An investigation on the effect of geometric shape of streams on stream/ground water interactions and ground water flow

Uğur Boyraz and Cevza Melek Kazezyılmaz-Alhan

ABSTRACT

Ground water should be used efficiently and improved for sustainable water management plans. For this purpose, comprehensive ground water flow models are developed incorporating surface/ground water interactions. Typically, these models require a significant amount of hydrological parameters and the sensitivities of these parameters on interaction mechanisms need to be clarified. Therefore, in this study, the role of the geometric shape of the stream on stream/ground water interactions is investigated. First, an analytical solution for two-dimensional ground water flow is developed with *sloping stream boundary* in an isotropic and homogeneous aquifer. Then, ground water head distribution and *hyporheic exchange flow* between stream and aquifer are obtained by conducting sensitivity analyses with prototype models developed using Visual MODular Finite-Difference FLOW in order to observe individual effects of each stream property. Finally, by incorporating the highest possible stream/ground water interaction conditions into a conceptual stream-aquifer model, the combined effects of different stream shapes are interpreted. Results show that slope, abrupt slope change, and flow path of stream affect the interactions significantly. Moreover, interaction flow rates increase further under the combined effects of these stream properties. The outputs of this work will ultimately be used in site investigations and in forecasting ground water hydrology.

Key words | analytical solution, conceptual models, hyporheic exchange flow, MODFLOW, stream-aquifer region, stream/ground water interactions

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INTRODUCTION

Ground water is an important element of a water resources system which affects the hydrological behavior of the watershed significantly. It contributes to water supply by wells and other water structures and affects the surface water quality and quantity through interaction with rivers, lakes, and wetlands. In order to use ground water resource efficiently, detailed hydrological models of ground water should be developed. Detailed models incorporate many parameters of ground water and the surface/ground water interaction component is quite an important one (Kazezyılmaz-Alhan & Medina 2008). Ground water may interact with all types of surface water such as streams, lakes, and wetlands. During these interactions, water flows either from surface to ground or from ground to surface according to the water level. These interactions not only affect the ground water hydrology, but they also affect the hydrological, chemical, and biological reactions in lakes, wetlands, and streams. Especially in streams, the direction of interaction flux between surface and ground may change frequently according to stream shape and properties. A gaining stream may become a losing stream when the surface runoff reaches the stream and causes a significant rise in stream water level. Stream/ground water interactions may occur in regions called bank storage, where water is accumulated and stored temporarily in stream banks during high flow periods. In addition, these interactions may be observed in the hyporheic

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zone, where stream water is separated from upstream, flows through the subsurface in a short segment, and joins the stream again at downstream. A hyporheic zone is typically observed either in a pool and riffle type of stream or in a meandering stream (Winter *et al.* 1998; Prudic *et al.* 2004; Cardenas 2009). These regions cause significant changes in aquifer recharge or discharge.

The physical mechanisms and importance of surface water/ground water interactions have been discussed in detail by Winter *et al.* (1998), Winter (1999), and Price & Wadington (2000). They emphasized that surface water and ground water have a continuous relation in nature and these systems should be modeled together by considering the surface/ground water interactions. Therefore, the interactions have been integrated into ground water flow models in recent studies. An important part of these studies involves MODular Finite-Difference FLOW (MODFLOW) and integrated programs with MODFLOW. MODFLOW is a three-dimensional finite-difference ground water flow and contaminant transport simulation model and works with multiple packages to simulate the effect of external water source/sink on ground water (McDonald & Harbaugh 1988; Restrepo *et al.* 1998; Sanz *et al.* 2011). For example, MODLFOW has the river package to simulate the effect of water bodies such as lakes and wetlands and the stream package to simulate the effect of streams on ground water. Stream-aquifer interactions may be calculated using one of these packages depending on the system (McDonald & Harbaugh 1988; Prudic 1989; Hill *et al.* 2000) and they are widely used in ground water modeling studies. Other examples of studies related to surface water/ground water interactions include field site investigations (Otz *et al.* 2003; Rodríguez *et al.* 2005; Cho *et al.* 2009; Safavi & Bahreini 2009), new model developments (Kazezyılmaz-Alhan *et al.* 2007; Ravazzani *et al.* 2011; Ivkovic *et al.* 2013), ground water-plant-root zone relations (Yasuda *et al.* 2013; Zhu *et al.* 2013), and numerical analyses on model grid resolution and spatial variability effects (Bruen & Osman 2004; Mehl *et al.* 2006; Knight & Rassam 2007; Mehl & Hill 2010). These studies discussed the impact of surface water/ground water interactions based on the specific field sites or complex numerical hydrodynamic models. The findings show that the contribution of surface and ground water systems to each other arising from interactions is worth considering for determining the field hydrology characteristics. In addition, analytical solutions are developed by Cooper & Rorabaugh (1963), Oakes & Wilkinson (1972), Tang & Jiao (2001), and Spanoudaki *et al.* (2010). These solutions include stream/ground water interactions considering a horizontal stream boundary typically with a stream water level changing as a sinusoidal wave function. However, the sensitivities of interactions subject to stream properties need further investigation.

To make a contribution to the aforementioned research efforts, this study focuses on the investigation of stream/ground water interaction mechanisms in stream-aquifer regions via quantifying the role of the geometric shape of the stream and stream properties on these interactions. For this purpose, an analytical solution for two-dimensional ground water flow is developed with *sloping stream boundary* in an isotropic and homogeneous aquifer. Then, prototype stream-aquifer models are developed in order to observe individual effects of each stream property. Finally, in order to study a case which represents a realistic stream-aquifer system and the combined effects of different stream shapes, a conceptual stream-aquifer model is developed that involves the highest possible stream/ground water interaction conditions. Visual MODFLOW is employed for analyses. The effect of stream/ground water interactions on the hydrological behavior of the stream-aquifer region is determined with ground water contours, ground water flow velocities, and the *hyporheic exchange flow* between stream and aquifer.

METHODOLOGY

Visual MODFLOW is a three-dimensional finite-difference ground water flow and contaminant transport simulation model. The program works with several modules and packages to model the hydraulic and hydrologic characteristics of a domain. The MODFLOW module solves the ground water flow rate and ground water level distribution under constant or variable head boundaries (Hill *et al.* 2000). The equation, which calculates the ground water flow, is given as follows (McDonald & Harbaugh 1988):

$$\frac{\partial}{\partial x}\left\{K_{xx}\frac{\partial h}{\partial x}\right\}+\frac{\partial}{\partial y}\left\{K_{yy}\frac{\partial h}{\partial y}\right\}+\frac{\partial}{\partial z}\left\{K_{zz}\frac{\partial h}{\partial z}\right\}+W=S_s\frac{\partial h}{\partial t} \quad (1)$$

where K_{xx}, K_{yy}, and K_{zz} are hydraulic conductivities in x, y, and z directions, respectively (L/T), h is hydraulic head (L), W is lateral flow ($1/T$) ($W > 0$ means inflow and $W < 0$ means outflow) or sink/source term, S_s is specific storage ($1/L$), and t is time (T).

MODFLOW has the option of usage of the stream water level as a boundary and solves the interactions between stream and ground water with the aid of STREAM (STR) package. This package calculates also the amount of flow in the stream and the losses in the streambed. The parameters defined in this package include stream inflow, stream stage, elevations of streambed top and bottom points, conductance, width, slope, and roughness (Schlumberger Water Service [SWS] 2010). The STR package considers uniform flow in the stream and uses Manning's equation to calculate the stream head. The interaction flow rate between streams and aquifers in the STR package of MODFLOW is computed using Darcy's Law as follows (Prudic 1989):

$$Q_{\text{int}} = C.(H_w - h) \tag{2}$$

$$C = \frac{K_{\text{bed}}.w.L}{M} \tag{3}$$

where K_{bed} is the hydraulic conductivity of streambed sediments (L/T), w is a representative width of stream or wetted perimeter (L), L is the length of stream reach (L), M is the thickness of the streambed deposits extending from the top to the bottom of the streambed (L), H_w is the stream head (L) and h is the head in the aquifer beneath the streambed (L) (Figure 1) (Hill *et al.* 2000). When the wetted perimeter is used in calculating the bed conductance, hyporheic exchange flow both in lateral and vertical directions is taken into account.

The interaction flow rate Q_{int} is incorporated into the ground water equation via the source/sink term W: W is replaced with Q_{int}. The ground water flow equation is solved by several numerical iteration techniques and at each iteration the interaction flow rate is re-calculated for each stream cell. MODFLOW comprehends the stream head as a boundary condition. The rest of the boundary conditions are automatically set to no flow boundary by the STR package unless a constant or variable head boundary is assigned by the user (Prudic 1989).

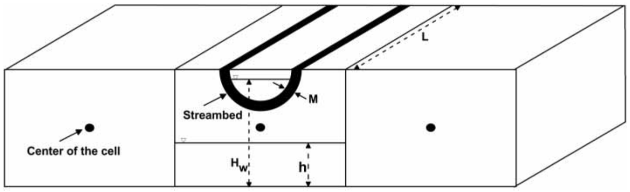

Figure 1 | Schematic of Stream Package.

AN ANALYTICAL SOLUTION FOR A SIMPLIFIED STREAM-AQUIFER SYSTEM

In this part of the study, an analytical solution for two-dimensional ground water flow is developed with sloping stream boundary in an isotropic and homogeneous aquifer. Under steady state and small source/sink term assumption, the ground water flow equation given by Equation (1) may be simplified as follows:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = 0 \tag{4}$$

As shown by Equation (4), the ground water flow equation is reduced to a two-dimensional Laplace's equation. The aquifer is defined in a finite domain, which involves a stream located at the left side of the aquifer. Thus, the problem is subject to the following boundary conditions:

$$h|_{x=0} = S.y + H_0 \tag{5}$$

$$\left.\frac{\partial h}{\partial x}\right|_{x=L_x} = 0 \tag{6}$$

$$\left.\frac{\partial h}{\partial y}\right|_{y=0} = 0 \tag{7}$$

$$\left.\frac{\partial h}{\partial y}\right|_{y=L_y} = 0 \tag{8}$$

where S is the streambed slope (L/L), H_0 is the stream head at $x = y = 0$ (L), and L_x and L_y are the lengths of the aquifer along x and y-directions (L), respectively. These boundary conditions are the same as the ones used in Visual MODFLOW as discussed in the next section. By using the separation of variables method, the following solution is obtained:

$$h(x, y) = a_0 + \sum_{n=1}^{\infty} \left(A_n e^{\frac{n\pi}{L_y}x} + B_n e^{-\frac{n\pi}{L_y}x} \right) \cos\left(\frac{n\pi}{L_y} y \right) \tag{9}$$

$$a_0 = \frac{S.L_y}{2} + H_0 \tag{10}$$

$$A_n = \frac{\frac{2}{L_y} \left[\frac{SL_y^2}{n^2\pi^2} \cos(n\pi) - \frac{SL_y^2}{n^2\pi^2} \right]}{1 + e^{\frac{2n\pi}{L_y}Lx}} \tag{11}$$

$$B_n = A_n \left(e^{\frac{2n\pi}{L_y}Lx} \right) \tag{12}$$

A synthetic example is solved in order to compare the analytical solution with Visual MODFLOW results. For this purpose, the parameters are selected as follows: streambed slope is 0.0015 m/m, aquifer domain is 2,000 (m) × 2,000(m) which means $L_x = 2{,}000$ m, $L_y = 2{,}000$ m and $H_0 = 6$ m. Figure 2 shows the ground water head distribution obtained by both methods. As seen from the figure, ground water head contours are very close for analytical and numerical solutions. Slight differences between the solutions occur due to the neglected source/sink term W in the governing equation of the analytical solution. According to both analytical and MODFLOW solutions, ground water head contours are symmetric with respect to the midpoint of the stream. The contours approach the stream water level at stream boundary and the aquifer recharges at upstream and discharges at downstream since the rest of the boundaries form a closed aquifer system. Consequently, the analytical solution gives accurate results which may be used for practical purposes.

MODEL DEVELOPMENT

In this part of the study, sensitivity analyses are conducted with prototype models by considering different streambed properties and stream flow paths. With hydrodynamic model simulations, hyporheic exchange flow rates and ground water contour and velocity for different streambed slopes, abrupt slope changes of streambed, stream width, and different flow paths of the stream are determined. Abrupt slope change of streambed represents steps in a pool and riffle type of stream. The sensitivity of streambed slope, abrupt slope change, and stream width on stream/ground water interactions and on ground water flow is discussed with a unidirectional stream model. In addition to the unidirectional stream model, a complex stream with tributaries and a meandering stream are developed in order to observe the flow path effects.

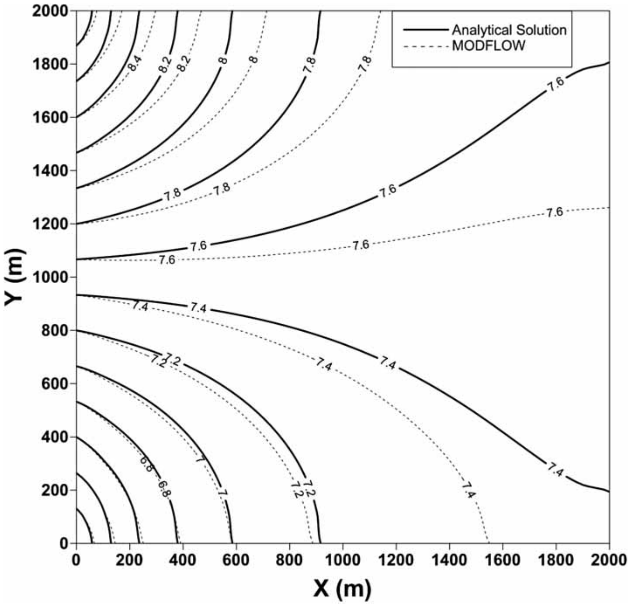

Figure 2 | Comparison of analytical and numerical (MODFLOW) solution results.

In the prototype models, the stream lies on an unconfined aquifer with one layer system having a thickness of 10 m on top of an impermeable rock formation. The soil type of the aquifer is selected as silt loam and the related parameters are provided by Chow *et al.* (1988). The prototype models have an aquifer domain of 2,000(m) × 2,000 (m) with a grid size of $\Delta x = 100$ m (20 × 20 cells). Before conducting the sensitivity analyses, the spatial scale and modeling resolution were checked by enlarging and refining the aquifer domain finding that the selected dimensions and grid sizes are reasonable.

The transient change of interactions is important if a rainfall or recharge event occurs or many wells are located around the stream. However, the focus of this study is the effect of the 'geometric shape' of the stream on interactions under natural conditions. Therefore, the simulations are done for steady state case and thus, no initial boundary condition is defined. But an initial guess of 10 m ground water head is assigned to do the iterative solution with the Strongly Implicit Procedure (SIP) solver with a head change criteria of 0.01 m. MODFLOW uses the stream head as a boundary condition. The rest of the boundary conditions are selected as no flow boundary ($\partial h/\partial x = 0$, $\partial h/\partial y = 0$). Inputs for all simulations are summarized in Table 1. Finally, a conceptual stream-aquifer model is developed which involves the most effective cases of the interactions that are obtained from the analyses of prototype models, and the hydrodynamic behavior of such a stream-aquifer system is investigated.

Prototype model simulations

Streambed slope

The first set of analyses is done to understand the effect of streambed slope on stream/ground water interactions by using a unidirectional stream in the prototype model. Three different streambed slopes are chosen in order to define low (A1), medium (A2) and high (A3) bed slopes, respectively (Table 1). Figure 3(a) shows the ground water contour and velocity pattern for different streambed slopes. Even though the magnitude of velocity differs for each case, the pattern is the same for three cases. While the direction of ground water velocity does not differ much among the models, the ground water depth and the stream velocity change with different streambed slopes. Stream velocity is calculated as 0.54, 0.78, and 1.03 m/s in the low, medium, and high bed slope models, respectively. Furthermore, the change in ground water head along the *y*-direction is much higher for high streambed slope than low-streambed slope, i.e. it changes from 9 to 2 m in high slope and from 9.8 to 8.8 m in low bed slope between upstream and downstream. Figure 3(b) shows the hyporheic exchange flow rates. In this graph, the positive flow rate values indicate a flow direction from river to aquifer and the negative flow rate values indicate a flow direction from aquifer to river. As streambed slope increases, interaction flow rate, i.e. hyporheic exchange flow also increases. The lowest interaction rate values are observed in the low bed slope model. The gradient of flow has the highest value in the high bed slope model. As the stream velocity increases with high bed slope, the stream depth and therefore the wet cross-sectional area decrease. Consequently, the area, through which the water exchange occurs between two regions, also decreases. Thus, we expect low hyporheic exchange flow for high bed slopes. However, high hyporheic exchange flow values are observed after simulations. We link this result to high velocities at stream-aquifer interface: exchange velocity is more dominant than the exchange area in determining the hyporheic exchange flow. To strengthen this conclusion, a set of analyses for different streambed widths is conducted in the next part.

Streambed width

Analyses of this part are done to understand the effect of streambed width on stream/ground water interactions by using a unidirectional stream. Two different stream width values are used in the prototype models to define narrow (A1) and wide channel (A3) (Table 1). Figure 4(a) shows the ground water contour and velocity pattern for different streambed widths. While the direction of ground water velocity does not differ much among the models, the ground water contours and the stream velocity change with different streambed width values. Stream velocities are 1.2 and 0.64 m/s in narrow and wide streams, respectively. Stream depth is also calculated as 2.48 m in the channel of 10 m width and 0.94 m in the channel of 50 m width. The wide stream has higher wetted perimeter and thus higher exchange area than the narrow stream. Even if the wetted perimeter is higher in the wide stream, it is observed that hyporheic exchange flow rates are lower (Figure 4(b)). As streambed width increases, hyporheic exchange flow decreases. This result supports the conclusion reached in the previous part: exchange velocity is more dominant than the exchange area in determining the hyporheic exchange flow.

Abrupt slope change

Stream/ground water interactions are effectively observed in pool and riffle streams (Winter *et al.* 1998). This condition

Table 1 | Parameters of prototype models

	Soil Type	Aquifer Type	Length (m)	Width (m)	Hydraulic Conductivity (m/s)	Aquifer Thickness (m)	Total Porosity	Effective Porosity/Specific Yield	Specific Storage (1/m)
Aquifer Properties	Silt Loam	Isotropic, Homogeneous, Unconfined	2000	2000	1.80×10^{-6}	10	0.501	0.4	0.001

	Analysis	Analysis Number	Segment Number	Streambed Elevation (m)		Slope	Bed Thickness	Bed Conductivity	Manning's roughness	Length	Width	Flow	Water Level	Wetted Perimeter	Bed Conductance
				Start p.	End p.	(m/m)	(m)	(m/s)	–	(m)	(m)	(m^3/s)	(m)	(m)	(m^2/s)
Stream Properties	Streambed Slope	A1	1	8	7	0.0005	1	1.80×10^{-6}	0.06	2000	10	10	1.84	13.68	0.002462
		A2*	1	8	5	0.0015							1.28	12.56	0.002261
		A3	1	8	1	0.0035							0.97	11.94	0.002149
	Abrupt Slope Change	A1	1	8	7	0.0011	1	1.80×10^{-6}	0.06	950	10	10	1.44	12.88	0.002318
			Abrupt Slope	7	5	0.02				100			0.56	11.12	0.002002
			3	5	4	0.0011				950			1.44	12.88	0.002318
		A2	1	8	7	0.0011	1	1.80×10^{-6}	0.06	950	10	10	1.44	12.88	0.002318
			Abrupt Slope	7	4	0.03				100			0.49	10.98	0.001976
			3	4	3	0.0011				950			1.44	12.88	0.002318
		A3	1	8	7	0.0011	1	1.80×10^{-6}	0.06	950	10	10	1.44	12.88	0.002318
			Abrupt Slope	7	3	0.04				100			0.45	10.9	0.001962
			3	3	2	0.0011				950			1.44	12.88	0.002318
	Width	A1	1	6	3	0.0015	1	1.80×10^{-6}	0.06	2000	10	30	3	16	0.002880
		A2	1								50		1	52	0.009360
	Complex Stream with Tributaries	A2	Main Channel	5.8	2	0.002	1	1.80×10^{-6}	0.06	1900	10	10	1.19	12.38	0.002117
			1st tributary	5.8	4.6	0.0017				705		5	0.82	11.64	0.001846
			2nd tributary	5.3	4.6	0.0008				875		5	1.04	12.08	0.002114
			3rd tributary	3.8	3	0.0009				890		5	1	12	0.002136
			4th tributary	3.5	3	0.0005				1000		5	1.19	12.38	0.002026
	Meandering Stream	A3	Channel	8	2	0.0016	1	1.80×10^{-6}	0.06	3750	10	10	1.3	12.6	0.002074
			1st meander Length: 900 m Width: 600 m					2nd meander Length: 400 m Width: 450 m							

*Used in comparison of interaction flow rates among different flow paths.

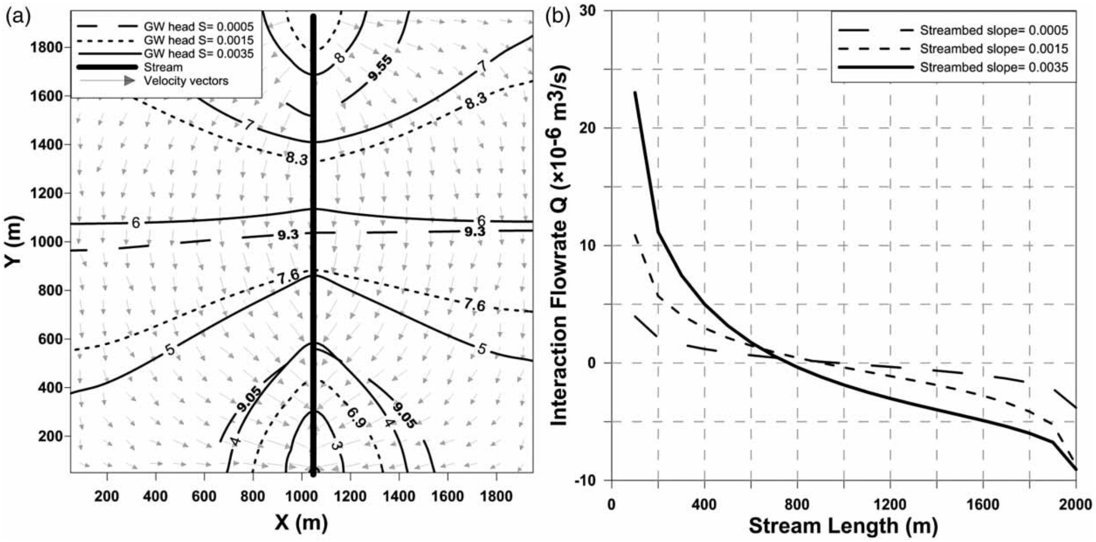

Figure 3 | (a) Ground water flow pattern and ground water level distributions and (b) the comparison of hyporheic exchange flow rates for different streambed slope models.

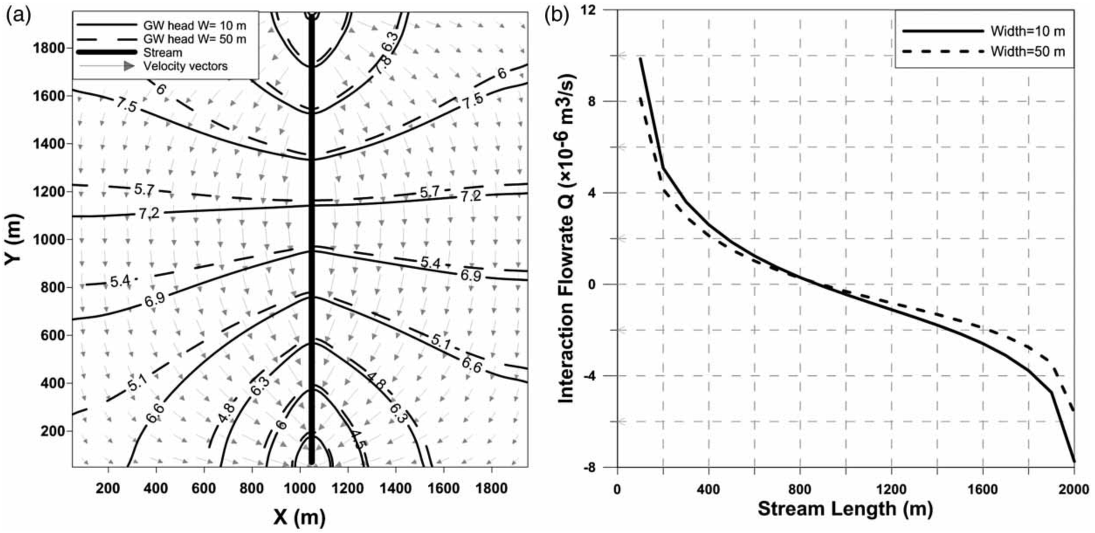

Figure 4 | (a) Ground water flow pattern and ground water level distributions and (b) the comparison of hyporheic exchange flow rates for different stream width models.

usually occurs in streams carrying gravel or coarser sediments. Prototype models with abrupt slope change are developed to simulate these types of streams. Streams are defined with three segments, where the first segment represents the pool part, and second and third segments represent the step and riffle part, respectively. The effect of abrupt slope change in streambed on stream/ground water interactions is observed by defining three different abrupt slope changes. The unidirectional stream model is used for analyses and abrupt slope change is defined in the second segment of the stream. As can be seen from Figure 5(a), the stream discharges water to the aquifer at the beginning of the segment where abrupt slope change is defined and gains water from the aquifer at the end of this segment. While approaching towards the middle part of the stream, an increase in ground water speed from 7.5×10^{-4} m/day to 4.2×10^{-3} m/day is observed. Figure 5(b) shows stream/ground water interaction flow rates. This graph shows that

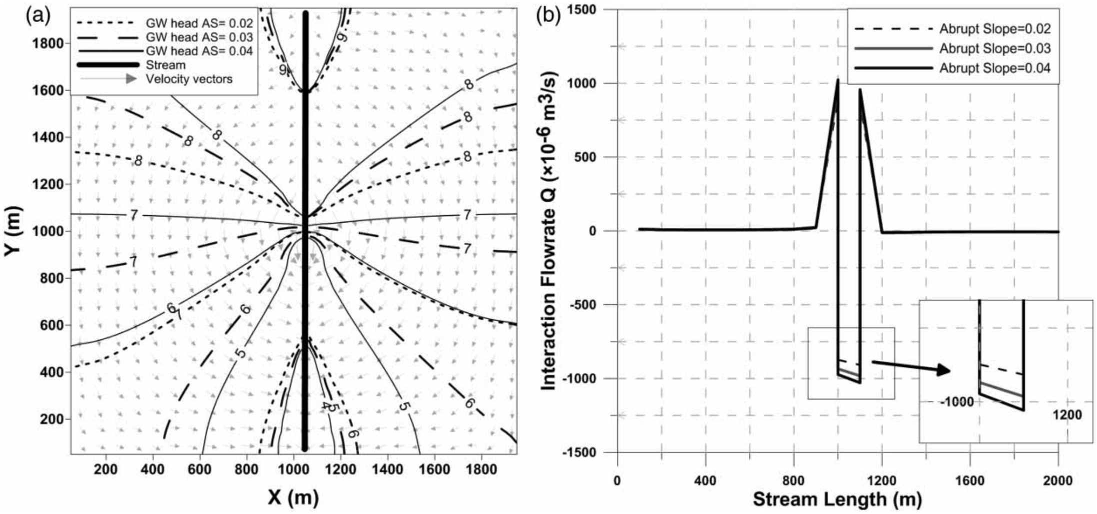

Figure 5 | (a) Ground water flow pattern and ground water level distributions and (b) the comparison of hyporheic exchange flow rates for different abrupt slope change (in streambed) models.

interactions are significantly high in the portion of the stream where an abrupt slope change is defined. A positive sudden jump at pool-step interface and a negative sudden jump at step-riffle interface in the interaction flow rate are observed. Thus, a fast transition from stream to aquifer and then from aquifer to stream took place. The hyporheic exchange flow rates are about $10^{-6}\,\mathrm{m^3/s}$ at upstream and downstream parts. It increases up to $10^{-3}\,\mathrm{m^3/s}$ at the point where the abrupt slope change is defined, and as this slope change increases, interaction flow rates also increase. Thus, interactions are significantly affected by abrupt slope change.

Complex stream

In this set of analyses, the interaction behavior for a complex stream with tributaries is observed. Figure 6(a) shows the ground water depth distribution obtained after simulations. We observed that tributaries affect ground water flow pattern significantly. As circled on the figure, in some parts, the flow velocity magnifies and changes direction from main channel to tributary under the hydraulic head difference effects. In these parts of the stream-aquifer system, we observe strong interactions. While the ground water speed is about $1.69\times10^{-5}\,\mathrm{m/day}$ at far distances

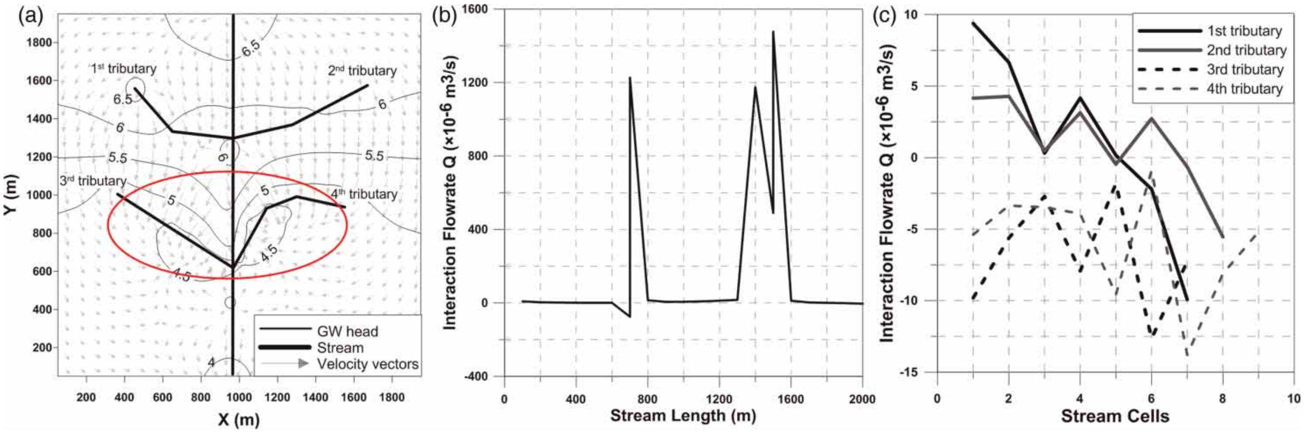

Figure 6 | Complex stream model results: (a) ground water flow pattern and ground water level distribution, (b) hyporheic exchange flow rates in main channel, (c) hyporheic exchange flow rates in tributaries.

from the stream, it increases up to 2.92×10^{-3} m/day around tributaries. This behavior shows that the flow pattern is complex around tributary areas. Interaction flow rates of tributaries also support this result. Figures 6(b) and (c) show the interaction flow rates obtained between aquifer and main channel and tributaries, respectively. Whereas the interaction flow rate is about 4×10^{-6} m^3/s in the main channel (except the junctions), it increases up to 13×10^{-6} m^3/s in tributaries. Along the main channel, interactions occur in general from stream to aquifer. At upstream tributaries (first and second), interaction direction is more dominant from stream to aquifer since a major portion of the interaction flow rate is positive as shown in Figure 6(c). On the other hand, water flows from aquifer to stream at downstream tributaries (third and fourth) since a major portion of the interaction flow rate is negative as shown in Figure 6(c). When the angle between a tributary and the main channel is acute, interaction flow rate increases. This behavior may be observed more clearly in third and fourth tributaries. Along the main channel, we observe significant water flux from the main channel towards the aquifer under the effect of head difference between stream and tributary (Figure 6(b)). Especially, at points 1,400 m and 1,500 m, which correspond to tributary junctions, water flows from stream to aquifer with a high flow rate. We predict that connection angle and geometric shape of the tributary are important parameters in determining the hyporheic exchange flow. To strengthen this result, another analysis is carried out by changing the flow path of the fourth tributary as shown in Figure 7(a). In this model, the fourth tributary has a wide angle. We observe more regular flow and the peak interaction flow at the point 1,400 m along the stream disappears. Thus, we attribute the double peak in Figure 6(b) to the acute angle between the main channel and tributary: first peak occurs due to the connection angle; second peak occurs due to the tributary junction. These results support that flow path and connection angle of a tributary play a crucial role in determining the hydraulics of the interactions. Moreover, we observe a sudden jump in interaction flow rate at two cells for both analyses (Figures 6(b) and 7(b)). These jumps occur at points 700 and 1,500 m along the stream where the tributary junctions are placed and they are on the order of 10^{-3} m^3/s. Therefore, we conclude that flow is more complex at tributary junctions and interaction is more pronounced in these regions.

Meandering stream

For a meandering type of stream, ground water level distribution and interaction flow rates are shown in Figure 8(a) and Figure 8(b), respectively. We observe that ground water flows towards the tips of the meanders. As the meander length decreases and the meander width increases, both ground water velocity and interaction flux increase. We

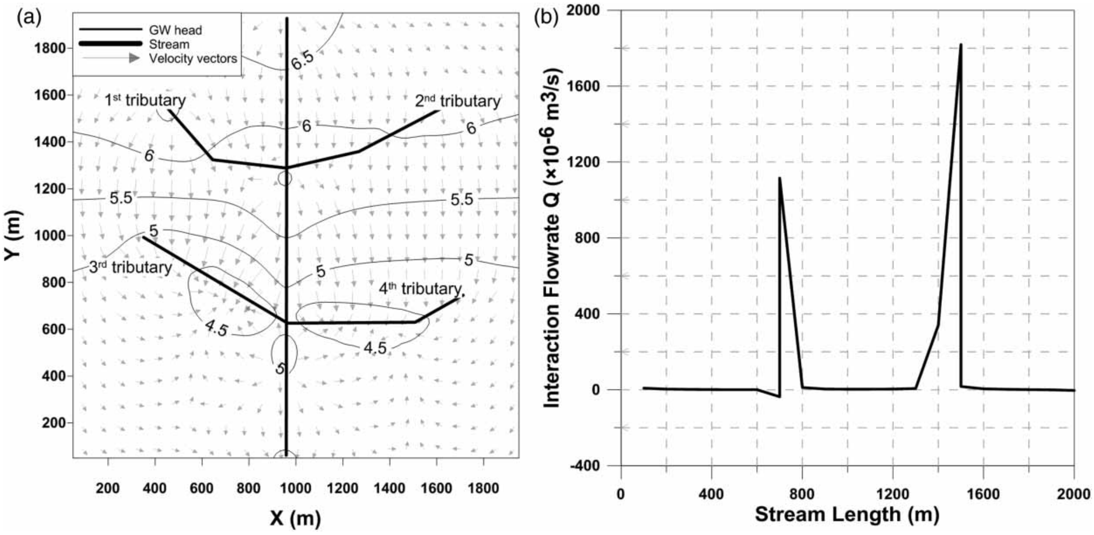

Figure 7 | Re-structured complex stream model results: (a) ground water flow pattern and ground water level distribution, (b) hyporheic exchange flow rates in main channel.

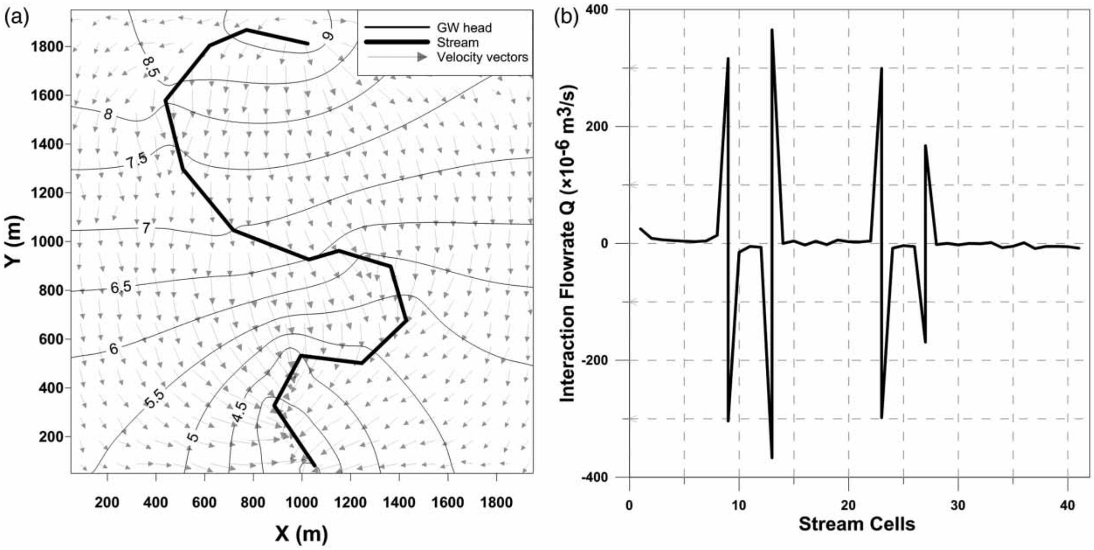

Figure 8 | Meandering stream model results: (a) ground water flow pattern and ground water level distribution, (b) hyporheic exchange flow rates.

observe that the direction of interaction, i.e. the flow direction between stream and aquifer changes frequently (Figure 8(b)). Moreover, the peak flows of interaction are higher in a meandering stream than the ones in a complex stream (except tributary junctions) and the peak flow increases up to $4 \times 10^{-4}\,\mathrm{m}^3/\mathrm{s}$ along the curvatures. In addition to high oscillation in direction of interaction flow rate, an irregular pattern in magnitude of interaction flow rate is also observed. In general, water flows from stream to aquifer at upstream parts of the meander; then, it flows through the aquifer and joins back to the stream at downstream parts of the meander.

The comparison of hyporheic exchange flow rates for different stream flow paths is shown in Figure 9. We observe variable interaction flow rate among the models which means that the type of flow path affects the interactions. In a complex stream model, especially tributaries play a crucial role in ground water and main stream flow because interactions are most pronounced around tributary junctions. The highest interaction flow rates are observed at these points in this model and this rate is higher than the ones in unidirectional and meandering streams. Whereas the direction of interactions is more uniform in a complex stream model, it changes frequently in a meandering stream model. Thus, interactions have the most complex behavior in a meandering stream.

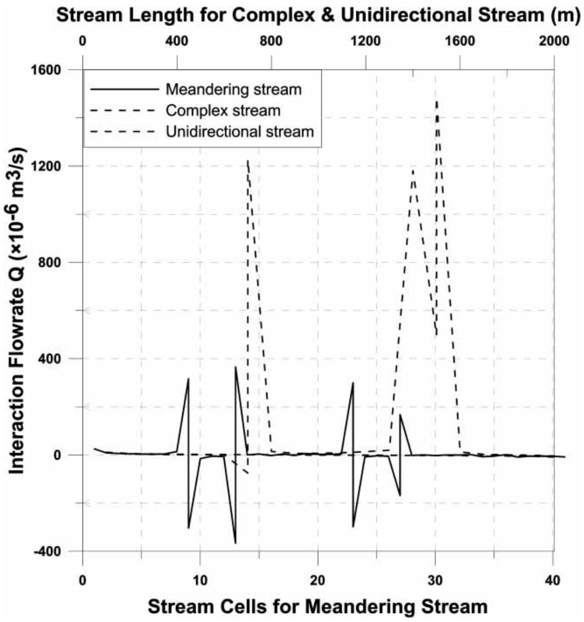

Figure 9 | Comparison of hyporheic exchange flow rates for different stream flow paths.

Conceptual stream-aquifer model

A conceptual stream-aquifer model (Boyraz 2010) is developed by incorporating the highest possible stream/ground water interaction conditions which are determined by evaluating the sensitivity analyses results. The conceptual model has $3{,}000 \times 3{,}000\,\mathrm{m}^2$ area defined by 30×30 cells.

A single layer aquifer is defined with a thickness of 20 m, and hydraulic conductivity of 1.8×10^{-6} m/s. The stream has two tributaries and several curvatures to observe the combination of complex and meandering stream effect. The mean slope of the main channel is selected as 0.0016 m/m. An abrupt slope change is generated at the third segment with a slope of 0.01 m/m. The first tributary has the same slope as the main channel and the slope of second tributary is 0.0025 m/m. Streambed elevation is defined as 17.7 m at upstream and 3 m at downstream. The width of the stream is 10 m. The flow rate is 10 m^3/s in the main channel and 5 m^3/s in tributaries.

Figure 10(a) shows the conceptual model and ground water flow distribution obtained after simulations. The stream-aquifer model is divided into four regions in order to better assess the ground water behavior. In the first region, ground water flows towards the first tributary junction with a low speed. In the second region, we observe an increase in ground water speed. The ground water flows both towards the tip of the meander part and the second tributary junction. In meanders, the flow direction is from upper segments to lower segments along the meander length. Significant interactions are observed in these areas. In the third region, ground water flows again towards the tip of the meander at upper parts, and towards the downstream point at lower parts. In the fourth region, the ground water flows towards the main channel as there is no obstruction. In the third segment of the stream, where an abrupt slope change is defined, the ground water flow suddenly changes direction, heads towards the point of abrupt slope change, and breaks the uniform flow regime.

The hyporheic exchange flow rates along the main channel are shown in Figure 10(b). Both the direction and magnitude of flow change frequently along the main channel. The value of interaction flow rate is on the order of 10^{-4} m^3/s. In the third segment, which corresponds to the 19th cell, we observe a sudden jump in interaction flow rate with a value of 3.6×10^{-3} m^3/s due to the abrupt slope change. There are two more jumps observed in the 41st cell (first tributary junction) and in the 96th cell (second tributary junction). In tributary junctions, the interaction flow rate increases up to 2×10^{-3} m^3/s.

DISCUSSION

The geometric shape of the stream including slope, width, and flow path plays a crucial role in determining the stream-aquifer interactions as shown in the previous section. Streambed conductance, length, and flow are also important stream parameters related with interactions in addition

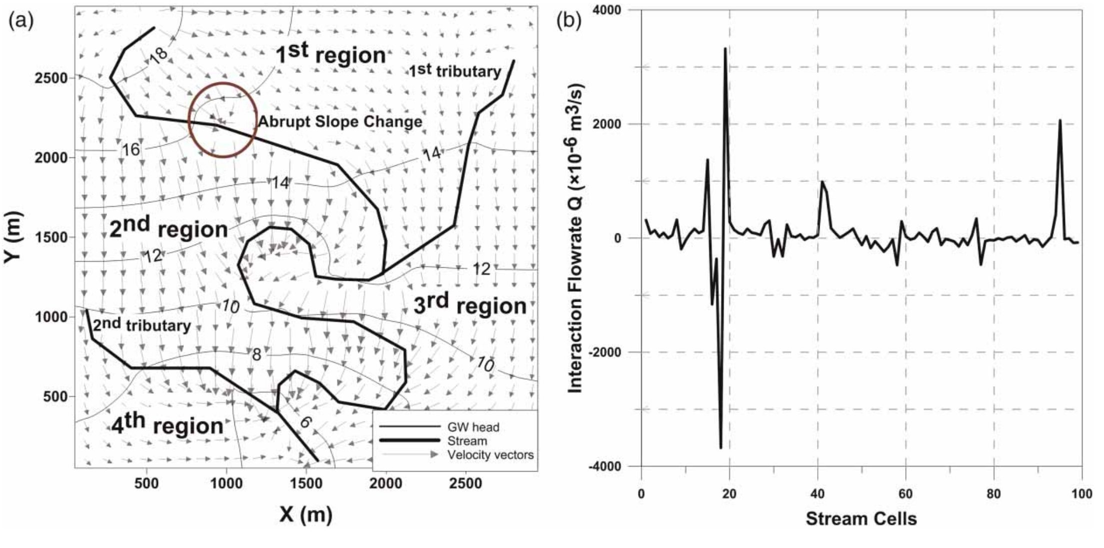

Figure 10 | (a) Ground water flow pattern and ground water level distributions and (b) the hyporheic exchange flow rates for conceptual model.

to aforementioned stream characteristics. Especially, streambed conductance is a key parameter in calculation of interaction flow rates as expressed by Equation (2). The conductance value is determined by the parameters of stream length, wetted perimeter, bed thickness, and bed conductivity which involve both stream and aquifer characteristics. Length and wetted perimeter differ according to stream shape properties. Stream shape also affects the hydraulic head of stream and thus head gradient between stream and aquifer. Therefore, it is important to determine the 'stream shape-interactions relation'.

Slope is a fundamental parameter of stream shape. It affects flow properties such as stream velocity and depth. Different stream widths also cause changes in stream depth and exchange area. Width and slope analyses conducted by unidirectional stream models reveal that the relation among 'velocity-depth-exchange area and interactions' is worth investigating. Although an increase in interaction flow is expected with high stream width and thus high exchange area, a decrease in hyporheic exchange flow is observed. This outcome is attributed to high head gradient between stream and aquifer, which results in high velocity at the stream-aquifer interface. The outcome of slope analyses is in line with this outcome.

Stream flow rate is another parameter that affects the interactions. As stream flow rate increases, stream velocity and exchange area also increase, so it is straightforward that interaction flow rate will rise. If the stream is dry, two different scenarios are expected: No interactions would occur if the ground water table is below the streambed. Ground water feeds the stream and interactions occur towards the stream in the opposite case.

Based on the prototype models, in the meandering stream, interaction flow rates fluctuate and are calculated as higher than complex and unidirectional flow paths. These analyses are conducted using the same streambed conductivity in the prototype models. In nature, sediment transport and accumulation of sediments may occur more frequently in meandering streams. Therefore, the hydraulic conductivity of the streambed for a meandering stream can be lower than the one defined for a unidirectional flow path. Even if K_{bed} is low, fluctuations in interaction flow rate are still expected because of the meander characteristics. However, the magnitude of interaction flow rate may decrease according to the field site but will still be higher than the ones for unidirectional flow.

CONCLUSIONS

In this study, the hydrologic and hydrodynamic characteristics of stream/ground water interactions in stream-aquifer systems are investigated. In particular, the effect of the geometric shape of the stream on interactions is considered. While the individual effects of each parameter are observed with prototype models, the combined effects are reflected by a conceptual model. In addition, the effect of a sloping stream boundary is shown with an analytical solution which is compared with MODFLOW numerical results. The analytical solution may be used in validation of the numerical models and provides a physical insight to ground water problems involving stream/aquifer systems. Results show that an increase in streambed slope or a decrease in stream width results in an increase in water flux between stream and aquifer. Sudden jumps in hyporheic exchange flow are observed where an abrupt slope change is defined which represents the step in a pool and riffle type of stream. The effect of the complexity of the stream flow path on interactions is illustrated by tributaries and meanders. The tributary junctions, connection angle between tributary and main channel, and meander length and width are among the important stream characteristics when interaction flow rates are determined. In light of the conceptual stream-aquifer model, which represents a realistic stream-aquifer system, we have seen that the hyporheic exchange flow rates in a stream-aquifer system involving all parameters and complexities resulting in strong interactions are very effective on ground water flow.

This study shows the importance of stream/ground water interactions in determining the hydrodynamic behavior of stream-aquifer regions. The outputs of this work will be useful in site investigations and in forecasting ground water hydrology which are important parts of sustainable water management plans. Future research will include the effect of the aquifer system such as anisotropy or heterogeneity on interactions. Detailed analyses on the effect of contaminant transport mechanisms such as dispersion or reaction are also worth investigating in the next studies.

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