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SPATIAL AND TEMPORAL VARIABILITY IN STREAMBED FLUXES, LEARY WEBER DITCH, INDIANA

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Abstract: The Agricultural Chemicals Sources, Transport and Fate Topical Study (ACT) of the U.S. Geological Survey's National Water Quality Assessment Program (NAWQA) has undertaken a nationwide study to assess the fate of agricultural contaminants. As part of this effort, surface-water/ground-water (SW/GW) interactions have been studied in the streambed of Leary Weber Ditch, a 7.2 km^2 subwatershed within the Sugar Creek Basin in Indiana, part of the White River-Miami River Basin NAWQA study unit. This is an intensively farmed corn and soybean region with poorly permeable surface and subsurface materials, predominantly till with interbedded lenses of outwash. Several methods were used to determine the streambed exchanges between surface water and ground water. Synoptic measurements were made with seepage meters at specific locations, and by differential discharge measurements over the entire reach, to obtain average flux between the stream and ground water during high and low flow seasons. Heat was used as a tracer to obtain an understanding of the spatial variability and seasonality of SW-GW exchanges in the streambed. Heads and temperatures were continuously monitored, with a 15-minute recording interval. Two-dimensional, cross-section modeling of water and heat flow was used to interpret the temperature and head observations and deduce the SW/GW fluxes. SW/GW exchange was influenced by physical heterogeneity of the stream channel with low flow where clay was observed in cores, and focusing of flow toward areas in the Ditch where the underlying clay layer was absent. During the study period of April through December 2004, flux was upward through the streambed during the early part of the record with the exception of flood events. Flood events resulted in rapid reversal of flow direction causing a period of surface water flow downward into the streambed that was followed by a return to ground water discharge to the stream. In the late summer season, regional ground-water levels dropped leading to surface-water loss to ground water that eventually resulted in drying of the ditch. Synoptic measurements of flux made using seepage meters and differential discharge measurements along the ditch generally support the temperature-based model flux estimates.

INTRODUCTION

The Agricultural Chemicals Sources, Transport and Fate Topical Study (ACT) of the U.S. Geological Survey's National Water Quality Assessment Program (NAWQA) has undertaken a nationwide study to assess the fate of agricultural contaminants (Capel et al., 2004). A goal of the ACT study is to determine the residence times and rates of water and agricultural chemical transport through the hydrologic compartments from the land surface to the stream as affected by natural factors and agricultural practices. As part of this effort, surface water - ground water (SW/GW) interactions have been studied in the streambed of Leary Weber Ditch (LWD), a small, intermittent stream draining a 7.2 km^2 subwatershed within the Sugar Creek Basinin Indiana, part of the White River-Miami River Basin NAWQA study unit (U.S. Geological Survey, 2003) (Figure 1). This is an intensively farmed corn and soybean region with poorly permeable surface and subsurface materials, predominantly till with interbedded lenses of outwash. Flow in the LWD is primarily tile drain fed and responds to snow melt and rainfall events, with flow falling off quickly following an event. Mean daily streamflow was 0.095 m^3/s for Water Years 2003 and 2004, with 73 days in the fall and early winter of 2004 when the ditch was dry. This area exhibits moderate temperatures ranging from an average of 24^{o}C in July to -4^{o}C in January (Lathrop, in press). The mean annual precipitation is about 1000 mm with the majority of rainfall occurring in spring and early summer. Soils are either loam or silt loam, generally deep, somewhat poorly drained, and nearly level.

Figure 1 Location of the Leary Weber Ditch drainage basin, stream gage (Gage) and surface- water/ground-water interaction site (SW/GW).

The surface-water/ground-water interaction study site on LWD is located approximately 330 m downstream from the LWD gaging station and 110 m upstream from the confluence with Sugar Creek (Figure 1). The main role of this site is to measure the movement and interaction of water and chemicals through the LWD streambed. This paper focuses on the estimation of surface- water/ground-water (SW/GW) fluxes for the year 2004. Direct measurement of streambed seepage rates, estimates from changes in discharge along a length of the stream, and analysis of streambed heads and temperatures were used to determine the SW/GW exchanges.

METHODS

Using heat as a tracer, in conjunction with water level measurements, has been shown to be an effective method for estimating SW/GW exchanges (Silliman and Booth, 1993; Silliman et al., 1995; Constantz and Stonestrom, 2003; Anderson, 2005). This method requires continuously monitoring temperature in the stream and at multiple depths within the streambed. Five transects across LWD were studied, and a series of piezometer nests were installed at two transects (Transect 1 and Transect 3 in Figure 2) to continuously monitor water level and temperature (Figure 3). The piezometers were installed by hydro-jetting inside a 10.2-cm diameter PVC casing. The lithology observed during jetting was recorded. A dense, gray, clay layer was present at most locations at a depth of about 0.5 m and had to be augered through before hydro-jetting could continue. The temperature of water in the piezometer, which was assumed to be in thermal equilibrium with the adjacent streambed temperature, was monitored with a 15-minute recording interval at multiple depths below the streambed by suspending temperature loggers within the piezometer clusters. Water levels in the stream and in each piezometer were also monitored continuously at 15-minute intervals.

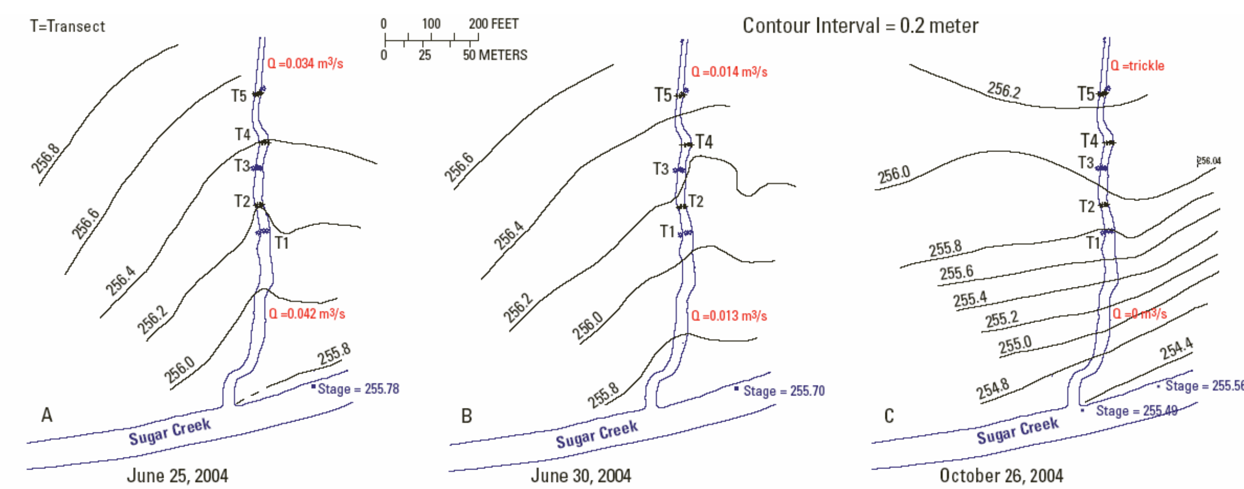

Figure 2 Maps showing study transects, discharge measurements, and ground-water level contours for three synoptic measurement times: A, June 25, 2004; B, June 30, 2004; and C, October 26, 2004.

Synoptic measurements of water level were made during high- and low-streamflow conditions in nearby wells, streambed piezometers, and streambed drive point transects (Transects 2, 4, and 5) (Figure 2). Streamflow discharge measurements were also made above and below the SW/GW interaction study site during these high- and low-flow synoptics. The change in discharge over the length of the ditch separating the measurement locations (differential discharge) was used to obtain average flux between the stream and ground water during high and low flow seasons.

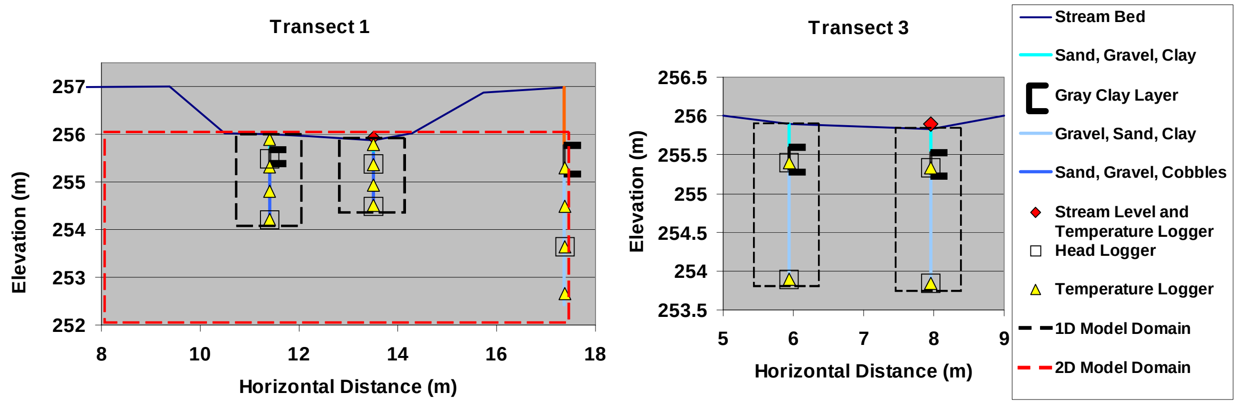

Figure 3 Cross-sections for Transects 1 and 3 showing lithology, measurement locations, and model domains for one-dimensional and two-dimensional simulations.

Discreet measurements of SW/GW flows were made using seepage meters. Seepage meters consisting of an open-ended drum connected to a flux bag were pushed into the streambed, and the change in volume of water in the bag over a specified time period was measured to determine the rate of SW/GW flow (Lee, 1977).

RESULTS AND DISCUSSION

Observed Head and Temperature Distributions: Synoptic measurements of ground water levels show that during the wet high-flow spring and early summer season shallow ground water in the vicinity of LWD discharges to the ditch (Figure 2A), especially in the vicinity of Transect 1, and the ditch is gaining. However, flows in the LWD decrease rapidly after recharge events, and the SW/GW interaction patterns become more complex with some reaches of the ditch losing water (near Transect 3 in Figure 2B) and some reaches gaining water (near Transect 1 in Figure 2B). As the year progresses and ground water levels decrease during the fall season, the ditch goes dry and ground water flow is towards Sugar Creek (Figure 2C). This suggests that the vertical head gradient below the streambed will change throughout the year, and consequently SW/GW fluxes will change with time. The continuous measurements of head and temperature allow quantitative examination of the spatial and temporal distribution of these fluxes.

Figure 4 shows the stream water levels, observed temperatures and the difference in ground water head between the lower piezometer and the upper piezometer (ΔH = lower head – upper head) for the four piezometer nests in LWD. Positive ΔH values indicate ground water flow upward into the ditch, and negative ΔH values indicate downward flow of water from the ditch into the streambed. When there is significant upward ground water flow, observed temperatures within the profile will approach the temperatures observed in the lowest measuring point because upward flowing water will carry the heat upwards. However, when there is downward flow into the streambed, the temperature profile will approach the stream temperature. Thus, by comparing the intermediate temperature observation depths to the stream and bottom observed temperatures, we can get a qualitative sense of the relative amount and direction of flux in the streambed. For example, if we examine the temperature profiles and ΔH for the right piezometer nest of Transect 1, we see that in late-May to mid-June there were three sharp, short-lived reversals in head gradient (induced by flood events) that coincided with rapid upward spikes in temperature resulting from warmer stream water entering the streambed. These spikes are more pronounced in the right piezometer nest (where no clay layer was encountered during hydro-jetting as shown in Figure 3) suggesting that there is a better connection between the stream and subsurface at this location. Also, comparing the temperature profiles of the left piezometer in Transect 3, the temperature at the intermediate depth is very similar to the temperature at the bottom, whereas, in the right piezometer, the intermediate temperature is in between the stream and bottom temperatures. This suggests that there is more upward flow at the left piezometer location than at the right piezometer location.

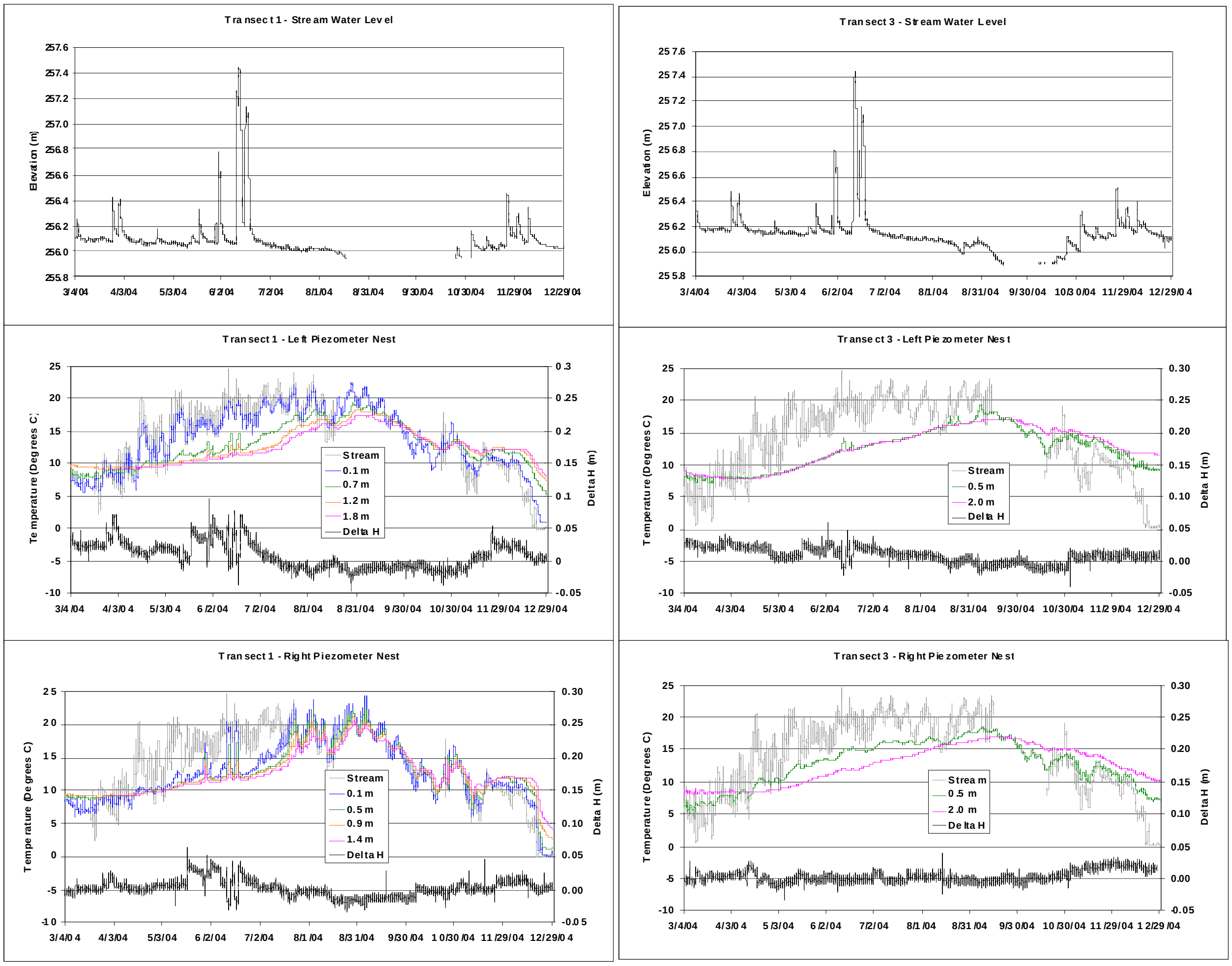

Figure 4 Plots of observed stream water levels, temperatures, and head differences between the lower piezometer and the upper piezometer (Delta H = lower head – upper head) for the four piezometer nests in LWD.

Flux Estimates from Heat and Water Flow Model Analysis: One- and two-dimensional, cross-sectional modeling of water and heat flow was used to interpret temperature and head observations and estimate SW/GW fluxes. The energy transport and water flow model VS2DH (Healy and Ronan, 1996) and its graphical user interface VS2DI (Hsieh et al., 2000) were used in conjunction with the universal inverse modeling tool UCODE (Poeter and Hill, 1998) to fit the observed temperatures and heads.

Vertical one-dimensional models with 0.02-m high grid-blocks were calibrated for each of the four piezometer nests (Figure 3). The stream temperature and level were used for the top boundary condition, and the bottom temperature and lower piezometer water levels were used for the bottom boundary condition. The Transect 1 left and right vertical models were inverted simultaneously by assuming that the bottom sediments and top sediments were uniform at both locations. Because the clay is absent in the right piezometer nest, it was possible to determine unique hydraulic conductivity (K) values for the bottom, clay layer, and top sediments (Table 1). Simultaneous inversion of the Transect 3 vertical models did not result in a good fit, suggesting that the K's are not uniform across the transect. Instead, the left and right locations were fit individually. Also, because observations were collected at only one intermediate depth, it was not possible to fit separate K's for the clay layer and overlying sediments. Instead, a lumped K representing the vertical average of these two layers was fit in the model (Table 1).

Table 1 Summary of information used for inverse model simulations, and the resulting parameter estimates and correlation coefficients for the calibrated model.

Transect Simulated	Time Period	Data used for Model Calibration	Fitted Hydraulic Conductivity of Bottom Sediments (m/s)	Fitted Hydraulic Conductivity of Clay Horizon (m/s)	Fitted Hydraulic Conductivity of Top Sediments (m/s)	Correlation Coefficient of Inverse Model Fit
Transect 1 Left	3/4/04 - 12/31/04	Heads at 1 depth, temperatures at 3 depths	7.91e-3	6.77e-6	1.03e-4	0.9876
Transect 1 Right	3/4/04 - 12/31/04	Heads at 1 depth, temperatures at 3 depths	7.91e-3	------	1.03e-4	0.9876
Transect 1 Two-Dimensional	4/2704 – 8/17/04	Heads at 1 depth, temperatures at 3 depths	2.42e-2 horizontal 6.84e-4 vertical	5.29e-6	Fixed at 1.0e-4	0.9915
Transect 1 Two-Dimensional	4/2704 – 8/17/04	Heads at 1 depth, temperatures at 3 depths	1.06e-2 horizontal 1.51e-4 vertical	8.11e-6	Fixed at 2.0e-4	0.9917
Transect 3 Left	3/4/04 - 12/31/04	Temperatures at 1 depth	1.36e-2	9.00e-6*	9.00e-6*	0.9853
Transect 3 Right	3/4/04 - 12/31/04	Temperatures at 1 depth	1.98e-3	4.54e-6*	4.54e-6*	0.9817

* The clay horizon and top sediments were treated as one layer in these simulations.

Figure 5 shows the calibrated model estimates of streambed flux (in m^3/s per unit stream bottom surface area) for the four one-dimensional vertical models, as well as the measured seepage meter and synoptic discharge fluxes. The highest streambed fluxes occurred in the right piezometer nest of Transect 1, the only location with no underlying clay layer. The model estimated flux at this location is higher than the June 25th synoptic discharge measurement, however, the estimated flux at the three other locations is generally lower than the discharge estimate. This suggests that there is considerable spatial variability in SW/GW fluxes to LWD with significant ground-water contributions occurring in localized high streambed K zones. Early June seepage meter measurements (Allison Craig, personal communication) have a very wide range of values. Seepage meter results can have a high uncertainty because of technical implementation difficulties and disturbances of the streambed hydrology caused during installation (Rosenberry, 2005). However, there does appear to be correspondence between the model flux estimates and the median of the distribution obtained by compiling all seepage measurements made in early June at each individual transect. The continuous model estimates of flux demonstrate the highly dynamic nature of SW/GW interactions, with flow reversals occurring during flood events and as a result of seasonal fluctuations in ground-water levels.

The results from the one-dimensional models suggest that there is considerable spatial and temporal variability in streambed flux along LWD, with high fluxes occurring in small areas of the ditch. This suggests that ground-water flow to the stream would be focused into these areas. Because of the availability of stream bank heads and temperatures for Transect 1, it was possible to construct and calibrate a two-dimensional model of heat and water flow with 0.15-m wide and 0.03-m high grid blocks. However, because the K's for the bottom and top sediments were correlated, it was necessary to fix the K of the top sediments in the inverse simulations and only fit the K's for the bottom sediments and clay layer. Two values of K for the top sediments (1e-04 and 2e-04 m/s) were used in two separate inverse simulations (see Table 1) and the results differed very little. The estimated fluxes for the simulation with the top K set at 2e-04 m/s are shown in Figure 5 because this simulation had a slightly higher correlation coefficient than the simulation with K set at 1e-04 m/s. The two-dimensional fluxes (black curve in Figure 5) are slightly smaller than the fluxes obtained from the one-dimensional simulation for the right piezometer nest because of the effect of lateral flow. Figure 6 shows the corresponding simulated temperature distributions, and lines showing the relative magnitude and direction of flow, for the simulation period. These results clearly demonstrate the focusing of flow toward the zone of high K (no clay layer) in the streambed during the wet season (4/27/04, 6/10/04 – before flood, and 7/3/04 – after flood), and also the reversal in flow direction during a flood event (6/12/04) and during the dry season (8/18/04). The plot for 7/25/04 represents a period of very little SW/GW interaction that corresponds to the transition between the wet and dry seasons.

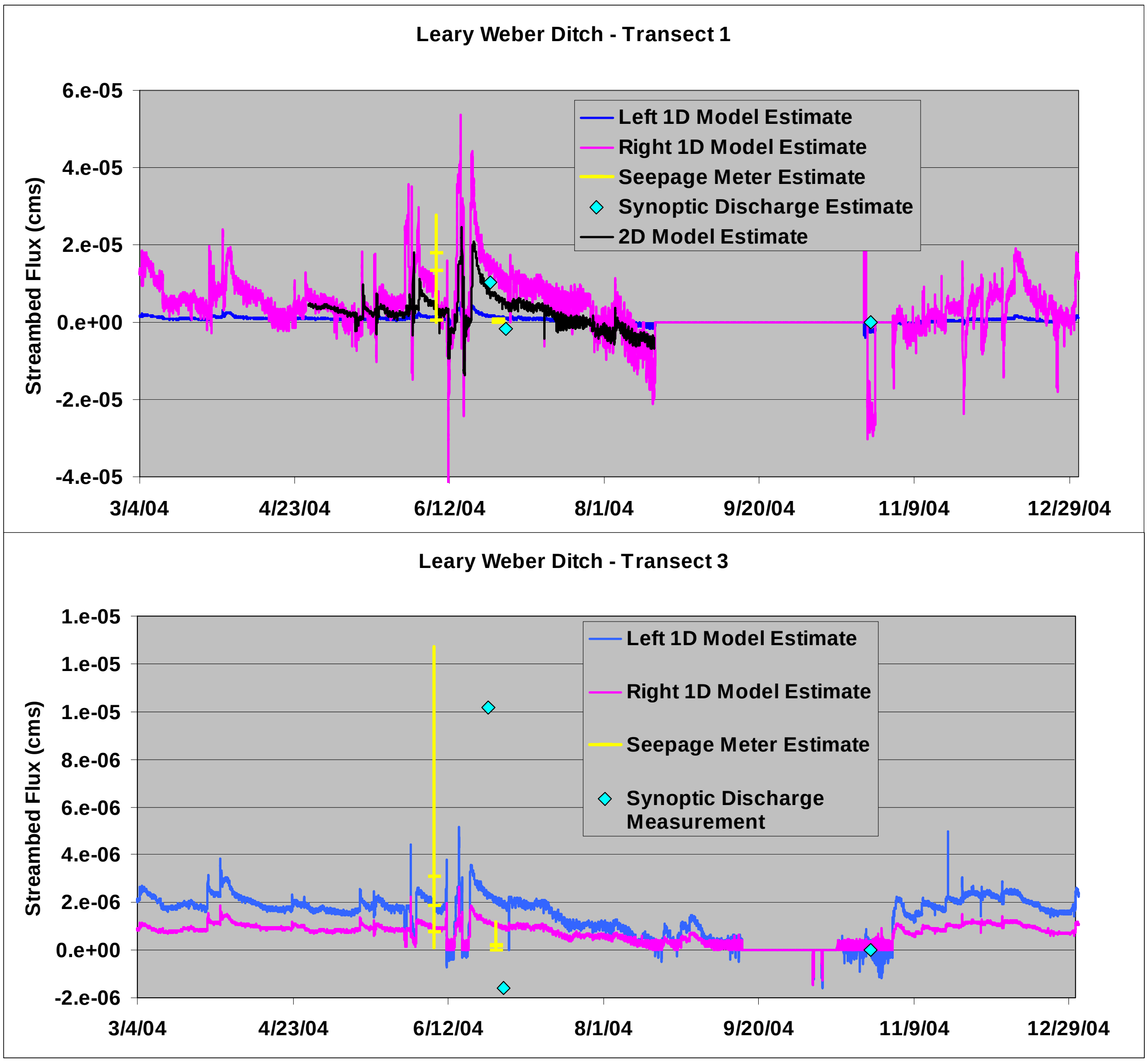

Figure 5 Plots of calibrated model estimates, synoptic discharge measurements (reported as m^3/s per unit stream bottom surface area), and the range of seepage meter measurements (showing the median and 1st and 3rd quartiles) of streambed flux at Transects 1 and 3.

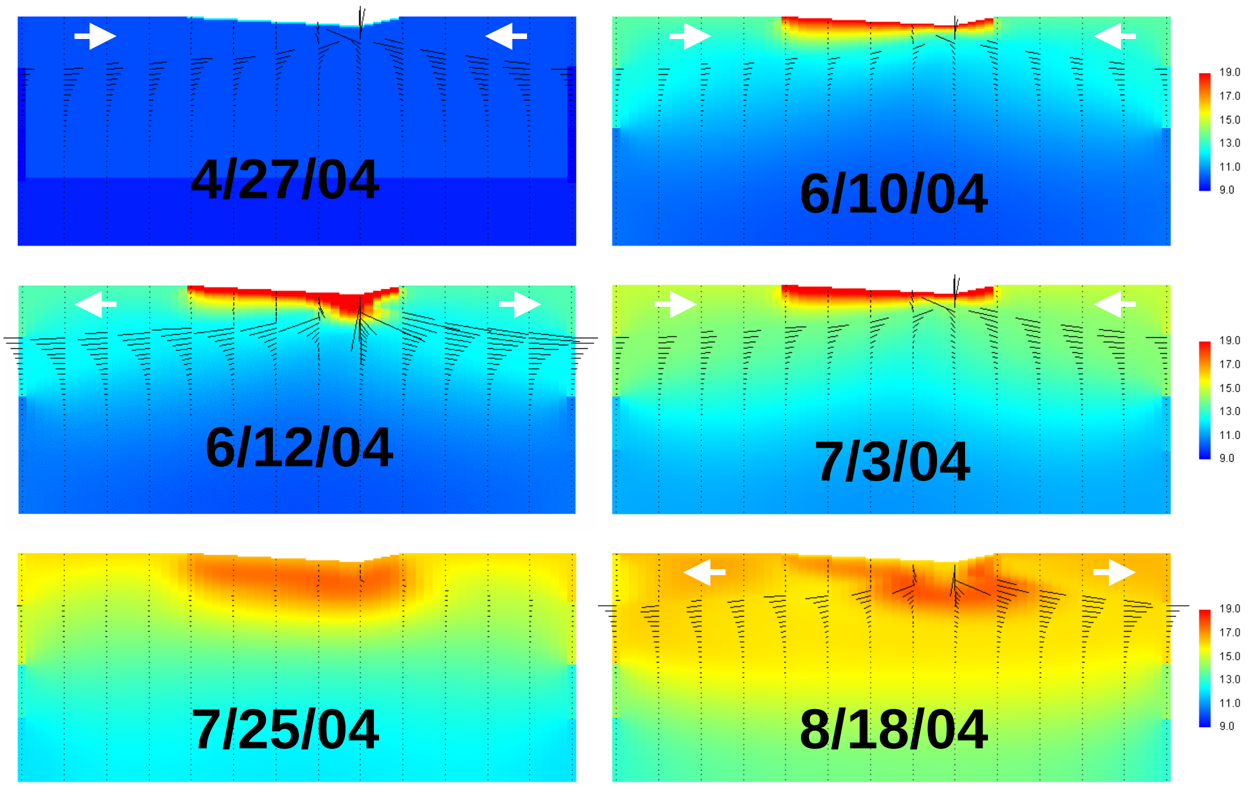

Figure 6 Simulated temperature distributions, lines showing the relative magnitude and direction of flow, and arrows showing the general ground-water flow directions for the calibrated two-dimensional model of Transect 1.

CONCLUSIONS

Heat was used as a tracer to obtain an understanding of the spatial variability and seasonality of SW/GW exchanges in the streambed. SW/GW exchange was influenced by physical heterogeneity of the stream channel with low flow where clay was observed in cores, and focusing of flow toward areas in LWD where the underlying clay layer was absent. Model estimates of flux magnitude and direction varied significantly during the period from March through December 2004. In general, flux was upward through the streambed during the early part of the record with the exception of flood events. Flood events resulted in rapid reversal of flow direction causing a period of surface water flow downward into the streambed that was followed by a return to ground water discharge to the stream. In the late summer season, regional ground-water levels dropped leading to surface-water loss to ground water that eventually resulted in drying of the ditch. ‘Snapshot’ measurements of flux made using seepage meters and differential discharge measurements along the ditch generally support the temperature-based model flux estimates.

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