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Use of heat-based vertical fluxes to approximate total flux in simple channels

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[1] Heat flux through shallow streambed sediments is often used to quantify streambed water exchange with groundwater. Although two-dimensional (2-D) and three-dimensional (3-D) models are available, one-dimensional (1-D) models still have advantages in terms of ease of use and cost effectiveness. This study investigated error associated with the vertical flow assumption for a lateral section of a synthetic channel of varying geometry, hydraulic gradient, and stage using 1-D and 2-D models. Hydraulic gradient had the greatest influence on total channel flux. Flux at the lateral edge of the channel was up to 8.3 times higher than at channel center, and seepage from the channel banks accounted for up to 50% of total flux. Despite this variation along the channel boundary, the difference between channel flux estimates using 1-D and 2-D models was less than 30%. The models were applied to data from a large irrigation canal, and 1-D channel flux estimates were 30% greater and 81% lower than from the 2-D model, using temperatures collected at channel center and at the left edge of the channel, respectively. These results stress the importance of placing probes to best capture water flux direction when using 1-D, temperature-based methods.

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1. Introduction

[2] The use of heat flux as a tracer has become an accepted technique for detecting interactions between surface and groundwater resources. Temperature data has been used successfully to estimate flow and infiltration beneath both perennial [e.g., *Silliman and Booth*, 1993; *Silliman et al.*, 1995; *Stonestrom and Constantz*, 2003, *Schmidt et al.*, 2006] and ephemeral [e.g., *Constantz and Thomas*, 1996; *Ronan et al.*, 1998] streams and is appropriate for both gaining and losing reaches. *Anderson* [2005] and *Constantz* [2008] provide thorough reviews of the development and applications of this method, including explanations of the influences of advective and convective flows, analytical and empirical equations, and one-dimensional (1-D), two-dimensional (2-D), and three-dimensional (3-D) model approaches. *Kalbus et al.* [2006] discuss the use of heat flux methods in comparison to other approaches for quantifying groundwater-surface water interactions. Each of these authors describes temperature measurements as being robust, cost-effective, and easy to collect, making temperature-based methods an attractive way to determine groundwater discharge or recharge. *Constantz* [2008] suggests that advancements in the use of temperature-based methods may lead to a new field of "streambed science" as our understanding of streambed processes as a distinct hydrologic unit increases.

[3] Quantitative investigation of streambed water exchange requires that temperature sensors be inserted at a range of depths below the streambed, so that attenuation of temperature at depth can be measured. Infiltration rates or hydraulic conductivity can then be solved for using either the advection-dispersion equation or a combination of the heat and hydraulic equations, respectively. Seepage into or out of the streambed is often assumed to be strictly vertical, allowing for simplification of the equations [e.g., *Schmidt et al.*, 2006; *Conant*, 2004; *Fryar et al.*, 2000; *Bartolino and Niswonger*, 1999; *Silliman et al.*, 1995; *Lapham*, 1989].

[4] Groundwater temperatures were first used to determine 1-D flux of water in saturated sediments by *Suzuki* [1960] and *Stallman* [1963, 1965]. Two-dimensional and even three-dimensional models have recently gained more widespread use because of increased computing capabilities [e.g., *Ronan et al.*, 1998; *Thomas et al.*, 2000; *Niswonger*, 2005]. These more complex models make it possible to address a wider variety of environments and more accurately characterize areas of heterogeneous geology. However, simple, 1-D models still hold value as a cost-effective and rapid method of determining streambed fluxes, where vertical flow can be assumed.

[5] Lateral movement of water, and differences in seepage through the stream banks, as opposed to the streambed, may play a significant role in total infiltration but have received little attention. Further, few studies mention the method for lateral selection of probe placement within the stream segment. We hypothesize that, at low gradients, lateral flow will be significant. However, for wide channels, the influence of lateral flow and stream bank seepage should be negligible and flow should be closer to vertical across more of the wide channel's streambed. When temperature

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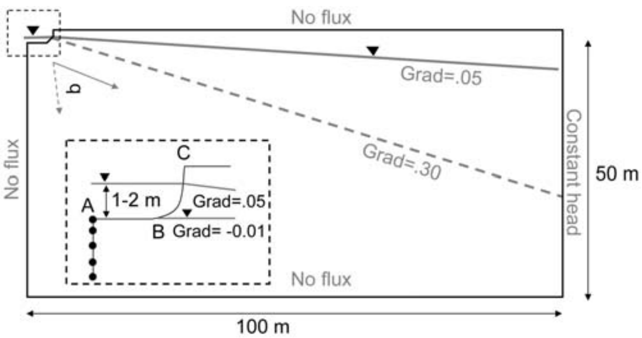

Figure 1. Diagram of the two-dimensional Hydrus model for one side of a hypothetical stream channel. Observation nodes used for determination of vertical flow are shown in the inset. Letters in the inset correspond to x axis locations in Figure 2. Note that for the −0.01 lateral hydraulic gradient, the flux was into the channel.

probes are placed to capture vertical flow through the center of the channel, a simple, 1-D model may be sufficient for obtaining a fast and cost-effective estimate of infiltration in homogeneous channels.

[6] This study investigated the error in channel infiltration estimates resulting from the vertical flow assumption. In the first part of this study, a synthetic model was used to examine the impacts of channel width, stage, hydraulic gradient, and anisotropy on flux and direction of infiltration. Results of these 2-D model runs were compared with 1-D estimates of flux by scaling up the Darcian flux at the channel center nodes, where flow was fully vertical. In section 2, estimates of infiltration from 1-D and 2-D numerical models were compared using field data collected from the Fort Lyon Canal, a wide, man-made channel in eastern Colorado. Because of its location parallel to the Arkansas River, regional groundwater flow was assumed to be essentially perpendicular to the Fort Lyon canal. Lateral flow in this study, therefore, only considers the simplified case of perpendicular flow, although a discussion of the applicability of 1-D and 2-D models in more complicated flow regimes is included.

2. Methodology

2.1. Synthetic 2-D Model

[7] The Hydrus 2-D/3-D software package [*Šejna and Šimůnek*, 2007; *Šimůnek et al.*, 2008] was used to simulate the simultaneous movement of heat and water flow in the subsurface. A 2-D, vertical cross section was constructed for half of a hypothetical stream channel (Figure 1). Although the channel section was only 4 m wide and 2 m deep, the model domain was extended out to a total width and depth of 100 and 50 m, respectively, to limit boundary conditions effects and the influence of aquifer thickness. Because of the large model dimensions, changes in the constant head boundary at the right edge had only minor effects on the aquifer in the area of interest directly adjacent to the channel boundary. Observation nodes were placed at depths of 0, 15, 45, 75, and 105 cm below the channel center.

[8] No flow boundary conditions were applied along the top and bottom boundaries, and the left and right boundaries were set at a constant, hydrostatic pressure head that fixed the water table at a prescribed distance above the bottom, resulting in a regional, horizontal hydraulic gradient of approximately −0.01, 0.05, 0.15, or 0.30 (as determined from the slope in water table across the model domain from channel center to the right boundary) when steady state conditions were achieved. This range of gradients was selected to include a wide range of environments, from gaining streams (as represented by the −0.01 gradient) to arid, ephemeral channels where the depth to groundwater may be great and a steep gradient would be expected.

[9] To achieve moderate attenuation of temperatures down to a depth of at least 1 m below the channel boundary, the hydraulic parameters for a sandy loam were selected from the built-in soil catalog in Hydrus (saturated conductivity = 4.42 cm/h, saturated water content = 0.41). The model was given the simplified thermal properties for the *Chung and Horton* [1987] parameters ($b1 = 6.8 \times 10^{-10}$, $b2 = 0$, $b3 = 0$). Longitudinal dispersion was set at 5 cm, and transverse dispersion was neglected to allow for a better comparison between the 1-D and 2-D models.

[10] To reproduce a wide range of flow fields, a series of model simulations was run in which the hydraulic gradient, channel stage, channel width, and presence of anisotropy in the channel bed were systematically varied. Table 1 summarizes the parameters and assumptions for each of these four sets of 2-D simulations. For each set of conditions, the model was run until steady state flow conditions were achieved. For the simulations run at the −0.01 gradient, the stage was reduced to 0 m to induce water flow into the channel (gaining channel). For the wide channel, the overall model dimensions remained the same, and the width of the channel was extended 10 m to the right. Thermal and soil hydraulic properties were kept constant for all model runs. For each simulation, the flux along the channel boundary and at each observation node was calculated internally in Hydrus.

2.2. Synthetic 1-D Estimates

[11] In Hydrus, flux across the channel boundary was calculated by numerical solution of the global discretized Richards equation. Velocities perpendicular to the boundary at the individual nodes were then calculated by dividing the total flux by the length of the boundary segment association with the node. At channel center, the direction of flow was nearly 100% vertical; therefore, this point would be the most likely place to get an accurate measurement of seepage under the vertical flow assumption. To test the error associated with scaling such a 1-D measurement up to full bank width, the Darcian flux provided for the boundary node at channel center was multiplied by the lateral wetted width. Estimates of total channel infiltration by this method were compared with the total boundary flux provided by Hydrus (designated "true channel flux") (Figure 2).

3. Field Application

3.1. Study Site and Field Methods

[12] The Fort Lyon Canal is an agricultural water delivery canal created in 1884 [*Milenski*, 1990], diverted from the Lower Arkansas River near La Junta in southeastern Colorado. The canal is 177 km long and has a capacity of over

Table 1. Parameters and Assumptions Used in the 2-D Model Simulations in Hydrus[a]

Model Run	Channel Width (m)	Channel Stage (m)	Lateral Groundwater Hydraulic Gradient (m/m)	Assumptions
Narrow	4	0	−0.01	Isotropic, homogeneous porous medium, steady state
		1	0.05, 0.15, 0.30	Isotropic, homogeneous porous medium, steady state
Narrow, deep	4	2	0.05, 0.15, 0.30	Isotropic, homogeneous porous medium, steady state
Wide	14	0	−0.01	Isotropic, homogeneous porous medium, steady state
		1	0.05, 0.15, 0.30	Isotropic, homogeneous porous medium, steady state
Anisotropy	4	0	−0.01	K_h/K_v = 10/1, homogeneous porous medium, steady state
		1	0.05, 0.15, 0.30	K_h/K_v = 10/1, homogeneous porous medium, steady state

[a]For each set of model runs, channel stage was set to 0 m to induce water flow into the channel during model runs at the −0.01 lateral hydraulic gradient. For all other model runs, water flow was from the channel into the subsurface.

20 m^3/s. The channel was dug through an undulating area of porous, loamy, and gravelly soils underlain by limestone shale. The upper alluvium is up to 30 m in thickness and has an estimated horizontal hydraulic conductivity of up to 530 m/d, whereas the lower confining layer has an estimated hydraulic conductivity of 0.001 m/d [*Burkhalter and Gates*, 2005]. The study site was located in the Limestone division, approximately 85 km downstream from the headgates (Figure 3). This site was chosen because it was unlikely that cattle in the area could get to the equipment and because of the proximity to a seasonal wetland on the down-gradient side of the canal, which we suspected was fed by seepage from the canal.

[13] Two thermocouple probes were installed into the right side of the channel bed in August 2007. Each probe had five thermocouples, which were taped to a dowel rod with the top two thermocouples spaced 15 cm apart and the lower thermocouples each 30 cm apart, for a total probe length of 105 cm. For each probe, a hole was made in the channel bed using a 1.25 cm diameter metal pipe, and then the pipe was removed and the dowel rod was inserted into the channel bed, with the top thermocouple approximately at the sediment-water interface.

[14] The first probe was oriented perpendicular to the channel bed, and the second probe was set at an angle of approximately 45° into the bank (Figure 4). The thermocouples were attached to a Campbell Scientific AM25T multiplexer (Logan, Utah) containing a precision thermistor for cold-junction compensation and temperatures were recorded at 20 min intervals utilizing a Campbell Scientific CR10X or CR1000 data logger. Water and soil temperatures were included for reference.

[15] In March 2008, four thermistor rods (Rapid Creek Research, Boise, Idaho) and a pressure transducer for stage were added to the channel. Holes were drilled into the channel bed with a 1.25 cm drill bit, three thermistor rods were spaced laterally along the bed of the channel, and the fourth was set at a 45° angle into the left bank (Figure 4). Each stainless steel rod contained six thermistors spaced at 0, 15, 30, 60, 100, and 140 cm from the top of the rod, with the top thermistor inserted approximately 10 cm below the channel surface. The holes were back filled with sand and capped with bentonite. Temperatures were recorded at 20 min intervals. Three wells with pressure transducers were also added in a cross-section perpendicular to the channel. Wells 1, 2, and 3 were located at distances of 2.1 m upgradient, and 14.6 and 31.4 m downgradient of the channel, respectively. All temperature probes, channel geometry, and well locations were surveyed during the March 2008 installation.

3.2. One- and Two-Dimensional Field Data Model Methods

[16] A 2 week period with stable flows between 4 and 18 June 2008 was used for model simulations. Water levels in wells 1 and 3 were used to define pressure head at the left and right boundaries of the 2-D model. The surveyed data points were used to recreate the lateral channel geometry within the model domain, and the bottom boundary was set to 15 m below the channel bed to avoid effects of boundary conditions on vertical water flow in the shallow groundwater. Qualitative observation of the channel substrate and soil maps for the area indicate that shallow bed materials were mostly composed of silty sand. Therefore, the built-in [*Chung and Horton*, 1987] thermal properties for sand ($b1$ = 1.064×10^{12}, $b2 = -1.12 \times 10^{13}$, $b = 2.29 \times 10^{13}$) were selected in Hydrus. Using average well levels from the

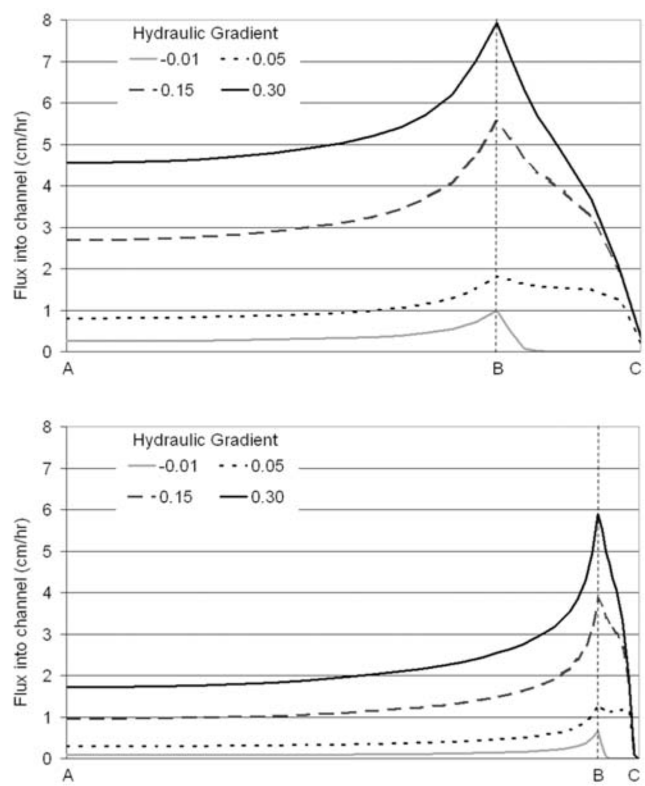

Figure 2. Water flux along the channel boundary for the (a) narrow and (b) wide models. Positions along the x axis correspond to locations on the boundary as shown in the inset in Figure 1.

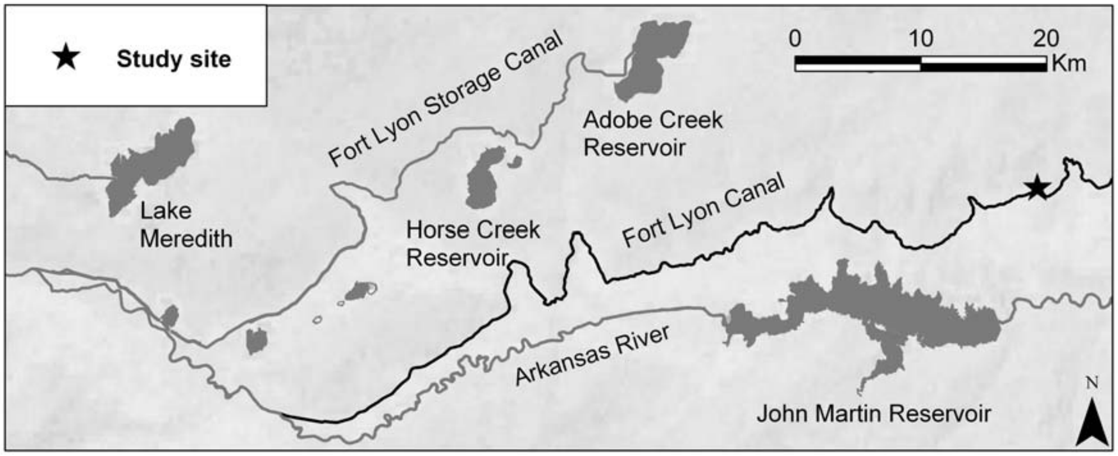

Figure 3. Map of the Fort Lyon Canal (highlighted in black) along the Lower Arkansas River and location of the study site on the canal. The canal continues another 65 km beyond the map border. The regional groundwater direction in the vicinity of the study site is toward the river.

4–18 June time period, the model was then run forward until steady state conditions were reached to equilibrate temperature and pressure gradients.

[17] The inverse solution was used to solve for saturated conductivity using the temperature data from 30 observation nodes. From the 34 temperature sensors installed in the channel, two sensors that had apparently failed were excluded from the analysis, and two sensors located directly at the sediment-water interface were excluded because they were measuring surface water temperature, which had already been defined.

[18] A simple, 1-D numerical model of the heat transport equation was used for comparison with the calculation of channel flux from Hydrus 2-D. The model consisted of a 1-D finite element approximation of the heat advection-conduction equation [*Stallman*, 1965]. Input for the model consisted of observation node depth and thermal and soil hydraulic parameters needed for the longitudinal dispersion and advection terms. These variables were calculated to match corresponding input parameters in the 2-D model. The simple complexing evolution [*Duan et al.*, 1994] inverse method was used to backward solve for flux from temperatures from the probe located at channel center. Before using the model on the real data collected from the Fort Lyon Canal, model error was tested using data from the synthetic models described in section 3.1. Temperatures at the observation nodes at channel center in the narrow synthetic model were input into the numerical model and vertical flux was solved for using the same inverse method. This estimate for the channel center was multiplied by the wetted perimeter, and the resulting total channel flux was compared to the true channel flux calculated by Hydrus. Estimated fluxes from the 1-D model were similar to the synthetic 2-D model, with error between 1.4% and 33.3%, which is relatively small for a parameter that can vary over several orders of magnitude.

[19] Groundwater flow was assumed to be perpendicular to the model domain because of the location of this canal along a topographical contour perpendicular to the Arkansas River, and because data from a well located 15 m downstream of the model domain (35 m from the right channel bank) did not differ from the well data within the lateral cross section. Well data showed that regional groundwater flow is from left to right within the model domain, and probes 9, 11, and 10 were selected for comparing 1-D vertical flux estimates.

4. Results of Synthetic 2-D Model and Comparison to 1-D Estimates

[20] A comparison of water flux along the wetted perimeter of the channel showed that the magnitude of water movement into (or out of, in the case of the gaining channel) the subsurface was not constant along the boundary. In each case, the magnitude of water flux increased along the channel in the direction away from channel center, and peaked at the place where the boundary transitioned from a flat channel bed into a sloped bank (Figures 2a and 2b, respectively). As expected, seepage into the subsurface increased with higher hydraulic gradient, and the channel bank accounted for less of the total channel flux at these higher gradients. The higher hydraulic gradient case decreases the aquifer thickness, which does not allow as much flow from the upper bank region. As hypothesized, channel bank seepage played less of a role in the wider channel, with a maximum of 23% of the total channel infiltration resulting

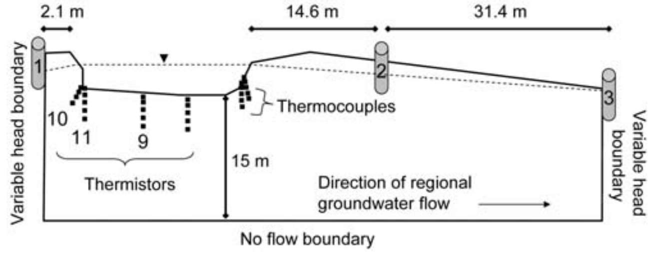

Figure 4. Diagram of the two-dimensional Hydrus model for the Fort Lyon Canal study site, showing temperature sensors (points), location of wells (cylinders), and approximate groundwater level. The numbers for probes used in one-dimensional modeling are indicated below the sensors.

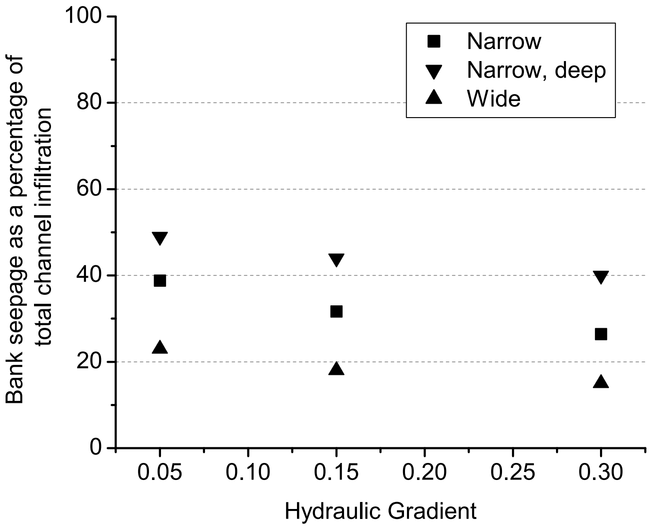

Figure 5. Percentage of total seepage resulting from bank seepage in the narrow, narrow deep, and wide models.

from bank seepage in the 14 m wide model, as compared to a maximum of nearly 50% in the 4 m wide model (Figure 5). This difference is logical, since the bank portion of total channel perimeter was 25% in the 4 m wide channel, as compared to only 6% of the 14 m wide channel.

[21] Although bank seepage provided a lower percentage of total channel seepage in the wide channel compared to the narrow channel, the flux at the base of the channel bank was 2.9–8.3 times higher than at channel center in the wide channel, compared to only 1.7–3.9 times higher for the narrow channel and (Figures 2a and 2b). Despite this variability in velocity along the channel perimeter, estimates of total channel infiltration using only the channel center velocity were reasonably accurate. There was a parabolic relationship between the true channel flux and flux estimated using only the channel center vertical velocity (Figure 6). However, as the channel widened or deepened, this relationship became more linear. A polynomial trendline (power = 2) fit each model in Figures 6 and 8 with an r-squared value greater than 0.99.

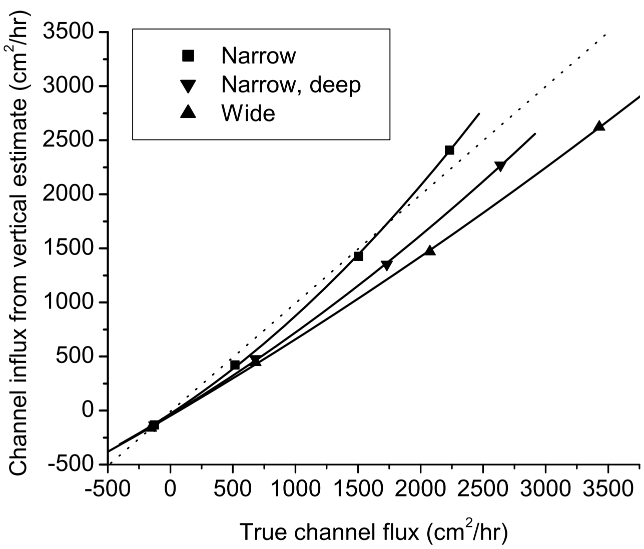

Figure 6. Comparison between true channel flux from the two-dimensional Hydrus model and channel flux calculated one dimensionally from velocities along the vertical probe at channel center.

[22] Almost all estimates using the channel center velocity underestimated the total channel flux, with errors between 4.6% and 29.8% overall (Figure 7). Error increased for the wider channel (4.8%–34.7% error) and higher stage (5.6%–29.8% error) compared with the basic narrow model (4.6%–18.5% error). Increases in the hydraulic gradient generally resulted in lower error, while the lowest errors were found in the gaining channel variations.

[23] Initial model runs for the narrow and wider channels assumed isotropy in the porous medium. When anisotropy of 10:1 was introduced in the narrow channel, total boundary flux was reduced, but the relationship between the vertical estimate and true channel flux was preserved (Figure 8). The error associated with these estimates was lower than for the isotropic narrow channel at 5.2%–17.7%.

5. Results of Field Data Models

[24] Using the 2-D Hydrus model (Figure 4), the best fit for saturated conductivity was found to be 4.04 cm/h, resulting in an average flux across the entire channel boundary of 407.7 cm^2/h. The model was able to fit the data with an r-squared value of 0.91.

[25] Temperatures from probe 9, located at channel center in Fort Lyon Canal (Figure 4), were input into the 1-D numerical model, and the flux was inversely solved to minimize the sum of error between observed and modeled temperatures for the thermistors located depths of 15, 30, and 60 cm below the top of the probe. Depth to the top of the probe was measured at 5 cm below the sediment-water interface when the probe was removed in November 2008, resulting in total depths of 20, 35, and 65 cm below the sediment-water interface for these probes. The modeled temperatures showed overall good agreement with the observed data (Figure 9) for the two upper thermistors, despite the daily spike in modeled temperatures above the observed

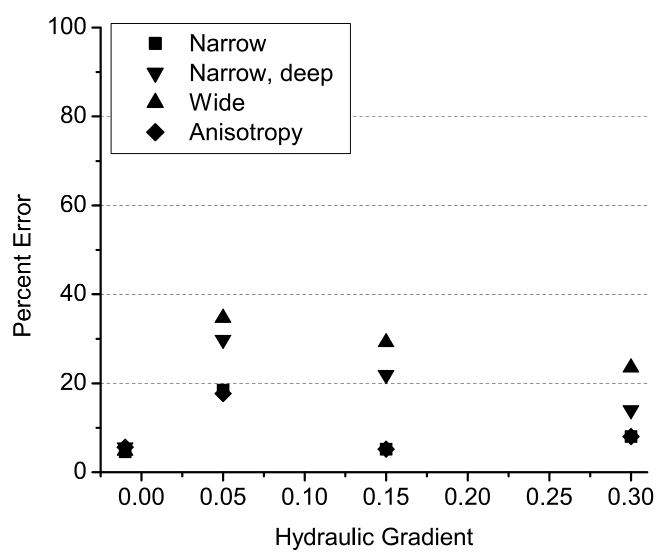

Figure 7. Percent error for one-dimensional estimates of channel flux as compared to the two-dimensional Hydrus model.

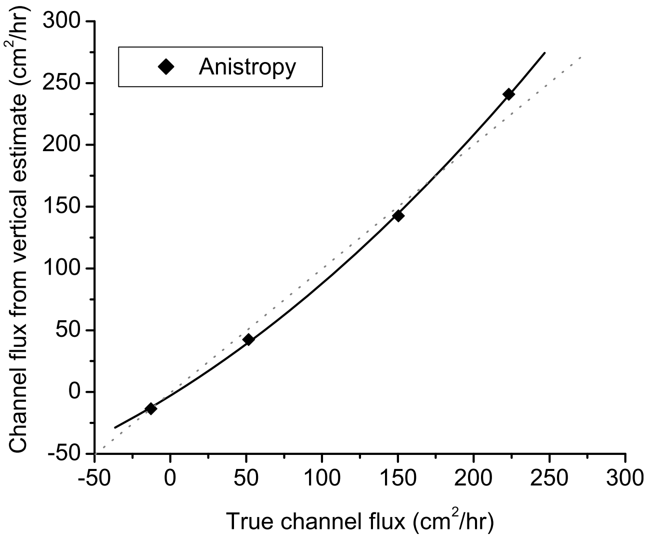

Figure 8. Comparison between true channel flux from Hydrus and channel flux calculated one dimensionally from velocities along the vertical probe at channel center for the anisotropic model.

canal temperatures, but underpredicted the temperatures in the bottom thermistor. Optimal flux predicted by the model was 0.36 cm/h, which, when multiplied by the wetted width of 1638 cm, resulted in a total channel flux of 589.7 cm^2/h.

[26] One-dimensional model simulations were repeated using observed temperatures from probe 11, located on the left side of the channel (Figure 4). For probe 11, the top of the probe was directly at the sediment-water interface, and temperatures from the thermistors located at depths 15, 30, and 60 cm below the top of the probe were again chosen. Total error was minimized for all three sensors. Model fit for this probe was very good for all three thermistors (Figure 10), and the best value of flux was 0.05 cm/h, resulting in a total channel flux of 76.1 cm^2/h.

[27] Since the synthetic model showed that direction of flux was at an angle into the channel sides at the edges of the channel bottom, we applied the 1-D model to temperatures observed in probe 10, set into the left bank at an angle of approximately 45° (Figure 4), to see whether a 1-D estimate would capture flux into the bed at this location. However, the difference in angles between the probe placement and water flow direction was apparently significant, because the 1-D model was unable to fit the thermistor data from this probe, and produced either very high or very low flux rates, depending on which of the thermistor depths was optimized.

6. Discussion

[28] Synthetic models demonstrated the influences of hydraulic gradient, combined with channel stage, width, and anisotropy, on the direction and magnitude of flow, and showed the importance of probe placement for heat tracer studies. Hydraulic gradient was found to be the most important variable influencing infiltration into the synthetic model. Previous studies have used heat tracer techniques in a wide range of environments from a humid environment in which the water table is close to the surface and the channel can switch between gaining and losing conditions depending on streamflow [*Barlow and Coupe*, 2009] to an extremely arid area where only flood conditions produce streamflows that infiltrate to the groundwater [*Kulongski and Izbicki*, 2007; *Izbicki and Michel*, 2002]. Therefore, a wide range of gradients was examined, from gaining conditions (−0.01 gradient) to extremely deep groundwater (0.30 gradient). Highest channel flux was observed at the steepest gradient (0.30), regardless of channel width or stage. The synthetic 2-D model showed that as the gradient increased, the total infiltration was higher and, more importantly, more infiltration shifted toward the sides of the channel. This shift in flow direction from mostly vertical at the shallowest gradients to more lateral (in this case, perpendicular to the channel) flow implies that probe placement may be extremely important when 1-D models are used with heat tracer techniques in environments with steeper gradients (i.e., arid climates). However, by calculating total channel flux from a location in the channel where flow remained essentially vertical even for the 0.30 gradient, our total channel infiltration estimates, using the 1-D model, were reasonably accurate. This result shows under best-case scenarios, 1-D models may be sufficient even in areas with significant lateral flow.

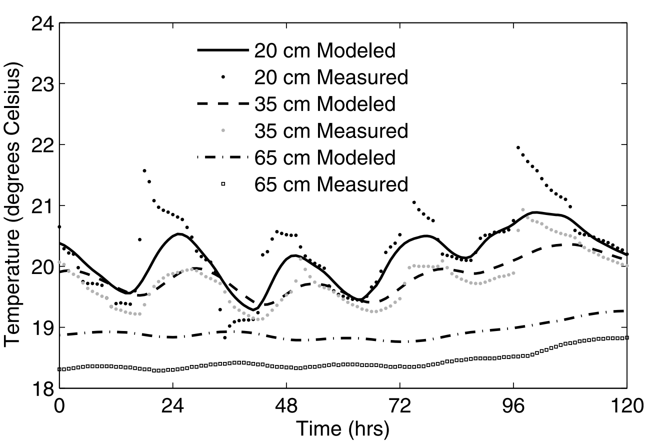

Figure 9. Model fit for temperature sensors on probe 9 at a depth of 20, 35, and 65 cm below the sediment-water interface for a period of 5 days.

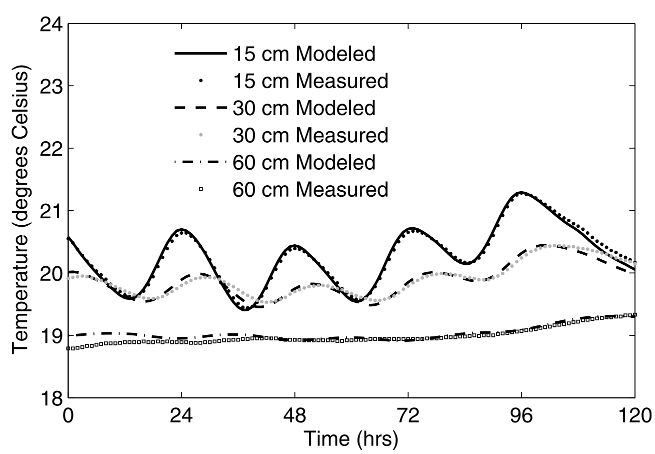

Figure 10. Model fit for temperature sensors on probe 11 at a depth of 15, 30, and 60 cm below the sediment-water interface for a period of 5 days.

[29] The 1-D and 2-D models of data from our field site on the Fort Lyon Canal also demonstrated the influence of hydraulic gradient on flow direction. Although the hydraulic gradient in the Fort Lyon was only approximately 0.03 during the modeling period, and 1-D estimates of channel flux differed, depending on the location along the cross section that was chosen for estimation. Contrary to the results of the synthetic models, the 1-D field model most closely matched observed temperatures in the probe at the left channel. Yet, although the 1-D field model fit was not as close for the probe at channel center, the best channel infiltration estimate was comparable to the 2-D field model estimate. The poor model fit may have resulted more from heterogeneities in the bed sediments than lateral flow.

[30] Error between 1-D and 2-D synthetic models increased as the stage or width of the channel increased. The increases in error for wider and deeper channels may have resulted from the larger difference between baseline flux at the center of the channel and maximum flux. For example, peak flux was almost 4.0 times greater than center flux in the wide channel, but only 2.3 times greater in the narrow (shallow) channel (Figures 2a and 2b). For both the synthetic and field models in this study, flux calculations using only the center inflow rate was well within one order of magnitude of the "true" flux from the Hydrus model.

[31] Several previous studies use heat tracer techniques to determine the transition from gaining to losing stream conditions as channel stage varies [*Barlow and Coupe*, 2009, *Essaid et al.*, 2006]. Consistent with our results, *Essaid et al.* [2006], found that flux estimates in a ditch in Indiana varied both as channel stage varied over time, and depending on where in the channel, the temperatures were collected. Variability in 1-D model error over time due to changing channel stage has not been considered, and would provide for an interesting study on the basis of our results.

[32] Anisotropy in the channel bed did not have a major influence on error in 1-D results in the synthetic models. It is interesting to note that the increased lateral flow associated with higher gradients did not magnify error in the 1-D estimates of flux in the synthetic channel in our study. However, this variable is difficult to assess in natural environments and it is unknown how possible anisotropy at the field site did or did not influence flux estimates.

[33] Variability in infiltration has been examined for the longitudinal direction [*Niswonger et al.*, 2008, *Schmidt et al.*, 2007, *Conant*, 2004]; however, little emphasis has been given to changes along a lateral section of channel. *Ronan et al.* [1998] collected temperature data on the right, center, and left sides of a channel to calculate flux. They found it difficult to match temperatures obtained from the sides of the channel, likely because of the influences of lateral water flow in the subsurface. For our study, the synthetic model originally included observation nodes at the transition between channel bed and bank at the area of highest infiltration. However, because the orientation of the probes was not the same as the direction of the flow, estimations of flux from these probes were several orders of magnitude too low. Therefore, if only one or a few probes are being used, probe placement is very important for correct flux estimation. Although *Schmidt et al.* [2007] focused on longitudinal changes in infiltration along a channel, data collected at the two transects in that study also showed some variability laterally within the channel. Approaches such as *Conant* [2004] or *Schmidt et al.* [2007] may be appropriate for preliminary examination of lateral variability in flux estimates to guide the placement of long-term deployment of probes.

[34] The conditions found at this field site allowed for the examination of lateral flow as strictly perpendicular to the channel, which simplified the modeling exercise and provided a neat comparison to the results of the synthetic model. This channel was excavated above the natural valley flow. However, in most natural environments, lateral flow is likely to occur at an oblique angle to the channel due to channel slope, regional groundwater tables, and layering in the alluvial deposition. Because of their complexity and more extensive data requirements, use of 3-D models in heat tracer studies has so far been rare. Little research has been done to examine the affects of oblique lateral flow on flux estimates from 1-D, 2-D, and 3-D models using heat tracer methods. Further study in this direction is warranted to better understand the impacts of oblique lateral flow beneath the channel.

[35] Recent advances in computing power have resulted in increasing use of 2-D and 3-D models to analyze temperature data from natural environments. However, simple 1-D models still retain several advantages in some applications. For channels that can be considered quasi-homogeneous, or with simple geometry, 1-D models provide a cost-effective, fast method of determining movement into and out of the subsurface. Several workers have recently demonstrated the applicability of 1-D models. *Keshari and Koo* [2007] developed a simple empirical model, and suggested that numerical models have several advantages over analytical models, since they are applicable to any temperature variation and to different kinds of initial and boundary conditions. *Schmidt et al.* [2007] showed that when steady state conditions can be assumed, a 1-D analytical model shows good agreement with results from more complicated methods, and can save both field and computing time. However, as seen by *Essaid et al.* [2006], for heterogeneous streambeds, it is important to take measurements in several places. When subsurface flow intersects the channel at an oblique angle, it may also complicate flow direction and necessitate a more complicated model [*Ronan et al.*, 1998]. Results from the present study agree with these studies. In the homogeneous, synthetic 2-D model, fully vertical flow was only achieved at channel center. Like the synthetic model, the field site selected for this study was also relatively homogeneous across the channel cross section, resulting in realistic channel flux estimates from channel center; however, best model fit was achieved at the side of the channel, showing that heterogeneities in natural streambeds are often significant, and require more careful consideration of probe placement. In a complex channel, bed heterogeneities limit efforts to upscale flux estimates from 1-D and event 2-D models, and optimal probe placement is unlikely to correspond with the center of the channel.

7. Conclusions

[36] This study investigated the error associated with the assumption of 1-D, vertical flow for a lateral section of a synthetic channel of varying geometry and hydraulic gradient. We found that hydraulic gradient played the largest role in influencing total channel flux and that the flux was

not uniform laterally along the channel boundary. For the synthetic channel, the 1-D model reproduced flux estimates reasonably well, suggesting that in this case a simple, 1-D model would be sufficient if proper attention was given to probe placement within the channel.

[37] Analysis of field data collected in the Fort Lyon Canal, Colorado, showed that a 1-D model was able to provide flux estimates that agreed well with estimations from a 2-D model. As compared with the 2-D model, 1-D estimates of channel flux from the probe at channel center slightly overestimated total channel seepage. Although seepage was likely highest near the channel banks, 1-D flux estimates produced from the probe located at the left edge of the channel underpredicted total seepage, since water movement was not strictly vertical at that location. This application stresses the importance of placing heavy consideration on probe placement when collecting information for heat flux tracer investigations.

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