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Effect of streamflow stochasticity on bedform-driven hyporheic exchange

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A B S T R A C T

The interactions between the stream and the geomorphologic units that compose the stream channel result in an exchange of water, heat, and chemicals that is an important component of the flows of energy and nutrients in the river ecosystem. This exchange is characterized by complex spatial and temporal dynamics that depend on the characteristics of the stream flow and morphology. At present, many studies have addressed the development of spatial patterns of hyporheic exchange that are induced by many geomorphological factors at different scales. However, much less is known about the temporal evolution of the surface–subsurface exchange in response to the dynamics of the stream discharge. In order to investigate this problem, the present work analyzes the influence of streamflow variability on the hyporheic exchange induced by fluvial bedforms. A stochastic approach is employed to generate streamflow series whose statistical properties are representative of streams with different hydrological regimes. The resulting exchange fluxes and travel times are then computed, and the relationships between the streamflow regime and the dynamics of the exchange flux and travel times are investigated. The results show that the mean stream discharge can be used to estimate the average features of the temporal dynamics of hyporheic exchange. Moreover, exchange fluxes and residence times distributions exhibit significant fluctuations, which are tightly related to the coefficient of variation of the streamflow hydrograph.

1. Introduction

Hyporheic exchange, i.e. the exchange of water, solutes, and colloids between surface water and groundwater, has been recognized to be one of the most important elements that govern the dynamics of water quality in riverine ecosystems [1,2]. For example, oxygen supply from stream water to the hyporheic sediments depends on the magnitude of the exchange, which thus controls the survival of aerobic microbes as well as of salmonid embryos buried in the sediments [3]. Biochemical transformations of nutrients performed by microbial biofilms in the hyporheic zone represent another example of the role of surface–subsurface exchange for stream ecology [4,5].

A large number of field and modeling studies have been carried out to elucidate the relations between the stream characteristics and the resulting patterns of hyporheic exchange [6–15]. There is now a considerable amount of knowledge about the influence of stream hydrology and morphology on the spatial patterns of exchange. However, the implications of the temporal variations of stream discharge and depth for the dynamics of hyporheic exchange are less clear. The rate of water exchange through the stream bed and banks is known to be influenced by the hydraulic properties of the stream flow [16–18], and thus the supply of oxygen and nutrients from stream water to sediments changes in response to discharge fluctuations. Similar variations of mass exchange have been observed to occur during the first phase of storm events [19], when increased stream discharge results in higher levels of oxygen saturation in shallow stream sediments. Moreover, the rate of nutrient consumption by hyporheic microbes depends on the contact time between water and sediments, which is another factor that is influenced by streamflow variability [20]. Temporal variations in nitrogen transformation rates between baseflow periods and storm events have been inferred from field observations [21,22], pointing out the need for a better understanding of the temporal dynamics of the surface–subsurface exchange.

The mentioned studies have demonstrated the existence of complex feedbacks between stream hydrology and hyporheic exchange. However, a clear and comprehensive framework for the interpretation of the temporal dynamics of the exchange is still missing. In particular, little is known about the long-term dynamics of exchange across periods of several weeks or months. The reasons that hinder further advancements in this topic are manifold. A thorough field characterization of unsteady exchange would require extensive collection of surface–subsurface exchange data with fine temporal resolution. Unfortunately, similar time series of hyporheic exchange are very difficult to obtain because of technical and financial constraints, which commonly lead to a compromise choice between high sampling frequency and long periods of data acquisition. Given these limitations, numerical models represent an alternative way to explore the long-

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term behavior of surface–subsurface interactions. However, it is important to stress that the unsteady dynamics of a turbulent flow over a streambed with complex morphology still represents a challenging modeling issue. In this context, there is a strong need for a better understanding of the physical processes that drive exchange between surface and subsurface water.

In order to improve our understanding of this issue, this work presents a numerical analysis of the temporal variations of the exchange that result from unsteady stream discharge. We consider the case of the exchange induced by fluvial bedforms, which represents an important and well-studied exchange process in stationary conditions [7,23,24]. Among the time-dependent factors that shape the exchange flow field, we focus on the pressure distribution on the streambed and on its temporal fluctuations caused by unsteady streamflow. Stream discharge series are generated with a stochastic process, which provides very long time series that reproduce the statistical features of typical streamflow dynamics. This simplified modeling framework allows to analyze the effect of streamflow stochasticity on the magnitude and residence times of hyporheic exchange, and helps to elucidate the relationships between the statistical properties of streamflow series and those of hyporheic exchange.

2. Model

2.1. Streamflow time series

A stochastic approach is adopted in order to obtain long time series of simulated data that reproduce the typical features of daily streamflow for different flow regimes. The river discharge $Q_{tot}(t)$ is expressed as the sum of a baseflow component Q_{bf} and an unsteady part $Q(t)$. The baseflow discharge Q_{bf} is assigned a constant value since its variations are small and can be combined with the larger variations of $Q(t)$. The stochastic component $Q(t)$ is obtained with a stochastic approach, which has frequently been adopted for the simulation of streamflow time series. Flood events are modelled as sudden, exponentially distributed increase of discharge (jumps). These sudden jumps occur at randomly selected times, with exponentially distributed interarrival times. Between two jumps, the discharge recession follows an exponential decay. This behavior corresponds to the stochastic process

$$\frac{dQ}{dt} = -\omega Q + \xi_{sn}, \tag{1}$$

where the deterministic term $(-\omega Q)$ governs the discharge recession and the additive noise component (ξ_{sn}) is a white (i.e., uncorrelated) shot-noise process [25,26]. Stochastic jumps ξ_{sn} are exponentially distributed, and the interval between two consecutive jumps is also a random variable with an exponential distribution. For such dynamics, the steady-state probability distribution of $Q(t)$ is described by a Gamma distribution [27]

$$p(Q) = \frac{Q^{(\lambda/\omega)-1} \cdot e^{-\gamma Q} \cdot \gamma^{\lambda/\omega}}{\Gamma[\lambda/\omega]}, \tag{2}$$

where $1/\gamma$ is the average value of the jumps, $1/\lambda$ is the mean time between two consecutive jumps, and $\Gamma[\cdot]$ is the Euler gamma function [28]. The resulting autocorrelation function is simply $\rho_Q = exp(-\omega s)$, where s is the time delay.

The parameters ω, λ, and γ are linked to the mean $\overline{Q}$, the coefficient of variation CV_Q, and the autocorrelation scale τ_Q, of the discharge time series by the relations

$$\omega = \frac{1}{\tau_Q} \quad \lambda = \frac{\omega}{CV_Q^2} \quad \gamma = \frac{\lambda}{\omega \overline{Q}}. \tag{3}$$

Therefore, once the values of mean discharge, variance, and correlation scale are chosen the probabilistic structure of the discharge time series (i.e., $p(Q)$ and τ_Q) is completely defined. It is important to recall that the autocorrelation scale — also called integral scale — is the integral of the autocorrelation function of the discharge time series $\rho_Q(s)$, that is, $\tau_Q = \int_0^\infty \rho_Q(s) ds$. This timescale can be interpreted as the 'memory' of the river flow time series: higher values of τ_Q imply that the 'memory' is long and that discharge variations are slower than in the case of lower τ_Q.

The statistical properties of the total discharge series that are considered in the present work are the mean value $\overline{Q}_{tot}$, the coefficient of variation $CV_{Q_{tot}}$, and the correlation time $\tau_{Q_{tot}}$. It is important not to confuse these quantities with those of the stochastic component, namely, $\overline{Q}$, CV_Q, and τ_Q. Since $Q_{tot}(t) = Q_{bf} + Q(t)$, the relationship between the different quantities are

$$\overline{Q}_{tot} = \overline{Q} + Q_{bf} \tag{4}$$

$$CV_{Q_{tot}} = CV_Q \cdot \left(1 + \frac{Q_{bf}}{\overline{Q}}\right)^{-1} \tag{5}$$

$$\tau_{Q_{tot}} = \tau_Q \tag{6}$$

where the last equation is valid for the normalized (zero mean) time series. In the next section, we will simulate time series characterized by different values of the triplet ($\overline{Q}_{tot}$, $CV_{Q_{tot}}$, $\tau_{Q_{tot}}$) — or equivalently ($\overline{Q}$, CV_Q, τ_Q) — in order to explore the significance of discharge stochasticity on the dune-induced hyporheic flow. The stochastic component in Eq. (1) is an additive noise and its numerical evaluation is straightforward [29], and an explicit finite difference scheme is adopted to simulate the deterministic component. Streamflow seasonality, which could be reproduced with a time-dependent CV_Q, is not considered in the current work.

For each simulated discharge time series $Q_{tot}(t)$, the corresponding time series of the water stage $d(t)$ is obtained with the Chezy equation, $Q_{tot} = n^{-1} d^{2/3} A i_b^{1/2}$, where n is the Manning coefficient, A is the cross-sectional area, and i_b is the longitudinal bed slope. The adoption of the Chezy equation means that hysteresis phenomena in the stage-discharge relationship are not considered.

2.2. Hyporheic exchange

In this paper, we focus on bedform-driven exchange as the only process driving water exchange between stream and sediments. Other types of surface–subsurface interactions that may contribute to the overall exchange are not considered. In order to quantify the bedform-driven hyporheic exchange induced by the streamflow series $Q_{tot}(t)$, the residence time approach adopted by [30] for the case of a steady flow and successively extended by [17] to unsteady flow conditions is adopted. Here, we summarize the most important steps of the approach in order to better focus on the novel aspects of the analysis. A thorough description of the method can be found in the cited papers.

A stream with a sand bed covered by dunes is considered. Interactions between free surface flow and bed topography result in spatial variations of hydraulic head on the streambed. A quantitative description of this hydraulic head profile is required in order to model the exchange flow between surface and subsurface water. Unfortunately, predictions of hydraulic head profiles on streambeds are affected by considerable uncertainty because the hydrodynamics of free surface flows on complex boundaries like streambeds is still partially unclear. The problem is made even more complex by the fact that bedform height and length vary during floods, usually displaying hysteresis [31]). Predictions of the migration celerity of dunes as a function of stream discharge are also subject to considerable uncertainty.