

2012

Quantification and Heterogeneity of Infiltration and Transport in Alluvial Floodplains

Derek M. Heeren

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

Garey A. Fox

Oklahoma State University, gafox2@ncsu.edu

Daniel E. Storm

Oklahoma State University, dan.storm@okstate.edu

Peter Q. Storm

Oklahoma State University, peter.storm@okstate.edu

Brian E. Haggard

University of Arkansas, haggard@uark.edu

See next page for additional authors

Follow this and additional works at: <https://digitalcommons.unl.edu/biosysengfacpub>



Part of the [Bioresource and Agricultural Engineering Commons](#), and the [Civil and Environmental Engineering Commons](#)

Heeren, Derek M.; Fox, Garey A.; Storm, Daniel E.; Storm, Peter Q.; Haggard, Brian E.; Halihan, Todd; and Miller, Ronald B., "Quantification and Heterogeneity of Infiltration and Transport in Alluvial Floodplains" (2012). *Biological Systems Engineering: Papers and Publications*. 367.

<https://digitalcommons.unl.edu/biosysengfacpub/367>

This Article is brought to you for free and open access by the Biological Systems Engineering at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in Biological Systems Engineering: Papers and Publications by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.

Authors

Derek M. Heeren, Garey A. Fox, Daniel E. Storm, Peter Q. Storm, Brian E. Haggard, Todd Halihan, and Ronald B. Miller



2950 Niles Road, St. Joseph, MI 49085-9659, USA
269.429.0300 fax 269.429.3852 hq@asabe.org www.asabe.org

An ASABE Meeting Presentation

Paper Number: 12-1337097

Quantification and Heterogeneity of Infiltration and Transport in Alluvial Floodplains

Derek M. Heeren, P.E., Research Engineer and U.S. EPA STAR Fellow

Department of Biosystems and Agricultural Engineering, Oklahoma State University, 114
Agricultural Hall, Stillwater, OK 74078, derek.heeren@okstate.edu

Garey A. Fox, Ph.D., P.E., Associate Professor, Orville and Helen Buchanan Endowed Chair

Department of Biosystems and Agricultural Engineering, Oklahoma State University, 120
Agricultural Hall, Stillwater, OK 74078, garey.fox@okstate.edu

Daniel E. Storm, Ph.D., Professor

Department of Biosystems and Agricultural Engineering, Oklahoma State University, 121
Agricultural Hall, Stillwater, OK 74078, dan.storm@okstate.edu

Peter Q. Storm, Freshman Research Scholar

Department of Biosystems and Agricultural Engineering, Oklahoma State University, 111
Agricultural Hall, Stillwater, OK 74078, peter.storm@okstate.edu

Brian E. Haggard, Professor and Director, Arkansas Water Resources Center

Biological and Agricultural Engineering, University of Arkansas, 203 Engineering Hall,
Fayetteville, AR 72701, haggard@uark.edu

Todd Halihan, Associate Professor

School of Geology, Oklahoma State University, 203E Noble Research Center, Stillwater, OK
74078, todd.halihan@okstate.edu

Ronald B. Miller, Ph.D. Student

Department of Biosystems and Agricultural Engineering, Oklahoma State University, 209
Agricultural Hall, Stillwater, OK 74078, ron.miller@okstate.edu

**Written for presentation at the
2012 ASABE Annual International Meeting
Sponsored by ASABE
Hilton Anatole
Dallas, Texas
July 29 – August 1, 2012**

The authors are solely responsible for the content of this technical presentation. The technical presentation does not necessarily reflect the official position of the American Society of Agricultural and Biological Engineers (ASABE), and its printing and distribution does not constitute an endorsement of views which may be expressed. Technical presentations are not subject to the formal peer review process by ASABE editorial committees; therefore, they are not to be presented as refereed publications. Citation of this work should state that it is from an ASABE meeting paper. EXAMPLE: Author's Last Name, Initials. 2012. Title of Presentation. ASABE Paper No. 12-1337097. St. Joseph, Mich.: ASABE. For information about securing permission to reprint or reproduce a technical presentation, please contact ASABE at rutter@asabe.org or 269-932-7004 (2950 Niles Road, St. Joseph, MI 49085-9659 USA).

Abstract. *In order to protect drinking water systems and aquatic ecosystems, all critical nutrient source areas and transport mechanisms need to be characterized. It is hypothesized that hydrologic heterogeneities (e.g., macropores and gravel outcrops) in the subsurface of floodplains play an integral role in impacting flow and contaminant transport between the soil surface and shallow alluvial aquifers which are intricately connected to streams. Infiltration is often assumed to be uniform at the field scale, but this neglects the high spatial variability common in anisotropic, heterogeneous alluvial floodplain soils. In the Ozark ecoregion, for example, the erosion of carbonate bedrock (primarily limestone) by slightly acidic water has left a large residuum of chert gravel in Ozark soils, with floodplains generally consisting of coarse chert gravel overlain by a mantle (1 to 300 cm) of gravelly loam or silt loam. The process of alluvial sediment deposition is highly variable, and can cause gravel layers to outcrop on the soil surface at various locations within a floodplain. The objective of this research was to quantify heterogeneity in infiltration rates at three floodplain sites in the Ozark ecoregion of Oklahoma and Arkansas. Innovative field studies, including plot scale (1 by 1 m and 3 by 3 m) solute injection experiments along with geophysical imaging, were performed on both gravel outcrops and non-gravel outcrops. Plots maintained a constant head of 3 to 10 cm for up to 48 hours. Infiltration rates varied from 0.8 to 70 cm/h, and varied considerably even within a single floodplain. Electrical resistivity imaging was used to identify zones of preferential flow as well as characterize subsurface soil layering. Fluid samples from observation wells outside the plot (0.5 m from the boundary) indicated nonuniform subsurface flow and transport. Phosphorus was detected in the groundwater for 6 of the 12 plots and was positively correlated to the presence of gravel outcrops. Results indicated that flow paths are sub-meter scale for detecting infiltrating solutions. Tension infiltrometers showed that macropore flow accounted for approximately 85% to 99% of the total infiltration.*

Keywords. Electrical resistivity, gravel outcrops, Ozark ecoregion, preferential flow, subsurface nutrient transport.

Introduction

In order to protect surface water, all transport mechanisms of nutrients, pesticides, and bacteria within a watershed need to be understood. Surface transport mechanisms are well understood, but subsurface transport mechanisms are not as well characterized (Fuchs et al., 2009). Considerable research has been performed on properties of point soil samples, and some research has been done on transport in undisturbed soil columns (Ulen, 1999; Maguire and Sims, 2002; Djodjic et al., 2004). However, relatively few studies on both infiltration and transport have been done at the plot scale where infiltration and transport may be controlled by heterogeneity present at various scales (Nelson et al., 2005).

For example, research is currently limited in understanding the potential significance of connectivity between phosphorus (P) in surface runoff and groundwater and nutrient movement from the soil to groundwater in watersheds with cherty and gravelly soils (Fox et al., 2011; Heeren et al., 2011; Mittelstet et al., 2011). While optimum crop growth requires a range of P above 0.2 mg/L, preventing surface water enrichment generally requires P to be below 0.03 mg/L (Pierzynski et al., 2005). In fact, surface waters in the Ozark ecoregion in particular may have a threshold closer to 0.01 mg/L (D.E. Storm, 2012, personal communication). While surface runoff is considered to be the primary transport mechanism for P (Gburek et al., 2005), the potential for P leaching is commonly estimated based on point-measurements of soil test phosphorus (STP) or measurements of the sorption capability of disturbed soil samples representing the soil matrix. However, in many riparian floodplains, gravel outcrops and macropores are present (Heeren et al., 2011). These gravel outcrops can lead to extremely high infiltration rates, some of which are reported to be on the order of 10 cm/min (Sauer and Logsdon, 2002; Saur et al., 2005). In fact, infiltration of P-laden water during high flow discharges that exceed bankfull events can infiltrate in the floodplain subsoil and migrate back to the streams. Djodjic et al. (2004) performed experiments on P leaching through undisturbed soil columns, and stressed the need to consider larger-scale leaching processes due to soil heterogeneity. They stated that the "water transport mechanism through the soil and subsoil properties seemed to be more important for P leaching than soil test P value in the topsoil. In one soil, where preferential flow was the dominant water transport pathway, water and P bypassed the high sorption capacity of the subsoil, resulting in high losses."

A common best management practice in riparian floodplains is riparian buffers or vegetative filter strips (VFS), utilized to reduce sediment, nutrient, and pesticide loading to nearby surface water bodies (Popov et al., 2005; Reichenberger et al., 2007; Sabbagh et al., 2009). Reduced transport occurs through contact between dissolved phase solutes with vegetation in the filter strip, and/or by reducing flow velocities to the point where eroded sediment particles can settle out of the water. In floodplains with significant heterogeneity such as macroporosity and chert or gravel soils, the effectiveness in preventing loading to nearby streams and rivers may be less than originally anticipated if a significant transport pathway occurs into the shallow groundwater and then bypasses the filtering capacity of the VFS. The impact of such heterogeneous infiltration and leaching is not known at this time.

Gravel outcrops and macropores can significantly affect infiltration and leaching in these floodplains. For water movement through soil, macropores have been shown to have a large impact on flow and solute transport (Thomas and Phillips, 1979; Fox et al., 2004; Djodjic et al., 2004; Akay and Fox, 2007; Gotovac et al., 2009). Infiltration is often assumed to be uniform (piston flow) at the field scale, but this neglects the high spatial variability common in anisotropic, heterogeneous alluvial-floodplain soils. Therefore, the objective of this research was

to quantify infiltration and leaching at the plot scale and to evaluate the effects of gravel outcrops and macropores on these processes.

Methods

Alluvial Floodplain Sites

The alluvial floodplain sites were located in the Ozark ecoregion of northeastern Oklahoma and northwestern Arkansas. The Ozark ecoregion of Missouri, Arkansas, and Oklahoma is approximately 62,000 km² (fig. 1) and is characterized by gravel bed streams and cherty soils in the riparian floodplains. The erosion of carbonate bedrock (primarily limestone) by slightly acidic water has left a large residuum of chert gravel in Ozark soils, with floodplains generally consisting of coarse, chert gravel overlain by a mantle (1 to 300 cm) of gravelly loam or silt loam. The alluvium is spatially heterogeneous, resulting in preferential flow pathways which are hypothesized to be ancient buried gravel bars (Heeren et al., 2010). Similar hydrogeologic conditions exist near gravel bed streams in their associated alluvial floodplains worldwide.

The Barren Fork Creek site (fig. 1, latitude: 35.90°, longitude: -94.85°) was immediately downstream of the Eldon Bridge U.S. Geological Survey (USGS) gage station 07197000. With a watershed size of 845 km², the Barren Fork Creek site was a fourth order stream with a historical median discharge of 3.6 m³ s⁻¹. The study area at the Barren Fork Creek was located on the outside of a meander bend which was being actively eroded by the stream (Midgley et al., 2012). The soils were classified as Razort gravelly loam underlain with alluvial gravel deposits. Thickness of the loam ranged from 0.5 to 1.0 m. 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). Fuchs et al. (2009) described some of the soil and hydraulic characteristics of the Barren Fork Creek floodplain site, including estimates of hydraulic conductivity for the gravel subsoil between 140 and 230 m d⁻¹ based on falling head trench tests. Heeren et al. (2010) performed a tracer injection into a PFP, identified as a buried gravel bar, at the Barren Fork Creek site. Local transient storage and physical nonequilibrium was observed as evidenced by the elongated tails of breakthrough curves in some observation wells due to physical heterogeneity in the aquifer materials.

The Pumpkin Hollow floodplain site was also located in the Ozark ecoregion of northeastern Oklahoma (latitude: 36.02°, longitude: -94.81°). A small tributary of the Illinois River, Pumpkin Hollow Creek was a first order ephemeral stream in its upper reaches. The entire floodplain was 120 to 130 m across at the research site, with an estimated watershed area of 15 km². The land use at the site was pasture for cattle. The Pumpkin Hollow field site was a combination of Razort gravelly loam and Elsah very gravelly loam, although infiltration experiments were limited to the Razort gravelly loam soils. Topsoil thickness ranged from 0 to 3 cm, and bulk densities of the cohesive material were in the range of 1.4 to 1.6 g/cm³.

The Clear Creek alluvial floodplain site was located just west of Fayetteville, AR in the Arkansas River Basin and flows into the Illinois River (fig. 1, latitude: 36.13°, longitude: -94.24°). The total drainage area was 199 km² for the entire watershed. Land use in the basin was 36% pasture, 34% forest, 27% urban and 3% other. Soils were loamy and silty, deep, moderately well drained to well drained (U.S. EPA, 2009), and generally contained less chert or gravel than the Barren Fork Creek or Pumpkin Hollow floodplain sites. A fourth order stream with a flow of approximately 0.5 m³ s⁻¹ at the study site, the area of the watershed above that point was 101 km². The land use in the study area was pasture and consisted of Razort gravelly loam soils.

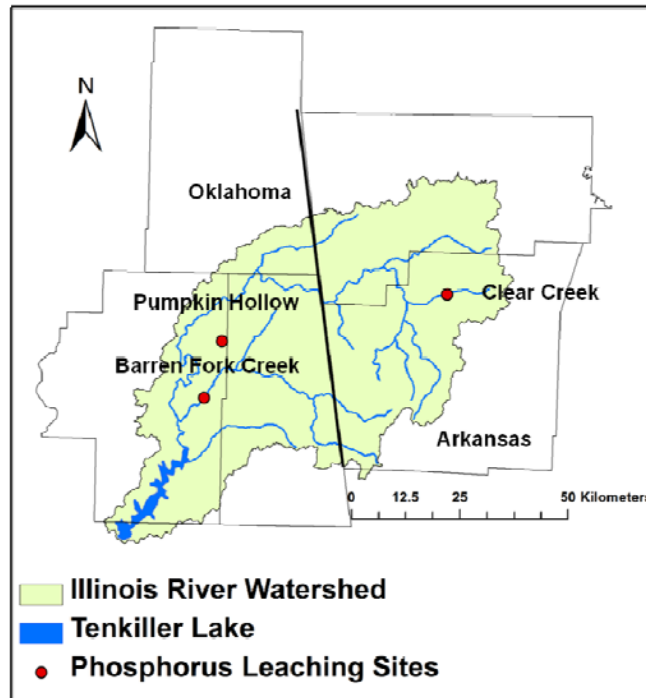


Figure 1. Selected alluvial floodplain sites in the Ozark ecoregion.

Berm Installation and Hydraulics

Measuring infiltration rates and/or leaching of solutes at a plot scale is difficult, especially for high hydraulic conductivity soils, without innovative field methods. In this research, a berm method (Heeren et al., 2012) was used to confine infiltration plots and maintain a constant head of water. Four infiltration experiments were performed at each site with plots selected to represent typical floodplain soils with and without gravel outcrops (Table 1). Plots were located on relatively level areas. Larger plots were required to have smaller slopes to ensure that the entire plot could be inundated without overflowing the berm.

Each berm was constructed of four sections of 15 cm vinyl hose which were attached to 90° steel elbows and surrounded the infiltration gallery (fig. 2). A shallow trench (3 to 5 cm) was cut through the thatch layer and a thick bead of liquid bentonite was used to create a seal between the berm and the soil.

High density polyethylene tanks (4.9 m³ and 0.76 m³) were used to mix stream water and solutes. A combination of 5.1-cm diameter PVC with manual valves and garden hoses with float valves were used to deliver water (gravity fed) from the tanks to the plots. When a tank was nearly empty, flow was temporarily stopped while the tank was refilled and solutes were added and mixed. Constant heads in the plots were maintained (Heeren et al., 2012) between 3 and 10 cm. Depth to the water table ranged from 50 to 150 cm.

Chloride (Cl⁻) was used as a conservative (nonsorbing) tracer. Target tracer concentrations were 100 to 200 mg/L KCl (correlating to 48 to 95 mg/L Cl⁻), depending on background EC levels. The RhWT was a slightly-sorbing dye and was introduced into the plots at concentrations of 10 to 100 mg/L. The RhWT was regarded as a slightly sorbing solute since the soils were expected to have organic matter contents of less than 2%, resulting in a minor amount of

Rhodamine WT sorption. The RhWT served as a visual indicator of hydraulic connectivity in the observation wells.

Table 1. Infiltration experiments at three alluvial floodplain sites in the Ozark ecoregion.

Site	Date	Plot Size	Treatment	Duration (h)	Infiltration (cm/hr)	Total Wells	Wells containing:		
							Cl ⁻	RhWT ^[a]	DP ^[a]
Clear Creek	4/12/11	1x1	control	41	5.6	4	-- ^[c]	4	0
Clear Creek	4/12/11	3x3	control	41	3.3	8	-- ^[c]	4	1
Clear Creek	7/27/11	1x1	outcrop	48	1.3	8	0	0	0
Clear Creek	7/27/11	3x3	outcrop	45	0.8	12	0	0	0
Pumpkin Hollow	5/4/11	1x1	outcrop	32	5.3	8	3	3	3
Pumpkin Hollow	5/5/11	3x3	outcrop	2.8	18	12	5	9	5
Pumpkin Hollow	6/1/11	1x1	outcrop	4.3	74	4	4	4	1
Pumpkin Hollow	6/2/11	3x3	control	24	6.3	12	-- ^[d]	0	0
Barren Fork	6/30/11	1x1	outcrop ^[b]	22	11	5	5	5	2
Barren Fork	6/30/11	3x3	outcrop ^[b]	22	13	12	10	10	3
Barren Fork	7/13/11	1x1	control	46	6.9	4	1	1	0
Barren Fork	7/13/11	3x3	control	48	3.8	12	5	5	0

^[a] RhWT = Rhodamine WT; DP = Dissolved phosphorus.

^[b] Gravel under 0.3 to 1 m of silt loam.

^[c] Chloride added but not sufficiently above background concentrations in the stream and groundwater.

^[d] Not measured.

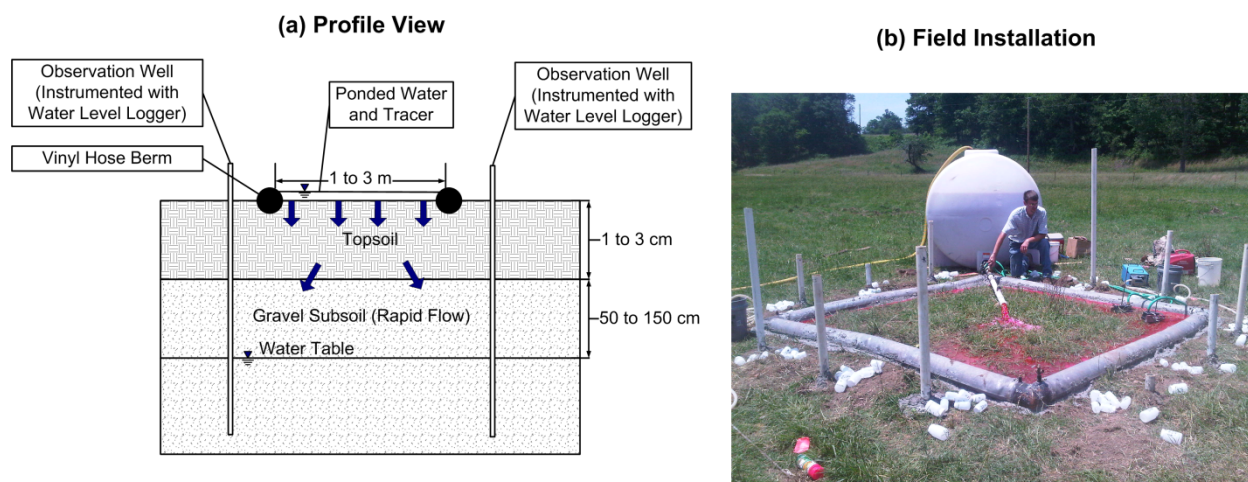


Figure 2. Berm infiltration method, including vinyl berms to contain water-solute solution and observation wells for collecting groundwater samples: (a) design and (b) implementation at the Pumpkin Hollow floodplain site.

Phosphorus (highly sorbing) concentrations of 3 to 10 mg/L (corresponding to 10 to 32 mg/L as phosphate) were used to represent poultry litter application rates (typically used as a fertilizer source in the Ozark ecoregion) in the range of 2 to 8 Mg/ha (1 to 3 ton/acre). Previous research (Kleinman et al., 2002; DeLaune et al., 2004; Schroeder et al., 2004) has observed dissolved

reactive phosphorus in the range of 5 to 40 mg/L in runoff from recently applied poultry litter in the range of 2 to 14 Mg poultry litter per hectare.

Phosphorus concentrations were achieved by adding phosphoric acid (H_3PO_4), which deprotonated to H_2PO_4^- and HPO_4^{2-} in the slightly acidic solution. The inflow water in the plot was sampled throughout the experiment to verify these concentrations. The source stream water was also sampled over time to quantify its P contribution. Redox conditions were not expected to be a concern for characterizing P fate and transport because of the lack of anaerobic conditions due to the high porosity and excessive drainage of both the soil and subsurface materials in Ozark floodplains. For example, dissolved oxygen (DO) of the groundwater at the Barren Fork Creek site (measured with a ProODO DO meter, YSI Inc., Yellow Springs, Ohio) ranged from approximately 8 mg/L near the creek to 4 mg/L up to 100 m from the creek.

In general, the P concentration in the groundwater samples were expected to decrease relative to input P concentration due to sorption as the water infiltrates down through the soil profile. Without considering macropore and/or gravel outcrop infiltration, P would be expected to only minimally, if at all, travel through the soil matrix. Comparisons in the breakthrough curves, peak concentrations, and the time to reach the peak concentration in the monitoring wells between the Cl^- , RhWT and P concentrations, which possess different sorption properties, were made to indicate differences in sorptive rates.

Monitoring with Electrical Resistivity

Vertical electrical resistivity profiles were collected at the floodplain sites during the infiltration/leaching experiments (fig. 3). Electrical resistivity was utilized to characterize the heterogeneity of the unconsolidated floodplain sediments, as well as locate the infiltrating plume of water and solutes by detecting changes in pore water. Electrical resistivity imaging (ERI) 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 $\Omega\cdot\text{m}$) compared to sands or gravels (10 to 800 $\Omega\cdot\text{m}$), which are lower than limestone bedrock (McNeill, 1980).

ERI data were collected using a SuperSting R8/IP Earth Resistivity Meter (Advanced GeoSciences Inc., Austin, Tex.) with 28-electrode arrays. The profiles employed electrode spacings of 0.5 m with an associated depth of investigation of approximately 3 m, which included the vadose zone as well as the top of the water table. The resistivity sampling with the SuperSting R8/IP, and subsequent inversion utilized a proprietary routine devised by Halihan et al. (2005), which produced higher resolution images than conventional techniques. The ERI resistivity data were interpolated into grids and contoured using Surfer 8 (Golden Software, Inc., Golden, CO). Inverted and interpolated resistivity data were termed "ERI profiles" as opposed to "ERI pseudosections", which were the raw resistivity measurements as collected in the field. Differencing was used to display the percent difference in resistivity between the background image and images collected during the infiltration experiments.

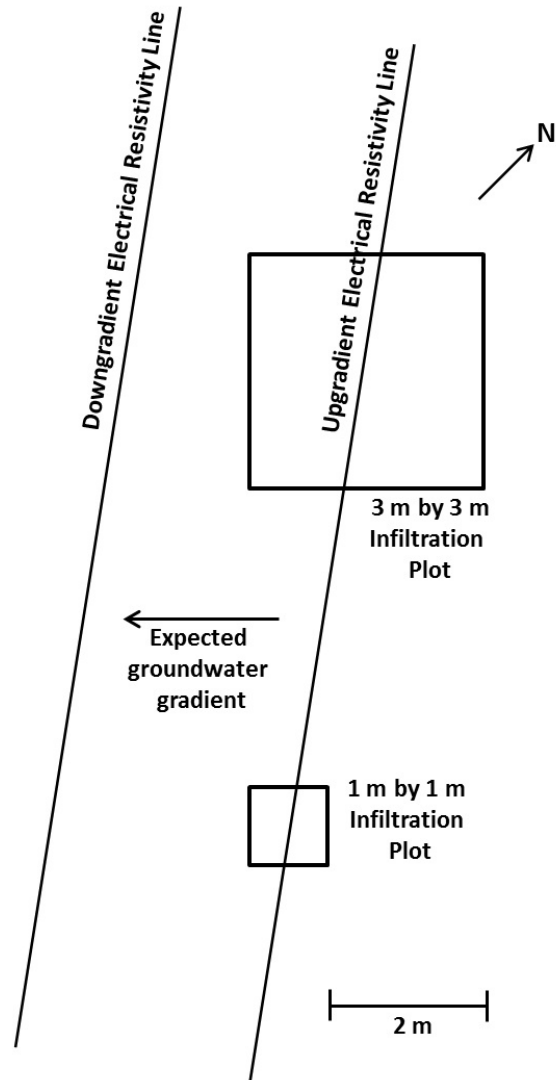


Figure 3. Electrical resistivity design for the control plots at the Barren Fork Creek site.

Observation Wells and Sample Analysis

Suction cup lysimeters were not used because of the difficulty of installation in gravelly soils, risk of creating preferential flow paths in vadose zone, and low likelihood of intercepting macropores. Since there are not currently any effective techniques for taking measurements from underneath a given plot in these gravelly soils, observation wells were installed every 0.5 to 2 m around the perimeter of the plots to collect groundwater samples (fig. 2). When a confining layer was present (based on soil cores), shallow observation wells were installed with alternating wells designed specifically to sample from the vadose zone (where perched water was expected) and the remaining observation wells designed specifically to sample from the phreatic zone.

A Geoprobe Systems drilling machine (6200 TMP, Kejr, Inc., Salina, KS), which has been found to be effective in coarse gravel soils (Heeren et al., 2011; Miller et al., 2011), was used to install four to twelve observation wells around each plot. Boreholes were sealed with liquid bentonite to

avoid water and solutes leaking down the borehole. Low flow sampling with a peristaltic pump was used to collect water samples from the top of the water table (Heeren et al., 2011). Sampling intervals were adjusted based on EC meter readings (to detect elevated levels of Cl^-) and visual observations of RhWT with the goal of having enough data points to characterize the breakthrough curve.

Well and plot water samples, as well as background stream and groundwater samples, were stored and transported on ice and were tested for both P and Cl^- at the AWRC Water Quality Laboratory on the University of Arkansas campus. The soluble reactive phosphorus (SRP) samples were filtered within 24 hours of sampling using 0.45 μm filters and acidified with sulfuric acid. The SRP was determined colorimetrically with the modified ascorbic acid method (EPA Method 365.2; Murphy and Riley, 1962) with a spectrophotometer (DU 720, Beckman Coulter, Indianapolis, IN, minimum detection limit of 0.002 mg/L). Autoclave per-sulfate digestions (APHA 4500 PJ) were performed on unfiltered total phosphorus (TP) samples in order to dissolve any particulate or organic P. The TP (minimum detection limit of 0.01 mg/L) was then determined colorimetrically with the modified ascorbic acid method. The Cl^- concentrations were determined with ion chromatography (minimum detection limit of 0.16 mg/L). The RhWT samples were analyzed at Oklahoma State University with a Trilogy laboratory fluorometer (Turner Designs, Inc., Sunnyvale, CA, minimum detection limit of 0.01 mg/L).

Automated water level loggers (HoboWare, Onset Computer Corp., Cape Cod, MA, water level accuracy of 0.5 cm) were used to monitor water levels at one minute intervals in the observation wells, plots, and tanks, from which flow rates were calculated. An additional logger was used to monitor atmospheric pressure. Logger data were processed with HoboWare Pro software, which accounted for changes in atmospheric pressure as well as changes in water density due to temperature.

Soil Cores and Particle Size Analysis

Soil core samples were collected during the installation of the observation wells. The large particles that make up gravel-dominated soils make them problematic for soil sampling. Difficulties occur with all sampling methods and include large particles blocking tube sampler openings and the collapse of pits excavated in unconsolidated gravel. Furthermore, gravel soils are resistant to penetration and thus core sampling often requires mechanical assistance that may cause breakage of large particles. If the largest particle sizes present in the soil exceed the sampler diameter, the collected sample may not truly represent the actual size distribution.

With a realization of these limitations, direct push cores were recovered from one to four wells per plot. Core samples were collected at known depths with a Geoprobe Systems (Salina, KS) 6200 TMP (Trailer-mounted Probe) direct-push drilling machine using a dual-tube core sampler with a 4.45 cm opening. The sampler opening (size) limited the particle size that could be sampled and large cobbles occasionally clogged the sampler resulting in incomplete cores for that depth interval.

A subset of the soil core samples were dry sieved with a sieve stack ranging from 2 to 12.5 mm for a particle size analysis. Samples preparation included disaggregation with a rubber-tipped pestle when necessary. If particles were retained on the 12.5 mm sieve, a measurement of the “b” axis (longest intermediate axis perpendicular to the long “a” axis) of the largest particle was utilized as the sieve size that 100% of the sample would pass through because that dimension largely controls whether a particle will pass a particular sieve (Bunte and Abt, 2001).

Tension Infiltrometers

After the plot infiltration experiments, mini-disk infiltrimeters (Decagon Devices, Pullman, WA) were used inside the plots (after the soil profile had dried) to measure soil matrix infiltration. Tension infiltrimeters are designed to measure unsaturated soil infiltration rates by exposing water that is under tension (negative pressure) to the soil surface. Water must flow from a higher potential to a lower potential. Therefore, water under tension infiltrated into the soil matrix, which had a more negative capillary pressure. However, the water did not infiltrate into the macropores, which had a less negative capillary pressure. Since the macropores remained dry, flow was restricted to the soil matrix with the infiltration rate equivalent to matrix infiltration. Saturated infiltration from the plot scale experiments represented total infiltration from both matrix and macropores. Macropore infiltration was estimated by subtracting the matrix infiltration from the total infiltration.

Suction levels of 1, 3, and 6 cm, spanning the ability of the infiltrimeter, were used. Equivalent radii were calculated for each suction level with the capillary rise equation (Scott, 2000):

$$h = \frac{2\sigma \cos \theta}{r \rho_w g} = \frac{0.15}{r} \quad (1)$$

where h is the capillary rise or suction (L), σ is the surface tension of water (F/L), θ is the contact angle, r is the equivalent radius (L), ρ_w is the density of water (M/L³), and g is the acceleration due to gravity (L/T²). The θ was assumed to be zero and σ was assumed to be 72.8 mN/m (for water at 20°C). The unit conversion coefficient of 0.15 arises for h and r in cm.

In order to enable the comparison between suction level and pore geometry, the following conceptual model was used. The soil pore space was conceptualized as circular tubes (not necessarily vertical) with a distribution of radii. Each pore was considered either activated (saturated) or dry. For a given suction level, the infiltration is limited to pores with radii less than or equal to the radius corresponding to the suction level. A comparison between plot infiltration data (all pores activated) and tension infiltrimeter was used to differentiate between matrix and macropore flow. The simplification in this conceptualization is that it neglects flow in a thin film along a pore wall when that pore is unsaturated. Accounting for thin film flow in macropores would increase their contribution; therefore, this approach gives a conservative estimate of the impact of macropores.

Soils pores have been classified as macropores (greater than 75 μ m), mesopores (30 to 75 μ m), and micropores (5 to 30 μ m) (SSSA, 2008). In this research, macropores were defined as pore spaces with equivalent diameters of 500 μ m (i.e. 6 cm capillary pressure) or more due to limitations of the infiltrimeter.

The unsaturated hydraulic conductivity was calculated from the tension infiltrimeter results using the method of Zhang (1997). Readings were taken until the infiltrimeter reservoir was depleted (14 to 121 minutes), which was sufficient to fit the hydraulic conductivity and sorptivity to the cumulative infiltration versus time data.

Results

Soil Infiltration Rates and Heterogeneity

Soils were heterogeneous, even within a small area of a given floodplain (fig. 4). Not surprisingly, infiltration rates also varied greatly, ranging two orders of magnitude (fig. 5, Table 1). Pumpkin Hollow generally had the highest infiltration rates, while Clear Creek had the lowest infiltration rates. Though not strong, there was a positive correlation between infiltration rate and

the presence of gravel outcrops (fig. 5). The geometric mean infiltration rate for gravel outcrops (7.2 cm/hr) was higher than the infiltration rate for control plots (5.0 cm/hr). In fact, the two lowest infiltration rates were on gravel outcrops at the Clear Creek site. In that particular location, there was significant gravel, but the fines (which were the limiting factor for water flow) had higher clay content than any of the other plots.

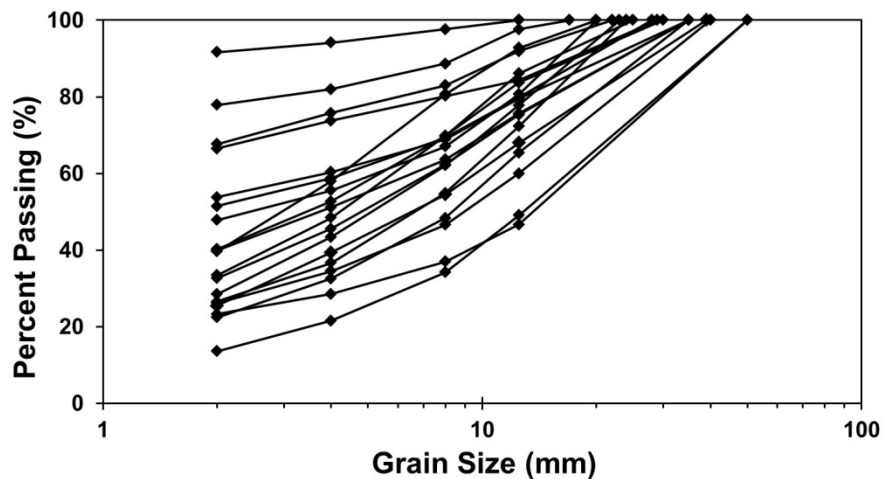


Figure 4. Particle size distributions of Pumpkin Hollow soil core samples.

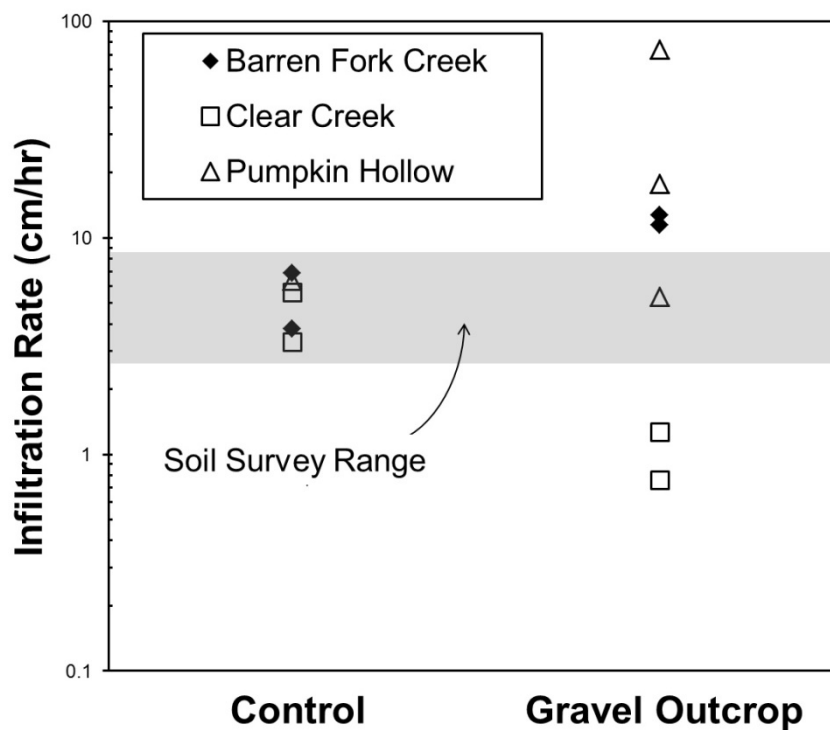


Figure 5. Infiltration rates from plot scale experiments for both control and gravel outcrop locations. The expected range of infiltration rates based on the permeability of the limiting layer

reported in the Natural Resources Conservation Service Soil Survey (NRCS, 2012) is shown in gray.

Measured infiltration rates were greater than the estimated permeability of the limiting layer reported by the U.S. Natural Resources Conservation Service (NRCS) for Cherokee County, Oklahoma (NRCS, 2012), which ranged from 1.5 to 5 cm/hr for the Razort gravelly loam soil (fig. 5). This difference indicates the need for larger scale field measurements of infiltration rate. For example, soil survey measurements may represent a typical soil pedon but miss gravel outcrops or large macropores which may be infrequent but have a disproportionate impact on infiltration.

Infiltrating water either reached the water table before moving laterally or lateral movement in the vadose zone was induced by a confining layer. Water table elevations in phreatic zone wells were used to discern the presence of a groundwater mound (fig. 6). Sharp decreases indicate the times when fluid samples were collected and the rate of recovery of the piezometric surface gives a qualitative indication of hydraulic conductivity.

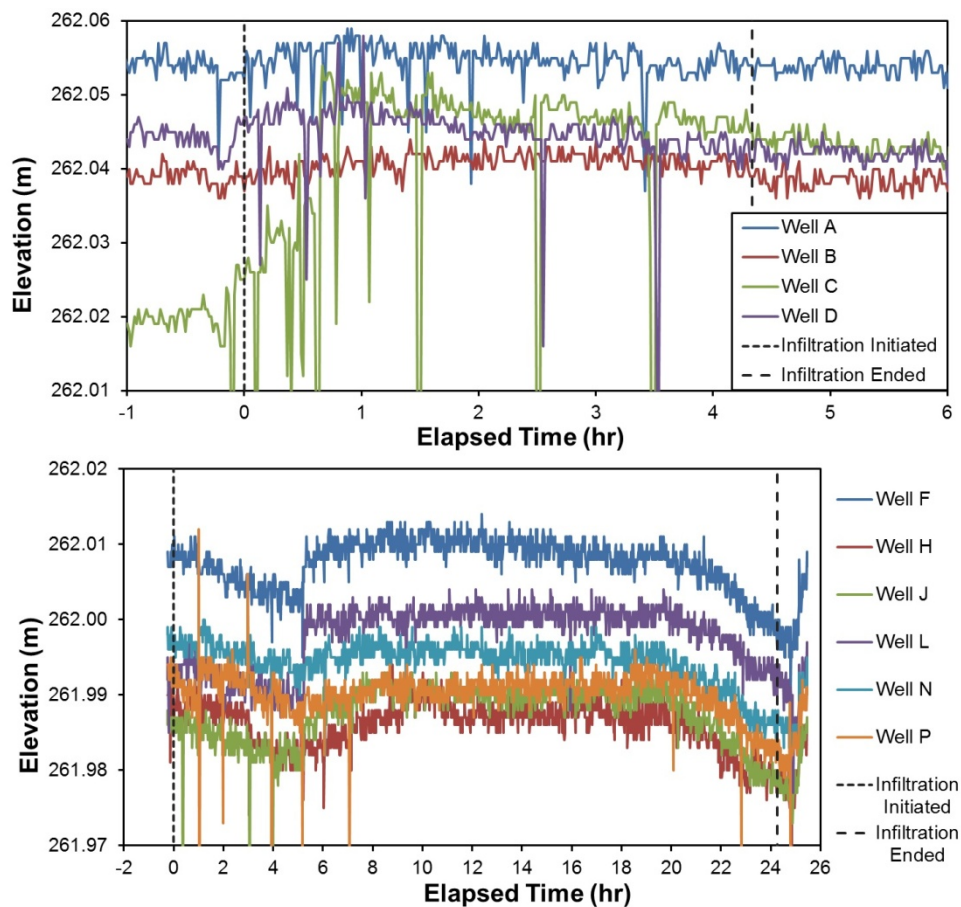


Figure 6. Water levels in phreatic zone observation wells of the 1 by 1 m gravel outcrop infiltration plot (June 1, 2011) and the of 3 by 3 m control infiltration plot (June 2, 2011) at the Pumpkin Hollow floodplain site.

Transport

Rhodamine WT and Cl^- were observed in no wells in some plots to all wells in other plots, while detection of P ranged from no wells to nearly half of the wells for a given plot (Table 1).

Response times ranged from 18 min to greater than 48 hr. Infiltration and leaching appear to correlate weakly to topsoil thickness and stream order.

For each solute, the concentration ratio ($C_r = C / C_0$) between the concentration in the well (C) and the concentration injected into the plot (C_0) was used to examine breakthrough curves (BTCs) (fig. 7). Concentration ratios began at background levels (near zero) and generally increased with time, approaching unity for Cl^- in some cases. Within a well, the Cl^- (conservative) BTC generally began first, followed by RhWT (slightly sorbing), and finally P (highly sorbing) (fig. 7, Table 2).

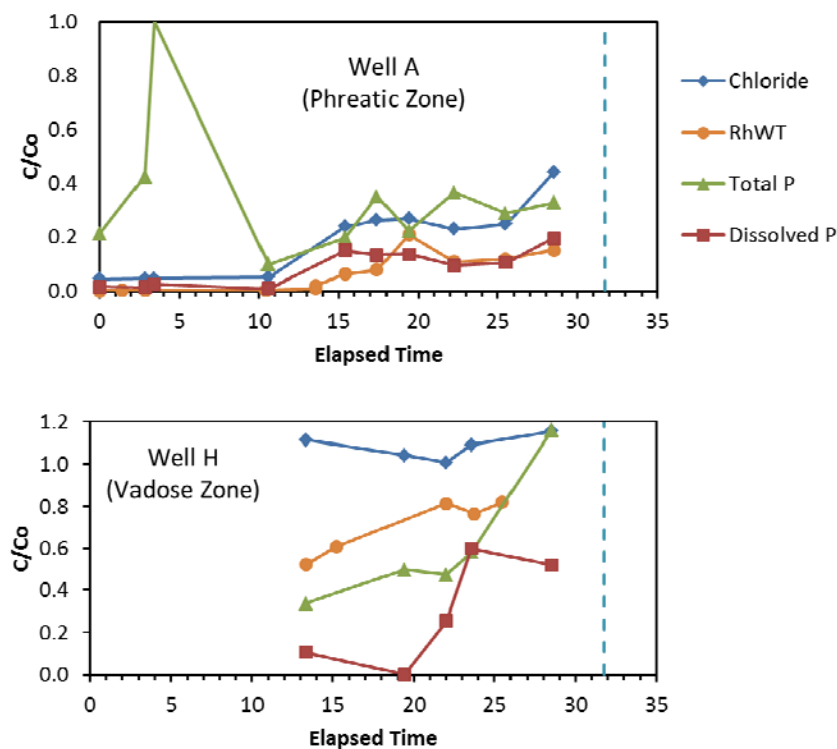


Figure 7. Concentration ratio (C/C_0) for two of the observation wells for the Pumpkin Hollow gravel outcrop 1 by 1 m (top, May 4, 2011) and 3 by 3 m (bottom, May 5, 2011) infiltration experiments.

For observation wells in the vadose zone, sample collection in the vadose was not possible until a sufficient level of water had perched, at which point concentrations were usually high (fig. 7, Table 2). In vadose zone wells, dilution was expected to be limited to displaced water from the unsaturated zone, so the C_r of a conservative tracer should be near 100%.

For the Barren Fork Creek gravel outcrop plots (June 30, 2011), the RhWT and Cl^- concentrations increased by the second sample after the start of the experiment, which was approximately two hours after initiating the leaching. In fact, slight increases in concentrations of both RhWT and Cl^- were observed after the first sample in some wells, which was taken approximately thirty minutes to one hour after the start of the experiment. Groundwater concentrations reached approximately 50% of the injected Cl^- concentration at a breakthrough

time less than two hours from the initiation of infiltration. Samples were collected from the water table approximately 300 cm below the surface, meaning the Cl^- had an advective transport rate, or pore velocity, up to 150 cm/hr. Combining measured infiltration rates of 11 to 13 cm/hr with an estimated porosity of 0.5 results in a pore velocity of only 24 cm/hr assuming uniform matrix flow. This indicates the importance of macropore flow, transporting water and solutes an order of magnitude faster than the average soil infiltration rate at the Barren Fork Creek site.

During the May 5, 2011, infiltration experiment at Pumpkin Hollow (3 by 3 m outcrop), RhWT was observed in the stream approximately 15 m from infiltration plot in less than 1.7 hr after initiation infiltration. The C_r of RhWT in the stream near the seep face reached 0.02 (Table 2).

Table 2. Transport data by well for the 1 m by 1 m (May 4, 2011, gravel outcrop, 32 hr duration, 5.3 cm/hr infiltration) and 3 m by 3 m (May 5, 2011, gravel outcrop, 2.8 hr duration, 18 cm/hr infiltration) plots at the Pumpkin Hollow floodplain site.

Plot	Well	Zone	Detection Time (hr)			Time to Peak (hr)			Peak Concentration Ratio		
			Cl^-	RhWT ^[a]	DP ^[a]	Cl^-	RhWT	DP	Cl^-	RhWT	DP
1x1	A	Phreatic	15	14	15	>29	19	>29	0.44	0.21	0.19
	B	Vadose	--	14	--	29	>29	>29	1.04	0.35	0.21
	C	Phreatic	>29	>29	>29	>29	>29	>29	--	--	--
	D	Vadose				remained dry					
	E	Phreatic	>29	>29	>29	>29	>29	>29	--	--	--
	F	Vadose				remained dry					
	G	Phreatic	>29	26	>29	>29	26	>29	--	0.001	--
	H	Vadose	13	13	13	29	>26	24	1.16	0.82	0.60
3x3	I	Vadose	0.7	0.5	0.8	1.4	0.8	0.8	0.51	0.49	0.03
	J	Phreatic	>3.1	0.7	>3.1	>3.1	0.8	>3.1	--	0.0003	--
	K	Vadose				remained dry					
	L	Phreatic	>3	0.7	>3	>3	1.1	>3	--	0.004	--
	M	Vadose				remained dry					
	N	Phreatic	0.6	0.6	0.6	1.5	0.8	0.8	0.58	0.28	0.06
	O	Vadose	--	0.7	--	1.0	1.0	>1.0	0.67	0.36	0.14
	P	Phreatic	>2.9	0.7	>2.9	>2.9	2.9	>2.9	--	0.01	--
	Q	Vadose	1.1	0.6	1.1	2.2	>1.8	>3.0	0.75	0.32	0.30
	R	Phreatic	>2.9	>2.9	>2.9	>2.9	>2.9	>2.9	--	--	--
	S	Vadose	0.8	--	0.8	0.8	1.1	1.6	0.80	0.40	0.13
	T	Phreatic	>2.9	>2.9	>2.9	>2.9	>2.9	>2.9	--	--	--
	Seep	Stream	--	--	>2.9	2.3	2.3	>2.9	0.08	0.02	--

^[a] RhWT = Rhodamine WT; DP = Dissolved phosphorus.

Spatial variability in flow and transport data was significant. Advection along the regional groundwater gradient generally resulted in higher concentrations on the down-gradient side of the plots (fig. 8). The soils in the alluvial floodplain were extremely heterogeneous, which corroborates previous research (Miller et al., 2010; Heeren et al., 2011). Even wells only 1 m apart showed significant variation in Cl^- (fig. 8).

At the Pumpkin Hollow 3 m by 3 m control plot (June 2, 2011), 1.5 m of infiltration occurred over 24 hr. With a shallow water table (0.9 to 1.0 m below ground surface), the infiltrating water must have moved laterally beyond the wells (0.5 m from the edge of the plot), especially when considering porosity. Yet, RhWT was never observed in any of the 12 observation wells, with observation wells in the phreatic zone spaced from 2 to 3 m apart. Either the flow must have been occurring at a small enough scale to flow between the well spacing, or RhWT sorption to organic matter was sufficient to reduce concentrations to below the minimum detection limit (over three orders of magnitude less than the plot RhWT concentration).

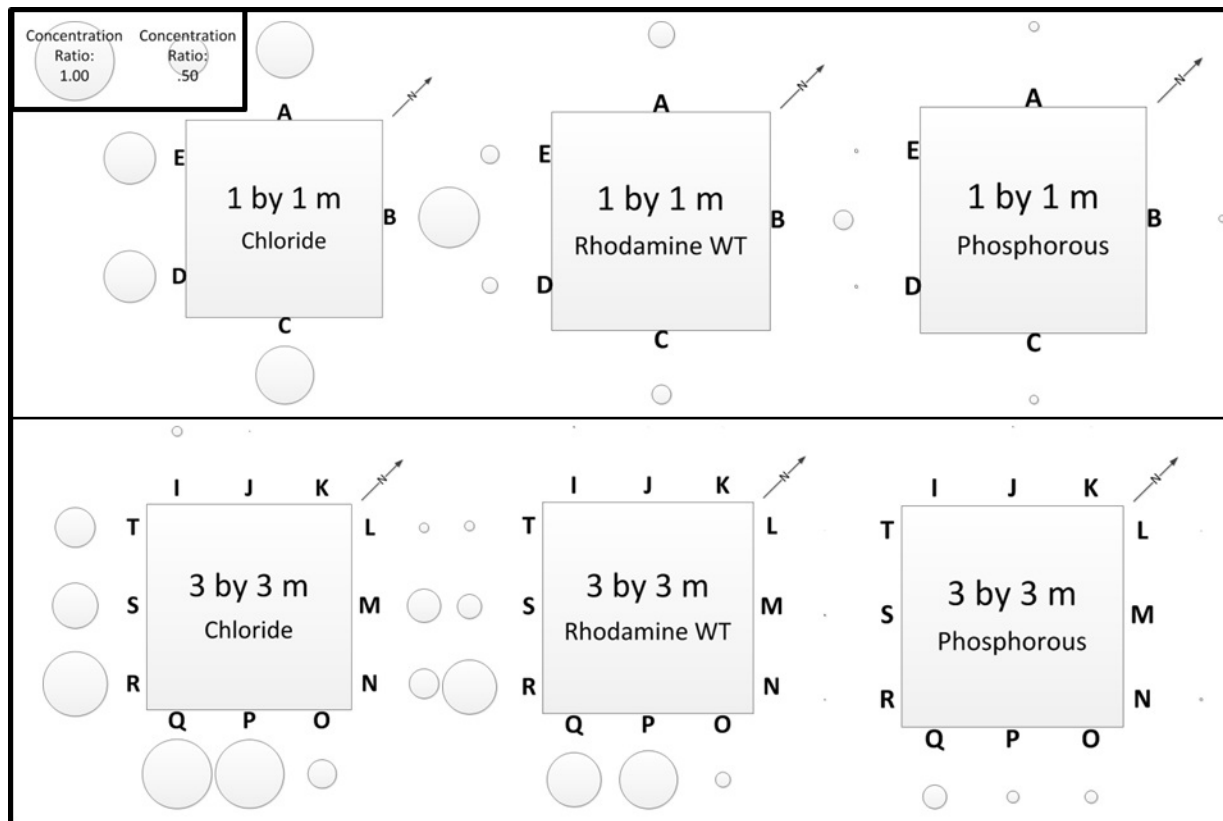


Figure 8. Maximum concentrations of samples from each well for the Barren Fork Creek gravel outcrop plots. Note that the plots are not drawn to scale. Size of the circle around each given well represents the concentration.

Electrical Resistivity of Infiltration Plume

Transient electrical resistivity results showed downward (fig. 9) and lateral (fig. 10) migration of the water and Cl^- plume. For the Barren Fork Creek control plots, Cl^- was detected in the water table (3 m below ground surface) only 7 hr after the initiation of infiltration for both the 1 m by 1 m and 3 by 3 m plots. Yet the ERI data shows only 1 to 2 m of infiltration after 19 hr. This indicates that rapid flow and transport may be occurring in macropores which only represent a small volume of the soil column, possible escaping detection by the electrical resistivity equipment. It is also possible that the gravel may have remained mostly unsaturated (except for fingering) while transporting all of the water delivered to it by the silt loam (top 1 m of soil profile). The limited downward movement may also indicate some lateral migration, which would

be consistent with the plume observed in the lateral line located 1.5 to 2.5 m down gradient from the edge of the plots (figs. 3 and 10).

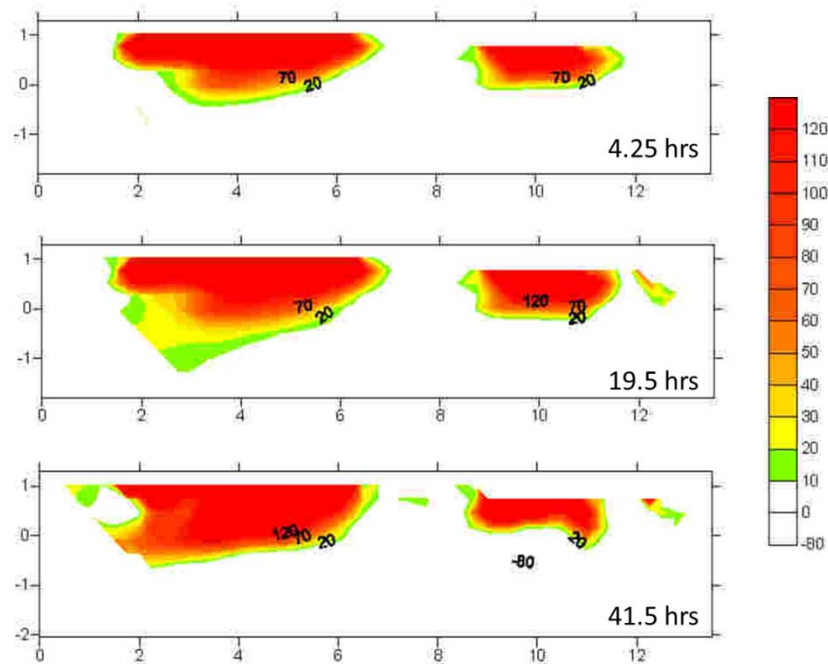


Figure 9. Vertical profile (y-axis is elevation in m) of percent difference in electrical resistivity of the upgradient lateral line (fig. 3) through the center of the 3 m by 3 m plot (left) and the 1 m by 1 m plot (right) of control area at the Barren Fork site, July 13, 2011. Horizontal axis is distance along the electrical resistivity line. Time is the elapsed time from the onset of infiltration.

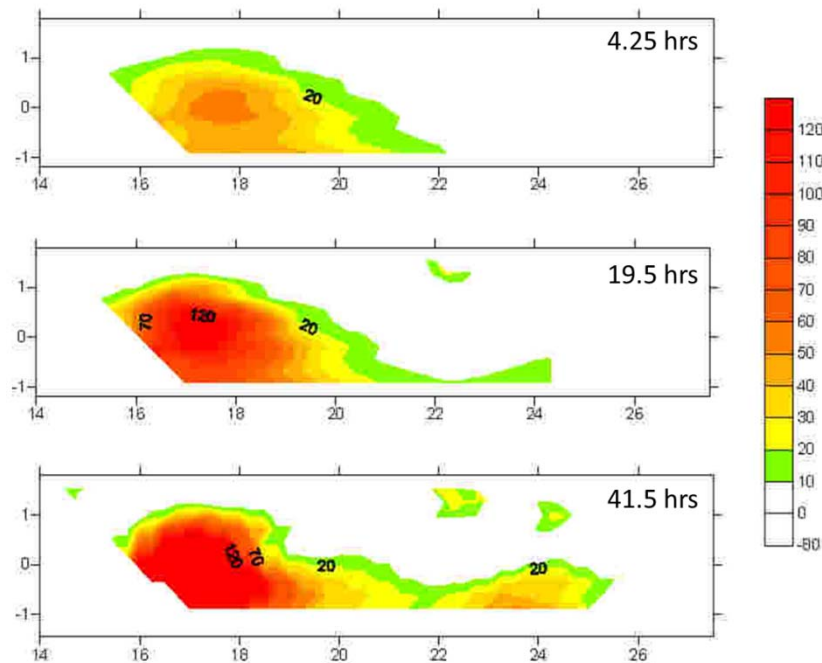


Figure 10. Vertical profile (y-axis is elevation in m) of percent difference in electrical resistivity of the down gradient lateral line (fig. 3) 3 m down gradient of the center of the 3 m by 3 m plot (left) and the 1 m by 1 m plot (right) of control area at the Barren Fork Creek site, July 13, 2011. Horizontal axis is distance along the electrical resistivity line. Time is the elapsed time from the onset of infiltration.

Tension Infiltrometers

Tension infiltrometers confirmed the importance of macropore flow. Matrix infiltration (in pore space less than or equal to 500 μm) was quantified with a tension of 6 cm and was one to two orders of magnitude lower than saturated infiltration rates (fig. 11). Macropore flow accounted for approximately 99% of the total infiltration at the Barren Fork Creek site, 85% to 87% at the Clear Creek site, and 97% to 99% at the Pumpkin Hollow site.

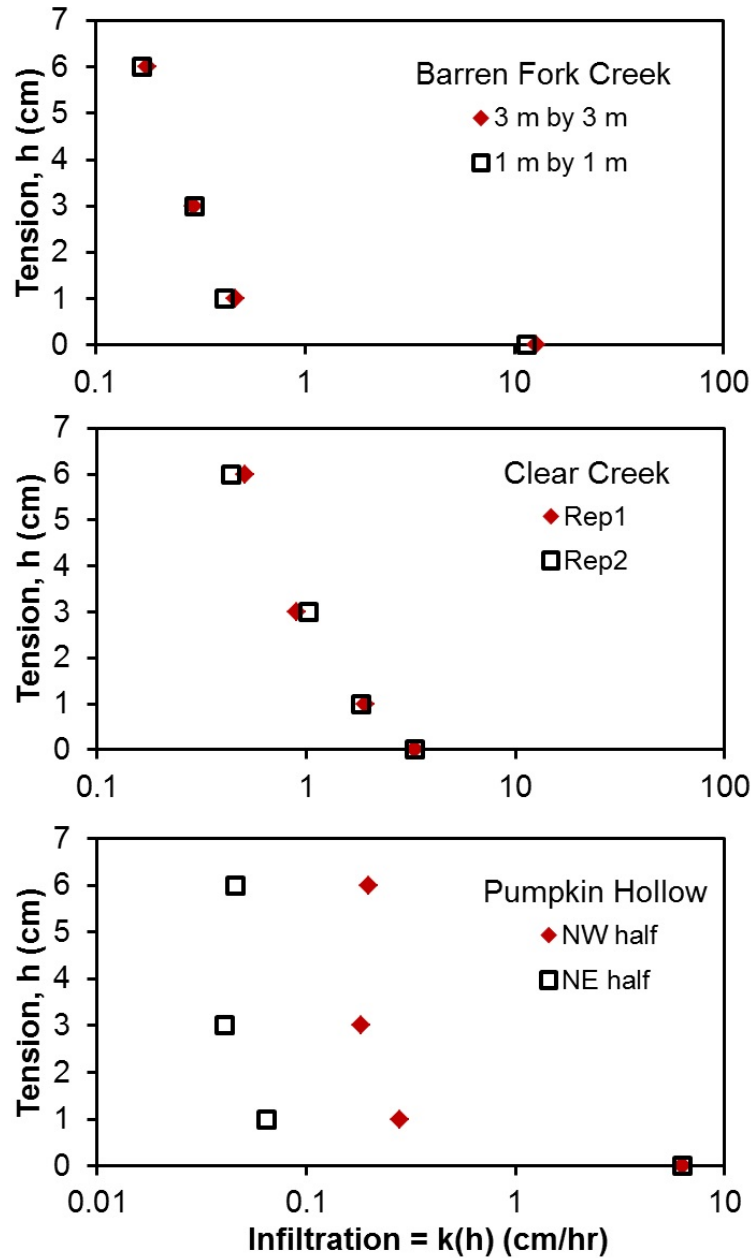


Figure 11. Infiltration rates based on infiltration plots for saturated infiltration ($h = 0$ cm) and unsaturated hydraulic conductivity (k) calculated from tension infiltrometer data. Locations included gravel outcrop plots at the Barren Fork Creek site, the 3 m by 3 m control plot at the Clear Creek site, and the 3 m by 3 m control plot at the Pumpkin Hollow site.

Conclusions

Plot scale experiments simulated field conditions more realistically compared to smaller infiltrometers and laboratory testing. Highly heterogeneous flow and transport indicated that the soils in the floodplains of the Ozark ecoregion are highly complex and not homogeneous. Infiltration rates in gravel outcrops were up to 70 cm/hr. For silt loam soils, infiltration was dominated by rapid macropore flow. This research highlighted the difference between the conceptual model of uniform piston infiltration and actual infiltration in field conditions. Elevated

chloride, RhWT, and P concentrations were observed in specific groundwater samples, showing that even a highly sorbing contaminant can be transported through the topsoil and the gravelly subsoils. Since floodplains are hydrologically well-connected to alluvial aquifers and streams in gravelly watersheds, a higher level of agricultural stewardship may be required for floodplains than upland areas. This has implications for the development of best management practices specifically for floodplains in the Ozark ecoregion due to their close proximity and connectedness to streams.

Acknowledgements

The project described in this publication was supported by Grant/Cooperative Agreement Number G10AP00137 from the United States Geological Survey. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the USGS. This material was also developed under STAR Fellowship Assistance Agreement no. FP-917333 awarded by the U.S. Environmental Protection Agency (EPA). It has not been formally reviewed by EPA. The views expressed in this paper are solely those of the author, and EPA does not endorse any products or commercial services mentioned in this paper. The authors also acknowledge Mr. Dan Butler, Mrs. Shannon Robertson, Dr. Bill Huff, and Mrs. Sara Boelkins for providing access to their alluvial floodplain properties. Finally, Dr. Chad J. Penn, David A. Correll, Qualla J. Parman, Taber L. Midgley, and Elliot W. Rounds, Oklahoma State University, and Jason Corral, University of Arkansas, are acknowledged for their assistance with field and lab work.

References

- Akay, O., and G. A. Fox. 2007. Experimental investigation of direct connectivity between macropores and subsurface drains during infiltration. *Soil Sci. Soc. Am. J.* 71(5): 1600-1606.
- Bunte, K., and S. Abt. 2001. Sampling Surface and Subsurface Particle-Size Distributions in Wadable Gravel- and Cobble-Bed Streams for Analyses in Sediment Transport, Hydraulics, and Streambed Monitoring. USFS General Technical Report 74, USDA. Rocky Mtn. Res. Sta. Fort Collins, CO.
- DeLaune, P. B., P. A. Moore, Jr., D. K. Carman, A. N. Sharpley, B. E. Haggard, and T. C. Daniel. 2004. Development of a phosphorus index for pastures fertilized with poultry litter: Factors affecting phosphorus runoff. *J. Environ. Qual.* 33(6): 2183-2191.
- Djodjic, F., B. Katarina, and L. Bergstrom. 2004. Phosphorus leaching in relation to soil type and soil phosphorus content. *J. Environ. Qual.* 33: 678–684. DOI: 10.2134/jeq2004.0678.
- Fox, G. A., R. Malone, G. J. Sabbagh, and K. Rojas. 2004. Interrelationship of macropores and subsurface drainage for conservative tracer and pesticide transport. *J. Environ. Qual.* 33(6): 2281-2289.
- Fox, G. A., D. M. Heeren, R. B. Miller, A. R. Mittelstet, and D. E. Storm. 2011. Flow and transport experiments for a streambank seep originating from a preferential flow pathway. *J. Hydrol.* 403(3-4): 360-366.
- Fuchs, J. W., G. A. Fox, D. E. Storm, C. J. Penn, and G. O. Brown. 2009. Subsurface transport of phosphorus in riparian floodplains: Influence of preferential flow paths. *J. Environ. Qual.* 38: 473-484. DOI: 10.2134/jeq2008.0201.

- Gburek, W. J., E. Barberis, P. M. Haygarth, B. Kronvang, and C. Stamm. 2005. Chapter 29: Phosphorus mobility in the landscape. In *Phosphorus: Agriculture and the Environment*, 941-979. Sims, J.T. and A. N. Sharpley, ed. Madison, Wis.: ASA-CSSA-SSSA.
- Gotovac, H., V. Cvetkovic, and R. Andricevic. 2009. Flow and travel time statistics in highly heterogeneous porous media. *Water Resour. Res.* 45, W07402, doi:10.1029/2008WR007168.
- Halihan, T., S. Paxton, I. Graham, T. Fenstermaker, and M. Riley. 2005. Post-remediation evaluation of a LNAPL site using electrical resistivity imaging. *J. Environ. Monit.* 7(4): 283-287.
- Heeren, D. M., R. B. Miller, G. A. Fox, D. E. Storm, C. J. Penn, and T. Halihan. 2010. Preferential flow path effects on subsurface contaminant transport in alluvial floodplains. *Trans. ASABE* 53: 127-136.
- Heeren, D. M., G. A. Fox, R. B. Miller, D. E. Storm, A. R. Mittelstet, A. K. Fox, C. J. Penn, and T. Halihan. 2011. Stage-dependent transient storage of phosphorus in alluvial floodplains. *Hydrol. Process.*, 25(20), 3230-3243.
- Heeren, D. M., G. A. Fox, and D. E. Storm. 2012. Berm method for quantification of infiltration and leaching at the plot scale in high conductivity soils. *J. Hydrol. Eng.* (in review).
- Kleinman, P. J. A., A. N. Sharpley, A. M. Wolf, D. B. Beegle and P. A. Moore, Jr. 2002. Measuring water-extractable phosphorus in manure as an indicator of phosphorus in runoff. *Soil Sci. Soc. Am. J.* 66(6): 1009-2015.
- Maguire, R. O., and J. T. Sims. 2002. Soil testing to predict phosphorus leaching. *J. Environ. Qual.* 31: 1601-1609.
- McNeill, J. D. 1980. Electrical conductivity of soils and rocks. Technical Note TN-5. Mississauga, Ontario, Canada: Geonics, Ltd.
- Midgley, T. L., G. A. Fox, and D. M. Heeren. 2012. Evaluation of the Bank Stability and Toe Erosion Model (BSTEM) for predicting lateral streambank retreat on composite streambanks. *Geomorphology* 145-146: 107-114, doi:10.1016/j.geomorph.2011.12.044.
- Miller, R. B., D. M. Heeren, G. A. Fox, D. E. Storm, T. Halihan, and A. R. Mittelstet. 2010. Geophysical mapping of preferential flow paths across multiple floodplains. ASABE Paper No. 1008730, ASABE, St. Joseph, Mich.
- Miller, R. B., D. M. Heeren, G. A. Fox, D. E. Storm, and T. Halihan. 2011. Design and application of a direct-push vadose zone gravel permeameter. *Ground Water* 49(6): 920-925.
- Mittelstet, A. R., D. M. Heeren, G. A. Fox, D. E. Storm, M. J. White, and R. B. Miller. 2011. Comparison of subsurface and surface runoff phosphorus transport rates in alluvial floodplains. *Agri. Ecosyst. Environ.* 141: 417-425, DOI: 10.1016/j.agee.2011.04.006.
- Murphy, J., and J. P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. *Anal. Chim. Acta.* 27: 31-36.
- Natural Resources Conservation Service (2012). Web Soil Survey (WSS). Washington, D.C.: USDA-NRCS. Available at: <http://websoilsurvey.nrcs.usda.gov/>. Accessed February, 2012.
- Nelson, N. O., J. E. Parsons, and R. L. Mikkelsen. 2005. Field-scale evaluation of phosphorus leaching in acid sandy soils receiving swine waste. *J. Environ. Qual.* 34: 2024-2035. DOI: 10.2134/jeq2004.0445.

- Pierzynski, G. M., R. W. McDowell, and J. T. Sims. 2005. Chemistry, cycling, and potential movement of inorganic phosphorus in soils. In *Phosphorus: Agriculture and the Environment*, Agronomy Monograph No. 46, Sims, J.T., and A.N. Sharpley (eds). American Society of Agronomy: Madison, Wis.
- 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. *Agr. Ecosyst. Environ.* 114: 351–359.
- Reichenberger, S., M. Bach, A. Skitschak, 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.
- 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. *Soil Sci. Soc. Am. J.* 66: 1947–1956. DOI: 10.2136/sssaj2002.1947.
- Sauer, T.J., S.D. Logsdon, J. Van Brahana, and J.F. Murdoch. 2005. Variation in infiltration with landscape position: Implications for forest productivity and surface water quality. *Forest Ecol. Manag.* 220: 118-127.
- Schroeder, P. D., D. E. Radcliffe and M. L. Cabrera. 2004. Rainfall timing and poultry litter application rate effects on phosphorus loss in surface runoff. *J. Environ. Qual.* 33(6): 2201-2209.
- Scott, H. D. 2000. *Soil Physics: Agricultural and Environmental Applications*. Iowa State University Press: Ames, Iowa.
- SSSA. 2008. Glossary of soil science terms. SSSA, Madison, WI.
- Thomas, G. W., and R. E. Phillips. 1979. Consequences of water movement in macropores. *J. Environ. Qual.* 8(2): 149-152.
- Ulen, B. 1999. Leaching balances of phosphorus and other nutrients in lysimeters after application of organic manures or fertilizers. *Soil Use Manag.* 15: 56-61.
- U.S. EPA (Environmental Protection Agency). 2009. Pathogen TMDLs for Clear Creek in Arkansas Planning Segment 3J, U.S. EPA Region 6, Water Quality Protection Division, Dallas, TX.
- Zhang, R. 1997. Determination of soil sorptivity and hydraulic conductivity from the disk infiltrometer. *Soil Sci. Soc. Am. J.* 61: 1024-1030.