ADVECTIVE HYPORHEIC EXCHANGE AT MULTIPLE SCALES

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River restoration efforts focus heavily on returning streams to natural states, which foster enhanced connectivity with the riparian and hyporheic zones. Regarded as a streams 'liver', the hyporheic zone not only filters and purifies stream water, but also provides nutrients and dissolved oxygen to benthic organisms. We show how hyporheic exchange in terms of a mass transfer coefficient can be separated into both steady and unsteady components. By examining a framework showing how steady and unsteady processes can be combined we contribute to a framework for predicting rates of hyporheic exchange and in turn assessing the effectiveness of river restoration measures.

1 INTRODUCTION

Over the past 20 years, mixing between streams and pore water, known as hyporheic exchange has become a major area of quantitative research [1]. Biogeochemical cycling is critical for benthic ecological processes [2, 3], allowing for the distribution of nitrates in the streambed [4] and facilitating the removal of contaminants from the water column [5]. Moreover, the significance of hyporheic exchange in the purification of streamwater has led to its description as the 'liver' of a stream [6]. Modeling hyporheic exchange has generally been scale specific: for instance, the Advective Pumping Model (APM) predicts exchange across triangular bedforms [7], yet hyporheic exchange extends to flow between meanders [8, 9] at much larger scales. While bedforms play a key role in the distribution of nitrogen in the hyporheic zone [10], nutrient cycling even occurs at the basin scale [11]. Furthermore, combined with regional scales of upwelling or downwelling from groundwater, advective mass transfer is increased [10, 12] as a result of the kinematics of the velocity fields [13]. However, upscalling these models to reach and basin scales remains a challenge [14].

Hyporheic mass transfer processes can be divided into those occurring on the streamside of the sediment-water interface (SWI) and those on the sediment or hyporheic side of the SWI [15]. On the streamside, shear instability and pressure gradients are established as energy dissipates from the water column. On the hyporheic side these pressure gradients establish the boundary for Darcian porewater flow into and out of the hyporheic zone. While models, such as the Elliot and Brooks [7] APM, have adopted this approach, they have neglected to consider the dynamic pressure fields. Some numerical studies [16, 17] have examined these unsteady processes, yet this has not been adopted in predictive models of hyporheic exchange. In this investigation the spatial distribution of both steady and unsteady exchange processes are examined, by initially looking at some theoretical aspects and then examining experimental results. Through this approach, we wish to shed light on the distribution of the advective hyporheic zone that limits nutrient availability to benthic organisms.

2 SPATIAL DISTRIBURIONS OF EXCHANGE

A high degree of spatial variability in hyporheic exchange is also associated with upwelling and downwelling. Moreover, unsteady processes associated with turbulent eddies induce unsteady waves that propagate across the SWI. Therefore, as shown in equation (1) steady components of hyporheic exchange can be associated with the mean pressure head $\overline{h}(x,y)$, while unsteady components can be associated with the variance in pressure field $h'(x,y,t)$.

$$h(x,y,t) = \bar{h}(x,y) + h'(x,y,t) \tag{1}$$

As a first step, the steady state velocity fields associated with bedforms and a stream gradient are examined. Second, unsteady pressure fields and their influence on hyporheic exchange patterns are presented.

2.1 Steady Exchange

The steady-state advective field in the streambed is controlled by two conditions. Firstly, periodic pressure variation at the SWI induces periodic downwelling and upwelling at the SWI. This establishes a flow field restricted by streambed permeability that penetrates indefinitely into the streambed in laterally confined downwelling-upwelling unit cells, as seen in the left panel of Figure 1. In the APM [7] there is a sinusoidal pressure head distribution at the SWI with a wavelength λ [m] modulated by a maximum head of h_m [m]. Superimposed with the potential of the stream gradient s_0, the APM leads to a steady pressure $\bar{h}(x,y)$ as seen in equation (2).

$$\bar{h}(x,y) = K_h\left(s_0 x - h_m \cos(kx) e^{ky}\right) \tag{2}$$

Here K_h is the hydraulic conductivity [ms^{-1}] and $k = 2\pi/\lambda$ is the wavenumber [m^{-1}]. The mass transfer coefficient k_m [ms^{-1}] associated with the APM is given by $K_h k h_m / \pi$ [7], but is unaffected by the stream gradient. Downwelling-upwelling unit cells become limited in depth with larger stream gradients, allowing an advective limit of hyporheic exchange to be defined. However, Biogeochemical transport processes in the hyporheic zone are not limited by advection alone and diffusion is significant in distributing nutrients within exchange cells [10].

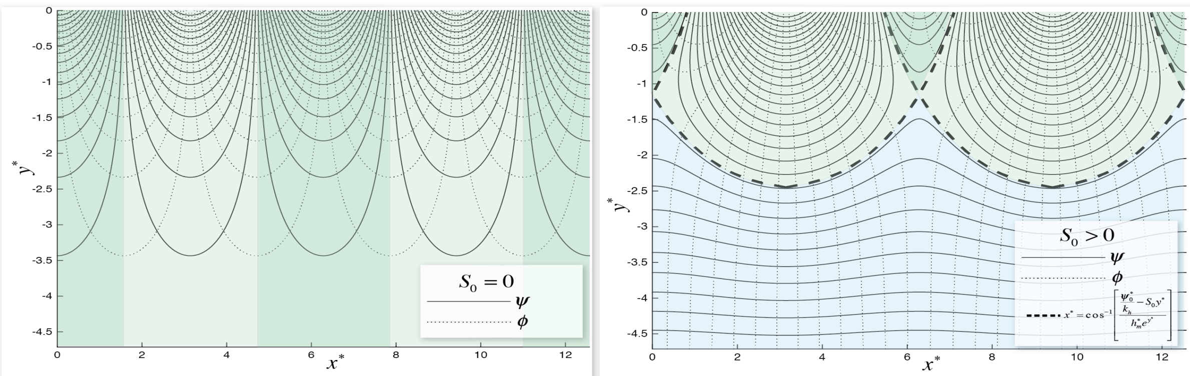

Figure 1. Left-hand panel shows the advective field of the Elliott and Brooks [7] APM in which S_0=0. The right-hand panel shows the combination of the APM with a stream gradient as seen in equation (1) to yield a maximum depth stream flow advected into the hyporheic zone.

2.2 Unsteady Exchange

Unsteady exchange is induced by eddies generated in the turbulent boundary layer [16]. In the water column, resistance to flow is a combination of (1) shear stresses induced turbulence above the SWI and (2) energy dissipation associated with the permeation of water into the porous sediment bed (the latter is referred to as the slip model). These two processes have been schematically shown in Figure 2. The former results from roughness at the SWI, inducing a slip condition in the horizontal velocity $u_x(y)$. The latter results in a turbulent wave propagating across the SWI, described in terms of a wavelength λ, propagation speed U_c and amplitude φ_m. Thus, the unsteady component of the presser field at the SWI can be described by equation (3).

$$h'(x,y,t) = \varphi_m \cos x^* \tag{3}$$

Adopting a reference frame traveling at the prorogation speed $x^* = k(x - U_c t)$, the solution for the mass transfer coefficient becomes analogous to the APM and can be defined as $K_h k \phi_m / \pi \rho g$. Thus, is it possible to describe both steady and unsteady pressure components presented in equation (1).

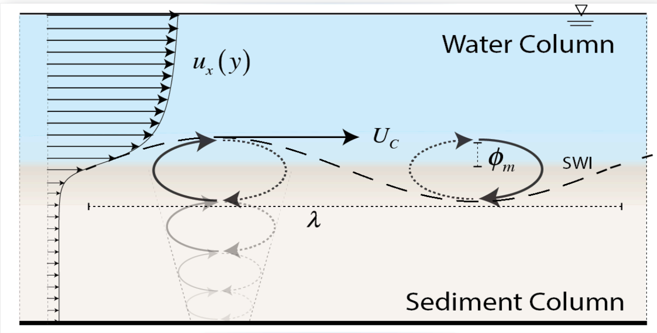

Figure 2. Schematic of the slip and turbulent pumping representations of hyporheic exchange.

3 EXPERIMENTS

Experiments were undertaken in a 5m flume with a sediment depth of approximately 29cm and poorly graded gravel (D_{50}=7mm) sediment. Artificial dunes were shaped periodically as a sinusoid with wavelength of 0.28m and height of 0.04m. Two experimental configurations were tested, with the flume either at horizontal (S_0=0.0%) or with S_0=1.0%, with shear velocities of 14 and 29mm/s respectively.

3.1 Dye tracer visualization

Dyes were injected sequentially into the streambed and recorded using a time-lapse video camera. Figure 3 shows snapshots for both horizontal and inclined slope and provides QR codes for the time-lapse videos that can be viewed online.

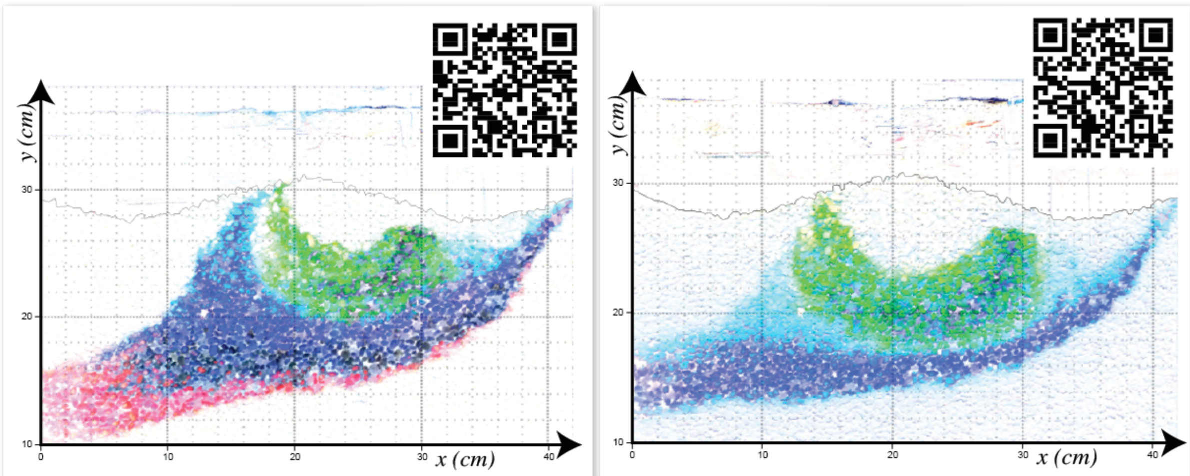

Figure 3. Snapshot of dyes released in the flume at three injection points in the downwelling zone on the right hand side for experiments with 0.0% slope (left panel) and 1.0% slope (right panel). Note that flow goes right to left in each case. QR codes have been provided which link to complete time-lapse videos.

3.2 Unsteady pressure field

Table 1 shows unsteady pressure fields measured with an array of 16 pressure transducers at the SWI. Using a Reynolds the unsteady component in equation (1) $h'(x,y,t)$ was isolated. Empirical orthogonal functions (EOF) were used to examine the spatial variance in the characteristic wave at the SWI. Figures presented in Table 1 result from the pressure wave corresponding to the top 3 statistically significant modes.

Table 1. Experimentally observed parameters for turbulent wave of the combined highest EOF modes.

Parameter	S_0=0.0%	S_0=1.0%
φ_m [Pa]	31	84
λ [cm]	20	20
U_c [cm/s]	8-10	20-40

4 CONCLUSION

Analysis and experimental results have demonstrated that both steady and unsteady advective fluxes lead to mass transfer across the SWI and the depth to which downwelling-upwelling cells extend is limited by the stream gradient. Since unsteady exchange parameters could be described in terms of migrating upwelling and downwelling zones, the mass transfer induced by both steady and unsteady exchange can be described relative to these unit cells. This provides a framework to examine the combined impact of unsteady processes with exchange induced by bedforms and meanders in stream reaches and exchange processes at larger scales. Predicting the combined mass flux of steady and unsteady processes is essential in understanding the spatial variability of ecologically significant processes in the hyporheic zone.

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