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Fluctuation of Hyporheic Zone Thickness Due to Inflow and Outflow across the Water-sediment Interface

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Abstract— **Determination of hyporheic zone thickness in streams is an important step for study of stream-aquifer interactions. Knowledge about hyporheic zone thickness is useful in stream restoration. However, because there is a lack of standard techniques for such study, evaluation of the hyporheic zone thickness for a given stream reach remains a challenge task for researchers. This paper presents Galerkin finite element flow and stream function models that can simulate the hyporheic zone thickness. The flow and stream function equations are solved for 2-D profile domains that can be across a stream or parallel to a stream. The numeral schemes for solving the flow and stream function equations and the treatment of boundary conditions are described. Hypothetical streams are used for simulation of the control of hyporheic zone thickness by the magnitude of inflow and outflow that occur at the stream-sediment interface. Groundwater flow velocity field is generated to examine the flow dynamics in hyporheic zones. The magnitude of groundwater flow velocity in hyporheic zone is greater than that of regional groundwater flow.**

Keywords- Hyporheic zone, numerical modeling. Stream-aquifer interactions

I. INTRODUCTION

Hyporheic zone below the stream-sediment interface has unique hydrologic, hydrogeological, biological, and geochemistry characteristics. Researchers from a variety of disciplines have conducted studies on hyporheic zone. The sediments in the hyporheic zone are generally permeable. Their hydraulic conductivities are heterogeneous and anisotropic [1,2,3,4]. Thermal transport processes and temperature gradients in hyporheic zones have been documented in numerous publications [5,6]. Hyporheic zones provide habitat for some invertebrates, the abundance of which can decrease rapidly in the top 50-cm layer [7,8]. Concentrations of many chemical compounds also show strong vertical gradients [9,10]. Hyporheic zone thickness can vary in space and time. The thickness of a hyporheic zone for a given stream reach is controlled by a number of hydrological and hydrogeological factors. However, determination of the hyporheic zone thickness is a challenge task for researchers because there are no standard techniques to quantify it.

Numerical modeling techniques have been demonstrated to be a useful tool in the simulation of hyporheic zone thickness[11,12,13,14]. These researchers used flow modeling and particle tracking methods to trace the paths of water particles that migrate into and out of the hyporheic zone. The morphology of hyporheic zone can thus be determined. In this study, the author proposes to use the stream function equation for determination of hyporheic zone thickness. This study models the flow dynamics in 2-D stream-aquifer vertical domains. Flow nets are constructed for examination of the effect of inflow and outflow at the stream-sediment interface on hyporheic thickness.

II. METHODS

A groundwater flow equation is solved for hydraulic head and a stream function equation is solved for constructing streamlines. The governing equation for transient groundwater flow in a 2-D vertical domain is written

$$\frac{\partial}{\partial x}(K_x \frac{\partial h}{\partial x}) + \frac{\partial}{\partial z}(K_z \frac{\partial h}{\partial z}) = S_s \frac{\partial h}{\partial t} \qquad (1)$$

where h is the hydraulic head, K_x and K_z are hydraulic conductivity along the horizontal (x) and vertical (z) directions, respectively, and Ss is the specific storage. For an unconfined aquifer, if the magnitude of groundwater fluctuations is relatively small compared to the thickness of the aquifer, the saturation thickness changes very little and Ss is nearly constant. The fluctuation of the water table in unconfined aquifers was described by

$$K_x \frac{\partial h}{\partial x} n_x + K_z \frac{\partial h}{\partial z} n_z = -(S_y \frac{\partial h}{\partial t} \pm I) \qquad (2)$$

where S_y is the specific yield; n_x and n_z are the directional cosines of a unit vector along the horizontal and vertical directions; and I is the recharge/inflow (+) or discharge/outflow (-). If a steady-state condition exists, equations (1) and (2) are simplified, respectively, into (3) and (4).

$$\frac{\partial}{\partial x}(K_x \frac{\partial h}{\partial x}) + \frac{\partial}{\partial z}(K_z \frac{\partial h}{\partial z}) = 0 \qquad (3)$$

$$K_x \frac{\partial h}{\partial x} n_x + K_z \frac{\partial h}{\partial z} n_z = I \qquad (4)$$

The flow equations (1) and (3) were solved using the Galerkin finite-element method [15]. The model domain was discretized into triangular elements. The numerical solution was based on linear basis functions. The inflow and outflow rates were imposed at the nodes along the water-sediment interface. A FORTRAN computer source code was developed to calculate the hydraulic heads for both transient and steady-state conditions.

The stream function is constant in value along a streamline and is related to the specific discharge q [16] with $q_x = \frac{\partial \psi}{\partial z}$ and $q_z = \frac{\partial \psi}{\partial x}$. The governing equation for stream functions over a vertical profile is expressed such that [16]

$$\frac{\partial}{\partial x}(\frac{1}{K_z}\frac{\partial \psi}{\partial x}) + \frac{\partial}{\partial z}(\frac{1}{K_x}\frac{\partial \psi}{\partial z}) = 0 \quad (5)$$

where ψ is the stream function (its dimension is L^2/T) and K_x and K_z are horizontal and vertical hydraulic conductivities. Use of the Galerkin finite-element method for solving equation (5) yields

$$\iint_\Omega \frac{1}{K_z}\frac{\partial \psi}{\partial x}\frac{\partial L_i}{\partial x} L_i dxdz + \iint_\Omega \frac{1}{K_x}\frac{\partial \psi}{\partial z}\frac{\partial L_i}{\partial z} L_i dxdz = \int_\Gamma (\frac{1}{K_z}\frac{\partial \psi}{\partial x} n_x + \frac{1}{K_x}\frac{\partial \psi}{\partial z} n_z) L_i d\Gamma \quad (6)$$

where L_i is the linear basis function, n_x and n_z are the directional cosines of a unit vector, is the 2-D domain area, and is the domain boundaries. Treatment of the boundary conditions of Equation (6) can be seen from Fogg and Senger [16] and Chen [17]. Equation (10) in Fogg and Senger [15] indicates that $\frac{1}{K_x}\frac{\partial \psi}{\partial z} = \frac{h_2 - h_1}{x_2 - x_1}$. This term can be plugged into the left-hand term of Equation (6), the boundary integration term, for evaluation of the stream function boundary values along the top boundary of the model domain (where $n_x = 0$), leading to $\int_x (\frac{h_2 - h_1}{x_2 - x_1}) L_i dx$. L_i is the linear basis function; integration of L_i over x gives a value of area.

After a slight modification, the FORTRAN source code for solving the groundwater flow equation (Eq. (3)) was used to compute the stream function. Contouring of ψ generates streamlines on the x-z profile.

In order to examine the groundwater dynamics in hyporheic zones, groundwater flow velocities for the horizontal direction X and for the vertical direction Z were calculated for each element. The hydraulic heads from the nearest four nodes to the central point of each element were used to compute the hydraulic gradients along the X and Z directions, respectively. The effective porosity was assumed to be 0.2.

III. Results and Discussions

Simulations were conducted on an 800 m by 16 m vertical profile. A stream of 130 m in width was placed on the top of the model domain. A regional groundwater flow, moving from the left to the right of the profile, was imposed by prescribing constant heads on the left and right boundaries of the model domain. The hydraulic gradient of the regional flow was 0.0015. Steady-state flow condition was considered for the simulation examples. The aquifer has homogeneous and anisotropic hydraulic conductivities with horizontal hydraulic conductivity K_x = 150 m/d, and the vertical hydraulic conductivity K_z = 20 m/d.

According to Gooseff et al. [11] and Chen et al. [18], inflows and outflows at the stream-sediment interfaces alternatively exist along the direction parallel to a stream and the direction perpendicular to a stream. Inflow and outflow rates vary in different streams and can range from several cm/d to near one meter/day in a stream of Nebraska, USA[18]. Simulations were first conducted on a profile that was perpendicular to the stream flow direction.

In the model simulation, the steady state groundwater flow equation was solved first. The hydraulic heads were used for defining the boundary conditions for the stream function modeling. Contours of hydraulic heads and stream functions were generated using Golden Software Surfer. Superimposing the contour maps gives a flow net. The hydraulic heads generated from the flow model were used to calculate the groundwater flow velocity components V_x and V_y.

In the simulation, part of the channel was assumed to have outflow and part having inflow. Fig. 1 shows the flow net and the velocity field for outflow rate of 5 cm/day and inflow rate of 5 cm/day.

The outflow rate was imposed on the top node of x = 360, 370, and 380 m, and the inflow rate was placed at the node of x = 420, 430, and 440 m. The hydraulic head contours near the left and right banks of the river are nearly vertical, suggesting that the regional groundwater flow was horizontal. This vertical pattern changes toward the middle part of the river width where the hydraulic head contours near the water-sediment interface become curved. Streamlines point from the left to the right, consist to the direction of the regional groundwater flow. Streamlines in the upper part of the aquifer have intersections with the water-sediment interface (the top boundary of model domain). They point toward the stream-sediment interface on the segment with outflows and point downward for the segment with inflows. The area above the red streamline (see Fig. 1) in the flow net represents the zone of stream and groundwater exchanges. The area below the red streamline is the regional groundwater flow regime.

The direction of groundwater velocity and magnitude were calculated based on V_x and V_y from each model element. The groundwater flow velocity field (the bottom plot of Fig. 1) was generated using Golden Software Surfer and shows the outflow (upward arrows) and inflow zones (downward arrows) near the water-sediment interface.

Fig. 2 is the flow net for the same model domain as that used for the previous simulation. The only difference is that the outflow and inflow rates were reduced to 2 cm/day, respectively. The surface water penetration is up to about 3 meter as indicted by the red streamline in the upper-right corner of Fig. 2. The thickness of this zone is smaller than that shown in Fig. 1.

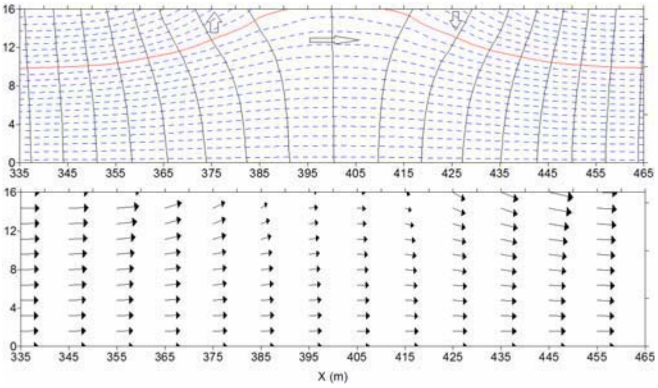

Figure 1. Flow net (top) across the river channel. The solid lines are hydraulic head contours; the dash lines are streamlines. The arrows (the plot in the bottom part) indicate the velocity field. The arrows point to flow directions and the length of each arrow represents the relative scale of velocity magnitude.

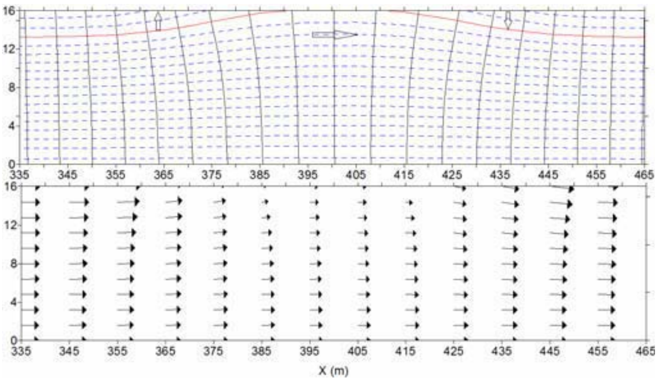

Figure 2. Flow net (top) across the river channel of 130 m wide. The solid lines are hydraulic head contours; the dash lines are streamlines. The arrows in the bottom plot are the velocity field. Compared with the velocity field in Fig. 1, the magnitude of the vertical flow component in the area below the water-sediment interface in Fig. 2 is much smaller.

Simulation was conducted for a hypothetical vertical profile that is parallel to the river. In this simulation two segments were assumed to have outflow and the other two segments were assumed to have inflow. The inflow and outflow segments were positioned alternatively. Fig. 3 shows the flow net and the groundwater velocity field.

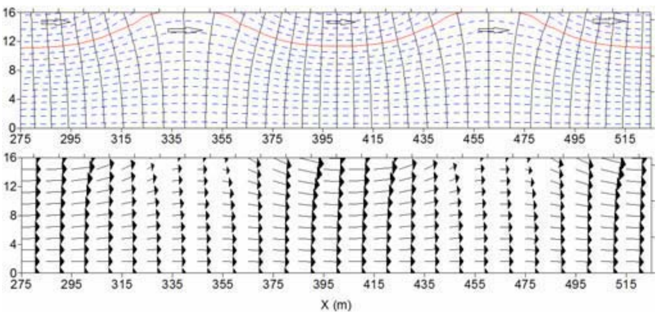

Figure 3. Flow net (top) along the river channel. The area above the red streamlines is the zone of water exchange between stream and the hyporheic zone. The velocity filed (bottom) indicates that the velocity magnitude is larger in the water exchange zone.

As suggested by Fig. 3, the water exchange zone (the area above the red streamline) can be up to about 4 meters in thickness. The hyporheic zone located in the middle of the stream segment (x = 350 to 450 m and z > 10 m in Fig. 3) has a length of about 100 m and is fully filled by stream water. The regional groundwater is not able to discharge to the stream in the area overlain by this hyporheic zone.

IV. CONCLUSIONS

Streamlines can clearly illustrate the dimension of hyporheic zones in streams. The thickness of hyporheic zone is controlled by inflow and outflow rates. Existence of hyporheic zone prevents from groundwater discharge to the stream.

Within hyporheic zone, the magnitude of groundwater velocity is generally larger than that in areas of regional groundwater flow. Thus, the motion of water particles is faster in hyporheic zones that the water movement of regional groundwater flows.

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