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Mixing interfaces, fluxes, residence times and redox conditions of the hyporheic zones induced by dune-like bedforms and ambient groundwater flow

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ABSTRACT

Recent studies highlighted the importance of the interface between streams and their surrounding sediment, known as the hyporheic zone, where stream waters flow through the alluvium. These pore water fluxes stem from the interaction among streambed morphology, stream hydraulics and surrounding groundwater flow. We analytically model the hyporheic hydraulics induced by a spatially uniform ambient groundwater flow made of a horizontal, underflow, and a vertical, basal, component, which mimics gaining and losing stream conditions. The proposed analytical solution allows to investigate the control of simple hydromorphological quantities on the extent, residence time and redox conditions of the hyporheic zone, and the thickness of the mixing interface between hyporheic and groundwater cells. Our analysis shows that the location of the mixing zone shallows or deepens in the sediment as a function of bedform geometry, surface hydraulic and groundwater flow. The point of stagnation, where hyporheic flow velocities vanish and where the separation surface passes through, is shallower than or coincides with the deepest point of the hyporheic zone only due to underflow. An increase of the ambient flow causes a reduction of the hyporheic zone volume similarly in both losing and gaining conditions. The hyporheic residence time is lognormally distributed under neutral, losing and gaining conditions, with the residence time moments depending on the same set of parameters describing dune morphology and stream flow.

1. Introduction

Stream waters downwell into the streambed sediment and then reemerge into the stream at upwelling areas, delineating a subsurface volume in which the sediments are saturated with stream waters [see e.g., 59,28]. These fluxes are chiefly controlled by the spatial and temporal variations of near-bed energy heads and sediment hydraulic conductivity, but are also influenced by the extension of the alluvial area, turbulence, sediment transport and water density gradients between stream and pore waters [6,62]. They form the so called hyporheic exchange, which is the primary mechanism bringing oxygen-rich and solute-laden stream waters within the streambed sediments [2,10,63,65]. Similarly, hyporheic exchange brings reduced-element laden waters from the low-oxygen concentration environment of the streambed sediment to the surface water environment [37,69,77], thereby creating chemical and physical gradients that sustain an ecotone rich in organisms density and diversity [18]. These fluxes can extend vertically and laterally, depending on stream sinuosity, alluvial sediment stratification and bedrock outcrop [9,11,36,64,70]. They can be classified as fluvial hyporheic fluxes, which mainly extend vertically within the channel wetted areas, parafluvial fluxes, which flow below dry bars within the active channel, and floodplain fluxes, which include inter-meander fluxes and preferential flow paths along paleochannels [18,59].

Near-bed pressure distribution due to variations in dynamic head, hydrostatic head or a combination of the two, is recognized as the main mechanism driving hyporheic exchange in natural systems [6,26,27,61,64]. This distribution depends on the interaction between surface flow and streambed topography [13,19,42] at several spatial scales [9,43,57,62]. For small-scale bedforms, such as dune, dynamic head variations generate low pressure zones downstream from the dune crests, where flow detaches, and high pressure zones along dune stosses, where flow reattaches [53,58,71].

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List of symbols

Da_O	biogeochemical Damköhler number
d_b	alluvium depth, m
d_{50}	mean grain size, m
DO_0	dissolved oxygen concentration, mg/l
$DO_{0,\,lim}$	dissolved oxygen concentration limit, mg/l
D_m	molecular diffusion coefficient, m^2/s
D_t	transverse dispersion coefficient, m^2/s
g	gravitational acceleration, $m\,s^{-2}$
h	hydraulic head, m
h_m	amplitude of the dynamic head fluctuations at the bed surface, m
h_b^*	dimensionless head
H_d	bed form height, m
K	hydraulic conductivity, m/s
K_{RN}	reaction rate of nitrification and respiration, 1/s
L	dune length, m
n	Manning's n coefficient
NP	number of released particles
$\bar{q}_{H,G}$	mean groundwater flux under gaining condition, m/s
$\bar{q}^*_{H,G}$	mean dimensionless groundwater flux under gaining condition
$\bar{q}_{H,L}$	mean groundwater flux under losing condition, m/s
$\bar{q}^*_{H,L}$	mean dimensionless groundwater flux under losing condition
Q	stream discharge, m^3/s
s	streambed slope
s_{lim}	slope of the underflow that suppress the upstream flux cell
s^*	dimensionless head gradient
T	temperature, °C
$t_{HZ,\,Lmax}$	residence time along the longest hyporheic streamline, s
$\mathbf{u}=(u,v)$	seepage velocity, m/s
u	longitudinal pore water Darcy velocity, m/s
u_m	maximum downwelling velocity for the neutral case, m/s
u_0	pore water Darcy velocity scale for an infinite hyporheic zone depth, m/s
u_s	underflow seepage velocity due to the stream slope, m/s
V	mean stream velocity, m/s
$\bar{u}_{HZ,Lmax}$	mean velocity along the longest hyporheic streamline, m/s
v	vertical pore water Darcy velocity, m/s
v_{gw}	groundwater vertical velocity, m/s
v^*_{gw}	dimensionless vertical groundwater velocity
$v(x,\,y)_{max}$	maximum value of the vertical velocity component under neutral conditions, m/s
x	longitudinal coordinate, m
x_l	longitudinal coordinate of the stagnation point under losing condition, m
x_g	longitudinal coordinate of the stagnation point under gaining condition, m
y	vertical coordinate, m
y_s	vertical position of the stagnation point under gaining and losing conditions, m
$y_{HZ,\,min}$	vertical position of the deepest hyporheic point, m
Y_0	mean flow depth, m
$y^*_{HZ,min}$	dimensionless vertical position of the deepest hyporheic point
y^*_s	dimensionless depth of the stagnation point under gaining and losing conditions
Y^*	dimensionless depth equal to Y_0/H_d
α_t	transverse dispersivity, m
δ_{mix}	thickness of the mixing layer, m
λ	dune wavenumber, m^{-1}
μ_z	mean of the lognormal random variable, s
σ^2	variance of the travel time, s^2
σ_z^2	variance of the lognormal random variable, s^2
σ^{*2}	dimensionless variance of the travel time
ς	dune height coefficient
τ	residence time, s
τ_{50}	median hyporheic residence time, s
τ_m	mean hyporheic residence time, s
τ_{lim}	residence time limit, s
τ^*_{50}	dimensionless median hyporheic residence time
τ^*_{lim}	dimensionless residence time limit
τ^*_m	dimensionless mean hyporheic residence time
$\psi(x,\,y)$	stream function, $m^2\,s$

The hyporheic flow field generated by dune-like morphology received a great deal of attention starting from the analytical solutions proposed by Elliott and Brooks [19] for the hyporheic flow field of an infinite alluvium thickness with only horizontal groundwater flow, called underflow. Their solution was successively extended by Packman et al. [45] for the case of a finite alluvium thickness to study infiltration of colloidal sediments into the streambed by adding the particle settling velocity [e.g., 46,47,48]. Marion et al. [36] investigated the effect of stratified sediments on hyporheic exchange. These cases did not consider the vertical component of the groundwater flow referred as basal flow [14], which Boano et al. [7,8] added to the solution of Elliott and Brooks [19] with the superposition of the effects by taking advantage of the linearity of the Laplace equation. They used the solution, derived for an infinite vertical domain, to investigate the effects of upwelling basal flows on limiting hyporheic zone vertical extension, residence time and mean downwelling flux. They also explored hyporheic exchange variations along a stream cross-section due to the decrease of upwelling basal flows from stream banks to the center. Cardenas and Wilson [14] numerically studied the effect of both upwelling and downwelling basal flows and finite alluvium depth on hyporheic flow induced by large dunes with different aspect ratios (the ratio between dune amplitude and depth, which they defined as steepness). The general trend of their numerical results was confirmed by the recent work of Fox et al. [23], who provided the first experimental support on the effects of groundwater flows on hyporheic zone extension and fluxes. With a numerical model, Hester et al. [31] underlined the importance of the interaction between surface water and groundwater on shaping hyporheic flow streamlines and therefore on the extension of the hyporheic zone. They showed that the separation surface between ground water and hyporheic flow cells delineates the effective volume of sediment where these two waters mix. Werth et al. [72] defined the depth of this surface as a "*dispersion distance*", which can be interpreted as an indirect measure of mixing between the two water systems: hyporheic and groundwater. The separation surface passes through the so called stagnation points where flow velocity has zero magnitude [3]. Jiang et al. [33] argued the importance of the location of those points as a useful index "*to characterize the location of topography-driven groundwater flow in drainage basins*" [33,67,73].