

Influence of perched groundwater on base flow

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[1] Analysis with a three-dimensional variably saturated groundwater flow model provides a basic understanding of the interplay between streams and perched groundwater. A simplified, layered model of heterogeneity was used to explore these relationships. Base flow contribution from perched groundwater was evaluated with regard to varying hydrogeologic conditions, including the size and location of the fine-sediment unit and the hydraulic conductivity of the fine-sediment unit and surrounding coarser sediment. Simulated base flow was sustained by perched groundwater with a maximum monthly discharge in excess of 15 L/s (0.6 feet³/s) over the length of the 2000-m stream reach. Generally, the rate of perched-groundwater discharge to the stream was proportional to the hydraulic conductivity of sediment surrounding the stream, whereas the duration of discharge was proportional to the hydraulic conductivity of the fine-sediment unit. Other aspects of the perched aquifer affected base flow, such as the depth of stream penetration and the size of the fine-sediment unit. Greater stream penetration decreased the maximum base flow contribution but increased the duration of contribution. Perched groundwater provided water for riparian vegetation at the demand rate but reduced the duration of perched-groundwater discharge nearly 75%.

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1. Introduction

[2] Restoring historic water table elevations is often impractical due to the growing consumption of water by humans. Consequently, present and future restoration of streams may benefit by taking advantage of focused areas of water availability, such as perched or mounded groundwater caused by geologic heterogeneity. Perched or mounded groundwater may act as a partial surrogate for regional groundwater that normally surrounds streams by limiting seepage loss, providing base flow and bank storage.

[3] Historically, the significance of aquifers has been evaluated with regard to water resources for human use, and it is often cast in terms of how much water could be produced by wells. This is one reason why there has been limited quantitative analysis of perched stream water/groundwater systems. However, perched groundwater may contribute in other ways, especially factors related to the functioning of lotic and riparian zones. An important measure of significance of a perched system would be how much water can flow to an ecosystem or wetland, which is in turn also indicative of temporal persistence of the perched system.

[4] Commonly, it is assumed that when a regional water table drops below and separates from the saturated zone

associated with a streambed, the interaction between a stream and groundwater is in one direction only, where water seeps vertically from the stream toward the water table below [McDonald and Harbaugh, 1988; Winter *et al.*, 1998]. Furthermore, it is assumed that once this so-called “disconnection” occurs, additional declines in the water table will cause no additional increases in stream seepage losses. This conventional view may be sufficient in certain cases; however, it does not consider the possibility of perched or mounded groundwater due to geologic heterogeneity that may diminish seepage losses and support gaining conditions in a stream. Fleckenstein *et al.* [2006] presented model results indicating that geologic heterogeneity was responsible for localized groundwater mounding as high as the free surface of the Cosumnes River, California, where regional groundwater levels away from the river were greater than 15 m below the channel.

[5] The occurrence of shallow perched groundwater beneath streams and other surface-water bodies has been reported in the literature [Palkovics *et al.*, 1975; Rassam *et al.*, 2006; Fleckenstein *et al.*, 2006; Rains *et al.*, 2006]. In these cases, groundwater was perched due to a fine-sediment unit, usually referred to as a fragipan. All of these studies indicated that water perched above a fine-sediment unit due to high infiltration into overlying coarse-sediment unit or lateral flow from adjacent recharge. Changes in perched-groundwater storage have been related to fluctuations of stream water levels in Pennsylvania [Palkovics *et al.*, 1975], to the onset of flow in ephemeral and intermittent streams in Queensland, Australia [Rassam *et al.*, 2006], and California [Fleckenstein *et al.*, 2006], and to the storage and chemistry of vernal-pool complexes in California [Rains *et al.*, 2006].

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[6] Although perched groundwater has been reported to occur over 82×10^6 ha in the continental United States [McDaniel *et al.*, 2001], minimal quantitative analysis has been applied to better understand perched stream water/groundwater systems. Most of the work regarding perched systems has pertained to the migration of contaminants in the vadose zone [Robertson, 1977; Orr, 1999] or flow and transport in hillslopes, called subsurface storm flow, or interflow [Whipkey, 1966; Betson *et al.*, 1968; Hammermeister *et al.*, 1982a, 1982b]. However, Reid and Dreiss [1990] examined the effects of low-permeability lenses on stream infiltration and tested various models for simulating this situation. Reid and Dreiss [1990] identified the formation of saturated regions above low-K lenses but did not evaluate the interaction between streams and perched groundwater. Because perched stream water/groundwater systems have been studied minimally, there is a strong need to begin to develop a basic understanding of their behavior.

[7] As indicated by field studies, perched groundwater may form where focused infiltration is obstructed from flowing downward by sediment with low hydraulic conductivity (K). Because streams may be a source of high infiltration, they may create perched or mounded groundwater if they flow over layered sediment with contrasting K. Alluvial depositional environments typically consist of layered sediment with varying texture [Miall, 1996]. Coarse sediments such as sands and gravels tend to be more permeable units, and fine floodplain deposits such as silts and clays tend to be less permeable units. In addition to unconsolidated sediment, consolidated or partially consolidated clay layers, hardpans, and paleosols that are formed by pedogenic and cementation processes may also be present in alluvial sediment near streams [Miall, 1996; Weissmann and Fogg, 1999]. Shallow, low-K stratigraphic units or aquitards have been documented in several studies of alluvial valleys as being laterally extensive and to substantially limit vertical groundwater flow [Johnson *et al.*, 1968; Croft, 1969; Fogg, 1986; Weissmann and Fogg, 1999].

[8] Perched stream water/groundwater systems may be common because fluvial processes tend to form layered sediment structure near streams. In part, this is due to episodic aggradation and degradation of streambed deposits. The layered structure of sediment near streams can be a result of changes in sediment supply, transport capacity, channel competence, bed load transport, and other processes [Leopold *et al.*, 1964; Dietrich *et al.*, 1989; Buffington *et al.*, 1992; Buffington and Montgomery, 1999]. Song *et al.* [2007] speculate that hyporheic processes can enhance K in shallow streambed sediment due to upwelling and downwelling of water, upward flow of gas, and invertebrate activities. This effect would also favor the formation of perched stream water/groundwater systems where regional groundwater levels decline well below a stream.

[9] Recently, there have been studies that have analyzed the relationships between hyporheic exchange and K heterogeneity surrounding streams [Cardenas *et al.*, 2004; Salehin *et al.*, 2004]. An in situ experiment for a small stream in Philadelphia, Pennsylvania, indicated that the effects of streambed K heterogeneity were masked by regional groundwater gradients [Ryan and Boufadel, 2007]. Salehin *et al.* [2004] showed that because streambed

sediments tend to be strongly horizontally layered, the resulting affective anisotropy tends to limit vertical penetration of water from streams. Although the scale of layering analyzed by Salehin *et al.* [2004] was much smaller than what is considered herein, similar layering is known to occur at larger scales (e.g., paleosols, floodplain deposits) that could limit vertical penetration of seepage and favor the development of perched groundwater.

[10] In this paper we examine the effects of K heterogeneity at a lateral scale of hundreds of meters and a vertical scale of 2–5 meters on exchange rates beneath streams supported by perched groundwater. We focus on this scale and a particular arrangement of sediment heterogeneity that consists of a low-K unit underlying a high-K unit. This scale and configuration is of interest here because it is required to produce perched-groundwater conditions that have been observed [Palkovics *et al.*, 1975; Rassam *et al.*, 2006; Fleckenstein *et al.*, 2006; Rains *et al.*, 2006; Niswonger, 2006].

[11] Small-scale heterogeneities (<1 m vertically and <10 m laterally) that are known to exist within larger-scale sediment units are neglected and effective K values are used [Gelhar, 1986]. Sediment heterogeneity within the high- and low-K units is not considered here because we are focused on larger-scale average flow conditions. Although small-scale heterogeneities have been shown to affect streambed seepage, this has been shown to occur only in systems in which the regional groundwater is in contact with the stream [Cardenas *et al.*, 2004; Salehin *et al.*, 2004]. The purpose of this present work is to establish whether base flow can occur due to large-scale heterogeneity where regional groundwater levels are well below a stream.

[12] Because of the complex stratigraphic architecture of fluvial environments, there is a large amount of uncertainty regarding the effective vertical K and lateral continuity of a fine-sediment unit. Similarly, coarse-sediment channel deposits are also heterogeneous and the effective K of channel deposits is highly variable. These uncertainties form the basis for the simulation modeling presented herein. We use generic simulations to develop ranges in effective K for coarse- and fine-sediment units that result in the formation of perched groundwater that discharges to a stream. Additionally, spatial configurations of the fine-sediment unit are varied, including the length, width, and depth of the unit relative to the stream.

[13] We rely on a numerical solution of partial differential equations that govern multiphase flow of air and water through porous material (TOUGH2 [Pruess *et al.*, 1999]) to more realistically consider the physics of flow between perched groundwater and streams. Simulation of air and water allows for a realistic representation of seepage faces that occur on the surface of stream banks following the cessation of flow in streams. The amount and persistence of perched-groundwater discharge to a stream is compared in the simulations presented herein. To include the interaction with the riparian zone, evapotranspiration (ET) is simulated to evaluate the amount of root uptake that can be provided by perched groundwater near streams as well as the effects of ET on perched groundwater.

[14] Constraints on the effective K of coarse- and fine-sediment units can be imposed based on previous studies that have measured K of sediment samples taken from

streambeds and shallow alluvial depositional environments. An extensive study of alluvial sediment K of the Central Valley, California, was done by *Johnson et al.* [1968]. *Johnson et al.* [1968] found vertical K for fine sediment to range between 1.0×10^{-5} and 1.0×10^{-6} m/d, and vertical K of coarser sediment to range between 1.0×10^{-2} and 0.4 m/d. *Johnson et al.* [1968] were not able to retrieve coarse sands and gravels, so the range in the effective vertical K was likely to be greater than reported. Another study by *Riley* [1969] took averages of K values measured using the same methods as those of *Johnson et al.* [1968] from aquitard material in alluvial sediment of California and estimated an average vertical K of 2.5×10^{-6} m/d. There is also an abundance of unpublished driller's logs taken from alluvial systems that show similar layering and variability in sediment texture. *Fleckenstein et al.* [2006] analyzed 350 driller's logs and estimated the average thickness of sediment units and found them to range between 2.5 and 4.0 m. These data and the aforementioned published K values were used to establish ranges in the K and the fine-sediment unit thickness.

2. Methods

[15] A numerical model was used to evaluate certain hypothetical models of perched groundwater near streams. Perched-groundwater conditions are governed by a myriad of different combinations of system geometry, parameters, and boundary conditions. It is difficult and beyond the scope of this work to analyze all possible hydrogeologic conditions that results in perched groundwater near streams. Rather, the goal is to provide quantitative analyses of many of the key characteristics governing perched-groundwater hydrology, providing some new insights about processes as well as the foundation for future studies. Although limited in scope, this work may provide the impetus for future theoretical work based on a more complex sensitivity analysis that explores the full ranges of input parameters and system geometries. Future studies may be aided by the development of analytical solutions that provide an efficient means of exploring a more complete conceptualization of stream water/perched-groundwater systems.

2.1. Model Code

[16] A three-dimensional (3-D), variably saturated groundwater flow model (TOUGH2 [*Pruess et al.*, 1999]) was used to simulate stream/perched-aquifer interaction. TOUGH2 was chosen for this study because it is one of the few 3-D, variably saturated flow codes available that has been widely used and documented. TOUGH2 has many modules that can simulate various types of problems. The module used in this study is called EOS3, which simulates nonisothermal flow of water and air through porous rock material [*Pruess et al.*, 1999]. However, isothermal conditions were assumed, and the heat transport equations were not solved in these simulations. The purpose of simulating air was to provide a realistic approach for simulating seepage faces. Simulating seepage surfaces with Richards' equation requires switching of the boundary conditions when the sediment pressure drops below zero to avoid water flowing back into the sediment through the seepage face. This approach can lead to instabilities and inaccuracies in the model. A seepage face in the EOS3 module is simulated using model cells that are saturated with air and

represent the atmosphere, such that water cannot flow back into the sediment, and no switching of the boundary condition is required.

[17] The 3-D flow that occurs during the interaction between streams and perched groundwater is important when considering the total inflow to a stream over a discontinuous fine-sediment unit. It is the boundaries of the fine-sediment unit that cause the groundwater flow to deviate from being contained in a 2-D cross-sectional plane or 3-D axisymmetric domain with respect to the stream. Thus the 3-D model will provide a better estimate of seepage from perched groundwater to a stream. Later in this paper we compare results from 2-D and 3-D simulations of perched-groundwater flow to demonstrate the difference.

2.2. Generalized Model Domain of Stream Water/Perched-Groundwater System

[18] A hypothetical model was developed that consisted of a half section of a stream profile and the surrounding sediment that includes a low-K fine-sediment unit beneath the stream (Figure 1). The stream reach is 2000 m in length. Lateral extent of the fine-sediment unit is 600 m perpendicular to the stream and 1000 m parallel to the stream, and the edges of the layer stop 1000 m short of the downstream model boundary and 400 m short of the distal (away from the stream) boundary. Symmetry was assumed with respect to the stream and fine-sediment unit. The stream bank is 4 m tall, the active channel was 15 m wide, and the depth of the fine-sediment unit beneath the stream thalweg was 4.5 m. However, some of these values were adjusted in some simulations, as noted in the results section.

[19] The model domain consisted of 30 cells that were 67 m long in the direction parallel to the stream, and 31 cells that ranged between 2.5 and 50 m long in the direction perpendicular to the stream, where the shortest cells were located near the stream. The domain consisted of 30 layers that ranged between 0.25 and 1 m thick, where the thinnest cells were located near the stream and fine-sediment unit.

[20] The relative permeability (relative K) and retention functions of *Mualem* [1976] and *van Genuchten* [1980] were used with separate sets of parameters to describe the coarse-sediment channel deposits and fine-sediment unit. These parameters were estimated by relating measurements of sand-silt-clay percentages, bulk density, porosity and K to relative K, and retention parameters using neural networks [*Minasny et al.*, 2004]. *Minasny et al.* [2004] provide software that performs the neural network analysis based on a database of physical and hydraulic properties and unsaturated flow parameters calculated using the multistep outflow method.

[21] Unsaturated flow parameters for the two facies represented in the model were inferred based on measured sand-silt-clay percentages, bulk density, porosity, and K on nine coarse-sediment and five fine-sediment core samples taken from the riverbed of the Cosumnes River, California [*Niswonger*, 2006]. Laboratory measurements were averaged within each texture group, which were used to compute the unsaturated flow parameters using neural networks [*Minasny et al.*, 2004] (Table 1, Figure 2).

2.3. Simulations, and Boundary and Initial Conditions

[22] Each hypothetical model was run in two parts representing two periods of the annual hydrologic cycle

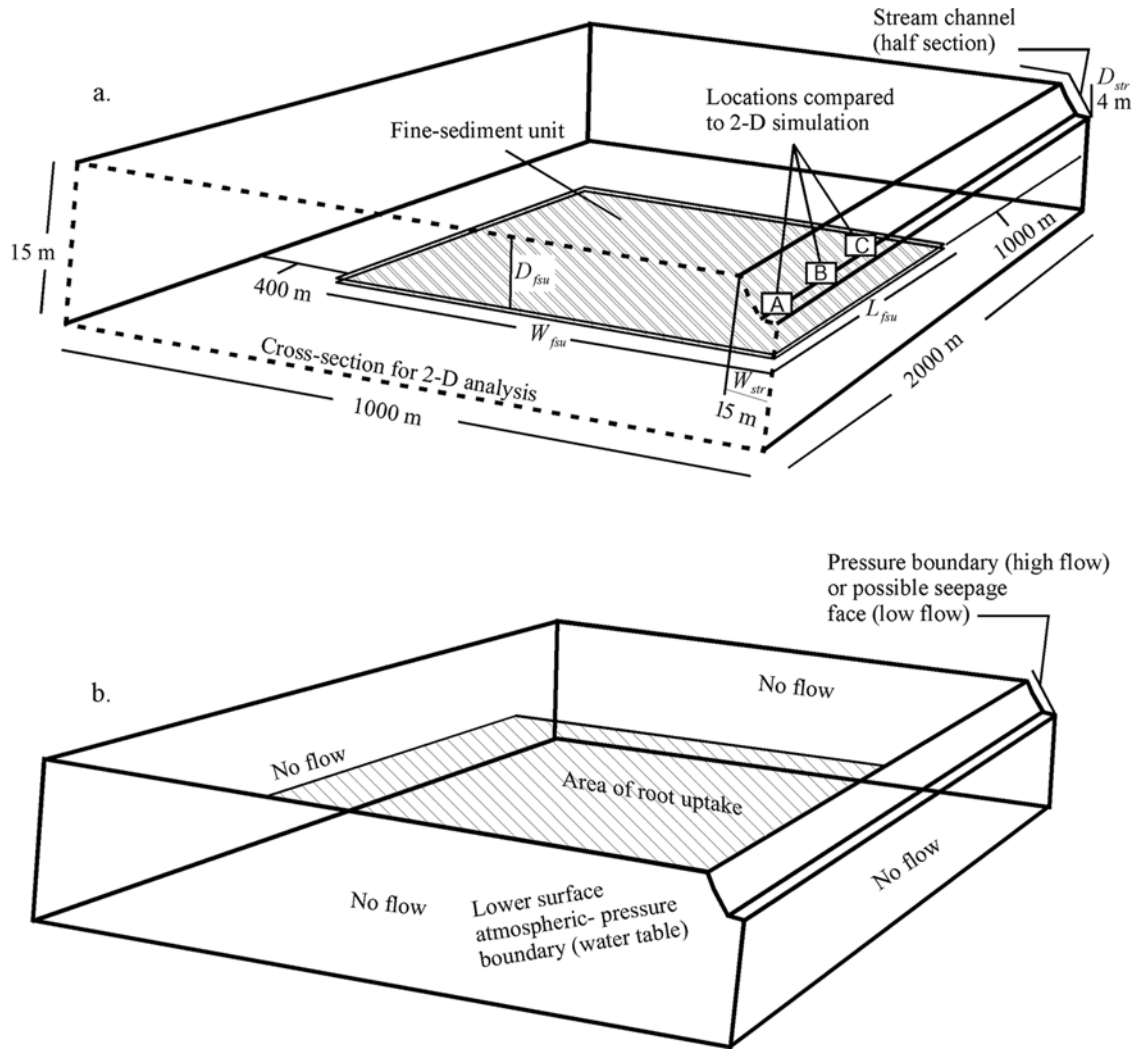


Figure 1. The model domain assumed symmetric with respect to the stream and fine-sediment unit: (a) model boundaries, fine-sediment unit, and location of two-dimensional (2-D) cross section, and (b) dimensions of model domain. Hatched region represents region where evapotranspiration was simulated. Root uptake extended to 4 m below top of model.

and the boundary conditions can be described by the following set of equations:

$$\begin{aligned} p &= p_{atm} & \text{on A} \\ X_{air} &= 0 & \text{on A} \end{aligned} \quad (1)$$

$$\begin{aligned} p &= \gamma_l y_{str} & \text{on B} \\ X_{air} &= 0 & \text{on B} \end{aligned} \quad (2)$$

$$\begin{aligned} p_g &= p_{atm} & \text{on C} \\ S_g &= 1 & \text{on C} \end{aligned} \quad (3)$$

$$q_{ET}(x, y, z, t) = q_{ET}(h) \quad \text{on D.} \quad (4)$$

where p is pressure; X_{air} is the partial pressure of air assumed equal to the sum of the partial pressures of air and vapor in the gas phase; γ_l is the specific gravity of liquid

water; y_{str} is the stream depth; p_g is the gas phase pressure; S_g is the gas saturation; q_{et} is the uptake of water by roots and h is the capillary pressure; and A, B, C, and D are model domain regions (Figure 3). Region D includes all cells above the root depth. The first part was run with the stream at bankfull conditions ($y = 3.5$ m; Figure 3a) for 6 months to represent the high-flow season (October–March in Mediterranean-type climates). During the first part of the simulation, flow could not occur through the top of the stream bank. The resulting subsurface fluid conditions at the end of the simulation were then used as initial conditions in the second simulation with boundary conditions defined in Figure 3b.

[23] The second simulation represented the low-flow season consisting of a 6-month period (April–September). Consequently, the stream boundary conditions were changed such that the lowermost cells representing the stream were assigned a pressure corresponding to low-flow conditions ($y = 0.25$ m), and boundary cells above the surface water line were assigned conditions representing the

Table 1. Average Physical and Hydraulic Properties of 14 Cores Taken From the Cosumnes Riverbed and Banks

Averages Within Each Category	Coarse-Sediment Channel Deposits	Fine-Sediment Unit
Porosity, cm ³ /cm ³	0.36	0.41
Bulk density, g/cm ³	1.66	1.64
K, cm/h	7.7×10^{-2}	1.40×10^{-4}
Percent sand	68.7	14.3
Percent silt	27.8	3.6
Percent clay	4.0	82.1
θ_r , cm ³ /cm ³	0.191 ^a	$(6.38 \times 10^{-12})^a$
θ_s , cm ³ /cm ³	0.37 ^a	0.59 ^a
α , 1/cm	0.0083 ^a	0.0036 ^a
n , unitless	2.178 ^a	1.113 ^a

^aValues were estimated using NeuroMultistep based on averages of measured physical and hydraulic properties listed in this table [Minasny *et al.*, 2004].

atmosphere or seepage face adjacent to the stream bank (equation (3)).

[24] The area of the seepage face is calculated by the model during the dry-period simulation as the sum of cell surfaces adjacent to the stream banks that have pressures greater than atmospheric. Perched-groundwater conditions following one simulation cycle (1 year) were very similar as those following two cycles. Because of this similarity, initial conditions used in the hypothetical models (HMs) were generated by cycling through the boundary conditions described in Figures 3a and 3b one time. Initial conditions for the TOUGH2 module EOS3 are defined in terms of pressure and the air mass fraction for single-phase conditions, and gas phase pressure and gas saturation for two-phase conditions [Pruess *et al.*, 1999].

[25] Eleven cases, hereinafter referred to as hypothetical models (HM) 1–11, were simulated with varying hydro-geologic conditions. Models were constructed to evaluate the effect of variations in K of the coarse-sediment and fine-sediment unit, the horizontal extent of the fine-sediment unit, and the thickness of the coarse-sediment above the fine-sediment unit (Table 2). The amount and duration of perched-groundwater discharge to the stream is compared among the HMs.

[26] ET losses were included in the HMs to examine the influence of ET on perched-groundwater discharge to the stream. Representative ET demand rates were determined based on ET measurements made by J. Korchendorfer and K. T. Paw U (written communication, 2004) using an energy-balance method from willow trees growing along the Cosumnes River, California. Seasonal variations in ET demand rate used in HMs 10 and 11 were generated by taking weekly averages of the measured ET rates, and fitting a smooth curve to the averages. Smoothing was applied to the data to simplify imposing the ET boundary condition in the model. The ET demand was 1 mm/d during midwinter and reached a maximum of 6 mm/d during the summer period, which corresponds to 3 months into the low-flow period.

[27] ET was simulated by removing water from all model cells within the assumed root zone of the riparian vegetation at a rate according to a supply-dependent root-water-uptake function. Coincident with the footprint of the fine-sediment layer, the root zone was assumed to extend 1000 m along

the stream axis, 600 m laterally away from the stream, and to a depth of 4 m below the stream bank, consistent with maximum root depths reported in other studies [Busch *et al.*, 1992; Snyder *et al.*, 1998]. We used the root-water-uptake model developed by van Genuchten and Hoffman [1984] in which the uptake is calculated in terms of sediment capillary pressure:

$$\frac{T(h)}{T_R} = \frac{1}{1 + (h/h_{0.5})^R}, \quad (5)$$

where $T(h)$ is the root uptake rate at the capillary pressure head h , T_R is the potential (demand) root uptake rate, $h_{0.5}$ is the value of h where the root uptake is half the potential (demand) rate, and R is an empirical parameter. Van Genuchten and Hoffman [1984] and van Genuchten [1987] applied equation (5) in a modeling study and attained good fits to data for a variety of agricultural crops with a value of $p = 3$. Values of $h_{0.5}$ vary based on plant type and can be estimated from data provided by Feddes and Raats [2004] for many crops. Parameters used in the root-uptake function for phreatophytes were $p = 3$ and $h_{0.5} = -1.0$ kPa, resulting in a root-uptake curve that drops off sharply as the sediment drains below saturation, representative of phreatophyte vegetation.

[28] TOUGH2 [Pruess *et al.*, 1999] was modified to simulate a root-uptake model as a function of capillary pressure (equation (5)). The root-uptake function was coupled to TOUGH2 such that the root-uptake model was included in the system of nonlinear equations solved by TOUGH2.

3. Results

3.1. Comparison of 2-D and 3-D Models

[29] The effects of spatial dimension of the model results are analyzed by comparing the amount of groundwater flowing into the stream per unit area of streambed at three points located along the stream (points A, B, and C, Figure 1a). A 2-D simulation was made that consisted of a cross section of the 3-D model domain perpendicular to the stream axis (point A, Figure 1). The physical and hydraulic parameters used in this analysis are represented as HM1 (Table 2).

[30] Comparison among the 2-D and 3-D model results show that the 2-D model over-predicts the amount of base flow contributed by perched groundwater (Figure 4). For a 2-D analysis, an approximation of the amount of base flow provided by the perched groundwater could be calculated by multiplying the simulated seepage at point A by the length of the fine-sediment unit parallel to the stream. As shown by points B and C for the 3-D simulation, the quantity and duration of base flow contribution decreases in the direction toward the end of the perching unit along the stream. This occurs due to a thinning of the perched saturated zone near the edges of the perching unit, where water can seep around the edge of the fine-sediment unit. A 2-D representation of the system cannot consider thinning near the edge of the perching unit beneath the stream, and thus the hydraulic gradient that causes groundwater to flow into the stream is overestimated.

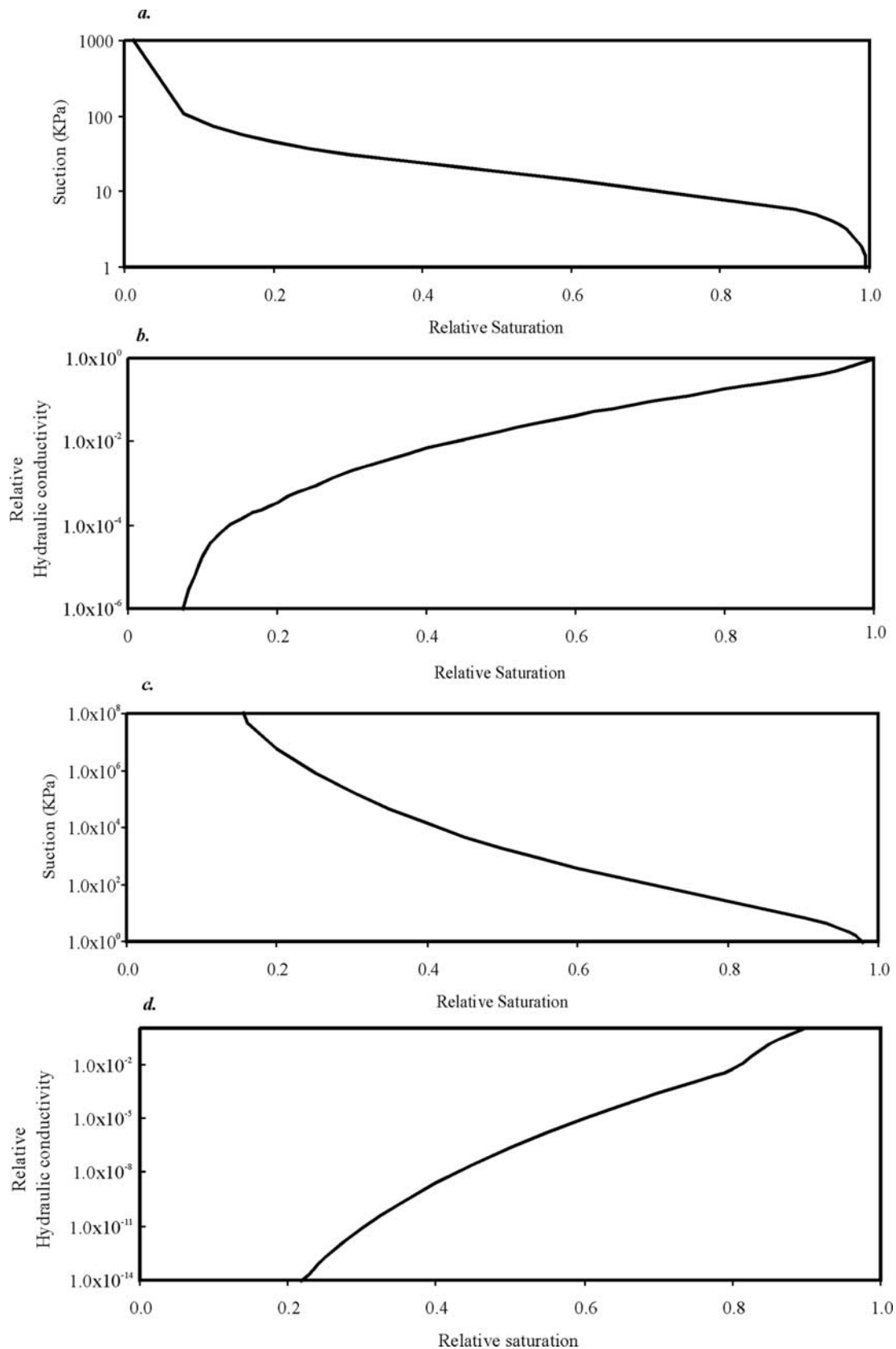


Figure 2. (a) Capillary pressure curve for coarse-sediment channel deposits. (b) Relative hydraulic conductivity curve for coarse-sediment channel deposits. (c) Capillary pressure curve for fine-sediment unit. (d) Relative hydraulic conductivity curve for fine-sediment unit. The function of van Genuchten-Mualem was used to represent the relative permeability curve [van Genuchten, 1987; Mualem, 1976], and the function of van Genuchten [1987] was used to represent the capillary pressure curve.

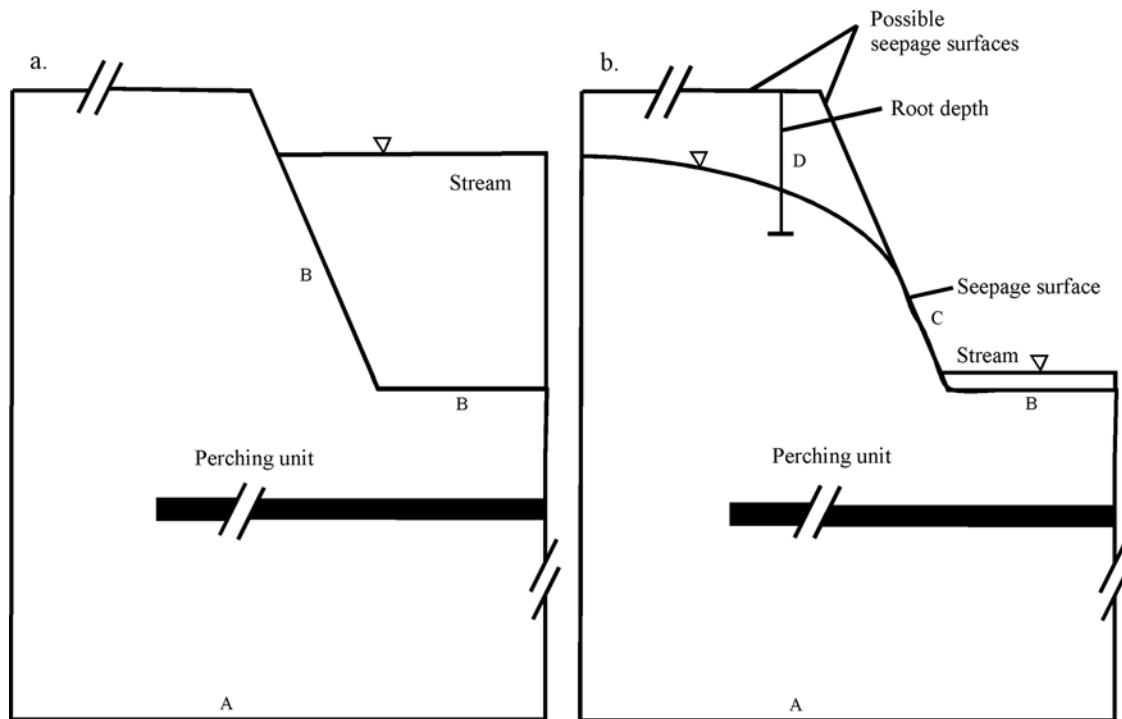


Figure 3. Boundary conditions: (a) simulation part 1 and (b) simulation part 2.

[31] For HM1, the 2-D model overestimated the total base flow by 15%, and the duration at point C by more than a month. For simulations considering shorter fine-sediment units, the error is much greater because the groundwater flow to the stream is overestimated at point A, B, and C. This result emphasizes the 3-D aspect of stream/perched system arising from the finite area of the fine-sediment unit, which causes more flow away from the stream and enhances vertical seepage around the edges of the fine-sediment unit. The 2-D case would be suitable for fine-sediment layers that extend greater than 1000 m parallel to the stream.

3.2. Effects of K

[32] As described, the K of coarse- and fine-sediment units is highly variable in alluvial systems. For example, a coarse-sediment unit could represent coarse sediment deposited during a large flood event. Channel deposits

generally have a much larger K relative to a paleosol or relic silty-clay floodplain deposit that could act as a perching unit. The effective K of a channel deposit could have a wide range of values, depending on the source material, the shape of the streamflow hydrograph, and other processes. Because of the expected variation of K for a coarse-sediment unit, it is of interest to evaluate base flow contribution for a range of effective K.

[33] The effect of variations in coarse-sediment unit K on base flow was investigated with three simulations. HM1 and HM2 had coarse-sediment unit K values of 0.83 and 5.81 m/d, respectively, and both had a fine-sediment unit 4.5 m beneath the streambed surface and with a K of 5.0×10^{-6} m/d. The perched-groundwater discharge over the length of the stream averaged over the first month of the low-flow season was 5.5 L/s (0.2 feet³/s) and 16 L/s (0.6 feet³/s) for HM1 and HM2, respectively (Figure 5). HM3 had the same fine-

Table 2. Descriptions of Hypothetical Models Used to Evaluate Perched-Groundwater Conditions

Model	Coarse-Sediment Unit K, m/d	Fine-Sediment Unit K, m/d	Ratio of Hydraulic Conductivity (Coarse-Sediment K Divided by Fine-Sediment Unit K)	Depth of Fine-Sediment Unit Below Streambed, m	Fine-Sediment Unit Width, m	Fine-Sediment Unit Thickness, m	Fine-Sediment Unit Length, m
HM1	0.83	5.0×10^{-6}	1.66×10^5	4.5	600	2	1000
HM2	5.81	5.0×10^{-6}	1.16×10^6	4.5	600	2	1000
HM3	0.083	5.0×10^{-6}	1.66×10^4	4.5	600	2	1000
HM4	0.83	5.0×10^{-4}	1.66×10^3	4.5	600	2	1000
HM5	0.83	5.0×10^{-3}	1.66×10^2	4.5	600	2	1000
HM6	0.83	5.0×10^{-6}	1.66×10^5	4.5	300	2	1000
HM7	0.83	5.0×10^{-6}	1.66×10^5	4.5	600	2	500
HM8	0.83	5.0×10^{-6}	1.66×10^5	2.5	600	2	1000
HM9	0.83	5.0×10^{-6}	1.66×10^5	5.5	600	2	1000
HM10 ^a	0.83	5.0×10^{-6}	1.66×10^5	4.5	600	2	1000
HM11 ^a	5.81	5.0×10^{-6}	1.16×10^6	4.5	600	2	1000

^aRoot-water uptake was included in these simulations.

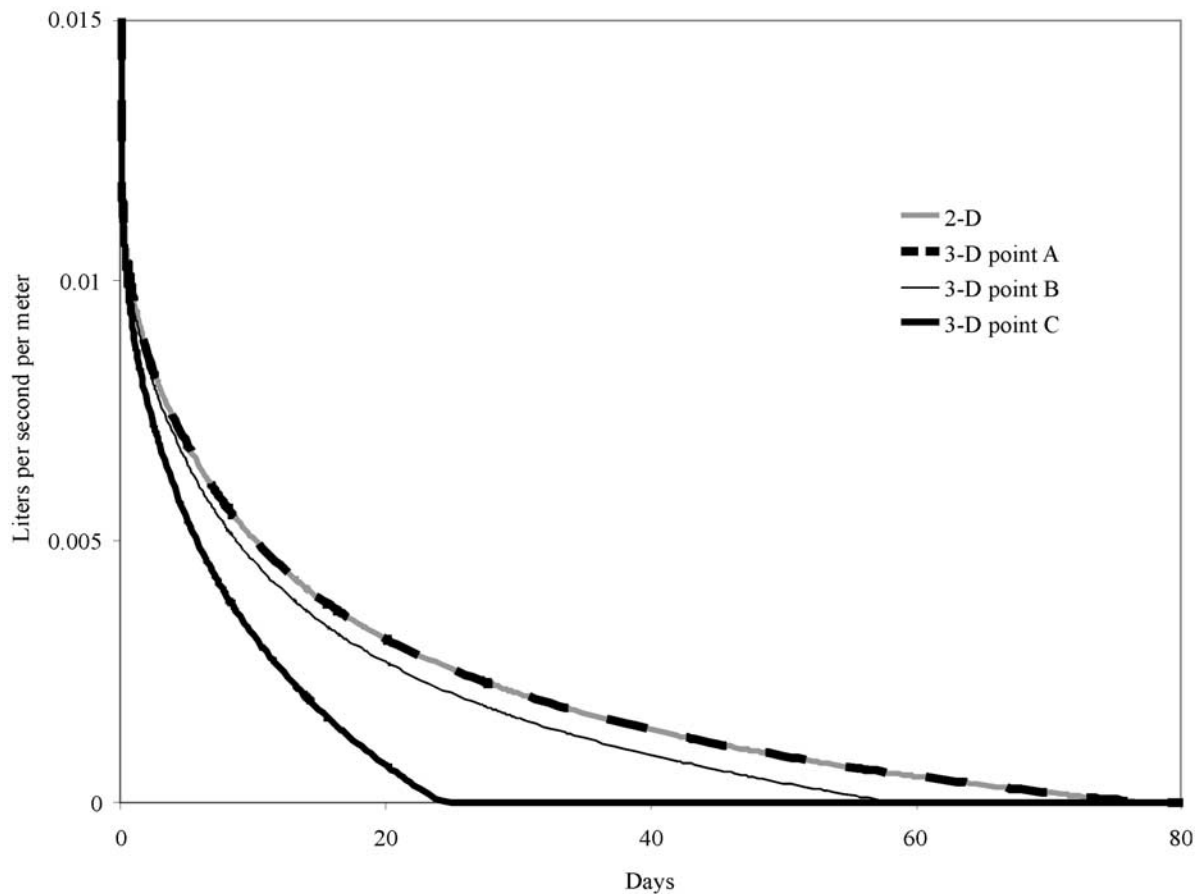


Figure 4. Difference between the 2-D and 3-D representation of the perched groundwater. Notice that the 2-D solution and the 3-D solution (point A; Figure 2a) lie on top of each other. Hydraulic properties and model dimensions are shown as HM1 in Table 1.

sediment unit K as HM1 and HM2 (5.0×10^{-6} m/d) but a lower coarse-sediment K than HM1 by a factor of 10 (0.083 m/d). Perched-groundwater discharge for HM3 was equal to 3.4 L/s (0.12 feet³/s) (Figure 5).

[34] Similar to the K of coarse-sediment units, variations in sediment texture as well as chemical and physical processes that affect sediment will result in variations of K for a fine-sediment unit. To consider these variations, two

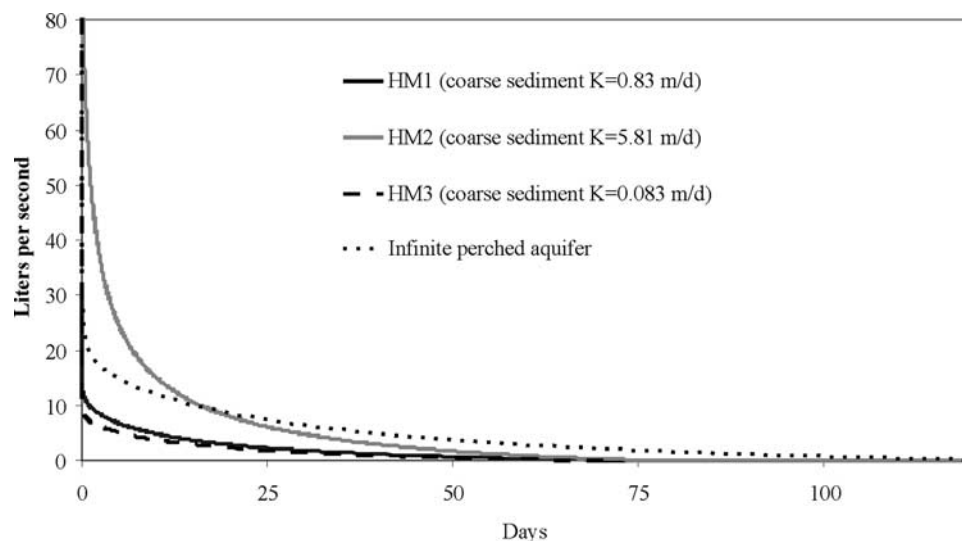


Figure 5. Comparison of perched-groundwater discharge to stream for a medium-K coarse sediment (HM1), a high-K coarse sediment (HM2), and medium-K coarse sediment with a laterally infinite perching layer.

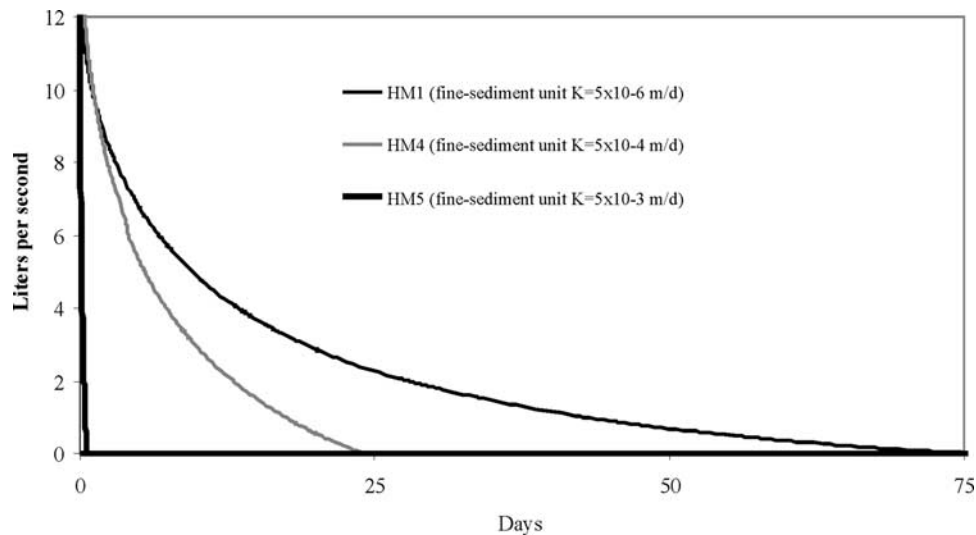


Figure 6. Perched-groundwater discharge for a medium- and high-K fine-sediment unit (HM4 and HM5). HM1 is included for comparison and the coarse-sediment unit K was 0.83 m/d for all three HMs.

simulations were run with a fine-sediment unit K values greater than HM1, referred to as HM4 and HM5. All other aspects HM4 and HM5 were the same as those for HM1.

[35] The duration of perched-groundwater discharge to a stream is much more sensitive to the fine-sediment unit K as compared with coarse-sediment unit K for the size of perching unit in these simulations (Figure 6). HM4 and HM5 represent perched groundwater supported by a high-K fine-sediment unit. The ratio of coarse sediment K to fine-sediment unit K was decreased to 1660 for HM4 and to 276 for HM5. Perched-groundwater discharge to the stream for HM4 was 3.1 L/s (0.11 feet³/s) averaged over 25 days, and declined to zero after 25 days (Figure 6). Perched-groundwater discharge to the stream for HM5 was 3.3 L/s (0.11 feet³/s) averaged over 0.5 days, and declined to zero after 0.5 days (Figure 6). Figure 6 clearly shows that increasing the fine-sediment unit K decreases the duration

of base flow as compared with decreasing the coarse-sediment unit K.

3.3. Geometry of Perched Water Tables

[36] Another relevant aspect of perched groundwater that may be of interest is the geometry and extent of the perched-groundwater region surrounding the stream. Perched water tables only are shown for HM1 and HM2 because the character of the water tables was similar among all HMs and is sufficiently represented by the water tables for HM1 and HM2.

[37] Generally, water can penetrate faster and farther into the bank for perched aquifers with higher K, generating more stored water than lower-K perched aquifers (Figure 7). The saturated thickness above the fine-sediment unit ranged from 5 to 2 m for HM1 and from 7 to 2 m for HM2, where greater thicknesses occurred near the stream (Figure 7). The perched water table dropped below the bottom of the

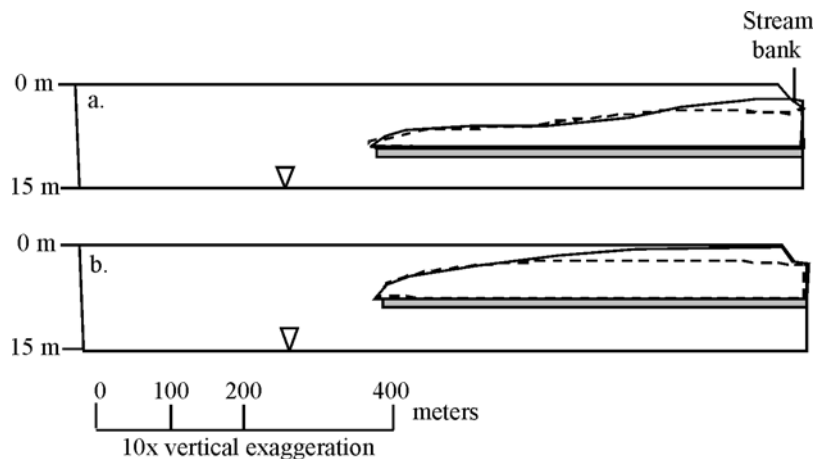


Figure 7. Vertical section of perched water tables: (a) HM1 and (b) HM2. Solid curves represent the water table the instant the low-flow simulation period begins, and the dashed curves represent the water table at the end of the low-flow period. Solid lines represent the model boundary, and the gray box represents the fine-sediment unit. Vertical sections shown correspond to the dashed section shown in Figure 1a.

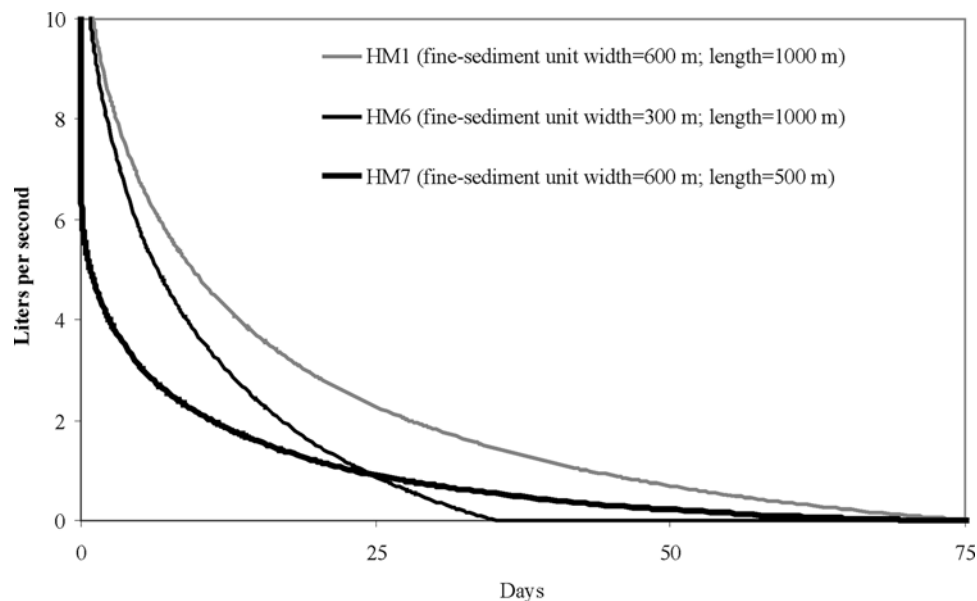


Figure 8. The effects of fine-sediment unit dimensions on perched-groundwater discharge: The fine-sediment unit in HM6 extends half the distance away from the stream as compared with HM1 and HM7; and the fine-sediment unit in HM7 extends half the distance along the stream's axis as compared with HM1 and HM6.

streambed approximately 2.5 months after the beginning of the low-flow period for HM1 and HM2; however, the water table covered all of the fine-sediment unit throughout the low-flow period.

[38] The lateral edges of the water tables for all HMs ended where groundwater drained over the edges of the fine-sediment unit. Model cells beneath the fine-sediment unit were unsaturated in all HMs due to limited vertical seepage through the fine-sediment unit and an assigned depth of the regional water table well below the region of interest.

3.4. Lateral Extent of Fine-Sediment Unit

[39] The physical and chemical processes that result in the development of a fine-sediment unit are variable in space. Fine-sediment units have been reported to vary in lateral extent between hundreds and thousands of meters [Weissmann and Fogg, 1999; Fleckenstein *et al.*, 2006]. HM6 demonstrates the effect of decreasing the fine-sediment unit width (perpendicular to the stream axis) from 600 m (as used for HM1) to 300 m. The large reduction in the fine-sediment unit width resulted in perched-groundwater discharge averaged over 1 month equal to 3.2 L/s (0.11 feet^3/s), as compared with the discharge rate for HM1, equal to 5.4 L/s (0.2 feet^3/s) (Figure 8). HM7 demonstrates that the effect of reducing the length of the fine-sediment unit from 1000 m (as used for HM1) to 500 m had a greater impact in perched-groundwater discharge as compared with the width of the fine-sediment unit.

[40] The large reduction in the fine-sediment unit length resulted in perched-groundwater discharge averaged over 1 month equal to 1.9 L/s (0.07 feet^3/s), which is significantly different than the discharge rate for HM1 equal to 5.4 L/s (0.2 feet^3/s) (Figure 8). Figure 7 shows that the perched groundwater extends to the edges of the fine-sediment unit. Thus reducing the length and width of the fine-sediment

unit decreases the size of the perched aquifer and decreases the amount of groundwater available to flow into the stream.

3.5. Depth to the Fine-Sediment Unit Beneath the Stream

[41] Hypothetical models 8 and 9 indicate that shallow perched aquifers have the potential to provide base flow to streams for a longer period, which could be important for supporting ecosystems near streams during the dry season. HM8 and HM9 evaluate the effect of changes in the depth to fine-sediment unit below the streambed, which is indicative of the depth of stream penetration into the perched aquifer. HM8 had a fine-sediment unit that was only 2.5 m below the streambed (greater stream penetration than HM1), which increased the duration of perched-groundwater discharge to the stream from 75 days (HM1) to 130 days. The 1-month average discharge to the stream for HM8 was equal to 3.6 L/s (0.16 feet^3/s).

[42] A deeper fine-sediment unit (less stream penetration than HM1) increased the maximum discharge to the stream as compared with HM1 by as much as 3 L/s (0.11 feet^3/s). However, after about 15 days, discharge to the stream for HM9 decreased below the discharge for HM1, and the 1-month average discharge was equal to 4.6 L/s (0.16 feet^3/s) (Figure 9).

3.6. Comparison Between Streams Supported by Perched and Regional Groundwater Systems

[43] Previous studies of perched stream water/groundwater systems are minimal, and the few studies there are do not provide estimates of base flow contribution to streams. However, there are several studies that have reported streamflow gain rates from regional aquifers [Conlon *et al.*, 2003; Prudic *et al.*, 2005; Rowe and Allander, 2000; Constantz *et al.*, 2003; Cox *et al.*, 2003]. Table 3 lists the gain rates and basic descriptions of the streams that were

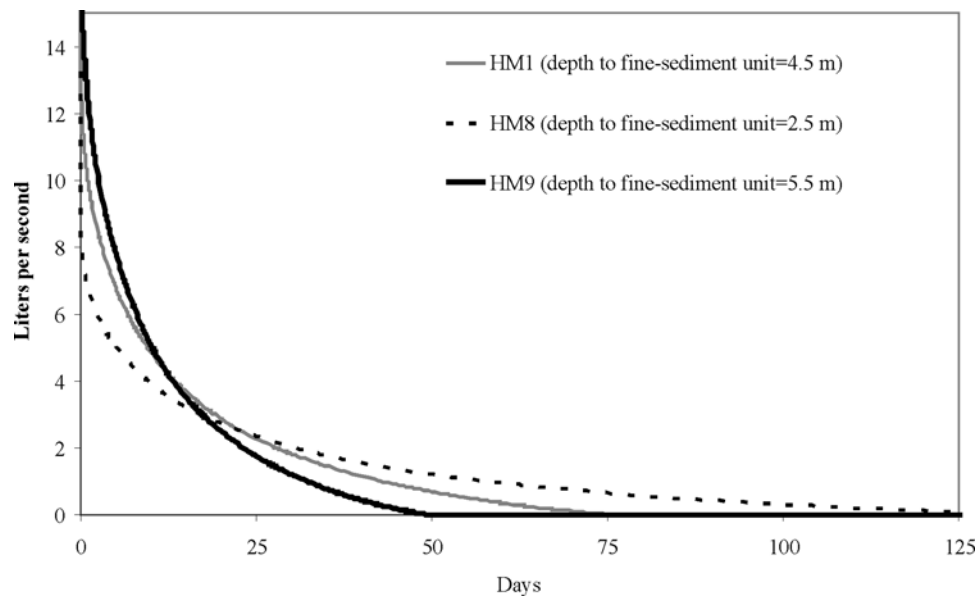


Figure 9. The effects of fine-sediment unit depth beneath the streambed on groundwater discharge. Fine-sediment unit depths were 4.5, 2.5, and 5.5 m for HM1, HM8, and HM9, respectively.

studied, including the streambed K where reported. Direct comparison cannot be made between the gain rates from these studies and the rates simulated herein because groundwater discharge to streams is dependent on many unknown hydrogeologic conditions. However, the base flow contributions simulated herein fall within the range of values reported in the studies of stream/regional groundwater systems. This is an indication that although limited in spatial extent, perched groundwater near streams can provide base flow of the same order of magnitude as base flow provided by regional groundwater systems, the main difference being the length of stream and duration of time over which base flow is provided.

[44] The difference between base flow provided by a perched aquifer limited in lateral extent (HM1) and a laterally infinite perched aquifer is shown in Figure 5. These simulations were identical in all aspects other than the lateral dimensions of the fine-sediment unit. The duration of base flow for a laterally infinite aquifer was approximately 50 days longer than for HM1. The base flow

rates for the infinite perched aquifer are approximately twice as high.

3.7. Evapotranspiration

[45] ET losses affected perched-groundwater discharge (Figure 10). The period of time that perched groundwater discharged to the stream was reduced by 58 days for HM10 and by 65 days for HM11 (Figure 10). The actual ET rates were 79% and 100% of the demand rate for HM10 and HM11, respectively. This result indicates that for models analyzed herein, perched groundwater has the potential to support riparian vegetation; however, diminished perched-groundwater storage due to uptake by riparian vegetation reduces base flow.

4. Discussion

4.1. Comparisons of Simulations

[46] To compare the effects of the variables varied in the HMs, the total amount of base flow and the duration of base

Table 3. Comparisons of Simulated Perched-Groundwater Discharge Rates With Measured Discharge Rates in Streams Sustained by Regional Groundwater^a

Location	Gain Rate Over 2000-m Length of Channel, L/s	Sediment Description	K (m/d) of Sediment Surrounding Stream	Average Stream Width, m	Average Flow, m^3/s
Butte Creek (Oregon) ^b	5.4	silt	0.04	~8	1.65
Cold Creek (California) ^c	40	sand	6–18	3.5	0.22
Trout Creek (California) ^d	21–50	sand	not reported	~7.5	0.45
Upper Truckee River (California) ^d	14–39	sand	not reported	~9	0.33
Santa Clara River (California) ^{e,f}	33.1–52.6	sand	36–72	~5	0.86
HM1	5.5 ^g	...	0.83	15	...
HM2	16 ^g	...	5.81	15	...

^aGroundwater discharge values were measured in all these studies by differencing streamflow at measurement points along the channels.

^bConlon *et al.* [2003].

^cPrudic *et al.* [2005].

^dRowe and Allander [2000].

^eConstantz *et al.* [2003].

^fCox *et al.* [2003].

^gAverage simulated discharge for 1 month after streamflow subsided.

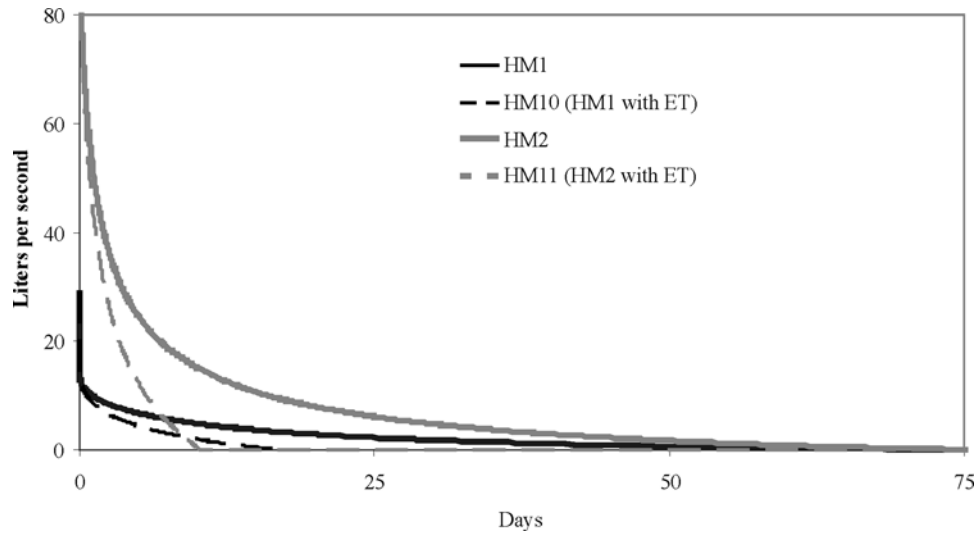


Figure 10. The effects of evapotranspiration on perched-groundwater discharge to a stream with sediment properties of HM1 and HM2.

flow were plotted against a normalized composite number reflecting the values of the variables of interest. The normalized composite number is calculated as

$$\bar{V} = \frac{K_{csu}}{K_{fsu}} \frac{D_{fsu}}{D_{str}} \frac{L_{fsu}}{L_{str}} \frac{W_{fsu}}{W_{str}}, \quad (6)$$

where $\bar{V}$ is a composite number reflecting the values of the variables of interest, K_{csu} is the hydraulic conductivity of the coarse-sediment unit, K_{fsu} is the hydraulic conductivity of the fine-sediment unit, L_{fsu} is the length of the fine-sediment unit (parallel to the stream axis), L_{str} is the length of the stream represented in the model, D_{fsu} is the depth of the fine-sediment unit below the streambed, D_{str} is the depth of the streambed below top of the stream bank, W_{fsu} is the width of the fine sediment (perpendicular to the stream axis), and W_{str} is the width of the stream. The variables L_{fsu} and W_{fsu} were used to represent the fine-sediment unit area to show the difference between units that are laterally extensive beneath the stream versus laterally extensive perpendicular from the stream. These variables are shown in Figure 1.

[47] Figures 11a and 11b show the effects of perched-aquifer variables on the total base flow volume and duration plotted against $\bar{V}$. For low values of $\bar{V}$, the ratio K_{csu}/K_{fsu} has the greatest effect on the quantity and duration of base flow; however, this effect subsides for larger values $\bar{V}$, that is, when K_{csu}/K_{fsu} is greater than 1×10^5 . Contrastingly, the effects of the fine-sediment unit length on base flow contribution increased for larger values of $\bar{V}$. The ratio D_{fsu}/D_{str} had the greatest effect on base flow duration when K_{csu}/K_{fsu} is greater than 1×10^5 . Smaller values of the ratio D_{fsu}/D_{str} resulted in greater base flow rates and duration, which indicates that streams with greater penetration into perched aquifers will experience longer periods of base flow.

4.2. Model Limitations and Transferability

[48] Although the present work attempts to evaluate the basic interplay between streams and perched systems, we

only address a few of the possible variations in stream/perched systems that may be found in nature. For example, we did not evaluate many geometric configurations of stream/perched systems, such as the effects of stream-channel morphology (e.g., variations in width, meandering, ripple-pool sequences), sloped fine-sediment unit configurations, or variations of the streamflow hydrograph. Additionally, other sources of perched aquifer recharge were not considered, such as infiltration from precipitation or subsurface flow from upslope perched aquifers.

[49] Another issue that was not thoroughly addressed was how climate and the resulting precipitation, recharge, and streamflow variations affect perched systems. Variations in perched-groundwater storage from one season to the next would likely affect perched-groundwater storage and discharge to the stream following the wet season. We leave these analyses for future work, which may be more easily done following the development of analytical or semianalytical solutions for stream/perched system interaction. The present work provides a means for evaluating necessary assumptions required to develop analytical solutions of perched-groundwater flow.

[50] A limited amount of sensitivity analysis was done to test the effects of the unsaturated hydraulic conductivity and retention parameters on perched-groundwater discharge to the stream. Substituting parameters representative of fine sediment for the parameters representing the coarse sediment reduced the discharge to the stream by less than 20%, and did not affect the duration of discharge, indicating that these parameters are less important as compared with the saturated hydraulic conductivity values.

[51] The effects of grid cell size also were analyzed by comparing results for a model with grid cells twice the size of those presented in this paper. The larger grid cells resulted in discharge rates that were nearly twice as large for the first few days of the low-flow period; however, the results for the fine- and coarse-grid models became the same following the first week of the simulation. The finer-grid models were used to more realistically represent seepage during the initial part of the simulations; however, further

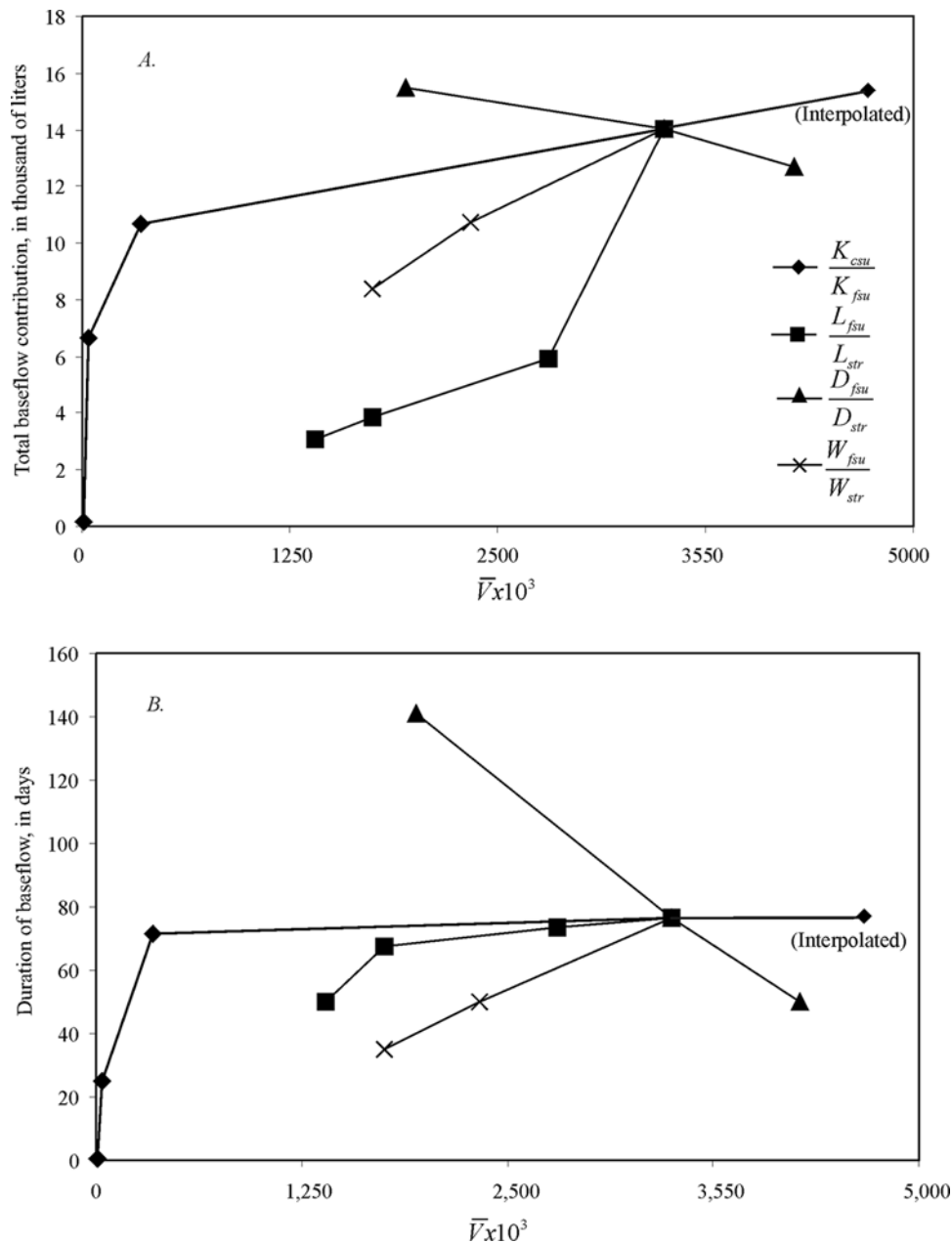


Figure 11. The effects of perched aquifer hydraulic and physical variables on (a) the quantity of base flow and (b) the duration of base flow. Points were interpolated between HM1 and 2, and variables in legend are shown in Figure 1.

refinement of the grid was not done to avoid intractable computational requirements. The simulations presented herein required 4–6 hours on a Xeon 3.2-GHz, 2.6-GB RAM computer.

5. Conclusions

[52] Simulations of stream water/perched-groundwater systems indicate that perched aquifers can provide base flow to streams that are not in contact with regional groundwater. Perched groundwater provided base flow for longer than 2 months after flow in the stream receded. This amount of flow could likely enhance biological activity in a stream by maintaining flowing conditions and supporting

riparian vegetation. However, the simulated base flow rates for a 2000-m length of stream are not sufficient solely to support migrating salmon in a river such as the Cosumnes River. The minimum streamflow for the passage of salmon in the Cosumnes River is ~ 550 L/s (20 feet³/s) [Fleckenstein *et al.*, 2006]. Nonetheless, perched groundwater maintained gaining conditions, and could supplement water already in the stream. For example, the Cosumnes River is in contact with a regional aquifer over the upper end of the alluvial valley and flows perennially over this section. Perched aquifers likely enhance base flow farther down the channel, possibly allowing the Cosumnes to maintain minimum flow requirements for longer periods. Perched aquifers may be critical for minimizing seepage losses during the first fall

flow event in the channel to allow salmon to migrate to spawning habitat; these benefits could be enhanced through management of perched aquifers.

[53] Competition among lotic (stream) and riparian ecosystems was addressed to a limited extent by simulating the effect maximum ET rates would have on perched-groundwater discharge to the stream. The simulations showed that perched groundwater supported riparian vegetation above the footprint of the fine-sediment unit; however, diminished perched-groundwater storage due to ET reduced the amount of water provided to the stream.

[54] Although this work is focused on perched groundwater beneath streams, perched groundwater may also play a vital role in other ecosystems such as lakes, wetlands, and floodplains. Surface-water bodies and floodplains that are supported by perched groundwater could theoretically be managed by recognizing where conditions are suitable for perching and by maximizing recharge to perched groundwater at appropriate times. Perched systems near streams could be recharged by either diverting water from another source into the stream during the low-flow season, or by irrigating the land above the perched system.

[55] On the basis of results presented herein, some generalizations can be made that relate the characteristics of a stream and perched-aquifer system to the potential base flow provided by a perched aquifer:

[56] 1. Ratios of the horizontal coarse-sediment K to the vertical fine-sediment K (K_{csu}/K_{fsu}) greater than 1×10^5 can provide base flow to a stream for longer than 2 months. Ratios less than 300 have very little potential to provide base flow.

[57] 2. Greater stream penetration (smaller values of D_{fsu}/D_{str}) results in longer base flow duration; and changes in stream penetration have the greatest effect on base flow as compared with all other analyzed variables for values of K_{csu}/K_{fsu} greater than 1×10^5 .

[58] 3. Larger areal extents of the fine-sediment unit produce greater amounts of base flow for a longer duration; changes in the fine-sediment unit lengths (parallel to the stream axis) have a greater effect on the base flow rate as compared with changes in the fine-sediment unit width (perpendicular to the stream axis).

[59] 4. Permeable perched aquifers can support riparian vegetation; root uptake by riparian vegetation reduced the duration of the perched-groundwater discharge to the stream by nearly 75%, indicating that there is a potential for competition among riparian and lotic ecosystems for perched groundwater.

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