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# Comparison of a vertically-averaged and a vertically-resolved model for hyporheic flow beneath a pool-riffle bedform

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ABSTRACT

The interaction between surface water and groundwater through the hyporheic zone is recognized to be important as it impacts the water quantity and quality in both flow systems. Three-dimensional (3D) modeling is the most complete representation of a real-world hyporheic zone. However, 3D modeling requires extreme computational power and efforts; the sophistication is often significantly compromised by not being able to obtain the required input data accurately. Simplifications are therefore often needed. The objective of this study was to assess the accuracy of the vertically-averaged approximation compared to a more complete vertically-resolved model of the hyporheic zone. The groundwater flow was modeled by either a simple one-dimensional (1D) Dupuit approach or a two-dimensional (2D) horizontal/vertical model in boundary fitted coordinates, with the latter considered as a reference model. Both groundwater models were coupled with a 1D surface water model via the surface water depth. Applying the two models to an idealized pool-riffle sequence showed that the 1D Dupuit approximation gave comparable results in determining the characteristics of the hyporheic zone to the reference model when the stratum thickness is not very large compared to the surface water depth. Conditions under which the 1D model can provide reliable estimate of the seepage discharge, upwelling/downwelling discharges and locations, the hyporheic flow, and the residence time were determined.

## 1. Introduction

The surface water body and the groundwater body interlock together in an active dynamic zone called the hyporheic zone, existing beneath and alongside many river beds. The streambed topography, such as pool-riffle sequence, induces water surface variation which in turn creates pressure differential along the streambed and drives the surface-to-subsurface flow in and out of the hyporheic zone (Lawler et al., 2009). The hyporheic zone has been widely recognized as vital for the water quantity and quality management in both the stream and the aquifer systems (e.g. Kania et al., 2006; Boano et al., 2014; Cardenas, 2015). It also greatly influences many key ecosystem processes such as nutrient cycling and primary productivity (Boulton et al., 2010). Upwelling subsurface water provides stream organisms with nutrients and removes waste; and downwelling stream water provides dissolved oxygen and organic matters to microbes, invertebrates, and fish eggs within the hyporheic zone (Boulton et al., 2010). Water quality also depends on the residence time of the hyporheic flow path, which is the time it takes for the hyporheic flow to travel from the downwelling region to the upwelling region. Shorter residence time indicates that the hyporheic zone is dominated by surface water, characterized by low alkalinity and high concentration of dissolved oxygen (Shields and Malcom, 2009); while longer residence time facilitates the transformation of nutrients in the streambed (Marzadri et al., 2011, 2012). Since the hyporheic zone is the preferred incubation environment for many fisheries, this in turn may affect the burial depth of fish eggs and survival of embryos (Robert, 2003). Therefore, researchers have been highly motivated to study the characteristics of the hyporheic zone. Wondzell (2015) provides a review of the development of the science of the hyporheic zone over the past 20 years.

The hyporheic zone can be classified according to spatial scale as sediment scale, reach scale, and catchment scale (Boulton et al, 1998). This study focuses on the reach scale at which the hyporheic exchange is a function of river morphology and individual topographic elements. Numerical models have been extensively utilized to study the hyporheic zone. One approach to quantify hyporheic exchange is to analyze stream tracer using transient storage models. Conventional storage models consider

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the in-stream storage zone and the hyporheic zone as a single compartment (e.g. Wörman, 1998) while Choi et al. (2000) showed that they need to be distinguished when the two zones have completely different characteristics. Westhoff et al. (2011) analyzed temperature variations using a coupled 1D transient storage and energy balance model to quantify hyporheic dynamics.

Another approach utilizes surface water and groundwater models. Earlier studies modelled the two systems separately while in fact they are hydraulically interconnected (Liang et al., 2007). More recently, various coupling methods of the surface water and groundwater models have been developed. Modeling the interaction between the two flow systems is commonly based on the conductance concept that separates the surface from the subsurface domain where the magnitude and direction of the hydraulic gradient drive the exchange flux (Kollet and Maxwell, 2006). The two flow systems may be solved in separate matrices while improving the solution iteratively or simultaneously in a single global matrix (e.g. Gunduz and Aral, 2005; Peyard et al., 2008; Li et al., 2016). The coupled models have been developed with variable complexities in terms of the dimensions of the model. The most complex models involve 3D modeling of both surface flow and groundwater flow. For example, Menichino and Hester (2014) used a fully coupled computational fluid dynamics model of surface water and groundwater to study the effect of hydraulic conductivity on hyporheic exchange induced by in-stream weir. Approximate and reduced dimension models have also been developed. For example, Yuan et al. (2008) coupled 2D vertically-averaged surface flow model and groundwater model simultaneously for simulating the flood inundation extent on wetlands and floodplains. Gunduz and Aral (2005) coupled a 1D longitudinal surface flow component and a 2D vertical-averaged groundwater model and applied it to simulate the flow conditions in a watershed in southeastern United States.

The characteristics of the hyporheic flow induced by various bedforms have been investigated using 3D numerical models. For example, the hyporheic flow had been modeled under varying stream and ambient groundwater flow conditions in pool-riffle system (Tonina and Buffington, 2011; Trauth et al., 2013). Sinha et al. (2017) investigated the effects of bed permeability on hyporheic flow characteristics over river dunes. Käser et al. (2014) modeled three pool-riffle sites on the River Leith in the north west of England and evaluated the effect of different morphology on the hyporheic flux. However, the sophistications gained by conducting a full 3D analysis is often compromised by the difficulty of obtaining accurate representation of the highly variable real-world scenarios, e.g. the hydraulic conductivity of the stratum. A vertically-averaged Dupuit model on the other hand, is less data intensive due to the elimination of the vertical dimension and can still provide information on key characteristics of the hyporheic zone. Therefore, the objective of this study was to evaluate for a simple case, how a vertically-averaged Dupuit model compares to a more complete vertically-resolved model. Although the ultimate goal is to evaluate the accuracy of a 2D Dupuit groundwater model against full 3D models, for the present study, a simple 1D groundwater model based on Dupuit approach was developed and compared with a 2D vertically-resolved groundwater model. Both groundwater models were coupled with a 1D surface water model, linked via the surface water depth. The 1D Dupuit model therefore reduced to a simple calculation of flow rates using the water surface head solved by the surface water model. The 1D surface water model was verified with HEC-RAS (US Army Corps of Engineers) and the 2D groundwater model was verified with SEEP/W (One of the GEO-SLOPE model applications that solves 2D groundwater problems). The 2D groundwater model was considered accurate and taken as the reference model. Pool-riffle sequence was chosen to assess the model as it is one of the common bedforms where hyporheic flow is particularly important and can be approximated as a simple longitudinal structure. The results from the proposed 1D Dupuit model for an idealized pool-riffle sequence were compared to the reference model in terms of seepage discharge, upwelling/downwelling discharge and location, hyporheic flow, and residence time.

## 2. Model domain

An idealized periodic pool-riffle structure was employed to assess the proposed model (Fig. 1). The periodic ground level for one wavelength is given by a sinusoidal form as follows:

$$z = z_0 + A * \sin\left(\frac{2\pi x}{\lambda} + \delta\right) - S_o * x \tag{1}$$

where, $z$ is the ground level; $x$ is the distance in the stream flow direction; $S_o$ is the average bed slope of the channel; and $\lambda$ is the wavelength of the pool-riffle sequence; $z_0$ is a base elevation required to shift the mean value of the sine function; $A$ and $\delta$ are the amplitude and phase angle of the sine function, respectively. Based on many river morphology studies (Leopold et al., 1964; Keller and Melhorn, 1978; Rosgen, 1994; Robert, 2003), the pool-riffle was constructed in a 10 m wide straight channel with the wavelength $\lambda = 72$ m. $z_0$ was taken to be 9.84359 so that the model domain started with a riffle crest at bed elevation of 10 m. $A$ and $\delta$ were set at 0.15646 and 1.55856 respectively. The sinusoidal shape was chosen not only because it is representative of the shape of the pool-riffle bedform, but also because its smoothness eliminates noises when calculating derivatives.

The upper boundary of the modelled domain was the river bed which has a pool-riffle nature that links the surface water and the groundwater model. The domain extends downward to the impervious layer to include the local flow system where the pool-riffle form is effective in driving the hyporheic flow (Tóth, 1963). Two average mild bed slopes of 0.001736 and 0.003472 were tested as they correspond to a wide range of Froude numbers in the subcritical stream flow regime. For the surface water discharges tested, $Q_{surf} = 1, 2, 4, 6, 8$, and $10\ \mathrm{m^3/s}$, the corresponding Froude numbers range from 0.10 to 0.58 and 0.11 to 0.80 for the average bed slope of 0.001736 and 0.003472, with the maximum Froude number occurring over the riffle and minimum Froude number occurring over the pool. A constant Manning's $n$ of 0.033 was used for bed roughness. The pool and riffle form usually exists in low gradient streams where surface water is shallow. In all scenarios, the stream width was greater than ten times of the maximum water depth. Thus, the stream was considered as wide channel and the hydraulic radius was approximated to be equal to the water depth in the surface water model. To investigate the effect of the vertical position of the impervious layer, five average stra-

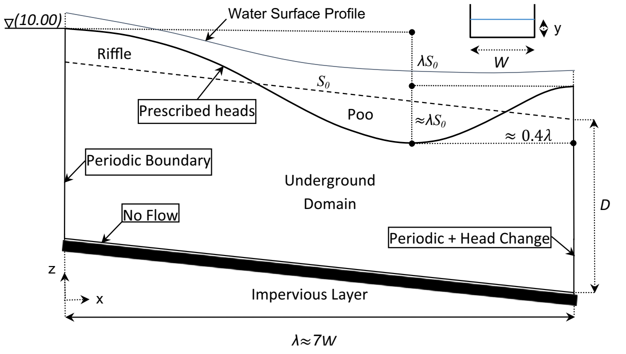

**Fig. 1.** Model domain of the idealized pool-riffle sequence.