PREFERENTIAL FLOW EFFECTS ON SUBSURFACE CONTAMINANT TRANSPORT IN ALLUVIAL FLOODPLAINS

Derek M. Heeren
University of Nebraska-Lincoln, derek.heeren@unl.edu

Ron B. Miller
Oklahoma State University - Main Campus

Garey A. Fox
Oklahoma State University - Main Campus, gafox2@ncsu.edu

Daniel E. Storm
Oklahoma State University - Main Campus, dan.storm@okstate.edu

Todd Halihan
Oklahoma State University - Main Campus, todd.halihan@okstate.edu

See next page for additional authors

Authors
Derek M. Heeren, Ron B. Miller, Garey A. Fox, Daniel E. Storm, Todd Halihan, and Chad J. Penn

Preferential Flow Effects on Subsurface Contaminant Transport in Alluvial Floodplains

D. M. Heeren, R. B. Miller, G. A. Fox, D. E. Storm, T. Halihan, C. J. Penn

Abstract. *For sorbing contaminants, transport from upland areas to surface water systems is typically considered to be due to surface runoff, with negligible input from subsurface transport assumed. However, certain conditions can lead to an environment where subsurface transport to streams may be significant. The Ozark region, including parts of Oklahoma, Arkansas, and Missouri, is one such environment, characterized by cherty, gravelly soils and gravel bed streams. Previous research identified a preferential flow path (PFP) at an Ozark floodplain along the Barren Fork Creek in northeastern Oklahoma and demonstrated that even a sorbing contaminant, i.e., phosphorus, can be transported in significant quantities through the subsurface. The objective of this research was to investigate the connectivity and floodplain-scale impact of subsurface physical heterogeneity (i.e., PFPs) on contaminant transport in alluvial floodplains in the Ozarks. This research also evaluated a hypothesis that alluvial groundwater acts as a transient storage zone, providing a contaminant sink during high stream flow and a contaminant source during stream baseflow. The floodplain and PFP were mapped with two electrical resistivity imaging techniques. Low-resistivity features (i.e., less than 200 Ω-m) corresponded to topographical depressions on the floodplain surface, which were hypothesized to be relict stream channels with fine sediment (i.e., sand, silt, and clay) and gravel deposits. The mapped PFP, approximately 2 m in depth and 5 to 10 m wide, was a buried gravel bar with electrical resistivity in the range of 1000 to 5000 Ω-m. To investigate the PFP, stream, and groundwater dynamics, a constant-head trench test was installed with a conservative tracer (Rhodamine WT) injected into the PFP at approximately 85 mg/L for 1.5 h. Observation wells were installed along the PFP and throughout the floodplain. Water table elevations were recorded real-time using water level loggers, and water samples were collected throughout the experiment. Results of the experiment demonstrated that stream/aquifer interaction was spatially non-uniform due to floodplain-scale heterogeneity. Transport mechanisms included preferential movement of Rhodamine WT along the PFP, infiltration of Rhodamine WT into the alluvial groundwater system, and then transport in the alluvial system as influenced by the floodplain-scale stream/aquifer dynamics. The electrical resistivity data assisted in predicting the movement of the tracer in the direction of the mapped preferential flow pathway. Spatially variable PFPs, even in the coarse gravel subsoils, affected water level gradients and the distribution of tracer into the shallow groundwater system.*

Keywords. *Alluvial groundwater, Electrical resistivity mapping, Floodplain, Preferential flow, Stream-aquifer interaction, Subsurface transport.*

In order to protect water systems and aquatic ecosystems, a complete understanding is needed of the nutrient transport mechanisms within a catchment. Riparian buffer zones have been installed adjacent to stream systems across the U.S. and abroad to prevent sediment, nutrient, and pesticide transport to streams. Because buffers primarily address the commonly observed and more easily understood surface runoff transport mechanism (Lacas et al., 2005; Popov et al., 2005; Reichenberger et al., 2007; Poletika et al., 2009; Sabbagh et al., 2009), effectiveness becomes an issue if a transport pathway through the subsurface circumvents the surface trapping objectives of the riparian buffer (Cooper et al., 1995; Lacas et al., 2005).

Spatial variability in hydraulic conductivity (Carlyle and Hill, 2001), preferential flow pathways (McCarty and Angier, 2001; Polyakov et al., 2005; Fuchs et al., 2009), and limited sorption capacity in riparian zone soils (Cooper et al., 1995; Carlyle and Hill, 2001; Polyakov et al., 2005) promote subsurface nutrient transport. It is well known that paleochannels, i.e., linear deposits of coarse-grained sediments, exist across floodplains and link modern channel flows to distal floodplain areas (Stanford and Ward, 1992; Poole et al., 1997, 2002; Amoros and Bornette, 2002; Naiman et al., 2005). Hydrologic pathways become complex with deposits of coarse alluvium (Naiman et al., 2005). Limited research has been performed on monitoring and understanding subsurface contaminant transport mechanisms in riparian floodplains (Lacas et al., 2005). Tellam and Lerner (2009) emphasize the impact of stream-aquifer interactions on

Submitted for review in July 2009 as manuscript number SW 8128; approved for publication by the Soil & Water Division of ASABE in January 2010. Presented at the 2009 ASABE Annual Meeting as Paper No. 095995.

The authors are **Derek M. Heeren, ASABE Member Engineer,** Research Engineer and Doctoral Student, **Ron B. Miller,** Graduate Research Assistant and Doctoral Student, **Garey A. Fox, ASABE Member Engineer,** Associate Professor, and **Daniel E. Storm, ASABE Member Engineer,** Professor, Department of Biosystems and Agricultural Engineering, Oklahoma State University, Stillwater, Oklahoma; **Todd Halihan,** Associate Professor, Department of Geology, Oklahoma State University, Stillwater, Oklahoma; and **Chad J. Penn,** Assistant Professor, Department of Plant and Soil Sciences, Oklahoma State University, Stillwater, Oklahoma. **Corresponding author:** Garey A. Fox, Department of Biosystems and Agricultural Engineering, Oklahoma State University, 120 Agricultural Hall, Stillwater, OK 74078; phone: 405-744-8423, fax: 405-744-6059; e-mail: garey.fox@okstate.edu.

  ISSN 2151-0032

stream chemistry and suggest electrical resistivity, piezometers with pressure loggers, and chemical tracers as potential methods for better characterizing sediment distributions and solute transport.

Local or regional conditions can lead to situations where subsurface transport may be important (Turner and Haygarth, 2000; Lacas et al., 2005; Fuchs et al., 2009). For example, in northeastern Oklahoma and northwestern Arkansas, phosphorus sources from the Illinois River basin to Lake Tenkiller are estimated to be 35% from point sources, 15% from poultry litter application, and 50% from other nonpoint sources (Storm et al., 2006). In this basin, there is a statistically significant (α = 0.05) correlation between baseflow phosphorus concentrations and poultry house density in nonpoint-source impacted streams, which are characterized by cherty soils and gravel bed streams (Storm et al., 2010). These baseflow data suggest that groundwater mechanisms may play an important role in phosphorus fate and transport in basins with gravelly subsoils. We hypothesize that these mechanisms include: (1) connectivity between phosphorus in surface runoff and shallow groundwater, and phosphorus consequently moving with the groundwater to the stream, and (2) alluvial deposits providing a transient storage zone, i.e., acting as a sink during high flow events (with elevated phosphorus concentrations) and a source during baseflow.

A study by Fuchs et al. (2009) at one field site along the Barren Fork Creek in northeastern Oklahoma demonstrated that subsurface transport of injected phosphorus during three tracer tests was significant in localized preferential flow paths (PFPs). Using a trench to inject phosphorus into the subsurface flow system, these high-velocity pathways transported phosphorus at the same concentrations as were applied to the trench. Fine material less than 2 mm in diameter in the non-preferential flow pathways appeared to adsorb phosphorus from the water and retard phosphorus movement. In addition, background phosphorus concentrations in the PFP were higher than background phosphorus concentrations in non-preferential flow paths, suggesting that a phosphorus transport connection exists between the PFPs and the stream and/or upland areas. However, this research was limited to monitoring flow and transport pathways of less than 3 m from the trench for the PFP and 5 to 7 m from the trench for non-preferential flow paths.

The objectives of this research were to investigate the presence and impact of subsurface physical heterogeneity (i.e., PFPs) on contaminant transport in alluvial floodplains. Specific tasks included determining the location and connectivity of the PFP to a stream using subsurface mapping techniques and documenting the movement of a conservative tracer (i.e., Rhodamine WT) along a mapped PFP and areas surrounding the PFP. This research also evaluated a hypothesis that the alluvial groundwater acts as a transient storage zone, providing a contaminant sink during high stream flow and a contaminant source during stream baseflow. It should be emphasized that this research does not address the fate and transport of contaminants in the vadose zone between the soil surface and the alluvial gravel. It is hypothesized that separate preferential paths occur in that zone, but such pathways were not explored in this research.

Materials and Methods

Barren Fork Creek Riparian Floodplain Site

The riparian floodplain site (fig. 1) along the Barren Fork Creek is located immediately downstream of the Eldon Bridge U.S. Geological Survey (USGS) gage station (07197000) in the Ozark region of northeastern Oklahoma (35.90° N, −94.85° W). The southern border of the floodplain is a bedrock bluff that rises approximately 5 to 10 m above the floodplain elevation and limits channel migration to the south. The Barren Fork Creek, a tributary of the Illinois River, flows in the vicinity of the bluff near the western boundary of the study region. Historical aerial photographs demonstrate the recent geomorphic activity of the site. An abandoned stream channel is present just upstream of the studied floodplain and shows that the stream historically flowed in a more western direction than its current southwestern flow path. In this watershed, in-stream phosphorus concentrations increase with flow (Tortorelli and Pickup, 2006).

Fuchs et al. (2009) described some of the soil and hydraulic characteristics of the Barren Fork Creek floodplain site. The floodplain consists of alluvial gravel deposits underlying 0.5 to 1.0 m of topsoil (Razort gravelly loam). Soil hydraulic studies on these soil types have shown that subtle morphological features can lead to considerable differences in soil water flow rates (Sauer and Logsdon, 2002). Topsoil infiltration rates are reported to range between 1 and 4 m/d based on USDA soil surveys (USDA, 1970). The gravel subsoil, classified as coarse gravel based on the Wentworth (1922) scale, consists of approximately 80% (by mass) of particle diameters greater than 2.0 mm, with an average particle size (d_{50}) of 13 mm. Estimates of hydraulic conductivity for the gravel subsoil range between 140 and 230 m/d based on falling-head trench tests (Fuchs et al., 2009). Soil particles less than 2.0 mm in the gravelly subsoil consist of secondary minerals, such as kaolinite and noncrystalline Al and Fe oxyhydrox–

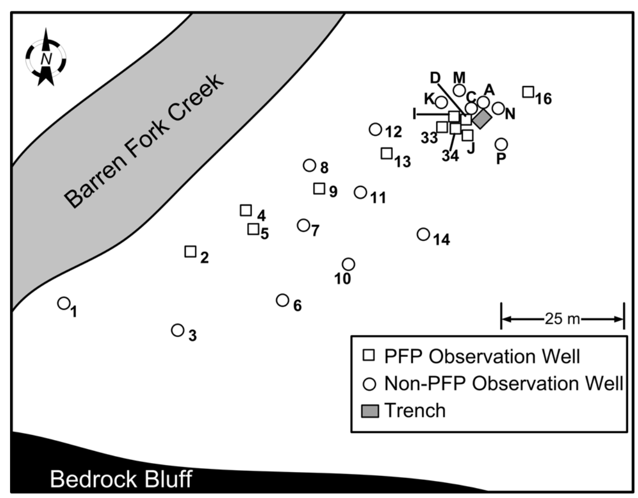

Figure 1. Barren Fork Creek field site with installed observation wells used for tracer injection studies. Observation wells were installed along the mapped preferential flow pathway (PFP) and outside the pathway (non-PFP). Lettered observation wells were originally used by Fuchs et al. (2009); numbered observation wells were installed to monitor tracer movement from the trench system over larger distances. The Barren Fork Creek illustration represents the width of the bankfull channel, not the actual width of the stream at the time of the test. Streamflow is from the northeast to the southwest. The bedrock bluff is at the south boundary of the image.

ides. Ammonium oxalate extractions on this finer material estimated initial phosphorus saturation levels of 4.2% to 8.4% (Fuchs et al., 2009).

Riparian Floodplain Subsurface Mapping

Resistivity mapping is based on measuring the electrical properties of near-surface earth materials (McNeill, 1980), which vary with grain size, pore-space saturation, pore water solute content, and electrical properties of the minerals. The electrical behavior of earth materials is controlled by Ohm's law, in which current is directly proportional to voltage and inversely proportional to resistance. Generally, electrical current travels readily in solute-rich pore water and poorly in air. In addition, cations adsorbed to soil particle surfaces reduce resistivity. Clay particles have a large surface area per volume and thus have generally lower resistivity (1 to 100 Ω-m) compared to sands or gravels (10 to 800 Ω-m), which are lower than limestone bedrock (McNeill, 1980). The potential voltage measured when a known current is injected into the ground will vary with the resistance of the subsurface material. The resistance, when normalized for length and area, becomes resistivity, a material property (McNeill, 1980). Varying the separation between paired current and potential electrodes produces resistivity values for different depths.

The subsurface of the alluvial floodplain at the Barren Fork Creek site was mapped using two methods of electrical resistivity and a high-precision base station global positioning system (GPS). General wide-scale mapping was accomplished with the Geometrics OhmMapper, a capacitively coupled, A-C dipole-dipole system, and more detailed imaging was performed with a SuperSting DC resistivity meter (Advanced Geosciences, Inc., Austin, Tex.) (Poole et al., 1997, 2002; Pellerin, 2002; McCorley et al., 2003; Robinson et al., 2008). The OhmMapper system consisted of a transmitter dipole and five receiver dipoles, each 5 m long with a transmitter-receiver offset (rope length) of 10 m. This produced an array 40 m long towed by an all-terrain vehicle mounted with a high-precision GPS receiver, providing data for a 5 m maximum depth into the soil profile. The smaller-scale, high-precision electrical resistivity mapping was planned based on results from the OhmMapper. The SuperSting used 56 electrodes placed in the ground at a spacing ranging from 1 to 2.5 m, producing data to a depth of 13 to 20 m, respectively (Halihan et al., 2005), to generate two-dimensional resistivity profiles (lines). The GPS (TOPCON HiperLite Plus) was configured with a base station and three rover units. The OhmMapper produced a grid of 21 resistivity sections, including 16 oriented east-west and five oriented north-south. The SuperSting was used to collect seven sections including three north-south, one east-west, and three angled from northwest-southeast. One of the SuperSting lines overlapped with an OhmMapper line, allowing the measured resistivity of the two methods to be compared. The magnitudes of the resistivity results were different, which was expected for different methods of measurement. However, the patterns in these data were the same for both the SuperSting and the OhmMapper.

Although the wide range of resistivity for materials generally prevents determination of the actual subsurface material from resistivity alone, the patterns and positions of resistivity can be used to make an initial prediction about subsurface structures, which can be tested later with additional ground truth data. Soil samples served as one source of ground truth data; however, undisturbed core samples were difficult to collect from the unconsolidated gravel at the study site. Therefore, disturbed soil samples were collected from layers on the Barren Fork Creek banks both within and below the mapped PFP. Sampling of the PFP was assisted through subsequent streambank erosion at the site during several rainfall/flow events following the injection test. Gravel was separated from the sample using a 2 mm sieve (No. 10), and the percentage of particles less than 2.0 mm by mass was calculated. An additional ground truth data set was also utilized in this research: electrical resistivity imaging of a gravel bar exposed during baseflow conditions in the Barren Fork Creek. Disturbed soil samples were also collected from the upper layers (i.e., 10 to 20 cm) of the gravel bar and sieved to determine the percentage by mass of particles less than 2.0 mm.

Installation of Observation Well Field

In the study by Fuchs et al. (2009), 15 observation wells were installed at various locations around a constant-head trench, with the majority of the observation wells located between the trench and the stream. Several of these observation wells (A, C, D, I, J, K, M, N, and P in fig. 1) were utilized for this tracer injection study. In order to monitor potential tracer movement over much larger distances, additional observation wells were installed in the riparian floodplain (fig. 1). The observation wells, installed to a depth of approximately 5 m, were constructed of schedule 40 PVC and had a 3 m screened section at the base. The observation wells were installed using a Geoprobe (Kejr, Inc., Salina, Kansas) drilling machine. Observation wells 2, 4, 5, 9, 13, 33, and 34 in figure 1 were located along the mapped PFP. Twenty-four of the observation wells (i.e., observation wells 1-14, 16, 33-34, A, C, D, I, J, and N) and the trench were instrumented with automated water level loggers (HoboWare, Onset Computer Corp., Cape Cod, Mass.) to monitor water pressure and temperature at 1 min intervals. One logger was placed above the water table to account for changes in atmospheric pressure. Observation wells were surveyed so that the actual water table elevations could be calculated from water depth data. Stream stage data from a nearby USGS gage station (07197000) was used in the analysis. Two stream sampling points were also utilized to collect water quality samples from the Barren Fork Creek.

Injection Experiment

The trench constructed by Fuchs et al. (2009) was utilized in this research to induce a constant water head and a tracer source to the subsurface alluvial gravel, with subsequent monitoring of flow and tracer transport in the observation well field. The dimensions of the trench were approximately 0.5 m wide × 2.5 m long × 1.2 m deep. The bottom of the trench was located approximately 25 to 50 cm below the interface between the topsoil and gravel layers. A bracing system consisted of a frame constructed with 5 cm × 13 cm wood studs covered with 2 cm plywood. The top and bottom were left open to allow water to infiltrate directly into the gravel layer.

Prior to the injection, each observation well and the Barren Fork Creek were sampled and analyzed for background Rhodamine WT levels. In addition, a water level indicator (Solinst Canada, Ltd., Georgetown, Ontario, Canada) was used to determine the depth to the water table in each observation well prior to injection. This provided a representation of the hydraulic gradient in the subsurface and a correlation between the water level and the pressure reading from the water level loggers. Next, water was pumped from the Barren Fork Creek into the trench using two pumps with a combined pumping rate of approximately 0.010 m^3/s (160 gpm) to induce water movement. Pumping started at 11:36 a.m. on 3 April 2009. The steady-state water level in the trench was held as constant as possible between 148 to 152 cm above the bottom of the trench.

Pumping continued for approximately 2.8 h prior to Rhodamine WT injection in order to reach pseudo-steady-state flow conditions. Rhodamine WT was injected into the trench in the pumped inflow water for 1.5 h at a constant rate using a variable-rate chemical pump to obtain a constant trench solution of 85 mg/L. This peak, constant concentration was achieved within approximately 15 min of injection initiation due to the storage volume of the trench. After the injection began, a total of approximately 260 samples were taken from the observation wells, trench, and creek for the duration of the experiment in order to monitor the movement of the Rhodamine WT tracer. A peristaltic pump sampled the observation wells at approximately 10 cm below the steady-state water level. Pumping ended 6.9 h from the beginning of Rhodamine WT injection for the first pump and 7.4 h from beginning of Rhodamine WT injection for the second pump. Rhodamine WT concentrations were measured with a Trilogy laboratory fluorometer (Turner Designs, Inc., Sunnyvale, Cal.), which had a minimum detection limit of 10 μg/L.

Results and Discussion

Riparian Floodplain Subsurface Mapping

The grid of OhmMapper resistivity sections showed a series of low-resistivity structures that were roughly parallel to the existing stream channel and separated by higher-resistivity features (fig. 2). These were interpreted as relict cut-off stream channels, which were subsequently filled with fine sediments (i.e., sand, silt, and clay) and gravel having low resistivity. The higher-resistance areas may have represented gravel-dominated lateral or mid-channel bars. The Barren Fork Creek, adjacent to the site, is a gravel-bed Ozark stream with prominent mid-channel and lateral gravel bars. The topography of the site is generally level, but several similar linear depressions coincided with the mapped low-resistance areas.

Unlike the larger-scale OhmMapper, the SuperSting lines could be placed within the well field, and the resulting two-dimensional resistivity profiles were used to attempt to locate the PFP. The wells affected by the PFP discovered in the original pumping test (Fuchs et al., 2009) were near a zone of high resistivity (i.e., 1000 to 5000 Ω-m) from the trench to the southwest (fig. 3). This trend in high resistivity was parallel to the low-resistivity features revealed by the OhmMapper lines, suggesting a common origin of formation.

The high-resistivity feature at the trench indicated that the structure was likely dominated by coarse gravel and may create a direct hydraulic connection with the adjacent Barren Fork Creek. An interesting feature from the imaging was the vertical position of the PFP above the shallow groundwater system, especially with increasing distance from the Barren Fork Creek (fig. 3). The SuperSting image of an exposed gravel bar verified the hypothesis of the PFP consisting of similar subsoils as the gravel bar. Resistivity of the coarse gravel layers within the gravel bar fell within the same range

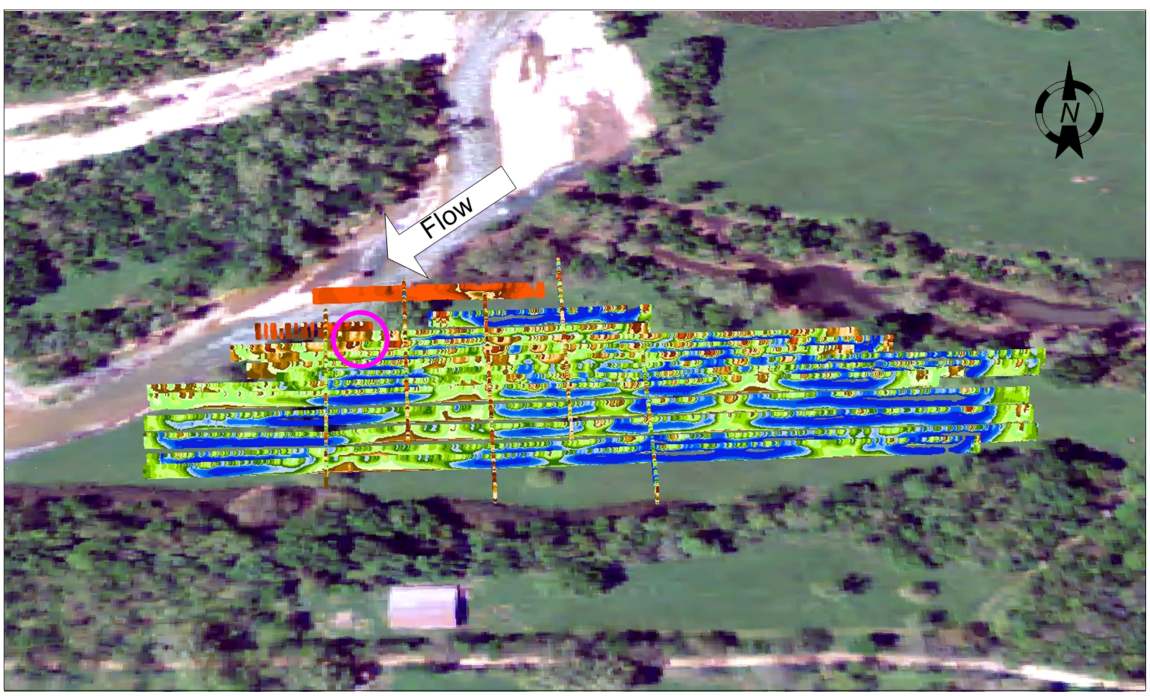

Figure 2. Three-dimensional rendering of OhmMapper resistivity showing low-resistivity (blue) structures. View is to the north; Barren Fork Creek is to the northwest of the image, with the arrow indicating the general streamflow direction. The location of the trench is identified with a pink circle. Underlying image is 2008 aerial photograph from USDA (2008).

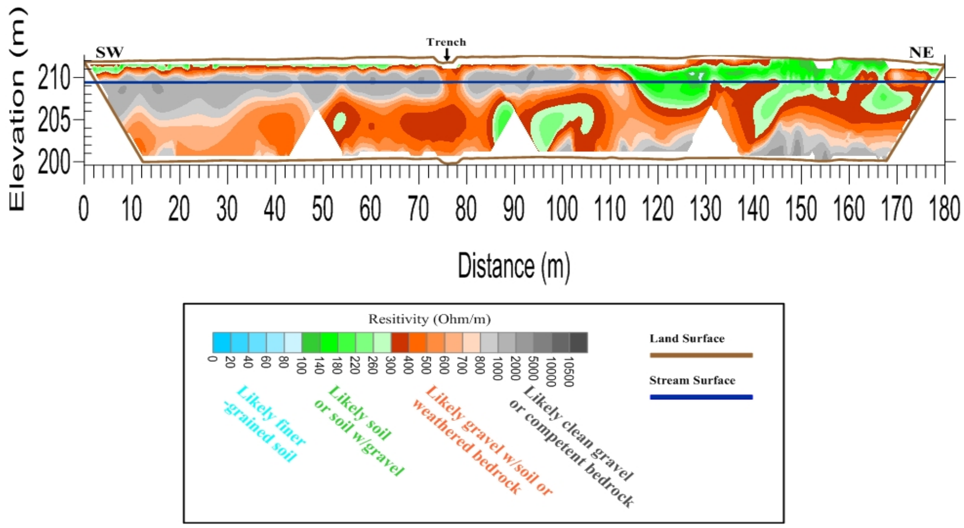

Figure 3. Composite SuperSting image, showing mapped electrical resistance (Ω-m), running southwest to northeast along the hypothesized preferential flow pathway. The *x*-axis represents the horizontal distance along the ground; the *y*-axis is elevation above mean sea level. The line, which is approximately parallel to the stream, begins only 5 m from the stream (near observation well 2 in fig. 1) and continues through the trench (at approximately 75 m).

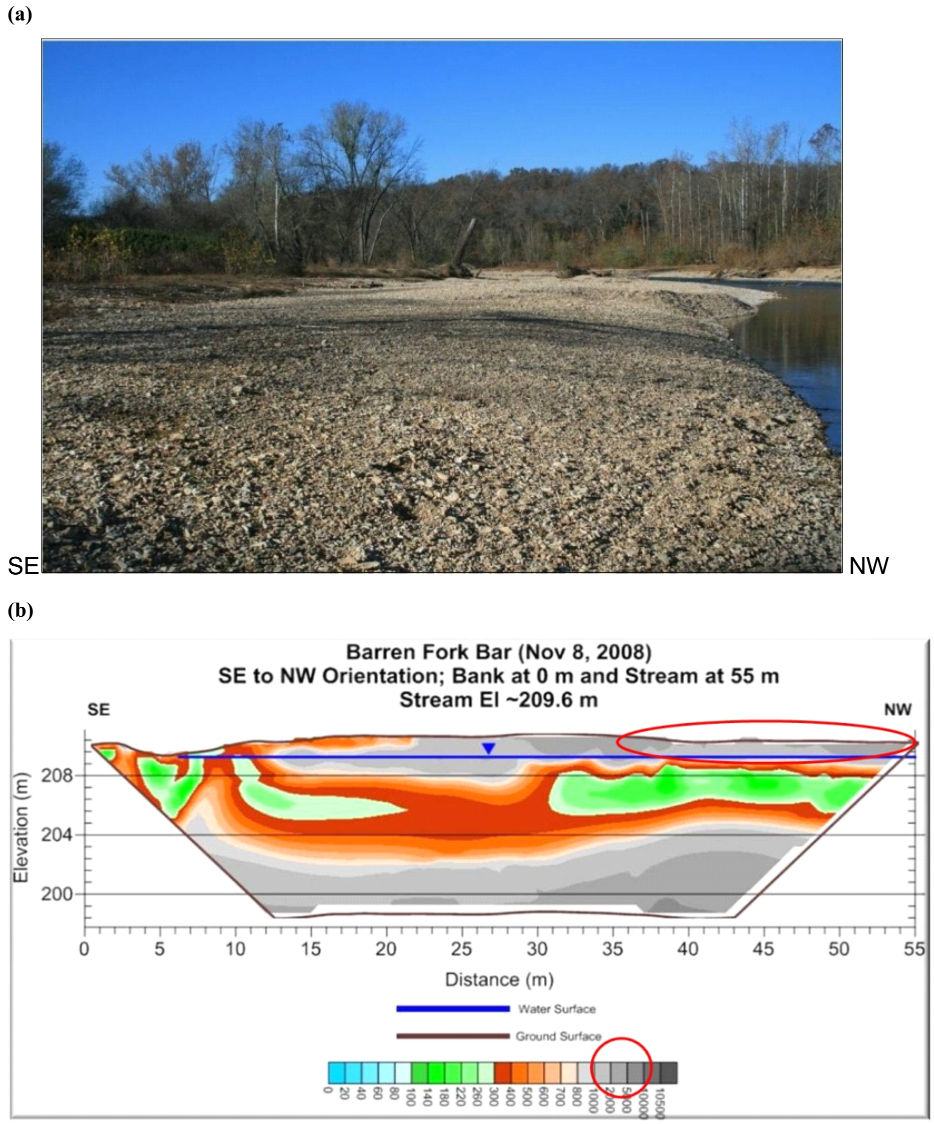

Figure 4. (a) Exposed gravel bar in the streambed of the main channel of the Barren Fork Creek and (b) electrical resistivity imaging of the gravel bar from the SuperSting. Color bar in (b) refers to electrical resistance in Ω-m. Red circle indicates recent deposits of gravel on the bar.

as the PFP (i.e., 1000 to 5000 Ω-m), as shown in figure 4. Furthermore, sieve analysis of disturbed soil samples confirmed the similarity of the PFP to the gravel bar. Percent of soil material less than 2.0 mm in the PFP, gravel bar, and in streambank samples not within the PFP were approximately 6%, 13%, and 20% by mass, respectively.

Injection Experiment

Since the injection experiment was conducted when the stage in the Barren Fork Creek corresponded to a recession limb of the streamflow hydrograph, the direction of the groundwater flow gradients was expected to be downstream and toward the stream. Surprisingly, the flow gradient direction prior to injection was directed into the alluvial groundwater and downstream along the Barren Fork Creek (fig. 5a). The water table profile during steady-state injection showed a mound in the shallow aquifer near the trench (fig. 5b, table 1). The mounding was limited in lateral extent because of the permeable nature of the shallow gravel subsoils. Therefore, artificially induced radial flow occurred near the trench; however, the water table rise moving away from the trench became negligible, so that tracer movement mimicked natural, groundwater flow conditions.

While groundwater flow was generally directed away from the stream and into the riparian floodplain at this location (i.e., a losing stream), some spatial heterogeneity was observed based on the groundwater level measurements. The primary source of this spatial heterogeneity occurred near the mapped PFP adjacent to the stream. Groundwater levels were higher along this linear feature, suggesting that the PFP was a spatially discrete hyporheic flow pathway (fig. 5). Such results suggested that equations for predicting hyporheic flux area and stream/aquifer interactions that neglect subsurface physical heterogeneity (e.g., Cardenas, 2009) were not appropriate at this scale or for these hydraulic conditions. This indicates that more research needs to be performed to better characterize stream-aquifer interactions at sites with highly conductive alluvial aquifers and that these highly conductive aquifers can possess significant spatial heterogeneity.

All background Rhodamine WT samples, including the Barren Fork Creek and the observation wells, were below the detection limit except two, which were both approximately 20 μg/L. Rhodamine WT concentrations induced in the trench were approximately 85 mg/L for approximately 1.5 h (fig. 6). Concentrations in observation well 34, located in the PFP and within 5 m of the trench, mimicked concentrations in the trench, except for the concentration tail. Peak concentrations in observation wells further downstream along the PFP (i.e., observation wells 34, 33, and 11) decreased with distance from the trench (table 1, fig. 6).

In the larger study area, Rhodamine WT was transported according to local gradients in the groundwater system. In fact, Rhodamine WT was detected in observation wells outside of the PFP at relatively large concentrations (i.e., 1000 to 10,000 μg/L), but only on the side of the PFP away from the Barren Fork Creek (table 1, fig. 7). The Barren Fork Creek, which never had Rhodamine WT concentrations above the detection limit, was recharging the alluvial groundwater (fig. 5), thereby transporting Rhodamine WT farther away from the stream. It should be noted that no Rhodamine WT concentrations above the detection limit were observed in several observation wells, including those located immediately adjacent to the Barren Fork Creek (i.e., 1-5, 7-9, K, and M) and several within 5 to 10 m of the trench.

Table 1. Water level change (Δ*h*) between the initiation of pumping and the start of Rhodamine injection, the maximum observed Rhodamine WT concentration (c_{max}), and the time after Rhodamine injection at which the peak concentration (t_{peak}) was measured.

Sampling Point	Δ*h* (cm)	c_{max} (μg/L)	t_{peak} (h)
Trench	151.5	86,000	0.3
1	-0.2[a]	<10	--[b]
2	-0.1[a]	<10	--
3	0.0	<10	--
4	0.3	<10	--
5	0.3	<10	--
6	0.1	83	8.2
7	0.4	<10	--
8	0.2	<10	--
9	0.3	<10	6
10	0.4	3,800	8.9
11	0.5	2,600	5.9
12	0.9	15	5.9
13	1.8	2,600	4.6
14	0.6	13,000	6.1
16	1.0	13	8.5
33	1.9	37,000	2.4
34	2.4	69,000	1.6
A	1.4	7,200	3.7
C	1.8	36,000	0.6
D	2.5	64,000	0.4
I	--	74,000	1.1
J	2.4	70,000	0.4
M	0.9	<10	--
N	1.3	4,000	3.7
P	2.1	16,000	4.5

[a] Stream stage was decreasing during the injection experiment (i.e., -0.9 cm between pumping and Rhodamine injection).
[b] No peak concentration due to the lack of observations above the limit of detection.

An interesting result from the trench test was the observation of asymmetrical breakthrough curves for the Rhodamine WT concentrations in many of the observation wells (fig. 6). This asymmetrical breakthrough, with the tail of the curve remaining high, suggested that the system was largely influenced by physical heterogeneity at the macroscopic scale (i.e., 10^{-1} to 10^{1} m), a result that was not surprising based on the electrical resistivity mapping. As discussed by Brusseau (1998), the presence of smaller hydraulic conductivity zones most likely created locations in the flow field with little advective transport. Of course, similar asymmetrical breakthrough curves can also be caused by chemical nonequilibrium (Wilson et al., 2004), but sorption-desorption processes were not expected to be primary transport mechanisms due to the use of the minimally sorbing Rhodamine WT in the low organic carbon content, gravel soils.

For example, consider observation well P in figure 6b. Rhodamine WT concentrations in this observation well increased to approximately 10,000 μg/L and remained elevated for most of the experiment, including after Rhodamine WT injection into the constant-head trench. However, observation wells along the PFP with a similar distance from the trench (i.e., observation well 34 in fig. 6b) more closely resembled the expected rising and falling

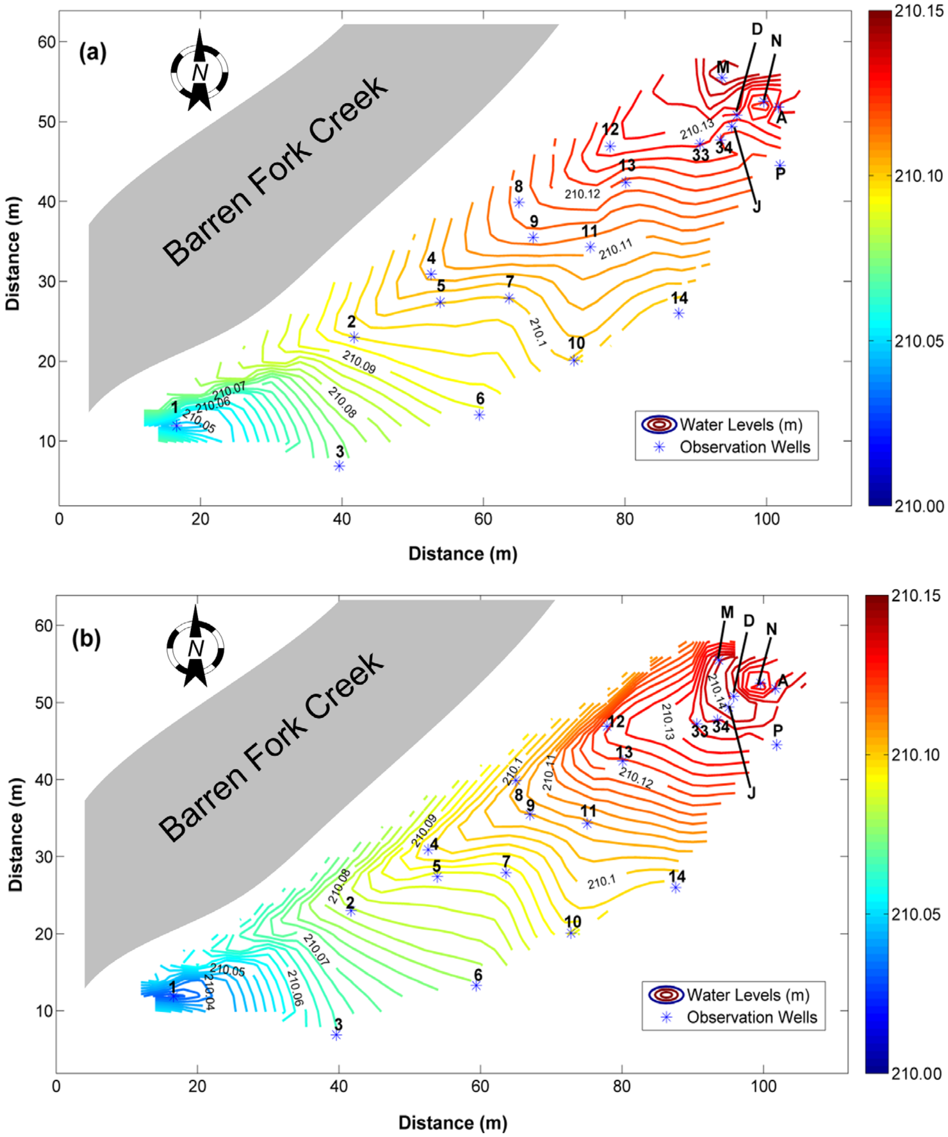

Figure 5. Water table elevations at (a) 11:15 a.m., before water injection into the trench, and (b) after 8 h of water injection. The scale on each graph is the water level contour level (above mean sea level in m). The Barren Fork Creek illustration represents the width of the bankfull channel, not the actual width of the stream at the time of the test.

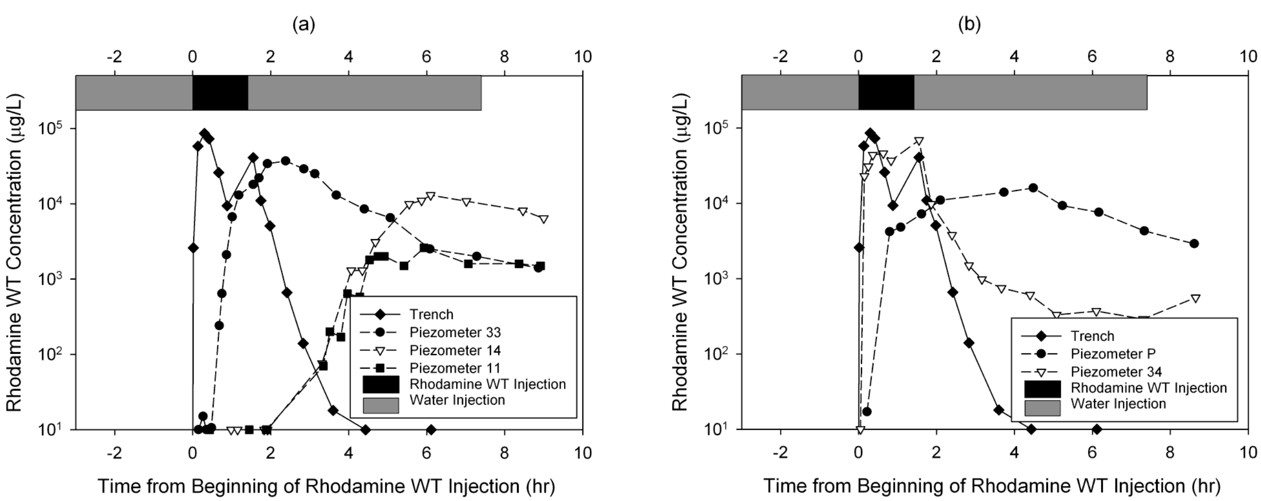

Figure 6. Rhodamine WT concentrations measured in the trench and observation wells during the injection experiments.

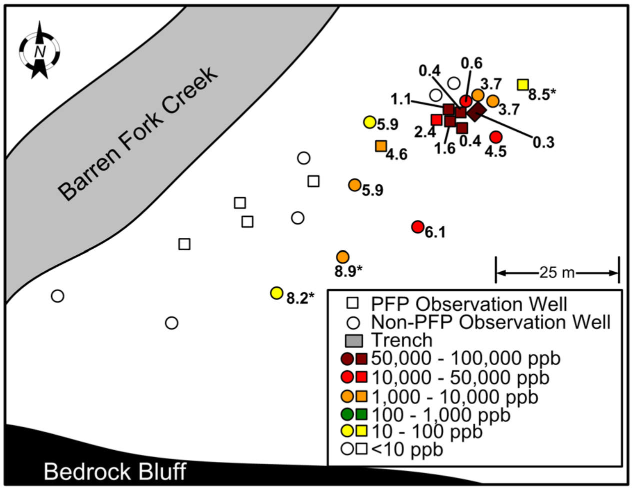

Figure 7. Peak Rhodamine WT concentrations in each observation well. Observation wells are labeled with the time (h) to the peak concentrations from the beginning of the injection. An asterisk indicates that there were not enough samples to characterize a complete curve for that observation well; the concentration and time correlate to the sample with the maximum concentration. The Barren Fork Creek illustration represents the width of the bankfull channel, not the actual width of the stream at the time of the test.

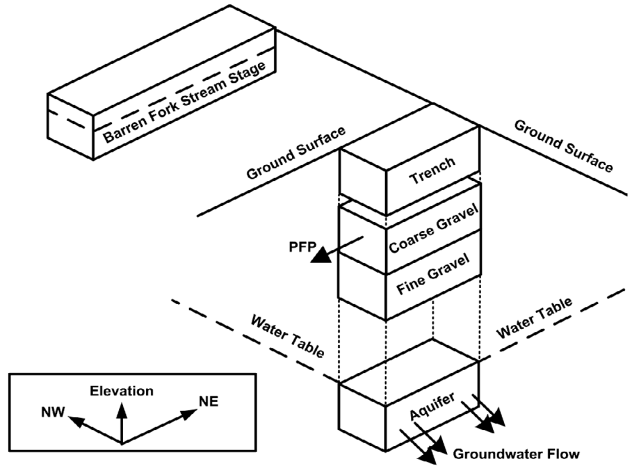

Figure 8. Conceptual model of the alluvial floodplain system. Rhodamine WT from the trench flowed through the preferential flow path (PFP) to the west before infiltrating through a fine gravel layer to the groundwater. The PFP essentially distributed the tracer across a wide extent of the aquifer.

breakthrough curve due to injection and cessation of Rhodamine WT into the trench. Concentrations in observation well P began to slowly decrease 4.5 h after initiation of Rhodamine injection or 3 h after the last Rhodamine WT injection into the trench, and concentrations remained above 1000 μg/L for 8 h after initiation of injection.

Therefore, it appeared that gravel subsoils surrounding observation well P acted as source/sink areas and contributed mass to the higher advective domains (i.e., PFP) over time. These results, combined with the influence of the PFP and the stream recharging the groundwater, confirmed the hypothesis of the alluvial groundwater acting as a transient storage zone, at both medium (i.e., 10^1 m) and larger scales (i.e., 10^2 m), as shown in the concentration plume map of figure 7.

Since the PFP was above the water table, it was not active before pumping began. During the injection, it was hypothesized that water from the trench flowed through the PFP (vertically positioned above the base flow groundwater table) and infiltrated into the alluvial groundwater system (fig. 8). In fact, manual water level sensors were not able to read a specific water table elevation in observation wells D and J, hypothesized to be the result of perched water flowing laterally along the PFP and then entering and dropping down the observation well shaft. While perching did occur, it should be noted that the PFP was not separated from the underlying subsoils by an impermeable layer. The potential for infiltration into the shallow groundwater as water flowed laterally along the PFP was relatively high.

A comparison between observation wells 33 and P supported the hypothesis that the PFP, when active, distributed tracer to the alluvial groundwater along the length of the PFP, after which movement was driven by the interaction between the stream and alluvial groundwater. While both observation wells were similar distances from the trench, only observation well 33 was located along the PFP (fig. 1). At the start of Rhodamine WT injection, the groundwater gradient from the trench to observation well P (i.e., approximately 0.4 m/m) was higher than it was from the trench to observation well 33 (i.e., approximately 0.3 m/m). If transport was only driven by groundwater gradients, then observation well P would be expected to have a higher peak concentration and a shorter time to the peak. However, due to the impact of the PFP, Rhodamine WT concentrations in observation well 33 peaked at 37 μg/L (compared to 16 μg/L for observation well P) at 2.4 h after initiation of the Rhodamine WT injection (compared to 4.5 h for observation well P). The PFP appears to account for the large spread of the plume to the west (e.g., observation wells 11-13 in fig. 7) when the general direction of the groundwater gradient was to the south.

Summary and Conclusions

This research identified the presence and demonstrated the impact of subsurface physical heterogeneity (i.e., a preferential flow pathway) on water and conservative tracer transport in a riparian floodplain system. The preferential flow pathway was successfully identified and mapped using electrical resistivity imaging and appeared to create a direct hydraulic connection between the Barren Fork Creek and the subsurface of the riparian floodplain. The preferential flow pathway also appeared to influence water level gradients in the riparian floodplain. The tracer injection further demonstrated that the preferential flow pathway influenced the movement and the distribution of tracer into the shallow groundwater system. The electrical resistivity data assisted in predicting the southwestern movement of the tracer in the direction of the mapped preferential flow pathway. The resistivity mapping demonstrated the presence of vertical layering, which resulted in a lateral distribution of water and tracer before entering the groundwater system. The interaction between the Barren Fork Creek and the alluvial groundwater then controlled the movement of the tracer in the shallow groundwater. This enhanced lateral distribution resulted in a greater westward migration of the tracer plume than would have been predicted based only on the water table gradient.

The results verified the hypothesis of the alluvial groundwater acting as a transient storage zone, as contaminants in the stream can be stored in the alluvial groundwater. The preferential flow pathway, vertically positioned above the shallow groundwater system, may not become hydrologically active except under high flow events. This is important, however, as high flow events usually contribute significantly to total contaminant loads to downstream water reservoirs. Additionally, the preferential flow pathways may become active during recharge between the surface and subsurface, affecting the distribution of material into the shallow groundwater system. Future research is needed to understand the connectivity between nutrient (i.e., phosphorus) concentrations on the surface with the PFP and the underlying alluvial aquifer, as well as to better characterize stream-aquifer interactions at sites with highly conductive alluvial aquifers.

Acknowledgements

This material is based on work supported by the Oklahoma Conservation Commission with a U.S. Environmental Protection Agency Region VI 319 grant, and an Oklahoma State University Team Initiative Proposal (TIP) grant through the College of Agricultural Sciences and Natural Resources. The authors acknowledge Dan Butler of the Oklahoma Conservation Commission for providing access to the riparian floodplain property along the Barren Fork Creek. The authors acknowledge Amanda K. Fox, Stillwater, Oklahoma, for assisting with figure development and reviewing an earlier version of the manuscript; Glenn V. Wilson, USDA-ARS, Oxford, Mississippi, for reviewing an earlier version of the manuscript; and Maria L. Chu-Agor and Jorge A. Guzman, Department of Biosystems and Agricultural Engineering, Oklahoma State University, for assisting with data collection.

References

Amoros, C., and G. Bornette. 2002. Connectivity and biocomplexity in waterbodies of riverine floodplains. *Freshwater Biology* 47(4): 761-776.

Brusseau, M. L. 1998. Multiprocess nonequilibrium and nonideal transport of solutes in porous media. In *Physical Nonequilibrium in Soils: Modeling and Application*, 63-82. H. M. Selim and L. Ma, eds. Chelsea, Mich.: Ann Arbor Press.

Cardenas, M. B. 2009. Stream-aquifer interactions and hyporheic exchange in gaining and losing sinuous streams. *Water Resour. Res.* 45: W06429, doi: 10.1029/2008WR0007651.

Carlyle, G. C., and A. R. Hill. 2001. Groundwater phosphate dynamics in a river riparian zone: Effects of hydrologic flow paths, lithology, and redox chemistry. *J. Hydrol.* 247(3-4): 151-168.

Cooper, A. B., C. M. Smith, and M. J. Smith. 1995. Effects of riparian set-aside on soil characteristics in an agricultural landscape: Implications for nutrient transport and retention. *Agric. Ecosyst. and Environ.* 55(1): 61-67.

Fuchs, J. W., G. A. Fox, D. E. Storm, C. Penn, and G. O. Brown. 2009. Subsurface transport of phosphorus in riparian floodplains: Influence of preferential flow paths. *J. Environ. Qual.* 38(2): 473-484.

Halihan, T., S. Paxton, I. Graham, T. Fenstemaker, and M. Riley. 2005. Post-remediation evaluation of a LNAPL site using electrical resistivity imaging. *J. Environ. Monit.* 7(4): 283-287.

Lacas, J.-G., M. Voltz, V. Gouy, N. Carluer, and J.-J. Gril. 2005. Using grassed strips to limit pesticide transfer to surface water: A review. *Agron. Sustain. Dev.* 25(2): 253-266.

McCarty, G., and J. Angier. 2001. Impact of preferential flow pathways on ability of riparian wetlands to mitigate agricultural pollution. In *Proc. 2nd Intl. Symp. on Preferential Flow: Water Movement and Chemical Transport in the Environment*, 53-56. D. Bosch and K. King, eds. St. Joseph, Mich.: ASAE.

McCorley, J., M. McPhail, T. Halihan, and S. Paxton. 2003. Direct push electrical resistivity tomography for evaluation of an LNAPL plume. In *GSA Abstracts with Programs*. Boulder, Colo.: Geological Society of America.

McNeill, J. D. 1980. Electrical conductivity of soils and rocks. Technical Note TN-5. Mississauga, Ontario, Canada: Geonics, Ltd.

Naiman, R. J., H. Decamps, and M. E. McClain. 2005. Catchments and the physical template. In *Riparia: Ecology, Conservation, and Management of Streamside Communities*, 19-48. Boston, Mass.: Elsevier Academic Press.

Pellerin, L. 2002. Applications of electrical and electromagnetic methods for environmental and geotechnical investigations. *Surv. Geophys.* 23(2-3): 101-132.

Poletika, N. N., P. N. Coody, G. A. Fox, G. J. Sabbagh, S. C. Dolder, and J. White. 2009. Chlorpyrifos and atrazine removal from runoff by vegetated filter strips: Experiments and predictive modeling. *J. Environ. Qual.* 38(3): 1042-1052.

Polyakov, V., A. Fares, and M. H. Ryder. 2005. Precision riparian buffers for the control of nonpoint-source pollutant loading into surface water: A review. *Environ. Rev.* 13(3): 129-144.

Poole, G. C., R. J. Naiman, J. Pastor, and J. A. Stanford. 1997. Uses and limitations of ground penetrating RADAR in two riparian systems. In *Groundwater/Surface Water Ecotones: Biological and Hydrological Interactions and Management Options*, 140-148. J. Gibert, J. Mathieu, and F. Fournier, eds. Cambridge, U.K.: Cambridge University Press.

Poole, G. C., J. A. Stanford, C. A. Frissell, and S. W. Running. 2002. Three-dimensional mapping of geomorphic controls on flood-plain hydrology and connectivity from aerial photos. *Geomorphology* 48(4): 329-347.

Popov, V. H., P. S. Cornish, and H. Sun. 2005. Vegetated biofilters: The relative importance of infiltration and adsorption in reducing loads of water-soluble herbicides in agricultural runoff. *Agric. Ecosyst. Environ.* 114(2-4): 351-359.

Reichenberger, S., M. Bach, A. Skitschak, and H.-G. Frede. 2007. Mitigation strategies to reduce pesticide inputs into ground- and surface water and their effectiveness: A review. *Sci. Total Environ.* 384: 1-35.

Robinson, D. A., A. Binley, N. Crook, F. D. Day-Lewis, T. P. A. Ferré, V. J. S. Grauch, R. Knight, M. Knoll, V. Lakshmi, R. Miller, J. Nyquist, L. Pellerin, K. Singha, and L. Slater. 2008. Advancing process-based watershed hydrological research using near-surface geophysics: A vision for, and review of, electrical and magnetic geophysical methods. *Hydrol. Proc.* 22(18): 3604-3635.

Sabbagh, G. J., G. A. Fox, A. Kamanzi, B. Roepke, and J. Z. Tang. 2009. Effectiveness of vegetative filter strips in reducing pesticide loading: Quantifying pesticide trapping efficiency. *J. Environ. Qual.* 38(2): 762-771.

Sauer, T. J., and S. D. Logsdon. 2002. Hydraulic and physical properties of stony soils in a small watershed. *SSSA J.* 66(6): 1947-1956.

Stanford, J. A., and J. V. Ward. 1992. Management of aquatic resources in large catchments: Recognizing interaction between ecosystem connectivity and environmental disturbance. In *Watershed Management*, 91-124. R. J. Naiman, ed. New York, N.Y.: Springer-Verlag.

Storm, D. E., M. J. White, and M. D. Smolen. 2006. Illinois River upland and in-stream phosphorus modeling: Final report. Stillwater, Okla.: Oklahoma State University, Department of

Biosystems and Agricultural Engineering.
Storm, D. E., P. R. Busteed, A. R. Mittlestet, and M. J. White. 2010. Hydrologic modeling of the Oklahoma/Arkansas Illinois River basin using SWAT 2005: Final report. Stillwater, Okla.: Oklahoma State University, Department of Biosystems and Agricultural Engineering.
Tellam, J. H., and D. N. Lerner. 2009. Management tools for the river-aquifer interface. *Hydrol. Proc.* 23(15): 2267-2274.
Tortorelli, R. L., and B. E. Pickup. 2006. Phosphorus concentrations, loads, and yields in the Illinois River basin, Arkansas and Oklahoma, 2000-2004. USGS Scientific Investigations Report 2006-5175. Reston, Va.: U.S. Geological Survey.
Turner, B. L., and P. M. Haygarth. 2000. Phosphorus forms and concentrations in leachate under four grassland soil types. *SSSA J.* 64(3): 1090-1099.
USDA. 1970. Soil Survey: Cherokee and Delaware Counties, Oklahoma. Washington, D.C.: USDA Soil Conservation Service.
USDA. 2008. USDA-NRCS geospatial data gateway. Salt Lake City, Utah: USDA Farm Service Agency (FSA), Aerial Photography Field Office (APFO). Available at: http://datagateway.nrcs.usda.gov. Accessed 28 July 2009.
Wentworth, C. K. 1922. A scale of grade and class terms for classic sediments. *J. Geol.* 30(5): 377-392.
Wilson, G. V., F. E. Rhoton, and H. M. Selim. 2004. Modeling the impact of ferrihydrite on adsorption-desorption of soil phosphorus. *Soil Sci.* 169(4): 271-281.