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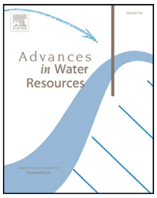

Short communication

Does streambed heterogeneity matter for hyporheic residence time distribution in sand-bedded streams?

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ABSTRACT

Stream water residence times within streambed sediments are key values to quantify hyporheic processes including sediment thermal regime, solute transient storage, dilution rates and biogeochemical transformations, such as those controlling degassing nitrous oxide. Heterogeneity of the streambed sediment hydraulic properties has been shown to be potentially an important factor to characterize hyporheic processes. Here, we quantify the importance of streambed heterogeneity on residence times of dune-like bedform induced hyporheic fluxes at the bedform and reach scales. We show that heterogeneity has a net effect of compression of the hyporheic zone (HZ) toward the streambed, changing HZ volume from the homogenous case and thus inducing remarkable differences in the flow field with respect to the homogeneous case. We unravel the physical conditions for which the commonly used homogenous field assumption is applicable for quantifying hyporheic processes thus explaining why predictive measures based on a characteristic residence time, like the Damköhler number, are robust in heterogeneous sand bedded streams.

1. Introduction

Hyporheic zone, HZ, is a fundamental component of the stream system (Harvey and Gooseff, 2015; Stanford and Ward, 1993) and exerts an important control in many ecological functions including ecosystem metabolism and bio-geochemical transformations (Boano et al., 2014; Findlay et al., 1993). It is formed by stream water flowing within the streambed sediment (Gooseff, 2010; Thibodeaux and Boyle, 1987), where many biogeochemical reactions occur (Zarnetske et al., 2011; Triska et al., 1993). Hyporheic fluxes modulate the streambed sediment thermal regime (Sawyer et al., 2012; White et al., 1987), its redox conditions (Briggs et al., 2015; Mulholland et al., 1997), its dissolved oxygen concentration (Tonina et al., 2015), nutrients turnover (Beaulieu et al., 2011; Mulholland and DeAngelis, 2000), its habitat quality (Wu, 2000; Baxter and Hauer, 2000) and organism distribution within streambed sediments (Findlay and Sobczak, 2000; Creuzé des Châtelliers and Reygrobellet, 1990). In turn, upwelling waters, those that exit the sediment and rejoin the stream surface water, bring transformed and waste products to the stream water thus affecting surface water quality (Marion and Zaramella, 2008). All these processes are chiefly controlled by the residence time of stream water within the streambed sediment (Zarnetske et al., 2011; Marzadri et al., 2012, Briggs et al., 2014). Streambed morphology modulates hyporheic residence time distribution, henceforth denoted as RTD, such that we identify this distribution as morphologically driven. Recently, Marzadri et al. (2014) showed that emissions of nitrous oxide, N_2O, from streambeds can be predicted with the Damköhler number, which is a dimensionless number defined as the ratio between the median hyporheic residence time, namely τ_{50}, and a biogeochemical characteristic reaction time. A similar approach has been recently applied by Gomez-Velez and Harvey (2014) and Gomez-Velez et al. (2015) to map hyporheic processes at the network scale. Consequently, the quantification of RTD and its statistical moments is of crucial importance at the local bedform scale but also at the network and global scales because of its effects on ecosystem metabolism and climate change through degassing of carbon dioxide and nitrous oxide.

Whereas the effect of streambed morphology on RTD is well understood, although it is predicted with semi-analytical or empirical models using few hydromorphological quantities only for

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few bedforms (Buffington and Tonina, 2009), other important aspects of streambeds influencing RTD distribution such as the heterogeneity of the hydraulic properties received less attention from the community. The natural heterogeneity of the hydraulic conductivity, K, of the streambed sediment leads to a seemingly erratic distribution of the velocity field in the sediments and generates hyporheic exchange fluxes due to conservation of mass (Tonina, 2012; Ward et al., 2011). The impossibility to characterize the actual spatial variability of K fully renders uncertain both the velocity field and the morphologically-driven RTD. Heterogeneity can manifest at mainly two distinct scales: at the single geological facies (continuous heterogeneity) and at multiple geological facies (categorical heterogeneity). The former is the intrinsic heterogeneity of a porous material due to random changes of porous size and directions (Dagan, 1989). The latter is caused by the arrangement of multiple facies, which form a composite porous media (Riva et al., 2006; Tartakovsky and Winter, 2002). Composite porous media are typically modeled with disjoint blocks, which are internally homogenous. A typical example of categorical heterogeneity in hyporheic zones is that induced by stratified streambeds (Marion et al., 2008; Pryshlak et al., 2015; Gomez-Velez et al., 2014) whereas continuous heterogeneity may be associated with sand-bedded streams below dune-likes bedforms (Hester et al., 2013; Salehin et al., 2004). The latter case is particularly interesting because of the substantial representation of dune-like bedforms in riverine systems (Montgomery and Buffington, 1997). Although previous studies highlighted that heterogeneity at both scales may affect hyporheic flux intensity and residence time (e.g., Marion et al., 2008; Pryshlak et al., 2015; Gomez-Velez et al., 2014; Hester et al., 2013; Salehin et al., 2004; Sawyer and Cardenas, 2009; Cardenas et al., 2004; Zhou et al., 2014), those for continuous heterogeneity did not provide relationship between heterogeneity and uncertainty on RTD and did not address the relationship between the heterogeneous structure of K and the statistical characterization of the RTD at both bedform and reach scales. With the aim of filling this gap and given its importance in global scale processes, we investigate the relationship among the statistical moments of the hyporheic RTD, heterogeneity and spatial correlation scales at the bedform scale and we present a new framework to upscale heterogeneity effects from the bedform to reach. For simplicity, and according to a large body of literature in stochastic hydrogeology (Dagan, 1989; Rubin, 2003), we assume that the spatial distribution of $Y = \ln(K)$ can be represented as a multi-Gaussian random space function model (e.g. continuous heterogeneity). However, we point out that our methodology can be extended to distinct heterogeneity models such as the categorical models (Riva et al., 2006; Tartakovsky and Winter, 2002). The analysis is carried out by making use of a stochastic model of subsurface flow to characterize in probabilistic terms the RTD of stream water within the bedform. Furthermore, we test the performance of the stochastic model in predicting N_2O emissions from hyporheic zone of the subset of LINXII streams (Beaulieu et al., 2011) that are sand-bedded with dune-like bedforms.

2. Methods

Sand-bed rivers are common along the river network. Their dominant bedforms are dune-like features, whose size ranges from small ripples of few centimeters of wavelength and millimeters of amplitude to large dunes of tens of meter wavelength and tenths of meters of amplitude (Montgomery and Buffington, 1997; Ferreira De Silva and Zhang, 1999). These bedforms are mostly composed of fine sediment in the range of sand. In order to investigate the effect of streambed heterogeneity on hyporheic RTD, we consider a statistically stationary spatially heterogeneous K field with uniform porosity equal to 0.3. The log-conductivity field $Y = \ln(K)$ is modeled as a stationary Gaussian random function with mean $<Y>$ and variance σ_Y^2, both constant (uniform). The spatial pattern of Y is controlled by the following exponential covariance function C_Y:

$$C_Y(\boldsymbol{r}) = \sigma_Y^2 \exp\left[-\sqrt{\left(\frac{r_x}{I_{Y,x}}\right)^2 + \left(\frac{r_z}{I_{Y,z}}\right)^2}\right], \tag{1}$$

where $\boldsymbol{r} = (r_x, r_z)$ is the two-point separation distance, with respect to which the covariance function is evaluated and $I_{Y,\,i}$ (with $i = x, z$) are the integral scales along the longitudinal (horizontal) and transverse (vertical) directions. Common values of heterogeneity degree, epitomized by σ_Y^2, in sand bed rivers range between near 0 (almost a homogenous case) and 0.6 (low heterogeneity), (Hess et al., 1992 and reference within) and may be larger above unity in case of mixed sand and fine gravel (Zhou et al., 2014). Stratification, which is manifested with layers with longest axis along the streambed slope direction (mainly horizontal layers), causes statistical K-field anisotropy, which can be measured with the ratio between the integral scales along the horizontal $I_{Y,x}$ and vertical $I_{Y,z}$ directions (i.e. $f = I_{Y,x}/\ I_{Y,z}$). Values for f may range from $f = 1$ (isotropic case) to $f \approx 18$ (strong anisotropy) (Kessler et al., 2013; Ritzi et al., 2004).

To quantify the impact of the randomness of Y on the statistical moments of the RTD, we used the Monte Carlo (MC) approach to generate multiple realizations of the heterogeneous K-field obeying the spatial correlation structure (1). The K-fields are generated by using Hydro_GEN (Bellin and Rubin, 1996) and specifying values for $I_{Y,x}$, $I_{Y,z}$, $<Y>$ and σ_Y^2. As in Hester et al. (2013), we model the hyporheic flow in one dune with 0.915 m wavelength, λ, and 0.138 m amplitude, Δ, with MODFLOW (Harbaugh, 2005) on a numerical domain represented by a 2D grid with 0.915 m in the horizontal extent and 1.14 m in the vertical extent with a 0.0025 m square cell size. The model simulates a steady state seepage flow in which: i) the pressure head boundary condition of Run 6 of the laboratory experiments conducted by Shen et al. (1990) is imposed at the water sediment interface and ii) a gaining flow condition is imposed at the lower boundary domain (constant groundwater flux: $q_{GW} = 3 \times 10^{-3}$ m/d). A number of particles ($N = 366$, i.e. large enough to stabilize the RTD moments) are released in the downwelling zone and tracked by MODPATH until they exit from the upwelling zone. We calculate the first three flux-weighted moments (mean, variance and skewness) of $\tau_i^{(j)}$, which is the residence time of a particle released at the ith downwelling position in the jth realization due to the streambed morphology:

$$\begin{aligned}
\bar{\tau}^{(j)} &= \frac{\sum_{i=1}^{N} \tau_i^{(j)}\ q_i^{(j)}\ \Delta A_i}{\sum_{i=1}^{N} q_i^{(j)}\ \Delta A_i}, \\
\sigma_\tau^{2(j)} &= \frac{\sum_{i=1}^{N} \left(\tau_i^{(j)} - \bar{\tau}^{(j)}\right)^2 q_i^{(j)}\,\Delta A_i}{\sum_{i=1}^{N} q_i^{(j)}\ \Delta A_i}, \\
\gamma_1^{(j)} &= \frac{\sum_{i=1}^{N} \left(\frac{\tau_i^{(j)} - \bar{\tau}^{(j)}}{\sigma_\tau}\right)^3 q_i^{(j)}\ \Delta A_i}{\sum_{i=1}^{N} q_i^{(j)}\ \Delta A_i}
\end{aligned} \tag{2}$$

where $q_i^{(j)}$ is the specific water discharge normal to the downwelling areas at the ith position where the particle enters the downwelling areas in the jth MC realization, and ΔA_i is the cross-sectional area of the streamtube originating from this location.

These moments coincide with the temporal moments of the BTC recorded at the upwelling area for a flux proportional injection of solute through the downwelling area, which is consistent with the hypothesis of in-stream well-mixed solute concentration. We also evaluate the median $\tau_{50}^{(j)}$. In addition, we calculate the