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Comparison of Hyporheic Exchanges in 2D and 3D Riffle-Pool bed form structures

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ABSTRACT: Exchanges of water and solute between stream flow and flow through river bed porous media are known as hyporheic exchanges. Hyporheic exchanges transfer water and nutrient to the organism lived in the hyporheic zone, so affect ecological conditions and food cycle. One of the important driving factors of these exchanges are pressure gradients along the bed form. Riffle-pools are geomorphic features of river beds which induce strong pressure gradient along the streambed, which control hyporheic exchanges and are therefore considered in river restoration projects. The goal of this study is to compare the hyporheic flux and residence time of flow within sediment bed underneath 2D and 3D riffle-pool structures. For reaching this goal, in a first step, the surface water flow is simulated by the CFD-software OpenFAOM, resulting in a detailed pressure distribution at the stream bed. In a second step, these pressure fields are then set as a top boundary condition of a groundwater model (MODFLOW software), for simulating the flow in porous media. The results show that, by increasing bed form amplitude, hyporheic exchanges flux increases by 26 % for both 2D and 3D models, and residence time decreases by 36 %for 2D and 41 % for 3D structures. Also, comparison of 3D riffle-pool with equal 2D model shows that hyporheic exchange flux and residence time increase by 2.9 % and 3.67 %, respectively.

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1. INTRODUCTION

The hyporheic zone is defined as the area beneath the river where exchange between surface flow and subsurface flow occur [1]. One of the important driving factors of the singular hyporheic exchange is pressure gradient along morphologic features in rivers such as dunes, riffle-pools and step-pools sequences [2]. Such exchanges can affect the river ecosystem, water quality and many biochemical processes in rivers [3, 4]. The hyporheic exchanges along two dimensional dunes and riffle–pools are widely investigated through experimental and numerical research. Due to the three dimensional nature of these morphologic features, the hyporheic exchanges has been investigated in 3D state [5, 6]. Chen et al. (2015) compared the hyporheic exchanges in 2D and 3D dunes. Their results show that in high Reynolds the hyporheic exchanges in 3D dunes are higher than at 2D dunes, but residence times are equal [7].

The goal of the present study is to investigate the difference between hyporheic characteristics in 2D and 3D riffle-pools. For reaching this goal, first the mechanism of the hyporheic flows in 2D riffle–pools were investigated experimentally in a flume, and then the results were used to evaluate the numerical simulations. Finally, after assuring the accuracy of the models to evaluate hyporheic characteristics, 2D and 3D riffle-pools for two different amplitudes were simulated and compared.

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2. MATERIALS AND METHODS

2.1. Laboratory Experiments

An experiment was carried out in a 12 m long, 1 m wide and 0.8 m deep rectangular flume. Five cycles of two dimensional riffle-pool sequences were constructed with sinuous form by mean of a wooden rob. The riffle-pools had a wavelength of 1 m and amplitude of 0.068 m. The sediment bed recess was equal to five times of the bed form amplitude (0.34 m) [8] and consists of sediments with median diameter of 6.8 mm. Besides measuring water surface and longitudinal velocity profiles, the porous media velocity was measured by injecting purple dye beneath the sediment bed and recording the time and length of each path line. All measurements were done at the middle cycle, from one pool to the next pool, to minimize boundary effects from the inlet and the outlet.

2.2. Numerical Simulation

Out of one flume experiments, three more models were investigated numerically (Table 1). The three dimensional riffle-pool sequences were created according to the following equation [5]:

$$z(x,y) = A \sin\left(\frac{2\pi}{\lambda}x\right)\cos\left(\frac{\pi}{w}y\right) \tag{1}$$

where A is half of the bed amplitude, λ is bed form

Table 1. Characteristics of investigated models

Model	Scenario	Bed form amplitude	Reynolds
Laboratory	2D1	0.068	22800
Numerical	2D2	0.141	
	3D1	0.068	
	3D2	0.141	

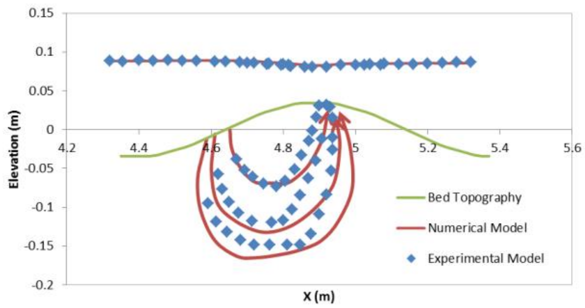

Fig. 1. Simulated and observed values for surface water level and hyporheic pathline

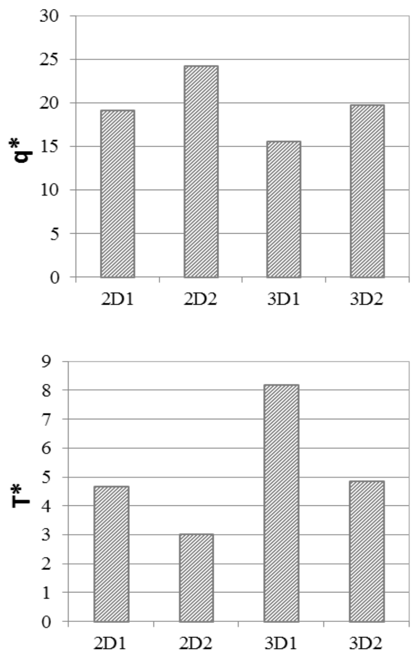

Fig. 2. Hyporheic zone characteristics; dimensionless: (a) hyporheic exchange, and (b) residence time

wavelength, *w* is flume width and *x*, *y* is distance along flume length and width, respectively.

OpenFOAM software with interFOAM solver was used for surface water flow simulations, whereas MODFLOW was used for subsurface flow simulations of the porous media. Then, MODPATH package was applied for particle tracking method.

3. RESULTS AND DISCUSSION

The laboratory experiment was used for calibrating surface and subsurface flow simulations (Scenario 2D1). The roughness height for wallFunction at bottom boundary was changed until the water surface and velocity profiles in laboratory and numerical simulations almost match. The results show that for roughness height equal to the d_{50}, the model is able to predict the water surface and velocity profiles well, with root mean square error (RMSE) of 1.7 mm and 0.04 m/s, respectively.

Then, the pressure along riffle-pools extracted from the OpenFOAM simulation, is set as Dirichlet boundary condition at top of the subsurface model i.e. MODFLOW. In order to evaluate subsurface model, the results of MODPATH were compared with dye path line which drew on flume glass wall. The hydraulic conductivity (K) was changed until the maximum hyporheic exchange depth and porous velocity become close to the laboratory observations. The results show that for K=0.2 m/s these conditions satisfied, as the average velocity for path line in laboratory was 1 cm/s and for numeric model was 0.79 cm/s. Fig. 1 shows the observed hyporheic path line and water surface level against simulation one for scenario 2D1.

As these models able to simulate surface and subsurface flows accurately, three more simulations were performed to investigate the effect of 3D riffle-pools with different amplitude (Table 1).

The dimensionless hyporheic exchanges (q*) and residence times (T*) are calculated as follows:

$$q^* = \frac{Q_{ex}}{\lambda w K} \tag{2}$$

$$T^* = \frac{MRT \times K}{\lambda} \tag{3}$$

where Q_{ex} is hyporheic exchanges (m^3/s) and MRT is median residence time (s).

As illustrated in Fig.s 2a and 2b, by increasing the amplitude by 50 %, the hyporheic exchange flux increases by 26 % for both 2D and 3D models and residence time decreases by 36 % and 41 % for 2D and 3D models, respectively. Also, the results show that if the average amplitude of 3D model set as amplitude of 2D models, i.e. comparing scenarios 2D1 and 3D2, the hyporheic exchange flux and residence time increases by 2.9 % and 3.67 %, respectively.

4. CONCLUSIONS

The results show that for riffle-pool sequences, if the average amplitude of 3D model set as amplitude of 2D model, the hyporheic flux and residence time increases by 2.9% and 3.67%, respectively. So, if the goal of a study is to investigate biochemical process in hyporheic zone, where residence time is a crucial factor, the simplification of the 3D model as a 2D model does not change the dimensionless residence time significantly in both dunes and riffle-pools.

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