantitative methods for evaluating this influence. Previous studies have already shown the potential of numerical groundwater models to characterize HEF and compare restoration scenarios. Although various sources of uncertainty are acknowledged, the potential effect of small streambed structures (or microforms), such as grains or ripples, embedded in channel-unit scale structures (or macroforms), such as riffle-pool sequences, is commonly ignored. Here, a simple conceptualization through a 2-D vertical model is used to test whether (i) ignoring microforms in groundwater models at the macroform scale can impact estimations of residence times; (ii) microforms can influence HEF patterns driven by macroforms; and conversely (iii) the uncertainty of head measurements in stream piezometers can affect our understanding of HEF patterns. Results show that (i) residence times and flux estimations can be strongly affected by the modeller's choice to represent microform-induced HEF or not; (ii) the interaction of the microform and macroform scales can induce various subsurface flow patterns; and (iii) the perceived significance of microform-induced HEF is highly sensitive to the uncertainty of in-stream measurements of subsurface heads. Little is known about the relative efficiency of these microform and macroform scales, which are effectively influencing exchange at different depths and interacting with each other. Future studies that consider biogeochemical cycling or streambed ecology should be placed in this context. It is also necessary to find ways of including this source of uncertainty in groundwater models of HEF.

KEY WORDS: hyporheic; river restoration; riffle-pool; groundwater; pumping exchange; scale

INTRODUCTION

Stream ecosystems and solute transport can be substantially affected by hyporheic exchange flows (HEF)—a process through which stream water is temporarily brought in contact with the underlying sediments (Bencala, 2005; Mullholand *et al.*, 2008). Yet, HEF is seldom considered explicitly in river restoration projects. When it is, it does not constitute the main target but, rather, a secondary process under scientific investigation (Kasahara and Hill, 2007; Lautz and Fanelli, 2008). Therefore, there has been a call to better understand the influence of 'vertical connectivity' on the ecosystem services (Boulton, 2007). Recent efforts in this direction include the use of numerical models of subsurface flow (or groundwater models for brevity) to quantify HEF characteristics. Studies carried out by Crispell and Endreny (2009), Hester and Doyle (2008), Lautz and Siegel (2006), and Kasahara and Hill (2006, 2008) are excellent illustrations of this approach in assessing or predicting flow characteristics at the reach scale.

In terms of processes, advective HEF is driven essentially by variations of the hydraulic gradient at the sediment–water interface. These can result from the fluctuation of hydrostatic and/or hydrodynamic pressure. *Hydrodynamically induced* HEF, which is perhaps best referred to as current–obstacle interaction (Hutchinson and Webster, 1998) or pumping exchange, is caused by the acceleration of flow over obstacles and the presence of an eddy that gives rise to pressure variations at the sediment–water interfaces, thus inducing flow in and out of the bed (Elliott and Brooks, 1997; Cardenas and Wilson, 2007; Boano *et al.*, 2011). *Hydrostatically induced* HEF is usually associated with geomorphological features such as in-stream structures (e.g. debris dams, step-pool sequences) or stream meanders, both of which produce relatively steep hydraulic gradients between two points of a streambed (Gooseff *et al.*, 2006). Other factors, including subsurface heterogeneity (Vaux, 1968; Cardenas *et al.*, 2004) and large scale groundwater

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flow patterns (Wroblicky *et al.*, 1998) can also create this type of hydrostatic head variation.

Since these two processes occur at slightly different scales, it is useful to refer to Jackson's classification (1975) of bed forms as microforms (e.g. ripples and grains), mesoforms (e.g. dunes) and macroforms (e.g. bars). Whereas microforms and mesoforms tend to generate hydrodynamic pressure variations, macroforms are more likely to induce changes in hydrostatic pressure. Here, for simplicity, we broadly distinguish these processes by the two-end terms, that is, *microform HEF* (0.01–1 m, possibly larger in the case of large dune systems) and *macroform HEF*, respectively (>1 m). It is worth noting that several studies highlight two scale components of groundwater–stream exchanges, in some cases irrespective of the underlying process. These are termed, for example, *near-stream* and *extended* hyporheic exchange (Gooseff *et al.*, 2003), *short-term* and *long-term* storage (Castro and Hornberger, 1991), *short* and *long flow paths* (Malard *et al.*, 2002), or *superficial* and *lower* layers (Triska *et al.*, 1989).

The ability of groundwater models to predict HEF characteristics can be limited by several sources of uncertainty, such as permeability characterization (see Wondzell *et al.*, 2009). What is largely and implicitly ignored, however, is the potential effect of microforms embedded in macroforms. As far as the authors are aware of, only macroforms have been represented in groundwater models covering areas equal to or larger than the channel-unit. Because this finer scale is poorly understood, caution must still be exercised in the use of groundwater models to characterize HEF, even if other uncertainties are controlled. To fully exploit such models as a hydro-engineering tool, we found that it is crucial that the choice of the riverbed boundary conditions be explicit and that the subsequent implications are understood by modellers and end-users. Here, the concept of microform and macroform scales are used to test whether (i) ignoring microforms in groundwater models at the macroform scale can impact estimations of residence times; (ii) microforms can influence HEF patterns driven by macroforms; and, conversely, (iii) the uncertainty of head measurements in-stream piezometers (commonly used to calibrate groundwater models) can affect our understanding of the flow pattern in the streambed.

SIMULATIONS OF HYPORHEIC EXCHANGE FLOW

Model setup

Assumptions. A simple 2-D vertical groundwater model is used to simulate advective HEF along a pool-riffle type structure, and to consider the interaction of microform and macroform HEF. Although a riffle is a macroform, it superimposes microforms consisting of gravels, cobbles or boulders. The dynamic head fluctuation, caused by microforms, is represented by a popular sine function that was initially defined for flow over ripples (Elliott and Brooks, 1997). This empirical function merely approximates the actual head variation, which is known to be more complex (Cardenas and Wilson, 2007), irregular and unsteady, particularly in coarse-grained beds (Vollmer *et al.*, 2002; Boano *et al.*, 2011). Such a model also ignores the turbulent velocity of surface flow that penetrates the thin superficial layer of the bed, its dissipation occurring over short distances relative to the advective flow (Packman *et al.*, 2004; Manes *et al.*, 2009). Finally, the stream water velocity is kept constant along the whole domain, and therefore, the expected increase of stream velocity over the riffle is not represented.

Model properties and boundary conditions. Steady-state runs were computed with the software FEFLOW™, which solves the continuity equation associated to Darcy's law by using finite elements. The model domain is a vertical rectangle that is 75 m long by 10 m deep. The bottom, upstream and downstream boundaries are impermeable, whereas the top boundary represents pressure variations at the sediment–water interface. A study of 25 m reach is placed at the centre of the domain, so it is not substantially affected by the upstream and the downstream boundaries. The mesh size is 0.78 cm along the top boundary and increases from 0.78 to 100 cm downward. The hydraulic conductivity is set to $10^{-4}\,\mathrm{m\,s^{-1}}$ and the porosity to 0.3. The stream stage is horizontal, except over the riffle, where it is represented by a segment of steeper slope. The fluctuation of the dynamic head h has the form of the sine function described by

$$h = h_m \sin kx \tag{1}$$

where h_m is the half-amplitude of the head variation; k is the wavenumber of the head disturbance equal to $2\pi/\lambda$, where λ is the bedform wavelength, and x is a downstream coordinate parallel to the bed surface. The half-amplitude is taken from an empirical correlation based on the data of Fehlman (1985):

$$\begin{gathered} h_m = 0.28\,\frac{U^2}{2g}\left(\frac{H/d}{0.34}\right)^n \\ \text{if } H/d \le 0.34,\quad n = 3/8, \\ \text{if } H/d \ge 0.34,\quad n = 3/2, \end{gathered} \tag{2}$$

where U is the stream velocity, g is the acceleration due to gravity, H is the bedform height, and d is the stream depth (Elliott and Brooks, 1997 *in* Packman and Bencala, 2000).

MODEL RUNS

Residence times, flow paths and velocities

The residence time distribution is estimated through particle tracking and flow budget. Particles are seeded at the top boundary every centimetre along the 25-meter study reach, and only those that return to the stream within this reach are counted. The first three runs simulate HEF induced by (i) a macroform, (ii) microforms and (ii) both macroforms and microforms. For the first run, the top boundary represents a pool-riffle sequence through two breaks-in-slope of the hydrostatic head. The resulting subsurface flow pattern is well known (Figure 1(b, c)): flow hinges approximately around the riffle's centre, with a downwelling zone upstream and an upwelling zone downstream (Gooseff *et al.*, 2006). The highest velocities (0.4 m day^{-1}) are found close to the breaks-in-slope where the hydraulic gradient is locally steeper (Figure 1(b)). Total flux is 0.8 m^2 day^{-1}(units are m^3 day^{-1} per metre stream width). The distribution of residence times is slightly skewed toward short times (Figure 1(d)) and has a flux-weighted mean of 63 days.

The second run simulates the effect of longitudinal head oscillations caused by microforms along a flat reach, that is, without pool-riffle sequence (Figure 1(e)). Particle tracking (Figure 1(g)) shows that water flows repeatedly from a local maximum head to the closest minimum, forming a series of flow systems no deeper than 0.3 m. As a result of high local pressure gradients, maximum velocities (1.3 m day^{-1}) are higher than those of the pool-riffle sequence alone, but the downward decrease is sharper (Figure 1(f)). Residence times are over an order of magnitude shorter than that of the pool-riffle case, with a mean value of 9 h (Figure 1(h)), whereas total flux is about one order higher (8.4 m^2 day^{-1}).

The third run reproduces the combined effect of microforms together with a macroform (Figure 1(i)). The velocity field and flow paths resemble a superposition of the two previous runs (Figure 1(j, k)). The residence time distribution (mean = 5.5 days) reflects both the longer flow paths induced by the riffle and the high fluxes caused by the pumping exchange (Figure 1(l)). Total flux is similar to the previous run: 8.4 m^2 day^{-1}. These nested, or Tothian, flow systems are well known by hydrogeologists (Tóth, 1963), who typically distinguish a relative hierarchy of local, intermediate and large systems (flow paths f1, f2, f3, respectively, in Figure 1(k)). Zijl (1999) and Cardenas (2008), for example, showed how such patterns can emerge from the superposition of spatially fluctuating head boundaries across a wide range of scales.

With the present model setup, including microforms in a pool-riffle sequence generates a total HEF flux of an order of magnitude higher and a mean residence time of an order of magnitude shorter, than for the case where microforms are

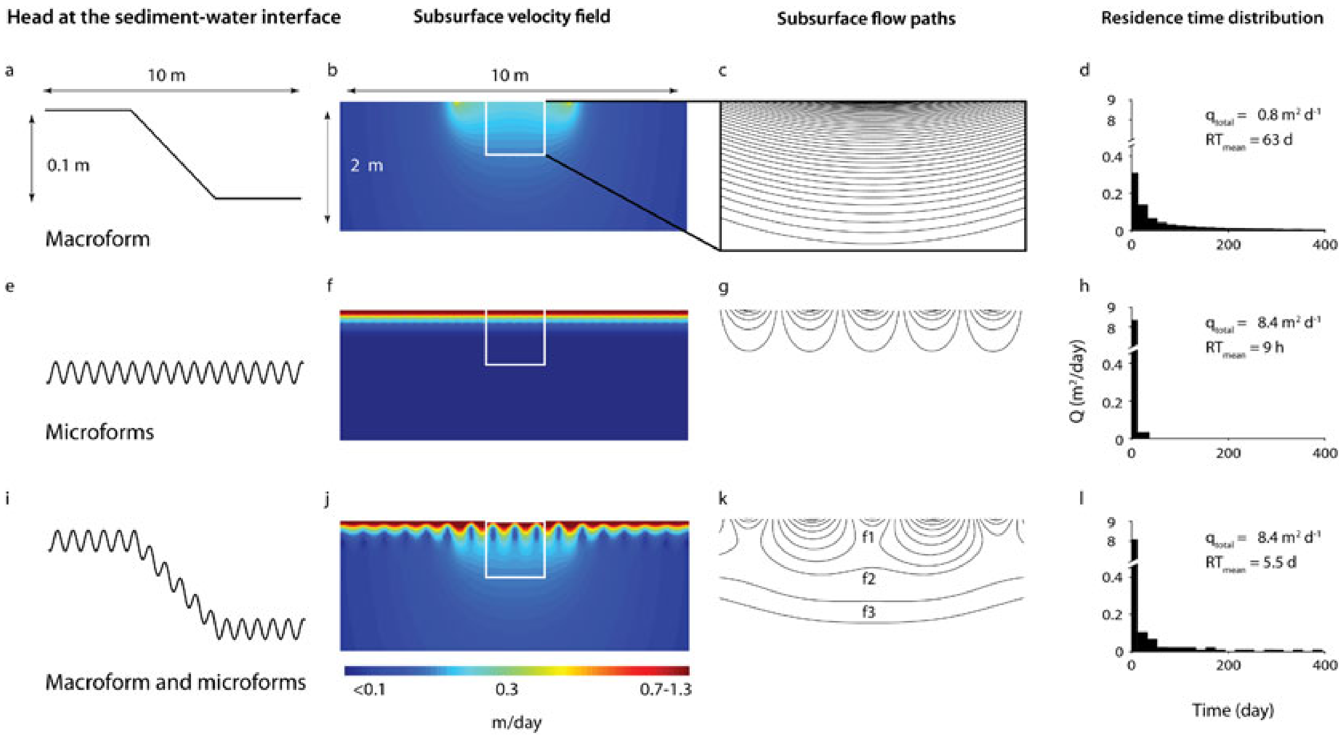

Figure 1. 2-D hyporheic exchange flow along a hypothetical pool-riffle-pool sequence and resulting velocity field, flow paths and residence time distribution. Parameters are as follow: stream velocity, 0.8 ms^{-1}; stream depth, 0.3 m; microform height, 0.12 m; microform wavelength, 0.6 m; riffle elevation drop, 0.1 m; riffle length, 3.3 m. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

ignored. Note, however, that this magnitude of change is associated here to a specific parameter set (stream velocity, riffle length, etc.), and therefore, cannot be generalized. Nevertheless, the conclusion is that residence times and fluxes estimated through groundwater models of HEF can strongly depend on the conceptual representation of bedforms at different scales.

Influence of obstacle height, obstacle length and riffle length on HEF

A basic sensitivity analysis (Figure 2) is conducted by increasing and decreasing the value of three parameters individually and observing the change of flow pattern through particle tracking. These parameters are (i) the *obstacle (microform) height*, thus, the ratio 'obstacle height : stream depth'; (ii) the *obstacle length* (i.e. the wavelength of the sinusoidal function); and (iii) the *riffle* (*macroform*) *length*, which is related to its slope because the head drop over the riffle is kept constant. The base case is represented in Figure 2(a), which corresponds to the run shown in Figure 1(i–l). Equation (2) shows that the amplitude of pressure oscillations at the bed level increases with the square of surface flow velocity. The latter is therefore a

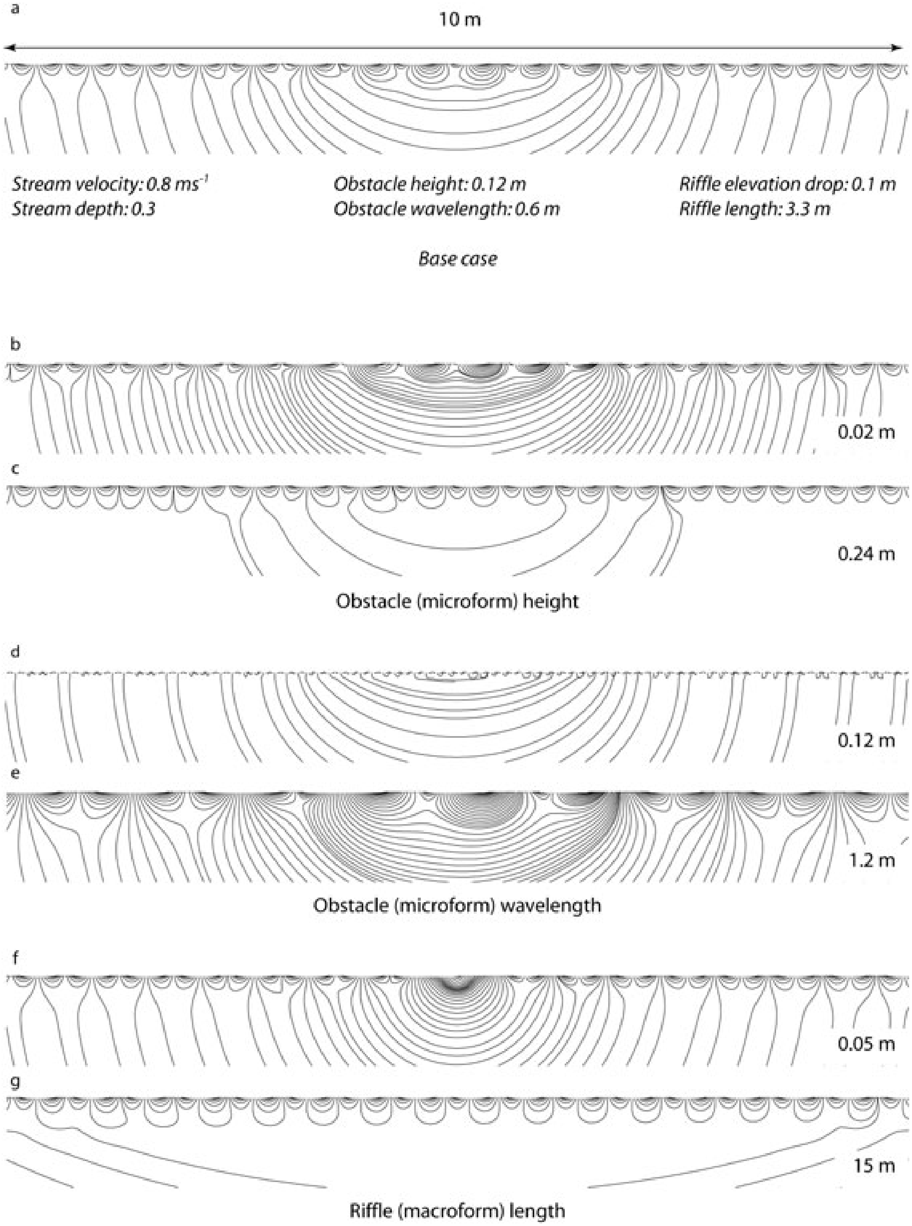

Figure 2. Hyporheic exchange flow paths along a pool-riffle-pool sequence with current–obstacle interactions (particle seeded every 4 cm instead of 1 cm, for clarity). The sensitivity of the flow patterns is illustrated for three parameters: obstacle height, obstacle length and riffle length

critical parameter. It is however not presented explicitly, for the qualitative change in flow pattern is similar to the one related to the obstacle's height.

As depicted in Figures 2(b, c), higher obstacles induce steeper local gradients, which capture the infiltrated stream water that would otherwise flow towards the tail of the riffle. Similarly, the long riffle of lower slope promotes the development of microform flow systems at its centre, whereas the step, by creating a high ambient hydraulic gradient, captures a higher fraction of particles in the macroform flow system (Figures 2(f,g)). As to the obstacle length, shorter obstacles create locally steeper hydraulic gradients that promote pumping exchange, as shown by the sparse flow paths of Figure 2(d), which reflect the predominance of shallow HEF systems. In the case of long obstacles, the upwelling and downwelling areas of the microform systems are larger, yet they capture a smaller fraction of the macroform flow. Although such relationships are somewhat trivial, they have not been formally studied yet and are seldom accounted for in practice.

IMPLICATIONS

The present paper emphasizes the hydrological significance of pumping exchange in modelling studies of HEF at coarser scales. Flow paths are considered an important control on the ecological functions and structure of the hyporheic zone. As such, it is worth reflecting on the implications of flow characteristics in terms of hydrology, biogeochemistry, habitat and monitoring aspects.

Hydrological implications

The occurrence of pumping exchange in studies of pool-riffle sequences based on head measurements is seldom reported, in spite of the simple expectation that any degree of bed roughness creates a potential for pumping exchange. This results probably from the difficulty of detecting head differences, either because they are too small or because it requires a very shallow screen. In fact, Rosenberry and Pitlick (2009) already suggested that hydraulic gradients should be determined over a relatively short vertical increment if used to indicate exchange across the sediment–water interface. Figure 3 illustrates the problem by representing the vertical flow direction (upward, downward, none), as it could be deduced from a head difference measured between the stream and any location of the subsurface. The 'no vertical flow' zone shows where head differences between the streambed and the subsurface are not captured, as a result of measurement uncertainty. (The maximum error on head measurement is arbitrarily set to 1.5 mm, which implies a 3-millimetre error on the head difference.) Figure 3(a, c) shows that a piezometer with a 3-centimetre deep screen enables the detection of a head difference caused by pumping exchange (Figure 3(c)), but in gravel/cobble beds such a setup is rather impractical. As the depth of the screen increases, the head difference is more likely to reflect macroform-induced HEF (70 cm beneath the bed, in Figure 3(c)), and in some intermediate zone (10 cm beneath the bed, in Figure 3(c)), the occurrence of pumping exchange is reflected by a longitudinal fluctuation between 'no flow' and either 'upwelling' or 'downwelling' but without gradient reversal. Interestingly, if one measures a head difference between the stream stage and the piezometric level of a point situated 3 cm below the bed, the assumed flow direction would be incorrect, as shown in Figure 3(b), because fluctuations of pressure head at the bed interface are not directly affecting the stream stage. Note that in a real stream, the unsteady nature of pressure perturbations would probably make it difficult to measure a head with conventional methods anyway (see Vollmer *et al*., 2002; Boano *et al*., 2011).

These field limitations can result in a poor estimation of HEF residence times through groundwater models calibrated on heads (see Wondzell, 2006). Indeed, graphs of residence time distribution derived from large-scale groundwater models that ignore pumping exchange give the misleading impression that because short time flow paths are represented, the residence time estimates are reliable. To the contrary, we expect the (mis)representation of microform roughness to result in substantial uncertainties on estimations of residence times and fluxes. This must be understood, of course, in the context of studies that have explored other sources of uncertainty, such as hydraulic conductivity (Cardenas *et al*., 2004; Salehin *et al*., 2004; Wondzell *et al*., 2009). There is still much to learn about the relative importance of these various sources.

Finally, these hypothetical simulations have shown that large and small HEF systems can influence each other mutually. Larger HEF systems may restrict smaller ones by increasing the ambient groundwater pressure (Storey *et al*., 2003; Cardenas, 2009) in areas of strong upwelling or downwelling. Conversely, small HEF systems, as a result of their sharp local gradients, may capture flow that would have otherwise been part of a larger system.

Biogeochemical and ecological implications

The residence time distribution and flux of HEF are key controls on the efficiency of the lotic system as a biogeochemical processor. Thus, if such flow characteristics are estimated by calibrated groundwater models that ignore pumping exchange, reactive transport simulations are unlikely to yield reliable results. The spatial distribution of the vertical flow at the sediment–water interface is another sensitive output that pertains to ecological processes. Again,

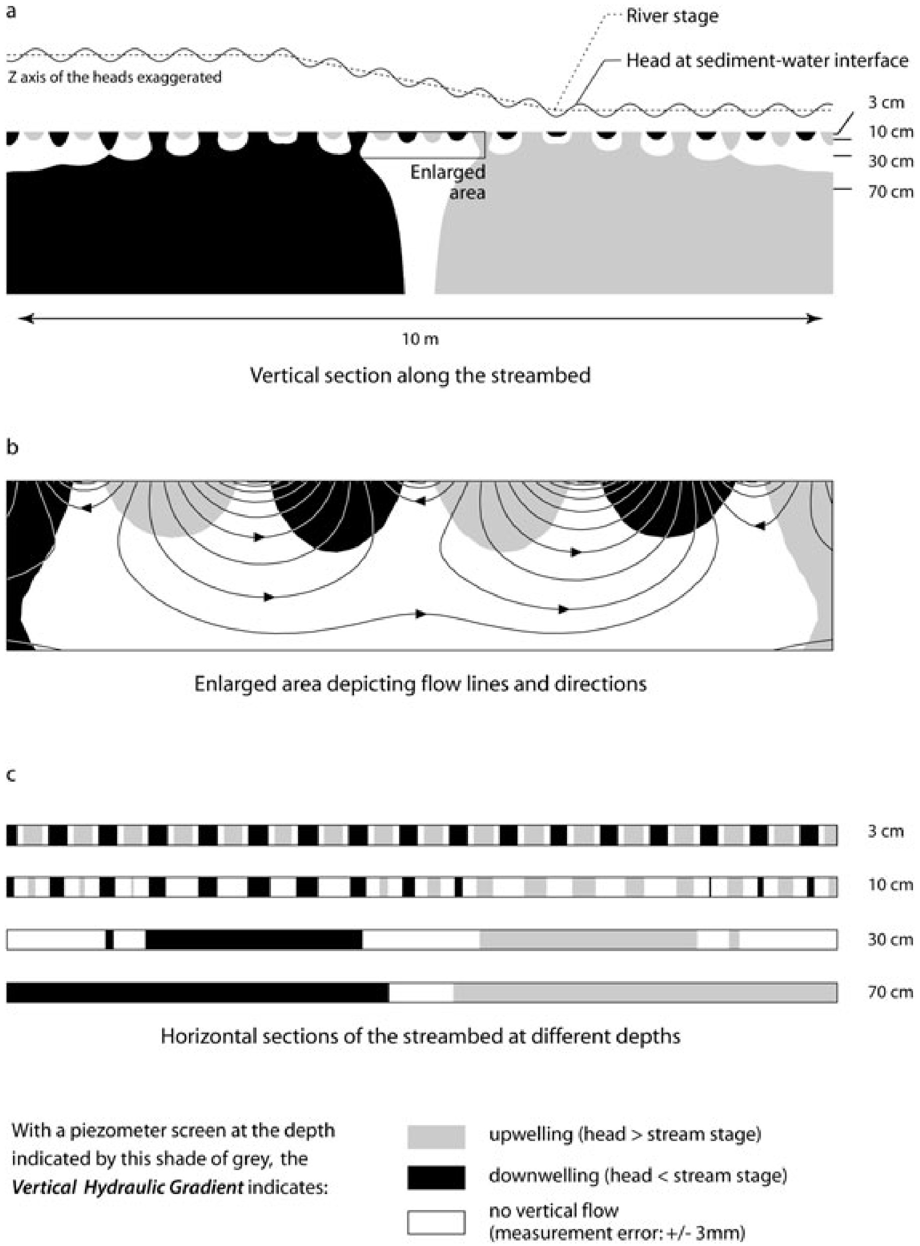

Figure 3. Profile of a streambed along a pool-riffle-pool sequence with current–obstacle interactions. Shades of grey indicate the direction of vertical hydraulic gradient as a function of the *x, z* coordinates of a hypothetical piezometer's screen

excluding pumping exchange can lead to an underestimation of hydrological patchiness, and consequently, of the actual microhabitat patchiness. Currently, the biogeochemical processing of nutrients associated with riffles is typically represented by 'head to tail' flow paths that are 'long enough' to induce anaerobic conditions (Hendricks and White, 2000). In terms of processing efficiency, however, shallow pumping exchange interacting with localized anaerobic zones may have been underestimated as a result of a coarse vertical sampling resolution. More generally, one may ask about the 'pool-riffle reach' type. Which geomorphic feature has the most influence on the stream's biogeochemistry: the microform HEF, which is characterized by high fluxes and short residence times, or the macroform HEF, which is characterized by lower fluxes but longer residence times? The answer to this question will depend on the case and site, but heretofore, the microform considerations have generally been ignored. Finally, the modelled interactions between hydrostatically-induced and hydrodynamically-induced pressure gradients highlight the need to combine the expertise of groundwater hydrologists and specialists of channel hydrodynamics, in order to improve our understanding of the abiotic controls on the hyporheic ecotone.

Summary

A hypothetical 2-D groundwater model of a pool-riffle sequence shows that groundwater models of HEF that cover a scale equal to or larger than a channel-unit but do not account for pumping exchange induced by microforms may impair our understanding of biogeochemical processes. Pumping exchange in riffles is controlled by several factors, among which are two opposing ones: high stream water velocities promote pumping exchange, whereas strong upwelling and downwelling fluxes caused by riffle-induced HEF may restrict it. This second factor is thought to be less influential in long riffles of low slope, which tend to induce lower vertical fluxes. Any permeable streambed that exhibits some degree of roughness has a potential for pumping exchange, although head differences between the stream and the shallow bed are often too small to be measured by standard methods, such as piezometers and pressure transducers. From an ecological standpoint, the interaction between pumping exchange and HEF caused by channel-unit structures may create a small-scale and complex pattern of downwelling and upwelling areas that may influence microhabitats in the shallow subsurface. ‘Head to tail’ flow paths through riffles are sometimes thought to explain variations in stream water chemistry. However, because riffles are zones of high stream flow velocity, they have a potential for pumping exchange that would typically be characterized by a small depth, short residence times and large fluxes. Little is known about the relative efficiency of these two scales, which are effectively influencing exchange at different depths and interacting with each other. Future studies that consider biogeochemical cycling or streambed ecology should be placed in this context. As a starting point, groundwater models of HEF could benefit from (i) using methods employed in surface hydrodynamics to define pressure distribution at the sediment–water interface (Cardenas and Wilson, 2007; Tonina and Buffington, 2007); and (ii) integrating in-stream tracer tests and heads in the calibration process (Saenger *et al*., 2005; Wondzell, 2006).

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