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Influence of a thin veneer of low-hydraulic-conductivity sediment on modelled exchange between river water and groundwater in response to induced infiltration†

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Abstract:

A thin layer of fine-grained sediment commonly is deposited at the sediment–water interface of streams and rivers during low-flow conditions, and may hinder exchange at the sediment–water interface similar to that observed at many riverbank-filtration (RBF) sites. Results from a numerical groundwater-flow model indicate that a low-permeability veneer reduces the contribution of river water to a pumping well in a riparian aquifer to various degrees, depending on simulated hydraulic gradients, hydrogeological properties, and pumping conditions. Seepage of river water is reduced by 5–10% when a 2-cm thick, low-permeability veneer is present on the bed surface. Increasing thickness of the low-permeability layer to 0·1 m has little effect on distribution of seepage or percentage contribution from the river to the pumping well. A three-orders-of-magnitude reduction in hydraulic conductivity of the veneer is required to reduce seepage from the river to the extent typically associated with clogging at RBF sites. This degree of reduction is much larger than field-measured values that were on the order of a factor of 20–25. Over 90% of seepage occurs within 12 m of the shoreline closest to the pumping well for most simulations. Virtually no seepage occurs through the thalweg near the shoreline opposite the pumping well, although no low-permeability sediment was simulated for the thalweg. These results are relevant to natural settings that favour formation of a substantial, low-permeability sediment veneer, as well as central-pivot irrigation systems, and municipal water supplies where river seepage is induced via pumping wells. Published in 2011 by John Wiley & Sons, Ltd.

KEY WORDS groundwater/surface-water relations; water supply; seepage; hydraulic conductivity; induced infiltration; riverbank filtration; clogging

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INTRODUCTION

Riverbank filtration (RBF) has become an important strategy for municipal water supplies throughout the world over the past few decades. RBF commonly involves wells that are located in an alluvial aquifer adjacent to a stream or river. Water pumped from the wells induces flow from the river or stream, through the sediments between the bed and the well screen, and into the well. The ready supply from the river or stream provides a stable and reliable source of water to the wells and results in less drawdown of hydraulic head in the riparian aquifer. Although RBF is widely used across the United States, it has been particularly popular in Europe and provides 16% of the potable water supply for Germany (Schmidt *et al.*, 2003) and 7% of the drinking-water supply for the Netherlands (Stuyfzand *et al.*, 2006). The method has the added benefit of removing many of the contaminants and pathogens contained in surface water, precluding, or reducing the need to treat the pumped water (Ray *et al.*, 2003).

Unfortunately, RBF usually results in clogging of the riverbed, reducing hydraulic conductivity at the sediment–water interface (Schalchli, 1992; Ray *et al.*, 2002; Schubert, 2002; Blaschke *et al.*, 2003; Goldschneider *et al.*, 2007) and flow of surface water to the supply wells. In some settings, water suppliers rely on episodic or seasonal high-flow events to flush the clogging layer and restore flow of surface water to the nearby pumping wells (Gollnitz, 2003; Mutiti and Levy, 2010).

Riverbed clogging also occurs under natural conditions and can reduce exchange between groundwater and surface water even in the absence of RBF (Beschta and Jackson, 1979; Kaleris, 1988; Schalchli, 1992; Brunke, 1999). In many parts of the world, where streamflow commonly is slow for prolonged periods, a layer of fine-grained sediment covers portions of riverbeds where water depths are shallow and velocities are slowest (Hatch *et al.*, 2010). Such is the case in the South Platte River, northeastern Colorado, USA, where earlier results indicated that a thin layer of fine-grained sediment is present over much of the bed during low-flow periods (Rosenberry and Pitlick, 2009b). Horizontal hydraulic conductivity, K, of this layer that ranged from several mm to over 1-cm thick was a factor of 20–25 smaller than the rest of the bed that consisted of medium sand to fine gravel. Sediment in the thalweg, however, remained mobile and a fine-grained sediment layer was never observed there. The clogging layer that formed under natural conditions at the South Platte River was

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much thinner than those commonly reported in the RBF literature. However, even a thin clogging layer may substantially alter distribution of seepage across the sediment–water interface. Disturbance of a millimeters-thick layer of fine-grained sediment at a lake in New Hampshire altered seepage rates by factors of 3–8 (Rosenberry *et al.*, 2010).

Does this matter beyond the local scale? Would the presence of a low-permeability sediment layer affect the capture of river water supplied to a pumping well installed in the adjacent alluvial aquifer? Would the presence of a thin, fine-grained layer affect the distribution of seepage with distance from the riverbank, or would local-scale hydraulic gradients across the thin layer adjust to compensate, in which case exchange across the sediment–water interface would remain largely unchanged? If a low-permeability sediment layer is draped across all but the thalweg of a river, would seepage exchange be shifted to be focused at the thalweg?

These questions are addressed here through the use of a numerical model designed to simulate both unsaturated and saturated flow, allowing the water table to fluctuate in response to various simulations, and allowing the sediment to become unsaturated beneath the river should conditions warrant (Su *et al.*, 2007). Rather than model a generic riparian-aquifer setting, the modelled setting is similar to physical conditions at the study reach of the South Platte River mentioned earlier, where previous studies have investigated groundwater–surface-water exchange and sediment transport and documented the presence and distribution of a thin, low-permeability layer that is present during low-flow conditions (Cronin *et al.*, 2007; Rosenberry and Pitlick, 2009b).

Flow across the sediment–water interface along a cross section perpendicular to the axis of a river was simulated in response to pumping from either a line of vertical pumping wells located a consistent distance from the river to simulate water supply for irrigation, or a horizontal well oriented parallel to the river to simulate a municipal water supply. We assumed that flow between the pumping well and the river, and beyond the well to the farthest extent of the simulated riparian aquifer, is essentially two-dimensional along a vertical plane that bisects the line of wells or the lateral extent of the horizontal well. In addition to quantifying change in distribution of seepage with distance from the riverbank, and determining the percentage contribution of river water to the pumping well, the model was used to determine the degree to which induced infiltration enhances seepage through the thalweg located near the bank of the river opposite the pumping well. In all simulations, the veneer of fine-grained sediment did not extend to the thalweg, the assumption being that shear stress in the thalweg was always sufficient to prevent deposition of fine-grained sediment. Although the thalweg was near the shore opposite the simulated pumping well, the fact that it was deeper and the alluvial gravel was thinner, and that it lacked a low-*K* veneer, led to the hypothesis that it would contribute a large proportion of river water to the well.

METHODS AND MODELLED SETTING

The computer code VS2DT (Healy, 1990; Hsieh *et al.*, 2000) was used to simulate steady-state flow between a gravel-bed river and a permeable riparian aquifer. This code, which uses finite-difference approximations to solve the Richards equation for flow, was selected because it meets the requirements mentioned above; it can allow the water table to adjust to fluxes to and from the river as well as to simulated pumping events, including simulation of an inverted water table if conditions warrant (Rosenberry, 2000; Hubbs, 2006; Su *et al.*, 2007; Brunner *et al.*, 2009; Wiese and Nutzmann, 2009). The tradeoff is that VS2DT can simulate flow in only 2D and was used in the cross-sectional mode here. This is appropriate if conditions along the third dimension, in this case parallel with the river, do not change. To meet this restriction, we assume that the conditions simulated for the riverbed are constant upstream and downstream of the study cross section and that boundary conditions of the alluvial aquifer do not change along the axis perpendicular to the cross section. We are interested in investigating (1) the influence of a typical irrigation well that is common in the South Platte River valley and (2) the influence of a horizontal municipal well similar to that used by a growing number of communities (Fournier, 2005; Timmer and Pittens, 2007). In the case of the irrigation well, to minimize radial-flow effects, we assume the presence of a gallery or line of closely spaced pumping wells installed parallel to the river. By assuming a virtual line sink, radial flow that would occur in the third dimension is insignificantly small in the vicinity of the riverbed. Given the 9000 high-capacity irrigation wells situated along the South Platte River (South Platte River Task Force, 2007), this is not an implausible assumption. Even if that assumption were violated, we are interested in relative changes in contribution of river water to the pumping well under various modelled settings, so a 2-D simulation is appropriate here. For simulations of a horizontal municipal well installed parallel to the river, we assume that the modelled cross section bisects the municipal well and that flow between the well and the river is 2D along the cross section. Pumping rates were set to be appropriate for a typical irrigation or municipal well.

The model was designed to simulate geologic conditions along the South Platte River 48 km north northeast of Denver, CO (Figure 1) (Dennehy *et al.*, 1993; McMahon *et al.*, 1995; Rosenberry and Pitlick, 2009b), a setting that is similar to many alluvial aquifers across the United States. The modelled setting extends horizontally 1 km west of the river and 300 m east of the river to specified-head boundaries and vertically from land surface to the base of the alluvial aquifer 10 m beneath the surface of the river (Figure 2). The modelled riverbed is 80 m wide and consists of a small channel along the west (left) bank 12 m wide and 0·3 m deep, a submerged mid-channel bar 56 m wide and 0·1 m deep, and a thalweg along the east

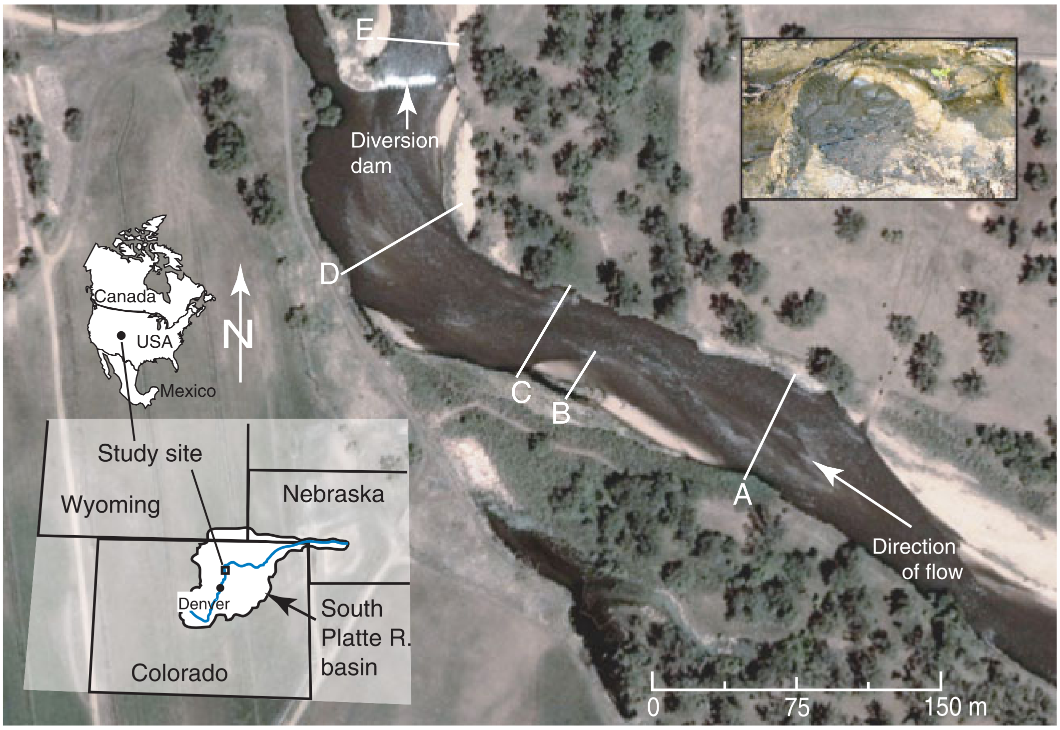


Figure 1. Location of field site on the South Platte River north of Denver, CO, USA, on which model geometry and geology are based. Labelled transects are from Rosenberry and Pitlick (2009b). Inset shows boot print in muddy veneer typical of this setting

bank 12 m wide and 1 m deep (Figure 2). The configuration of the cross section is similar to transects C and D in Figure 1 (Rosenberry and Pitlick, 2009b).

The simulated line of irrigation wells is situated 0·33 km from the west bank of the river, one third the distance from the river to the western boundary of the alluvial aquifer. The well in the model is pumped at a rate of 3 m^2 d^{-1} per meter of river reach. This rate was set to be representative of an aggressive pumping of water for irrigation and is slightly larger than the annual application of water (508–686 mm) over an area typically irrigated for a quarter section of land (506 000 m^2) to grow corn in northeastern Colorado (Schneekloth and Andales, 2009). The screened interval of the irrigation well is 5·3 m uniformly distributed vertically over six model nodes (Figure 2).

The simulated municipal well oriented parallel to the river is pumped at 15 m^2 d^{-1}, a rate more appropriate for a typical municipal water-supply well. The 15 m^2 d^{-1} pumping rate is distributed over one model node that is 0·7 m in diameter. The municipal well is located either at 100 m from the west bank of the river or directly beneath the river at a distance of 8 m below the deepest portion of the thalweg (Figure 2).

Model runs were conducted with or without the presence of a thin, low-*K* sediment veneer covering the bed of the side channel and the mid-channel bar, but not the thalweg. Model conditions were adjusted to test the effects of the depth and width of the alluvial aquifer, the anisotropy of the aquifer and the riverbed gravel, the presence or absence of riverbed gravel, the proximity of the irrigation or municipal well to the river, the hydraulic gradient across the aquifer on the western side of the river, and the thickness of the low-*K* sediment veneer on the surface of the riverbed. Two to four simulations were run for each model configuration, one with no low-*K* sediment veneer and the others with low-*K* veneers of various degrees of permeability reduction. For all model runs, the percentage contribution of water supplied to the pumping well from the river and the distribution of seepage across the river bed are determined.

The basic domain was modelled as 111 rows by 235 columns that vary in size from 0·017 m by 0·005 m to 13·8 m by 0·88 m in the horizontal and vertical directions, respectively. Cells are smallest at the sediment–water interface to simulate flow through a 0·02-m thick low-*K* veneer (Figure 2).

The alluvial aquifer was assigned a *K* of 30 m d^{-1} (Robson and Banta, 1995) and was modelled as either isotropic or with an anisotropy of 10 (*K* for horizontal flow is ten times larger than *K* for vertical flow). A gravel unit underlying the riverbed was assigned a value of 90 m d^{-1} based on slug-test results (Rosenberry and Pitlick, 2009b), and also was simulated with an anisotropy of 1 or 10. Both the sand and gravel deposits likely are substantially heterogeneous based on studies conducted in similar sediments (Cardenas and Zlotnik, 2003), but both units were modelled here as homogeneous because data were insufficient to characterize heterogeneity. Although measured anisotropy typically is on the order of 1–5 for the alluvium and gravel associated with the South Platte River (Chen, 2000; Landon *et al.*, 2001; Chen, 2004), anisotropy was increased to 10 to generate the largest simulated change in seepage

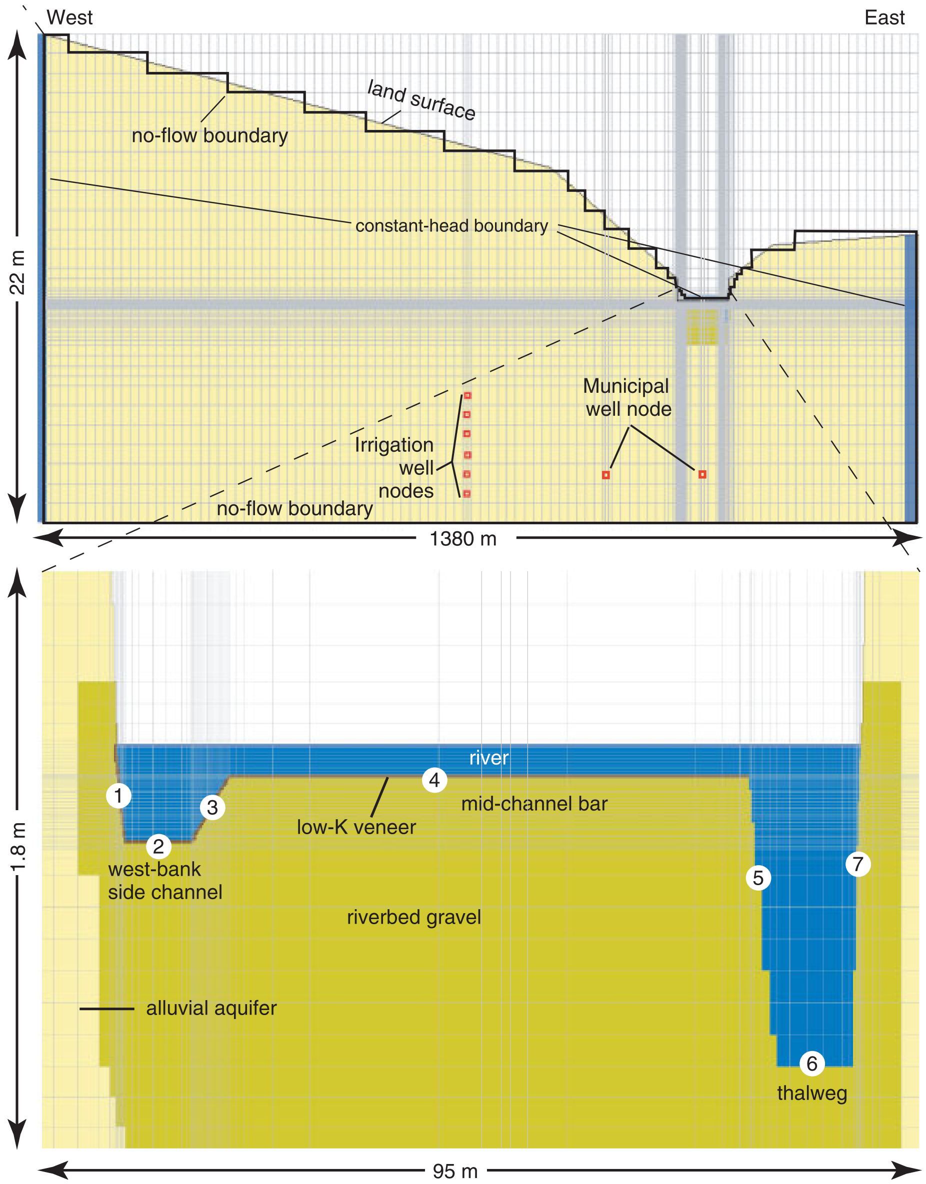


Figure 2. Modelled cross section showing model boundaries, mesh, aquifer (yellow), gravel (gold), and various locations of a pumping well. Numbers 1 through 7 in the enlargement of cross section of modelled riverbed indicate the seven modelled segments of the riverbed

distribution across the riverbed that would still be reasonable. The thin layer (veneer) of low-K sediments was simulated as homogeneous and isotropic for all model runs. Horizontal hydraulic conductivity of the veneer, K_{ven}, was set at 3·5 m d^{-1} (Rosenberry and Pitlick, 2009b). K_{ven} was further reduced to 0·35 m d^{-1} (and to 0·035 m d^{-1} if the model would converge) to simulate clogging conditions that might result following sustained pumping from the irrigation or municipal wells. For simulations in which the veneer was absent, K_{ven} was set equal to 90 m d^{-1}. Although flow across the sediment–water interface was assumed to be perpendicular to the slope of the bed, K tensors were either vertical or horizontal and flow was simulated across horizontally or vertically oriented cell boundaries. Flow within the river along the plane of the model was simulated with a K of 10 000 m d^{-1} and a porosity of 1.

The hydraulic gradient on the left (western) side of the aquifer was varied to simulate periods when irrigation canals either were carrying water and leaking to the aquifer, causing the water table to be elevated relative to the river surface, or were dry, so that the aquifer was at the same level as the river surface. Therefore, the total-head boundary at the western margin of the aquifer was either 4 or 0 m higher than the total head of the river surface, creating water-table slopes that were either 0·004 or 0. The portion of the aquifer to the right (east) of the river was simulated with a total-head boundary set to the same elevation as the river surface. The base of the aquifer was simulated with a no-flow boundary. The top boundary of the model is coincident with land surface. No recharge (other than that from the river) or evapotranspiration were simulated; thus, the top boundary (except for the river) was simulated with a no-flow boundary.

The percentage of water provided to the irrigation or municipal well that originated from the river was determined for each of the model runs that simulated a pumping well. Percentage contributions of river water originating from the west-bank side channel, the mid-channel bar, and the thalweg also were determined. The riverbed was divided into seven segments (Figure 2), three for the west-bank side channel, one for the mid-channel bar, and three for the thalweg. Average horizontal and vertical velocities were determined for each riverbed segment. Velocities were converted to volumetric flow rates per simulated model width by multiplying by cell length or height and porosity. Volumetric flow rates were summed for comparison with the pumping rate of the simulated well.

RESULTS

Riverbed seepage is focused at the western margin of the river under nearly all simulated conditions. In the simplest setting, with no veneer present on the bed, a western-boundary total head 4 m higher than the river, and no pumping well, 97·4% of the seepage to the riverbed occurs through the three segments making up the western side channel and 2·6% occurs through the 56-m wide mid-channel bar (Table I(A), Figure 3). No seepage occurs through the thalweg. Seepage decreases approximately exponentially with distance from shore (Figure 4a), as would be expected at the contact between an aquifer and a surface-water body with uniform geology (McBride and Pfannkuch, 1975). The horizontal component of seepage is focused almost entirely at the western-most 1-m-wide riverbed segment and rapidly decreases to zero where the western side-channel bed becomes horizontal. Almost half (46%) of all seepage across the 80-m wide riverbed occurs through the western-most 1 m of riverbed.

Introducing the presence of a 0·02-m thick veneer results in a slight redistribution of seepage along the sloping western margin of the bed. Seepage velocity is reduced at the shoreline and increased slightly at a distance of about 0·5–1 m from shore (Figure 4). Little change in seepage velocity occurs over the remainder of the riverbed.

The veneer slightly reduces flow through the entire riverbed. Seepage through the riverbed with a K_{ven} of 3·5 m d^{-1} is 92·1% of seepage without a veneer, changing from 2·03 to 1·87 m^2 d^{-1} (Table I(A)). If K_{ven} is reduced to 0·35 m d^{-1}, seepage is 86·9% of seepage without a veneer and slightly greater percentage (7·6%) of the seepage occurs through the mid-channel bar. Adding anisotropy reduces slightly the amount of water originating from the river but changes substantially the distribution of seepage across the riverbed. Depending on the value for K_{ven}, percentage contribution from the side channel ranges from 75 to 80% with nearly all the rest of the water originating from the mid-channel bar. Approximately, 1% of the water supplied from the river comes through the thalweg (Table I(A)).

Pumping the simulated irrigation well at 3 m^2 d^{-1} reverses the seepage direction at the riverbed and draws water from the river into the aquifer (Figure 5). If aquifer head at the western margin is 4 m higher than the river, the model indicates little sensitivity to the veneer. Nine percent of the water supplied to the pumping well originates from the river if there is no veneer. That value decreases to 8 and 7% as K_{ven} is reduced to 3·5 or 0·35 m d^{-1}, respectively (Table I(B)). If the western margin of the aquifer has the same head as the river ($\Delta h = 0$) the contribution from the river is much larger and more sensitive to K_{ven}, changing from 76 to 70 to 65% as K_{ven} is decreased from 90 to 3·5 to 0·35 m d^{-1} (Table I(B)). A reduction in K_{ven} from 90 to 3·5 m d^{-1} reduces the contribution of water to the well from the river by 6% and an additional order-of-magnitude reduction in K_{ven} reduces the river contribution by 11% (Table I(B)). Most of the change occurs in the western side channel, with a reduction in seepage velocity nearest to shore and an increase in seepage velocity through the flat, deepest part of the side-channel bed (Figure 6).

Adding anisotropy to the alluvium and gravel does not substantially affect the percentage contribution of river water to the simulated irrigation well relative to isotropic conditions, but it has a large influence on the distribution of seepage across the riverbed. For example, with a K_{ven} of 90, a Δh of 0, and isotropic sediment, seepage contributions through the beds of the mid-channel bar and thalweg are 2·6 and 0·0%, respectively (Table I(B)). However, with an anisotropy of 10 those percentages increase to 19·2 and 0·8.

Increasing anisotropy reduces the focus of seepage at the western margin of the riverbed and increases the percentage contribution to total seepage at the other riverbed segments (Figure 7). Anisotropy of 10 creates an effect similar to decreasing K_{ven} by about two orders-of-magnitude, although increased anisotropy results in a much greater percentage of seepage through the mid-channel bar than reducing K_{ven}.

Alternate modelled conditions

The cross-sectional configuration of the aquifer width and depth, K and anisotropy of the aquifer and gravel, type and location of a pumping well relative to the river, pumping rate, and thickness of a low-permeability veneer all vary along the South Platte River. Each of these variables was altered in the model, allowing comparisons of flow across the seven riverbed segments with values resulting from the original modelled conditions.

No gravel beneath riverbed. Assigning the sediment beneath the riverbed the same properties as the rest of the alluvial aquifer results in virtually no change in the percentage of water supplied to the irrigation well from the river (Table I(C) *vs* (B)), no matter whether Δh is 4 or 0 m. Without the higher K provided by the gravel, seepage is slightly less focused at the side channel; seepage flowing through the side channel relative to

Table I. Modelled parameters of alluvium, gravel, and low-K veneer, specified difference in head across western portion of the aquifer (Δh), seepage flux across riverbed, and percentage of water supplied to a pumping well from the river, percentage seepage contribution from channel segments, percentage change of riverbed seepage relative to no veneer, and percentage change in seepage associated with one or two-orders-of-magnitude reduction in K_{ven}

K (m/day), anisotropy						% seepage per channel segment					
Alluvium	Gravel	Veneer	Δh (m)	Total flux (m^2/day)	Percentage from river (%)	Side channel	Mid-channel bar	Thalweg	% seepage relative to no veneer	% difference 90 *versus* 3·5 m/day	% difference 90 *versus* 0·35 m/day
A. No well											
30, 1	90, 1	90, 1	4	2·026		97·4	2·6	0·0			
30, 1	90, 1	3·5, 1	4	1·866		96·8	3·2	0·0	92·1		
30, 1	90, 1	0·35, 1	4	1·760		92·5	7·5	0·0	86·9		
30, 10	90, 10	90, 1	4	1·889		80·1	19·2	0·8			
30, 10	90, 10	3·5, 1	4	1·761		78·3	20·8	0·8	93·2		
30, 10	90, 10	0·35, 1	4	1·698		75·0	23·9	1·1	89·9		
B. Irrigation well pumped at 3 m^2/day											
30, 1	90, 1	90, 1	4	−0·259	9	97·4	2·6	0·0			
30, 1	90, 1	3·5, 1	4	−0·238	8	96·8	3·2	0·0	92·1	−1	
30, 1	90, 1	0·35, 1	4	−0·221	7	92·4	7·6	0·0	85·4		−1
30, 1	90, 1	0·035, 1	4	−0·202	7	63·5	34·4	2·1			
30, 10	90, 10	90, 1	4	−0·251	8	80·0	19·2	0·8			
30, 10	90, 10	3·5, 1	4	−0·234	8	78·3	20·9	0·8	93·1	−1	
30, 10	90, 10	0·35, 1	4	−0·222	7	74·9	24·0	1·1	88·6		−1
30, 1	90, 1	90, 1	0	−2·286	76	97·4	2·6	0·0			
30, 1	90, 1	3·5, 1	0	−2·104	70	96·8	3·2	0·0	92·1	−6	
30, 1	90, 1	0·35, 1	0	−1·961	65	92·4	7·6	0·0	85·8		−11
30, 1	90, 1	0·035, 1	0	−1·817	61	63·3	34·6	2·1			
30, 10	90, 10	90, 1	0	−2·143	71	80·1	19·2	0·8			
30, 10	90, 10	3·5, 1	0	−1·996	67	78·3	20·9	0·8	93·1	−5	
30, 10	90, 10	0·35, 1	0	−1·920	64	74·9	24·0	1·1	89·6		−7
C. No gravel											
30, 1	30, 1	90, 1	4	−0·247	8	95·5	4·5	0·0			
30, 1	30, 1	3·5, 1	4	−0·237	8	95·1	4·9	0·0	96·1	0	
30, 1	30, 1	0·35, 1	4	−0·222	7	91·6	8·4	0·0	90·0		−1
30, 10	30, 10	90, 1	4	−0·244	8	74·2	24·5	1·4			
30, 10	30, 10	3·5, 1	4	−0·234	8	72·9	25·6	1·4	96·1	0	
30, 1	30, 1	90, 1	0	−2·181	73	95·6	4·4	0·0			
30, 1	30, 1	3·5, 1	0	−2·093	70	95·1	4·9	0·0	95·9	−3	
30, 1	30, 1	0·35, 1	0	−1·960	65	91·6	8·4	0·0	89·9		−7
30, 10	30, 10	90, 1	0	−2·084	69	74·2	24·4	1·4			
30, 10	30, 10	3·5, 1	0	−1·997	67	72·9	25·6	1·4	95·8	−3	
D. Extra thick veneer (10-cm thick)											
30, 1	90, 1	90, 1	4	−0·229	8	97·0	3·0	0·0			
30, 1	90, 1	3·5, 1	4	−0·212	7	94·8	5·1	0·0	92·5	−1	
30, 1	90, 1	0·35, 1	4	−0·197	7	76·5	23·1	0·4	86·1		−1
30, 10	90, 10	90, 1	4	−0·236	8	79·1	20·1	0·8			
30, 10	90, 10	3·5, 1	4	−0·218	7	76·1	23·0	1·0	92·3	−1	
30, 1	90, 1	90, 1	0	−2·021	67	97·0	3·0	0·0			
30, 1	90, 1	3·5, 1	0	−1·870	62	94·8	5·1	0·0	92·5	−5	
30, 1	90, 1	0·35, 1	0	−1·762	59	76·5	23·1	0·4	87·2		−9
30, 10	90, 10	90, 1	0	−2·018	67	79·1	20·1	0·8			
30, 10	90, 10	3·5, 1	0	−1·859	62	76·0	23·0	1·0	92·1	−5	
E. Aquifer 2 km wide on western side of river instead 1 km											
30, 1	90, 1	90, 1	4	−1·663	55	97·4	2·6	0·0			
30, 1	90, 1	3·5, 1	4	−1·536	51	96·8	3·2	0·0	92·4	−4	
30, 10	90, 10	90, 1	4	−1·565	52	80·1	19·2	0·8			
30, 10	90, 10	3·5, 1	4	−1·456	49	78·3	20·9	0·8	93·1	−4	
30, 1	90, 1	90, 1	0	−2·340	78	97·4	2·6	0·0			
30, 1	90, 1	3·5, 1	0	−2·154	72	96·8	3·2	0·0	92·1	−6	
30, 10	90, 10	90, 1	0	−2·188	73	80·1	19·2	0·8			
30, 10	90, 10	3·5, 1	0	−2·039	68	78·3	20·9	0·8	93·2	−5	
F. Aquifer twice as thick											
30, 1	90, 1	90, 1	4	1·047		86·3	13·5	0·2			
30, 1	90, 1	3·5, 1	4	0·987		84·8	15·0	0·2	94·2		
30, 10	90, 10	90, 1	4	0·985		63·4	31·5	5·1			

Table I. (*Continued*)

K (m/day), anisotropy						% seepage per channel segment					
Alluvium	Gravel	Veneer	Δh (m)	Total flux (m^2/day)	Percentage from river (%)	Side channel	Mid-channel bar	Thalweg	% seepage relative to no veneer	% difference 90 *versus* 3·5 m/day	% difference 90 *versus* 0·35 m/day
30, 10	90, 10	3·5, 1	4	0·937		61·3	33·3	5·4	95·2		
30, 1	90, 1	90, 1	0	−2·125	71	86·3	13·5	0·1			
30, 1	90, 1	3·5, 1	0	−2·001	67	84·8	15·0	0·2	94·1	−4	
30, 10	90, 10	90, 1	0	−2·028	68	63·5	31·4	5·1			
30, 10	90, 10	3·5, 1	0	−1·921	64	61·3	33·3	5·4	94·7	−4	
G. Irrigation well pumped at 6 instead of 3 m^2/day)											
30, 1	90, 1	90, 1	4	−2·566	43	97·4	2·6	0			
30, 1	90, 1	3·5, 1	4	−2·360	39	96·8	3·2	0	92·0	−3	
30, 1	90, 1	0·35, 1	4	−2·198	37	92·5	7·6	0	85·7		−6
30, 10	90, 10	90, 1	4	−2·409	40	80·1	19·1	0·7			
30, 10	90, 10	3·5, 1	4	−2·231	37	78·3	20·9	0·8	92·6	−3	
30, 1	90, 1	90, 1	0	−4·586	76	97·4	2·6	0			
30, 1	90, 1	3·5, 1	0	−4·216	70	96·8	3·2	0	91·9	−6	
30, 1	90, 1	0·35, 1	0	−3·919	65	92·4	7·6	0	85·5		−11
30, 10	90, 10	90, 1	0	−4·291	72	80·1	19·2	0·7			
30, 10	90, 10	3·5, 1	0	−3·985	66	78·3	20·9	0·8	92·9	−5	
H. Municipal well at 100 m pumping at 15 m^2/day											
30, 1	90, 1	90, 1	4	−11·436	76	93·4	6·6	0			
30, 1	90, 1	3·5, 1	4	−11·099	74	92·3	7·7	0	97·1	−2	
30, 1	90, 1	90, 1	0	−13·150	88	93·4	6·6	0			
30, 1	90, 1	3·5, 1	0	−12·770	85	92·3	7·7	0	97·1	−3	
I. Municipal well under river											
30, 1	90, 1	90, 1	4	−13·059	87	−12·5	110·8	1·8			
30, 1	90, 1	3·5, 1	4	−13·014	87	−12·4	110·5	1·9	99·7	0	
30, 1	90, 1	0·35, 1	4	−12·589	84	−11·7	108·3	3·4	96·4		−3
30, 1	90, 1	0·035, 1	4	−11·595	77	−6	87·7	18·3			
30, 1	90, 1	90, 1	0	−14·853	99	0·1	98·3	1·5			
30, 1	90, 1	3·5, 1	0	−14·807	99	0·1	98·2	1·7	99·7	0	
30, 1	90, 1	0·35, 1	0	−14·385	96	0·2	96·8	3	96·8		−3
30, 1	90, 1	0·035, 1	0	−13·493	90	2·5	81·7	15·8			
30, 1	90, 10	0·35, 1	4	−11·625	78	−9·9	100·7	9·3			
30, 1	90, 10	0·35, 1	0	−13·464	90	1·6	90·4	8			
J. Municipal well under river, thick veneer											
30, 1	90, 1	90, 1	4	−12·427	83	−13·6	111·8	1·8			
30, 1	90, 1	3·5, 1	4	−12·515	83	−12·2	109	3·2	100·7	1	
30, 1	90, 1	0·35, 1	4	−12·074	80	−6·8	89·8	17	97·2		−2
30, 1	90, 1	90, 1	0	−14·239	95	0·1	98·3	1·6			
30, 1	90, 1	3·5, 1	0	−14·237	95	0·2	97	2·8	100·0	0	
30, 1	90, 1	0·35, 1	0	−13·748	92	2·7	83	14·3	96·6		−3
30, 1	90, 10	0·35, 1	4	−11·785	79	−4·8	86·6	18·2			
30, 1	90, 10	0·35, 1	0	−13·551	90	4·1	80	15·9			

Pumping rate was 3 m^2/day for all simulations of an irrigation well (except where noted) and pumping rate was 15 m^2/day for all simulations of a municipal well.

total riverbed seepage decreases about 2% and seepage flowing through the mid-channel bar increases about 1–2%. Seepage is shifted from the side channel to the mid channel and thalweg to a slightly greater extent with anisotropy of 10 (Table I(C) *vs* (B)).

Increasing veneer thickness to 0·1 m. Increasing thickness of the veneer to 0·1 m results in very small changes in flow and distribution of flow from the river if $\Delta h = 4$ m. The river supplies 8 as opposed to 9% of the water to the irrigation well for K_{ven} of 90 and 7 as opposed to 8% for K_{ven} of 3·5 m d^{-1} (Table I(D) *vs* (B)). Changes are somewhat more substantial when $\Delta h = 0$. For K_{ven} values of 90, 3·5, and 0·35 m d^{-1}, contributions from the river are 9, 8, and 6% smaller, respectively, than river contributions with the 0·02-m thick veneer (Table I(D) *vs* (B)). Anisotropy causes little change relative to simulations with the thin veneer.

Distribution of seepage across the riverbed changes only slightly for large values of K_{ven}, but seepage is shifted away from the side channel to a greater extent as K_{ven} is decreased with a 0·1-m thick veneer. If K_{ven} is 90, and veneer thickness is increased from 0·02 to 0·1 m, percentage of total seepage through the side channel,

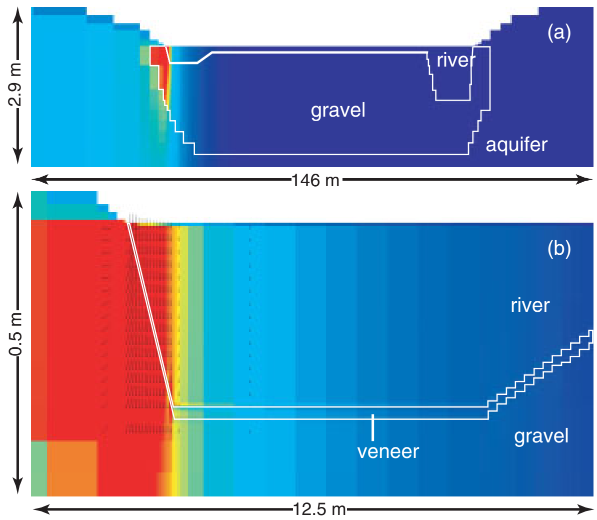


Figure 3. Distribution of seepage across riverbed cross section. Red colours indicate fast seepage; blue colour indicates slow seepage. Vertical exaggeration = 14. (a) Entire riverbed, (b) Western channel with K_{ven} of 3·5 m d^{-1}. Vector direction and length indicated for every fourth model cell

mid-channel bar, and thalweg changes by −0·4, 0·4, and 0·0%, respectively, with a homogeneous aquifer and a Δh of 4 or 0 m. If K_{ven} is 0·35, while thickness is increased from 0·02 to 0·1 m, percentages of seepage through the three riverbed features change by −15·9, 15·5, and 0·4 no matter the Δh (Table I(D) *vs* (B)).

Doubling aquifer width. Contribution of river water to the irrigation well is increased substantially when aquifer width is doubled, increasing from 7 to 9% for the standard modelled configurations (Table I(B)) to 49–55% for simulations where the aquifer width is doubled (Table I(E)). This substantial change is due to the slope of the aquifer being halved relative to the standard configuration; the aquifer width is doubled but the head difference across the aquifer remains the same. The change in percentage contribution from the river is much smaller (about 2%) when Δh is 0 (Table I(E) *vs* (B)). Little change is indicated in the distribution of seepage across the river channel resulting from doubling the aquifer width.

Doubling aquifer thickness. The screened interval of the simulated irrigation well is shifted downward when aquifer thickness is doubled, changing the vertical position of the well relative to the bed of the river. With the irrigation well located farther from the water table and from the river surface, the influence of the irrigation well is not sufficient to reverse the hydraulic gradient near the river and no water is provided by the river when Δh is 4 m. Therefore, values for total flux where $\Delta h = 4$ m are positive rather than negative (Table I(F)). Water continues to discharge across the entire width of the river at about half the rate relative to seepage without an irrigation well, and the distribution of seepage is altered substantially relative to the basic modelled conditions, especially when anisotropy is increased to 10 (Table I(F) *vs* (B)). As with previous simulations, the veneer has little effect either on reduction in water originating from the river or on distribution of seepage across the riverbed.

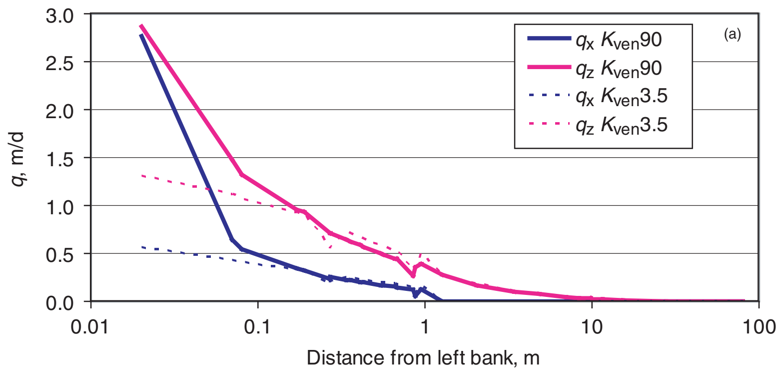
This is the only modelled setting with a 0·02-m thick veneer and an irrigation well located 0·33 km from the river in which seepage through the thalweg becomes significant, and even then only when anisotropy is increased to 10. Slightly more than 5% of the seepage takes place in the thalweg when anisotropy is 10, and approximately one third of the seepage occurs through the mid-channel bar (Table I(F)).

Doubling pumping rate. Doubling the pumping rate of the irrigation well when Δh is 4 m increases the percentage contribution from the river from about 9% to about 40% (Table I(G) *vs* (B)). The effect of decreasing K_{ven} is greater with a larger pumping rate. For the standard pumping rate of 3 m^2 d^{-1} and a Δh of 4 m, reducing K_{ven} by a factor of 25 decreases the contribution from the river by 1%. With a doubled pumping rate, the contribution from the river decreases by 3% with the same reduction in K_{ven} (Table I(G) *vs* (B)). Doubling the pumping rate with $\Delta h = 0$ has very little effect on the percentage contribution of water from the river or on the distribution of seepage through the bed relative to the standard modelled conditions (Table I(G) *vs* (B)).

Municipal well at 100 m. The river supplies 76% of the water to a municipal well located 100 m from the river when Δh is 4 m, and 88% when Δh is 0 m (Table I(H)). The relatively small difference related to the aquifer gradient is due to the larger pumping rate (15 m^2 d^{-1} as opposed to 3 m^2 d^{-1}), which induces supply from the western boundary of the aquifer even with zero aquifer gradient. Reducing K_{ven} has little effect on the amount of water supplied by the river or on the distribution of water across the river cross section.

Municipal well beneath river. Pumping from a municipal well located directly beneath and parallel to the river draws nearly all the water from the river, as one might expect. The river supplies 87% of the water with a Δh of 4 m and 99% with a Δh of 0 m whether a thin, low-permeability veneer is present or not (Table I(I)). Only when K_{ven} is reduced to 0·35 m d^{-1} does the percentage contribution from the river decrease, and then only slightly.

Distribution of seepage across the riverbed is greatly different when the well is located directly beneath the river. With zero gradient across the aquifer west of the river, nearly all the seepage occurs at the mid-channel bar; virtually no seepage occurs at the side channel and 1·5–3% of the seepage occurs at the thalweg. However, when Δh is 4 m, seepage distribution changes in a way that might be considered surprising. Horizontal flow across the aquifer, combined with strong pumping from the municipal well, results in water flowing to rather than from the river through the entire side channel, where values for percentage seepage through the side channel



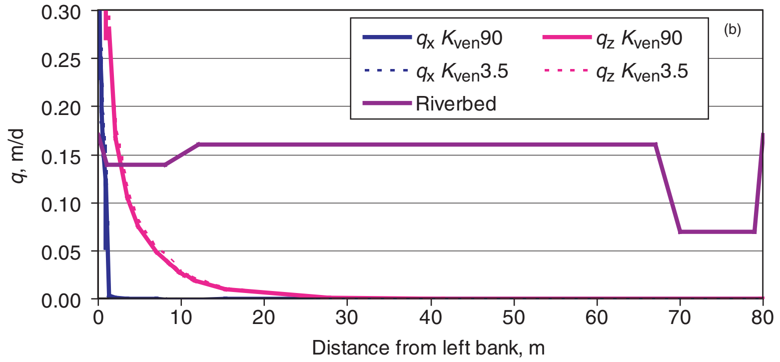


Figure 4. Seepage velocity (q) distribution across the riverbed with no irrigation well, aquifer head at the western boundary 4 m higher than river stage, and K_{ven} of 90 and 3·5 m d^{-1}. Subscripts x and z denote flow along horizontal and vertical axes, respectively. (a) Log plot showing exponential decrease in seepage with distance from western shoreline, (b) Riverbed profile included to show seepage distribution per riverbed segment

are negative (Table I(I)). The river provides a short circuit for water to flow from the portion of the aquifer west of the river to the municipal well beneath the river. Water that enters the river via the side channel is then pulled back into the aquifer through the mid-channel bar, where percentage contribution of seepage is greater than 100%.

Curiously, very little water is supplied to the municipal well via the thalweg. Even with large anisotropy and small K_{ven}, a condition most favourable for routing flow through the thalweg, seepage via the thalweg is only 8–9% (Table I(I)).

Municipal well beneath river with 0·1-m thick veneer. Draping all but the thalweg with a 0·1-m thick veneer reduces the amount of water supplied to the municipal well by about 4% compared to simulations of a 0·02-m thick veneer (Table I(J) *vs* (I)). If the gravel is anisotropic, the contribution of water from the river to

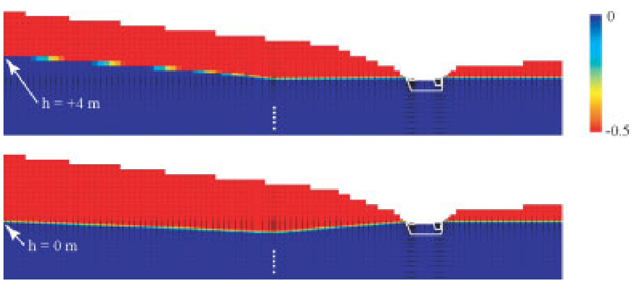


Figure 5. Water-table configuration with Δh between the western boundary and the river either +4 or 0 m and with a simulated well pumping at 3 m^2/day. Output is in pressure head (m of water)

the pumping well is virtually unchanged compared to the thinner veneer.

Thickening the veneer from 0·02 to 0·1 m results in very little redistribution of seepage across the riverbed, both without a veneer and with a K_{ven} of 3·5 m d^{-1}. However, reducing K_{ven} to 0·35 m d^{-1} results in the largest contribution of seepage via the thalweg of all simulations. Percentage contribution via the thalweg changes from about 3 to between 14 and 17% with an additional order-of-magnitude decrease in K_{ven}. Although percentage seepage via the thalweg is larger when Δh is 4 m than when Δh is 0 m, the opposite of what one would expect, that is due to the short-circuiting of water from the aquifer via the river as mentioned earlier. Water induced to flow from the aquifer to the river near the west bank is directed to the pumping well via the thalweg to a greater extent than when a thinner veneer is present on the rest of the bed (Table I(J) *vs* (I)).

Adding anisotropy to the gravel when a 0·1-m thick veneer is draped over the bed and K_{ven} is 0·35 distributes seepage even more uniformly across the bed and reduces slightly the percentage contribution of river water to the pumping well directly beneath the river. The thalweg delivers 15·9 and 18·2% of the river water to the municipal well, depending on the Δh across the aquifer (Table I(J)).

DISCUSSION

The presence of a thin veneer of low K sediment results in only a small change in the percentage contribution

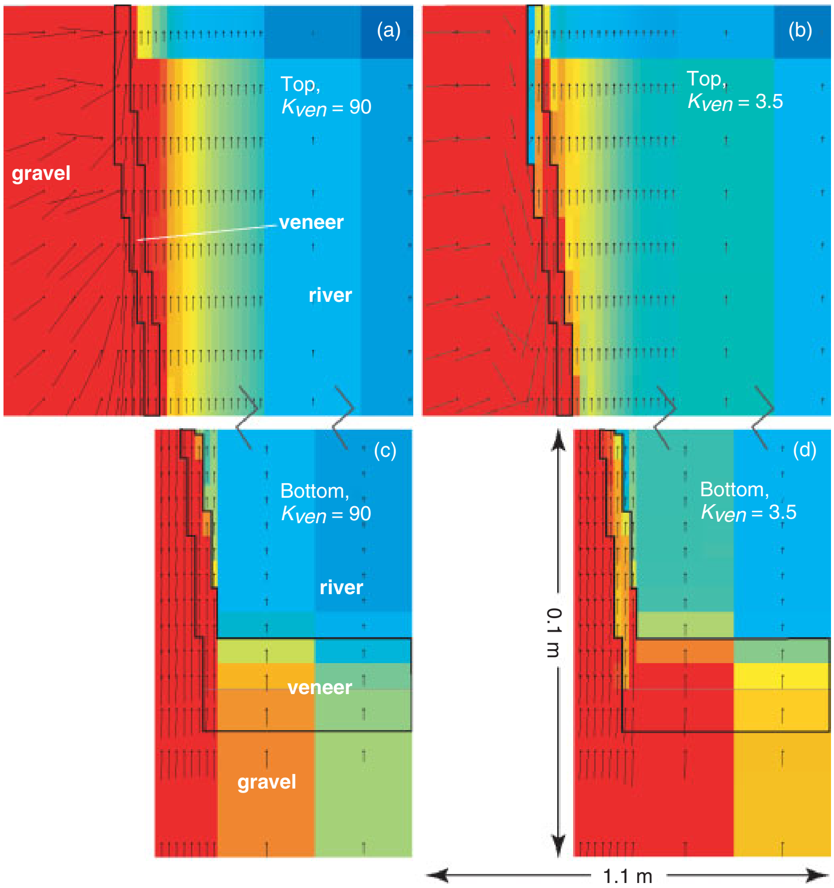


Figure 6. Seepage velocity through upper (panels a and b) and lower (panels c and d) parts of the western segment of the side channel for K_{ven} values of 90 and 3·5 m d^{-1}. Red depicts fast seepage and blue depicts slow seepage. Line segments indicate seepage direction and relative velocity, with the dot at one end of the line segment indicating the centre of a model cell. Vertical exaggeration = 14

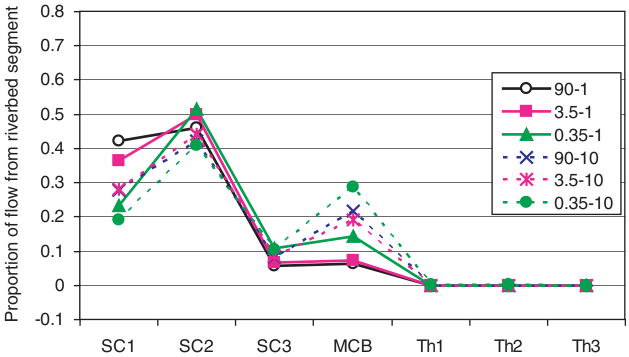


Figure 7. Distribution of seepage across river transect for 0·02-m thick sediment veneer of various hydraulic conductivities. SC, side channel; MCB, mid-channel bar; Th, thalweg. Values in legend indicate K_{ven} (m d^{-1}) followed by anisotropy of 1 or 10

of river water to a pumping well for most simulated settings. A sloping water table across the aquifer further reduces the influence on the veneer because it makes water from the western portion of the aquifer more readily available to the pumping well. Largest changes (3–11%) occur when Δh is 0 and K_{ven} is reduced to 0·35, one order-of-magnitude smaller than measured in the field. This indicates that the hydraulic gradient is largely compensating for reductions in K_{ven}, leaving seepage little changed.

Exchanges may be larger, however, for some river reaches if the assumptions associated with use of a 2-D model are substantially violated. The model was applied with the assumption that exchange between the river and aquifer is uniform along a river reach approximately as long as one side of a quarter section of land (805 m). Radial flow to a pumping well would result in contribution from the river being largest along the river reach that is closest to the well. However, conclusions from the modelling results were basically the same when the pumping rate was doubled (Table I(G)) or even when a well was located one third the distance from the river and pumped at five times the rate (Table I(H)). A low-K veneer still did not have a substantial effect on percentage contribution from the river or on the distribution of exchange across the riverbed. Therefore, it is unlikely that use of a 3-D model would generate substantially different conclusions.

Measured and simulated changes in K at the sediment–water interface were much larger than is typically assumed for fluvial settings. Others also have noted large changes in K at the sediment–water interface in laboratory, natural, and anthropogenically modified settings. K at the bed surface was reduced more than three orders-of-magnitude in a laboratory study where downward seepage was induced with a surface-water current (Rosenberry and Pitlick, 2009a). K and seepage from a lake were increased by three orders-of-magnitude following removal of the clogging layer of a natural lakebed setting (Rosenberry *et al.*, 2010). K was reduced one to two orders-of-magnitude in a natural streambed where seasonal low flow led to the deposition of fine-grained sediment on the streambed (Hatch *et al.*, 2010). K was reduced by nearly six orders-of-magnitude where the riverbed was severely clogged at a RBF site near Dusseldorf, Germany (Schubert, 2006).

To test the inference that a sediment veneer is substantial on a RBF scale only after three or more orders-of-magnitude reduction in K, the model was run with K_{ven} reduced from 90–0·035 m d^{-1}. The model would not converge for many of the simulations with such extreme contrasts in K, especially if sediments were anisotropic. However, the model was successful in simulating the irrigation well 0·33 km from the river and the municipal well directly beneath the river with isotropic sediment. With K_{ven} reduced by more than three orders-of-magnitude, the percentage contribution of river water was reduced by 2 and 15% for the irrigation well and by 10 and 9% for the municipal well beneath the river, depending on Δh (Table I(B) and (I)). Reductions would have been larger if not for seepage through the thalweg, which did not have a veneer.

With three-plus orders-of-magnitude reduction in K_{ven}, seepage distribution changed markedly. One additional order-of-magnitude reduction in K_{ven} (to 0·035 m d^{-1}) resulted in percentage contributions of seepage through the side channel, mid-channel bar, and thalweg changing from 92·4, 7·6, and 0 to 63·5, 34·4, and 2·1%, respectively in response to pumping from the irrigation well 0·33 km from the river (Table I(B)). This was a much larger change than previous order-of-magnitude reductions. A similarly large change occurred for the simulated municipal well located beneath the river. Reducing K_{ven} to 0·035 m d^{-1} changed the seepage percentages of the aforementioned river segments from 0·2, 96·8, and 3 to 2·5, 81·7, and 15·8% (Table I(I)). This more substantial redistribution of seepage across the riverbed indicates that it takes three or more orders-of-magnitude reduction in K_{ven} to result in sediment clogging that is important on an aquifer extraction scale. This indicates that clogging associated with ephemeral veneers that form under natural conditions generally is not significant to larger-scale exchange between the aquifer and the river. However, clogging associated with large or prolonged hydraulic gradients caused by pumping from the alluvial aquifer could further reduce K_{ven} and greatly change the rate and distribution of seepage across the riverbed.

The low-K veneer simulated here is thicker than that observed at most locations along the South Platte River. In some locations, a low-K veneer does not even occur (Chen *et al.*, 2008). A thicker veneer on the riverbed could form when prolonged periods of low flows during summer and fall are uninterrupted by substantial rainfalls, allowing sediment deposition to accumulate to a greater degree than observed during field studies thus far. However, increasing the thickness of the veneer by a factor of 5 had surprisingly little effect on seepage rate or distribution. Simulations of a 0·1-m thick bed with $\Delta h = 0$ indicate a decrease in water supplied to the irrigation well from the river by only 6–9% relative to the thin-veneer (0·02 m) model runs (76 *vs* 67% for $K_{\text{ven}} = 90$; 70 *vs* 62% for $K_{\text{ven}} = 3{\cdot}5$; 65 *vs* 59% for $K_{\text{ven}} = 0{\cdot}35$) (Table I(B) and (D)). The effect of a thicker veneer is even smaller when a simulated municipal well, pumping at triple the rate, is located directly beneath the river (Table I(I) and (J)). With a lower-K, thicker veneer, the river supplies nearly the same amount of water to the municipal well, but more of the water comes through the mid-channel bar and thalweg.

If the low-K layer is an order-of-magnitude thicker, however, it is likely that far greater redistribution of seepage exchange will occur and the reduction in river flow will likely be much more substantial (Chen *et al.*, 2008). Much larger sediment thickness could occur behind a dam, for example. Su *et al.* (2007) simulated flow to a large-volume pumping well in an impounded setting where the simulated thickness of a low-K layer was 1 m. Their results indicated that a reduction in K_{ven} of two orders-of-magnitude resulted in large areas beneath the riverbed becoming unsaturated and in substantial amounts of water coming from the river near the bank opposite the pumping well. Pumping rates were much larger in their simulations, however.

Seepage distribution

Distribution of seepage across the riverbed is independent of hydraulic gradient across the aquifer for most simulated settings. The percentage seepage through each riverbed segment is the same whether Δh is 4 or 0 m. Largest changes in the distribution of seepage with an irrigation well located 0·33 km west of the river occur in response to order-of-magnitude increases in anisotropy and changing the geometry of the aquifer; next largest changes result from order-of-magnitude reductions in K_{ven}. Other changes, such as removing the gravel or increasing veneer thickness, create changes in seepage distribution that are much smaller in comparison.

The presence of a low-K veneer shifts seepage slightly from the side channel to the mid-channel bar when a well is located lateral to the river. In the standard setting with an irrigation well, seepage is reduced by 5% in the side channel and increased by 5% at the mid-channel bar if K_{ven} is 0·35 m d^{-1} (Table I(B)). Shifts in seepage distribution due to the presence of the veneer are smaller yet when a municipal well is located beneath the river. A two orders-of-magnitude decrease in K_{ven} results in a 0·1% increase in seepage through the side channel, a 1·5% decrease at the mid-channel bar, and a 1·5% increase at the thalweg when Δh is 0 (Table I(I)).

It is somewhat surprising that so little water flows via the thalweg given that a low-K veneer is never present at the thalweg. This may be explained in part by the relative remoteness of the thalweg to a pumping well compared to the other river segments, especially

Table II. Modelled parameters of alluvium, gravel, and low-K veneer, specified difference in head across western portion of the aquifer (Δh), percentage seepage contribution from channel segments when a side channel exists in the river, and percentage seepage contribution from channel segments without the presence of a side channel in the river

K (m/day), anisotropy				% seepage per original channel segment			% seepage per channel segment—no side channel		
Alluvium	Gravel	Veneer	Δh (m)	Side channel	Mid-channel bar	Thalweg	Former side channel	Mid-channel bar	Thalweg
A. Irrigation well pumping at 3 m²/day									
30, 1	90, 1	90, 1	4	97·4	2·6	0·0	97·9	2·1	0·0
30, 1	90, 1	3·5, 1	4	96·8	3·2	0·0	97·5	2·5	0·0
30, 1	90, 1	0·35, 1	4	92·4	7·6	0·0	94·4	5·6	0·0
30, 1	90, 1	0·035, 1	4	63·5	34·4	2·1	68·3	29·8	1·9
30, 1	90, 1	90, 1	0	97·4	2·6	0·0	97·9	2·1	0·0
30, 1	90, 1	3·5, 1	0	96·8	3·2	0·0	97·5	2·5	0·0
30, 1	90, 1	0·35, 1	0	92·4	7·6	0·0	94·4	5·6	0·0
30, 1	90, 1	0·035, 1	0	63·3	34·6	2·1	68·0	30·0	1·9
B. Extra thick veneer (10-cm thick)									
30, 1	90, 1	90, 1	4	97·0	3·0	0·0	96·8	3·2	0·0
30, 1	90, 1	3·5, 1	4	94·8	5·1	0·0	95·1	4·9	0·0
30, 1	90, 1	0·35, 1	4	76·5	23·1	0·4	81·5	18·2	0·3
30, 1	90, 1	0·035, 1	4	no model convergence			44·6	37·4	18·0
30, 1	90, 1	90, 1	0	97·0	3·0	0·0	96·8	3·2	0·0
30, 1	90, 1	3·5, 1	0	94·8	5·1	0·0	95·1	4·9	0·0
30, 1	90, 1	0·35, 1	0	76·5	23·1	0·4	81·5	18·2	0·3
30, 1	90, 1	0·035, 1	0	no model convergence			42·1	39·1	18·8
C. Municipal well 100 m from river pumping at 15 m²/day									
30, 1	90, 1	90, 1	4	93·4	6·6	0·0	97·9	2·1	0·0
30, 1	90, 1	3·5, 1	4	92·3	7·7	0·0	97·5	0·0	0·0
30, 1	90, 1	90, 1	0	93·4	6·6	0·0	97·9	2·1	0·0
30, 1	90, 1	3·5, 1	0	92·3	7·7	0·0	97·5	0·0	0·0

Simulated irrigation well is 0·33 km from river and pumping at 3 m^2/day.

when the well is located beyond the riverbank opposite the thalweg. With a well located directly beneath the river, the vertical distance from the well to the mid-channel bar is only 8 m, whereas the horizontal distance to the closest portion of the thalweg is 28 m. The fact that the low-K veneer substantially re-routes water via the thalweg only when K_{ven} is reduced to 0·035 m d^{-1} suggests that the ~25-fold reduction in K observed at the South Platte River field site (Rosenberry and Pitlick, 2009b) would have little influence on river/aquifer interaction.

The side channel, because of its slightly deeper extent, may also have focused seepage exchange near the shoreline and may be largely responsible for the exceptionally small influence of the thalweg. To test this possibility, several conditions were simulated without the existence of a side channel: (1) an irrigation well 0·33 km from the river pumping at 3 m^2/day, (2) an irrigation well 0·33 km from the river pumping at 3 m^2/day with a sediment veneer 10-cm thick, and (3) a municipal well located 100 m from the river pumping at 15 m^2/day. For each of these three settings, simulations were run with Δh at 4 and 0 m. The low-permeability veneer was present everywhere except for the thalweg. Eliminating the side channel had very little effect on seepage through the thalweg (Table II). There was a small redistribution of seepage between the bed segment formerly occupied by the side channel and the mid-channel bar, but exchange through the thalweg was equally small with or without the presence of the side channel. The only simulation that routed substantial water through the thalweg was when K_{ven} was reduced by more than three orders-of-magnitude to 0·035 m/day. This extreme reduction in permeability at the sediment–water interface of all but the thalweg diverted nearly 20% of the seepage exchange to the thalweg.

Short-circuiting of flow, allowing water to flow from a more distant portion of the aquifer to the well via the river, was an unexpected but logical condition when the pumping well was located beneath the river. Even with no veneer on the bed, water could flow much more readily through the river than through the underlying gravel. The asymmetric conditions of higher head to the west of the river when Δh was +4, very large gradients directly beneath the central portion of the mid-channel bar, and the lack of a veneer in the thalweg was sufficient to induce flow from the aquifer to the side channel even as K_{ven} was decreased more than two orders-of-magnitude (Table (I) and (J)).

SIGNIFICANCE

The likelihood that pumping from the alluvial aquifer will have a substantial effect on the distribution of seepage through the bed of the South Platte River is small so long as the bed continues to be regularly mobile. Modelling results indicate that the bed would need to be stable long enough for a low-permeability veneer to form that is three orders-of-magnitude lower in permeability than the substrate. If, however, aquifer pumping either is sufficiently strong or continuous to enhance the formation of a clogging layer, the stability of the low-K veneer could be increased and the incidence of bed mobility could be reduced as the threshold of bed mobility is increased. Should that happen, biofilms and algal mats, which currently are regularly disturbed by flushing events, may accumulate and alter streambed metabolism (McCutchan Jr, *et al*., 2002; Cronin *et al*., 2007). Changes in bed stability also could substantially affect rates of denitrification (McMahon and Boehlke, 1996) and release of nitrogen gas to the atmosphere via ebullition (Higgins *et al*., 2008).

A thin clogging layer sufficient to reduce exchange at the sediment–water interface could be deleterious to benthic invertebrates in undisturbed and RBF-influenced riverbeds. Numerous studies have indicated an inverse relation between degree of clogging and both population density and species richness of benthic invertebrates (Wood and Armitage, 1997; Gayraud and Philippe, 2003; Weigelhofer and Waringer, 2003; Bo *et al*., 2007).

Stability, hydraulic properties, and thickness of a clogging layer also depend on duration of pumping. All model simulations were run to steady state, which required, depending on the simulation, about 250 to over 500 days. This pumping duration would be reasonable for simulations of a municipal water-supply well. However, most pumping wells for irrigation only operate during the growing season, which lasts no more than about 180 days. If a low-permeability veneer forms on the river on a seasonal basis, it likely would not form until shear stress decreased following spring runoff, which typically occurs sometime between early to late July, leaving only 2–3 months during which large hydraulic gradients in response to nearby pumping of groundwater could induce clogging of the bed. During those times, water supplied directly from the river could be reduced by up to 5–10%, depending on the thickness of the veneer compared to times when the veneer was not present. If the aquifer was being recharged by leaking canals, then this reduction would be largely irrelevant from a water-rights perspective because virtually all the water supplied to the well would have originated from the river via the canals. But, if the riparian aquifer was supplied by a source other than the river, such as an adjacent non-riparian aquifer, then the significance of the origin of the water supplied to the pumping well would be of concern to water regulators, and fluvial processes associated with the presence or absence of the low-permeability veneer could become relevant to water-rights issues.

CONCLUSIONS

Simulations of flow along a transect perpendicular to a river and associated riparian aquifer indicate that a veneer of low-permeability sediments as thin as 0·02 m can reduce the supply of river water to an irrigation well by 1 to nearly 10%. Degree of reduction depends on the hydraulic gradient and anisotropy of the aquifer and riverbed gravel sediments, the degree of reduction in K of the thin veneer, geometry of the aquifer, and the distance of the well from the river. Largest reductions in river water supplied to the irrigation well occur when the initial hydraulic gradient across the aquifer is 0 and in response to reduced K of the veneer and increased anisotropy of the aquifer. Vertical hydraulic gradient can largely compensate for a thin clogging layer for relatively small reductions in K of the veneer.

However, if K of the veneer is reduced an additional two orders-of-magnitude beyond that observed at the South Platte River field site, contribution of river water to an irrigation well is reduced by 2–15% if the well is lateral to the riverbank or 9–10%, if a municipal well is located directly beneath the river.

The distribution of seepage through the riverbed cross section is independent of the hydraulic gradient across the aquifer for most simulations and depends primarily on local-scale physical conditions. For most simulations, over 90% of the seepage flows through the 12-m wide west-bank channel, which constitutes 15% of the channel width. Virtually no seepage occurs through the thalweg unless (1) the well is located directly beneath the river, (2) K_{ven} is reduced while anisotropy is increased, or (3) K_{ven} is reduced by three or more orders-of-magnitude even though the thalweg was always modelled without a low-permeability veneer. Once K_{ven} is reduced by more than three orders-of-magnitude, the thalweg transmits 16–18% of the flow through the riverbed. Removing the side channel has little effect on percentage contribution from the thalweg.

The riverbed profile modelled here also maximizes the influence of fluvial processes on exchange between groundwater and surface water because the parts of the riverbed that experience marginal or no sediment transport are nearest to the pumping well. If the thalweg was on the same side of the river as the pumping well, the distribution of seepage would be confined entirely to the vicinity of the thalweg.

Results indicate that a thin veneer of low-K sediment causes little change in seepage rate or distribution unless K of the veneer is three or more orders-of-magnitude smaller than K of the riverbed gravel. Similarly large reductions in K are reported for clogged layers at RBF sites. Although reductions in K of the veneer at the South Platte River field site were never greater than about a factor of 25, much larger reductions have been reported for laboratory and undisturbed natural settings. A thin clogging veneer may exert a greater influence in many other riparian settings where flow in the river is slow for prolonged periods or where the streambed is largely immobile; for example, upstream of dams.

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