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Modelling three-dimensional interfacial flow with sand dunes

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Abstract

Hyporheic zone is considered as a dynamic hydrologic ecotone that critical for maintaining the health of river systems. The hyporheic flux occurs generally in response to variations in river bedforms. In this study, we first generated several typical bedforms. The turbulent flow over the 3D dunes and hyporheic flow in the sediment are simulated through a computational fluid dynamics (CFD) approach. Turbulent flow in the water column is simulated by solving the Reynolds-averaged Navier-Stokes (RANS) equations with the k-ω turbulence closure model, and a steady state groundwater flow model is applied for the underlying porous media. These two sets of equations are coupled through the pressure distribution at the sediment-water interface (SWI).Each case was subjected to different hydraulic conditions, i.e., increasing open channel Reynolds Numbers (Re). Results show that the pressure gradient along the SWI is highly controlled by the spatial structure of bedform, which consequently determines flow dynamics in the porous media. The interfacial flux is dominated by the pressure configuration over the SWI which is a function of Re via a power-law trend. The mean fluid residence time is related to Re by an inverse-power law relationship. This study has led to the basic understanding of hyporheic flow induced by more natural 3D dunes.

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*Keywords:*hyporheic flow; hydrodynamic; turbulent flow; CFD

1. Introduction

The interaction between river water and groundwater, referred to as hyporheic exchange, has been considered as a key process that is associated with nutrient cycling, oxygen demanding as well as other organic matter transformation [1, 2].Water flows over sand dunes would generate a net flow near the sand-water interface (SWI)

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which is called as bedform-induced hyporheic flow. During the past several decades, the bedform-induced hyporheic flow has been widely studied through experimental and numerical approaches, while most of the research works to date have been concentrated on two dimensional bedform conditions, only a few studies are conducted in three-dimension. Tonina and Buffington [3] conducted experiments to analyze 3D hyporheic exchange through alternating bars with pools and riffles. New insight on 3D exchange through bars was gained, but their flow fields may be far from natural due to the confined width of the flume. Wörman et al. [4,5] followed Elliott and Brooks' approach [6,7], prescribed pressure head on a flat SWI with a Fourier series translated from topographic data rather than a sine function. Recently, Käser et al.[8] have evaluated the preliminary characterization of hyporheic flux of three reaches on the River Leith located in the northwest of England by applying a 3D groundwater model based on high-resolution topography and stream elevation. Since the three-dimensional bedform has been proven to be more efficient in generating much more complex turbulent flow structures, which will result in anintricate pressure pattern over the SWI as well as the hyporheic process, understanding 3D bedform induced hyporheic is crucial for analyzing biogeochemical behaviors in a natural river.

In this paper, we first generate a group of sand dune shaped bedform based on the Rubin and Carter [9]. Acoupled surface-subsurface modeling approach is then applied to solve the RANS equations with *k-ω* turbulence closure scheme for the surface water and Darcy's flow for the groundwater flow. The flow structure and pressure pattern over the SWI, and consequently the hyporheic metrics (including the flux, residence time, and exchange depth/volume) are used to discuss the implications for understanding more naturally shaped bedform-induced hyporheic exchange.

2. Materials and methods

The geometry of sand dunes produced by changing and shifting of sediments during deposition is almost always complexly three-dimensional. The geometry of cross-bedding to the morphology and behavior of bedforms has been analyzed by Rubin and Carter [9] through computer modeling approaches. Figure 1 shows six different bedforms with similar wavelength (λ=0.35m) and dune height (H=0.04m) but different cross-bending shapes. From Fig.1(a) to Fig.1(f), the bedform gradually becomes more complex.

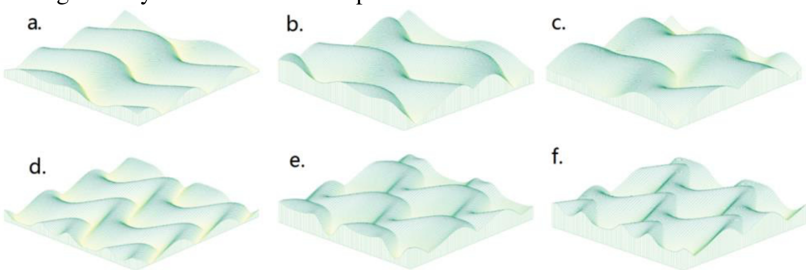

Fig.1 Bedformgenerated based on Rubin and Carter[2005]

All The turbulent flow over the 3D dunes and hyporheic flow in the sediment are simulated following the computational fluid dynamics (CFD) approach of Cardenas and Wilson [10] which has been shown to be robust. For an incompressible fluid, the steady state RANS equations read:

$$\frac{\partial U_i}{\partial x_i} = 0 \quad (1)$$

$$\rho U_j \frac{\partial U_i}{\partial x_i} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(2\mu S_{i,j} - \rho \overline{u_j' u_i'}\right) \quad (2)$$

where $i, j = 1, 2, 3$ are spatial indices corresponding to x, y and z directions, ρ and μ are fluid density and dynamic viscosity (assumed standard for water), U_i and u_i' are time-averaged and fluctuating velocity components in x_i directions, P is the time-averaged pressure. S_{ij} is the strain rate tensor defined as:

$$S_{ij} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) \quad (3)$$

while $-\overline{u_j' u_i'} = \tau_{ij}/\rho$ is the mean strain rates related to Reynolds stresses (τ_{ij}) by: