7-2013

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An ASABE Meeting Presentation

Paper Number: 131621213

Impact of Measurement Scale on Infiltration and Phosphorus Leaching in Ozark Floodplains

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Written for presentation at the

2013 ASABE Annual International Meeting

Sponsored by ASABE

Kansas City, Missouri

July 21 – 24, 2013

Abstract. *Increased nutrient loads have resulted in several adverse impacts on surface water quality, including excessive algal growth, fish kills, and drinking water taste and odor issues across the United States and especially in the Ozark ecoregion of northeastern Oklahoma and northwestern Arkansas. The significance of this problem has been highlighted by litigation, with one case even reaching the U.S. Supreme Court (*Arkansas et al. v. Oklahoma et al.*, 503 U.S. 91) which required the upstream state to meet downstream water quality standards. The overarching objective of this line of research was to characterize phosphorus leaching to alluvial aquifers in the coarse gravel floodplains of the Ozark ecoregion, while the specific objective of this paper was to quantify infiltration and hydraulic conductivity across a range of scales (point to 100 m^2) to evaluate the effect of the scale of measurement. It is hypothesized that hydrologic heterogeneities (e.g., macropores and gravel outcrops) in the subsurface play an integral role in impacting flow and contaminant transport between the soil surface and alluvial aquifers. Innovative field studies, including plot scale injection experiments, were performed across a range of soil types at each of three floodplain sites in the Ozark ecoregion. Solutes in the injection water included phosphorus, P (highly sorptive), Rhodamine WT (slightly sorptive), and chloride (conservative). Plots maintained a constant head of 2 to 9 cm for up to 52 hours. Effective saturated hydraulic conductivity (*K_{eff}*) data, based on plot scale infiltration rates, were high (0.6 to 68* *cm hr^{-1}) and varied greatly, even within a single floodplain. The* K_{eff} *was also measured with a double ring infiltrometer and estimated at the point scale using Retention Curve (RETC) along with particle size distribution data. Point scale estimates were significantly lower than plot scale* K_{eff}*, and also failed to capture the variability of* K_{eff} *within a field site. The estimated permeability of the limiting layer reported by the U.S. Natural Resources Conservation Service (NRCS) Soil Survey was consistent with point scale estimates of* K_{eff}*, but was lower than plot scale* K_{eff} *at most sites. Plot scale infiltration tests are recommended over double ring infiltrometer tests or point scale estimates, although only small plots (1 m by 1 m) are necessary.*

Keywords. *Gravel outcrops, infiltration, phosphorus litigation, plot scale, preferential flow.*

Introduction

Increased nutrient loads have resulted in several adverse impacts on surface water quality, including excessive algal growth and fish kills across the United States and especially in the Illinois River Watershed (IRW) (Andrews et al., 2009). Lake Eucha, a source of water for Tulsa, Okla., suffered from drinking water taste and odor issues that were attributed to algal production (Blackstock, 2003). Both Lake Eucha and the IRW are in the Ozark ecoregion of northeastern Oklahoma and northwestern Arkansas. Nitrogen is a concern, but phosphorus (P) is generally considered the limiting nutrient in most surface water systems (Daniel et al., 1998). While optimum crop growth requires P above 0.2 mg L^{-1}, preventing surface water enrichment generally requires P to be below 0.03 mg L^{-1} (Pierzynski et al., 2005). In fact, surface waters in the Ozark ecoregion in particular may have a threshold closer to 0.01 mg L^{-1} (D.E. Storm, 2012, personal communication).

A Legal Perspective on Excess Phosphorus in the Ozarks

Arkansas et al. v. Oklahoma et al., 503 U.S. 91 (1992), was the first lawsuit addressing excess P loading to surface waters in the Ozark ecoregion. This case reached the U.S. Supreme Court certiorari after the Court of Appeals for the Tenth Circuit. Justice Stephens delivered the opinion for the unanimous court. *Arkansas v. Oklahoma* focused on point source pollution of the Illinois River and the application of the 1972 Clean Water Act (CWA). In particular, a Waste Water Treatment Plant (WWTP) in Fayetteville, Ark., had obtained a U.S. Environmental Protection Agency (EPA) issued permit to discharge into a tributary of the Illinois River, although Oklahoma water quality standards allowed no degradation of the Illinois River. A significant finding was that the Supreme Court upheld the EPA in requiring an upstream state to meet downstream water quality standards, based on § 401(a)(2) of the CWA (33 U.S.C. §1341(a)(2)). Even if the CWA were silent on this, according to Justice Stephens, the EPA would be justified by the Chevron Doctrine (*Chevron U.S.A. Inc. v. Natural Resources Defense Council, Inc.*, 467 U.S. 837, 842-845 (1984)). The findings of *Arkansas v. Oklahoma* continues to have a bearing on water quality in the IRW today. Total Maximum Daily Load (TMDL) standards are being developed for the IRW and will have an impact on upstream sources in Arkansas (Pryor et al., 2011).

Progress has been made in cleaning the IRW, with the Illinois River being declared a scenic river by the state of Oklahoma. Initially the EPA recommended a P standard of 0.01 mg L^{-1}, but Arkansas was concerned about a very low P standard limiting opportunities for growth since the Fayetteville–Springdale–Rogers Metropolitan Area is one of the fastest growing areas in the nation (Soerens et al., 2003). Based on published data by Clark et al. (2000), the P standard was established at 0.037 mg L^{-1}, which is the standard set for Oklahoma Scenic Rivers (OWRB, 2010). Communities in Arkansas and Oklahoma have invested more than $225 million to improve water quality (Pryor et al., 2011). Flow adjusted total phosphorus (TP) concentrations in the Illinois River near the state line (Watts, Okla.) have been decreasing since about 2002 (Haggard, 2010), which matches a known change in WWTP effluent discharge. Engle (2008) also reported reductions in WWTP loads since 2003. Also, the feasibility of water quality trading in the IRW has been evaluated (Bastian, 2011), concluding that at least five of the seven success factors for water quality trading exist in the IRW. Water quality trading, which is being advocated by the EPA (U.S. EPA, 2003), is a market based approach to solving water quality problems and has been to shown to provide significant benefits where water quality trading is feasible (Ribaudo, 2008; Yandle, 2008; Pittman, 2011; Lee and Douglas-Mankin, 2011).

In *City of Tulsa v. Tyson Foods et al.* (2003, U.S. District Court for the Northern District of Oklahoma), the city of Tulsa, Okla., filed suit against the poultry industry and the city of Decatur, whose WWTP receives most of its waste from a poultry processing plant (Soerens et al., 2003). This dispute was over the Eucha watershed which is also in the Ozark ecoregion and provides roughly half of the water supply for the city of Tulsa. The water quality in Lake Eucha had deteriorated significantly, including taste and odor problems that were attributed to algal production (Blackstock, 2003). The poultry industry has grown tremendously in the last few decades in the Ozark ecoregion of northeastern Oklahoma and northwestern Arkansas and has been a great economic benefit to local communities (Soerens et al., 2003). The poultry waste, known as poultry litter, is a valuable fertilizer and is often land applied to pastures and hay fields. However, excess poultry litter application can result in high soil P levels, resulting in high P levels in rainfall runoff to streams. Storm et al. (2001) found that anthropogenic non-point sources, including poultry litter, were responsible for 73% of the P load to Lake Eucha. Engle (2003) found that on a watershed scale mass balance of P, much more P is imported than exported. These imports are largely associated with feed for the poultry industry. While concerned with the WWTP for the city of Decatur, Okla., *Tulsa v. Tyson* was focused primarily on non-point sources of P. The lawsuit was settled in 2003 with agreements regarding the management of nutrients (including poultry litter) in the watershed, including a P index specific to the Eucha watershed mandated by the court (DeLaune et al., 2006).

At least two interesting things came out of this case. The first issue regarded the admissibility of scientific models for expert witness (Blackstock, 2003). Storm et al. (2001) presented data from the Soil and Water Assessment Tool (SWAT) model, which was used to evaluate P sources and loads in the watershed. The court applied the Daubert test for admissibility of scientific evidence, which includes four factors: capability of empirical testing, publication in a peer-reviewed journal, error rate, and acceptance in the scientific community. The court found most of the SWAT results admissible, making it the first court case to use SWAT results as scientific evidence (Blackstock, 2003).

The second issue was the application of the 1980 Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) to agriculture (Warren, 2003). In *City of Tulsa v. Tyson Foods et al.*, poultry litter was considered a hazardous substance under CERCLA. This is significant because "CERCLA provides for strict liability for any person found responsible for depositing hazardous substances in such a way as to endanger human health or safety." The court held that a watershed could be considered a "facility", but failed to hold poultry companies liable for "arranging" the disposal of poultry waster (Warren, 2003).

In the ongoing litigation of *Oklahoma ex rel. Edmondson v. Tyson Foods et al.* (filed June 13, 2005), Oklahoma Attorney General Drew Edmondson sued 11 poultry companies. Oklahoma sought both monetary damages and injunctive relief under CERCLA (McBride, 2011) in the Tulsa federal court. Storm et al. (2010) found that 13% of the total P load in the Illinois River was directly from poultry litter, and 11% from elevated soil P levels. U.S. District Judge Gregory Frizzell found that the Cherokee Nation was a required party and dismissed the monetary claims of the suit for lack of standing. This was upheld by the Tenth Circuit (McBride, 2011), meaning that Tyson likely escaped paying damages and leaving Oklahoma limited to the pursuit of an injunction. Judge Frizzell later ruled that poultry litter is not a solid waste, but the Attorney General has appealed and the Tenth Circuit Court of Appeals (Denver, Colo.) will hear the case.

Phosphorus Transport Mechanisms

Scientists and engineers need to identify critical nutrient source areas and transport mechanisms within a catchment in order to cost effectively protect and enhance drinking water systems, recreation activities, and aquatic ecosystems. While surface runoff is considered to be the primary transport mechanism for P (Gburek et al., 2005), subsurface transport through coarse subsoil to gravel bed streams may be significant and represents a source of P not alleviated by current conservation practices (e.g., riparian buffers).

Several studies have been conducted to investigate subsurface P transport at alluvial floodplain sites in the Ozark ecoregion. Injection tests were performed which showed preferential flow paths and physical non-equilibrium in the coarse gravel vadose and phreatic zones (Fuchs et al., 2009; Heeren et al., 2010). Preferential flow paths were interpreted to be buried gravel bars (Miller, 2012; Heeren et al., 2010). Long-term flow and transport monitoring was performed at two floodplain sites, showing aquifer heterogeneity and large scale bank storage of stream water, as well as large scale, stage-dependent transient storage of P in the alluvial aquifer (Heeren et al., 2011). 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^{-1}near the creek to 4 mg L^{-1} up to 100 m from the creek (Heeren, 2012). Subsurface P transport rates in the alluvial aquifers were quantified and found to be significant compared to surface runoff P transport rates on well managed pastures (Mittelstet et al., 2011). Penn et al.

(2013) investigated P sorption mechanisms in Ozark soils and found that P sorption was limited by chemical kinetics in some soils and by physical nonequilibrium in others.

Relatively few studies on infiltration and P leaching have been done at the plot scale where infiltration and transport may be controlled by heterogeneity present at various scales (Nelson et al., 2005). In many riparian floodplains, gravel outcrops and macropores are present; Heeren (2012) found that macropore flow accounted for approximately 85% to 99% of the total infiltration based on tension infiltrometer measurements. 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. Accounting for spatial variability in infiltration rates is important not only for watershed flow and transport models, but also for variable rate irrigation which can account for in-field heterogeneity in soil properties.

As the scale of measurement increases, physical properties of a porous media like soil tend to have decreasing spatial variability until a representative elementary volume (REV) is reached (Brown et al., 2000). Increasing the diameter of double ring infiltrometers has been found to reduce the variability of measured infiltration rates (Sisson and Wierenga, 1981; Lai and Ren (2007). However, whether double ring infiltration can be scaled up to the plot or field scale has not been well established. Massman (2003) observed that hydraulic conductivities measured with flood tests in infiltration basins were up to two orders of magnitude higher or lower than hydraulic conductivities determined from air conductivity or estimated from grain size parameters. It was hypothesized that as the scale of measurement increases, measured infiltration rate and hydraulic conductivity of the topsoil will increase due to large but infrequent macropores, and that the spatial variability will decrease, until an REV is attained. Therefore, the overarching objective of this line of research was to characterize P leaching to alluvial aquifers in the coarse gravel floodplains of the Ozark ecoregion, while the specific objective of this paper was to quantify infiltration and hydraulic conductivity across a range of scales (point to 100 m^2) to evaluate the effect of measurement scale. Accurately understanding infiltration is essential for understanding P transport.

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 km^2 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 (Figure 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 km^2, the Barren Fork Creek site was a fourth order stream with a historical median discharge of 3.6 $m^3\ s^{-1}$. 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 0.3 to 2.0 m, with dry bulk densities ranging from 1.3 to 1.7 g cm^{-3}. 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; Sauer et al., 2005). Detailed electrical resistivity data for the Barren Fork Creek site are reported in the appendix of Miller (2012).

The Pumpkin Hollow floodplain site (Figure 2) 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 km^2. 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 between 1.3 and 1.5 g cm^{-3}. Detailed electrical resistivity data for the Pumpkin Hollow floodplain site are reported in the appendix of Miller (2012).

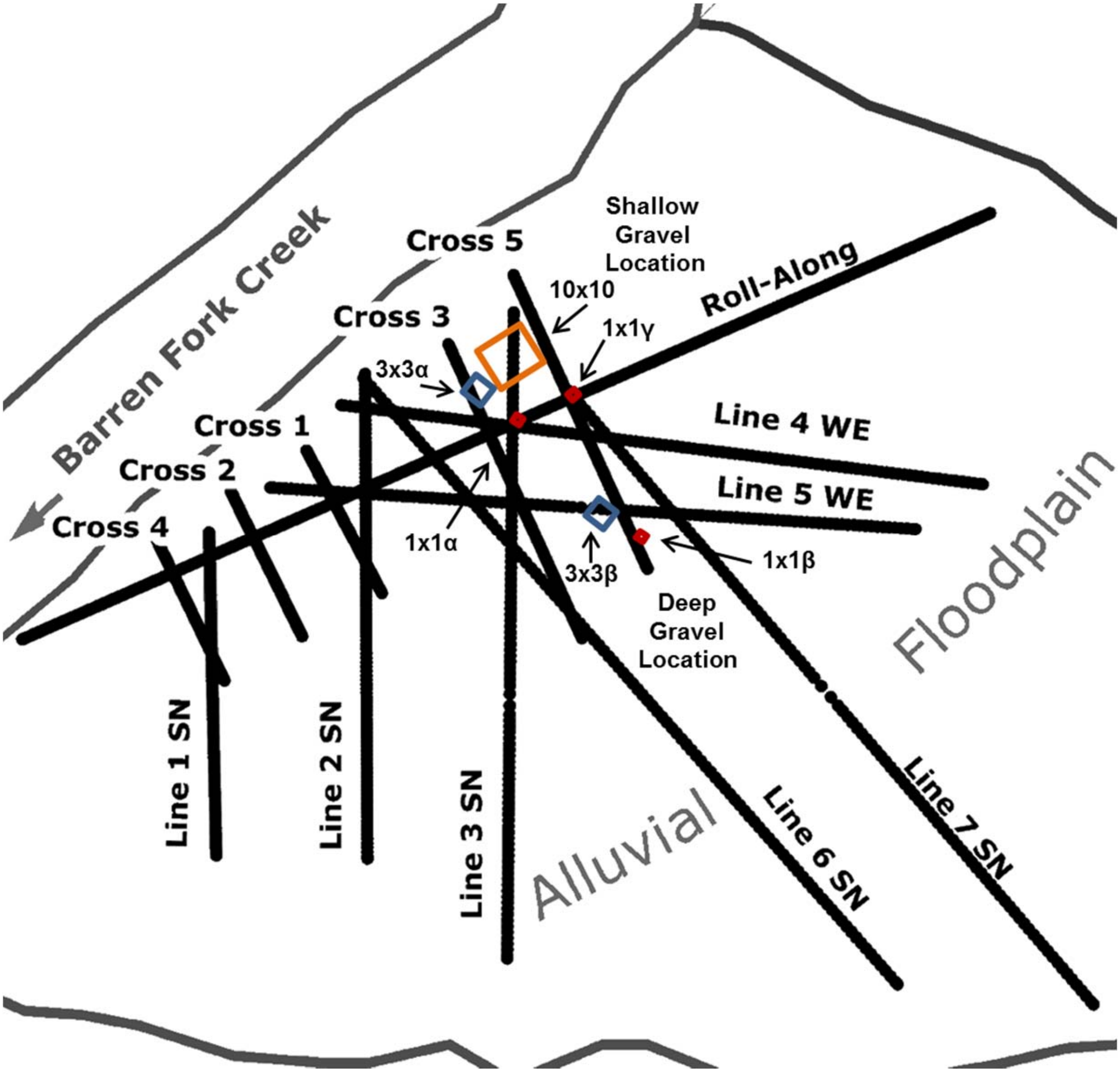

Figure 1. Barren Fork Creek floodplain site, including locations of plots for infiltration experiments (labeled according to plot size in m). Thick black lines are locations of electrical resistivity profiles from previous research (Miller, 2012), which were used to select plot locations. For orientation, north is up. The floodplain is bounded by the Barren Fork Creek to the northwest, a small tributary to the northeast, and a bluff to the south. Figure adapted from Miller (2012).

The Clear Creek alluvial floodplain site (Figure 3) was located just west of Fayetteville, AR in the Arkansas River Basin and flows into the Illinois River (latitude: 36.13°, longitude: -94.24°). The total drainage area was 199 km^2 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. Thickness of the top loam layer ranged from 0.3 to 2.0 m, with dry bulk densities ranging from 1.5 to 1.7 g cm^{-3}. A fourth order stream with a flow of approximately 0.5 m^3 s^{-1} at the study site, the area of the watershed above that point was 101 km^2. The land use in the study area was pasture and consisted of Razort gravelly loam soils. Detailed electrical resistivity data for the Clear Creek floodplain site are reported in the appendix of Heeren (2012).

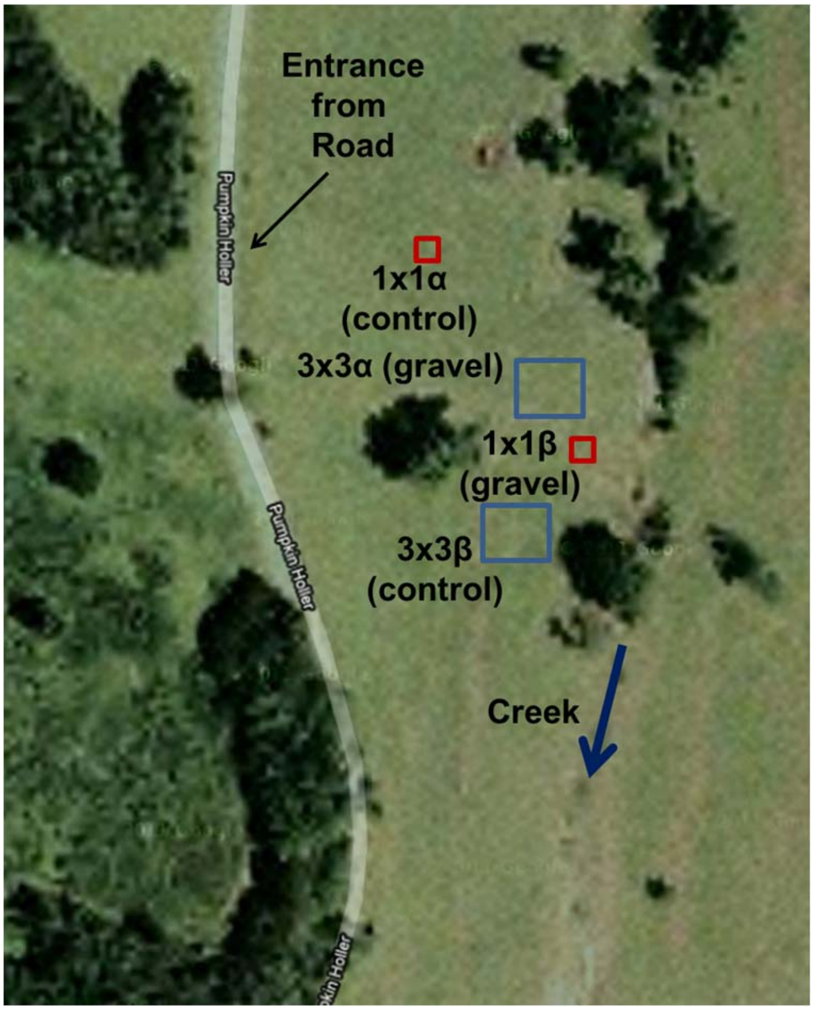

Figure 2. Pumpkin Hollow floodplain site, including locations of plots for infiltration experiments (labeled according to plot size in m). For orientation, north is up. The floodplain is bounded by Pumpkin Hollow Creek to the east and a bluff to the west. Background electrical resistivity profiles from previous research (Miller, 2012) were located south of the plot locations (not shown).

Infiltration Plots

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, the berm method (Heeren et al., 2013) was used to confine infiltration plots and maintain a constant head of water, with plot sizes ranging from 1 m by 1 m to 10 m by 10 m. Four to six infiltration experiments were performed at each site with plots selected to represent a range of infiltration rates at each floodplain site (Figures 1 to 3, Table 1). Plots were located on relatively level areas in order to minimize the variation in water depth across the plot. 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 90^0 steel elbows and surrounded the infiltration gallery. 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 m^3 and 0.76 m^3) 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. The largest plot sizes (10 m by 10 m) required continuous pumping and solute injection directly into the pump hose using Dosatron® injectors (D8R, Dosatron®, Clearwater, FL) instead of using tanks for mixing. Constant heads in the plots were maintained (Heeren et al., 2013) between 3 and 10 cm. Depth to the water table ranged from 50 cm at the Pumpkin Hollow site up to 350 cm at the Clear Creek site.

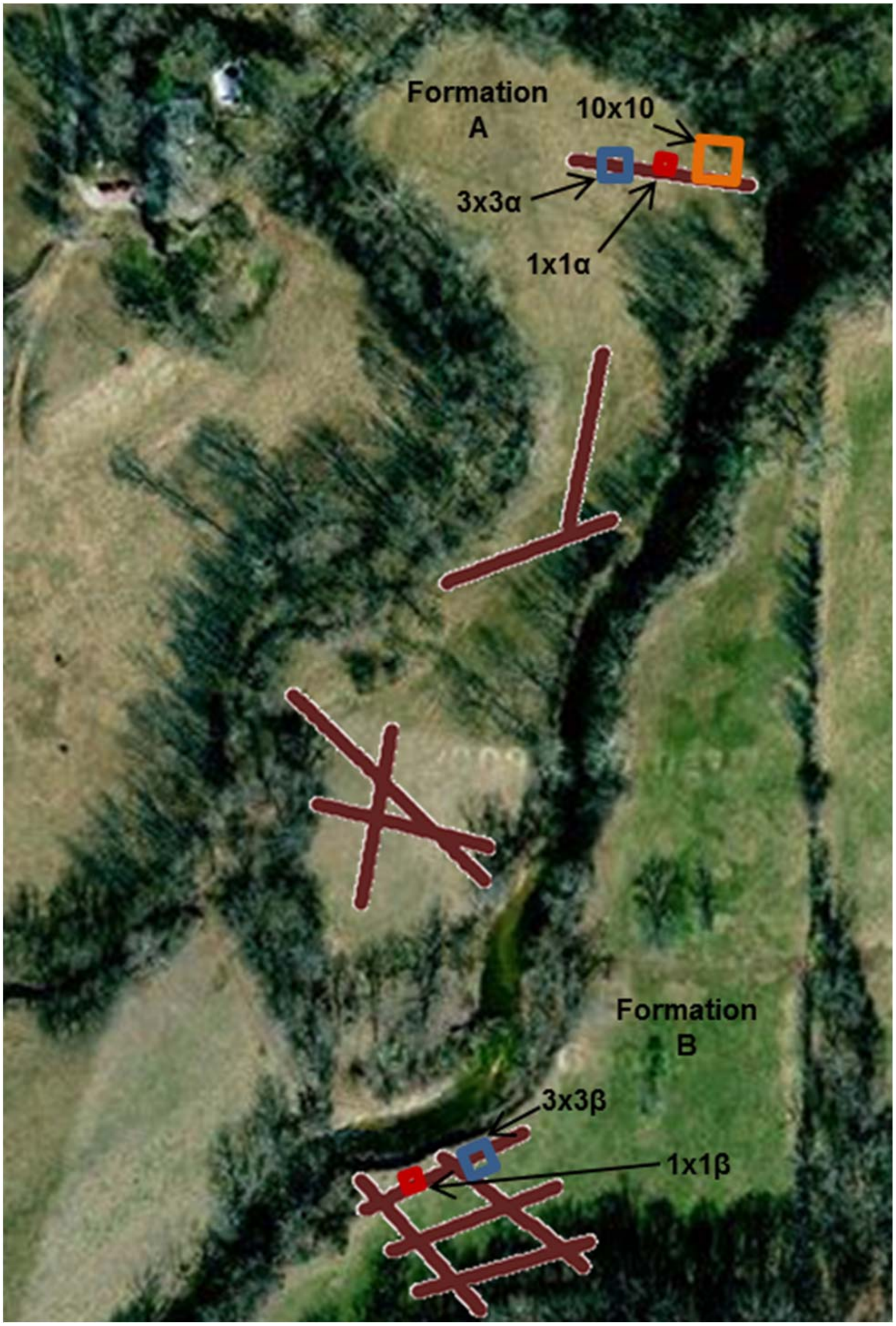

Figure 3. Clear Creek floodplain site, including locations of plots for infiltration experiments (labeled according to plot size in m). Thick maroon lines are locations of electrical resistivity profiles from previous research (Heeren, 2012), which were used to select plot locations. For orientation, north is up. Within the floodplain, Formation A is bounded by Clear Creek to the east and a small overflow channel to the north and west, and Formation B is bounded by Clear Creek to the north and a bluff to the south. Figure adapted from Heeren (2012).

Chloride (Cl^-) was used as a conservative (nonsorbing) tracer. Target tracer concentrations were 100 to 200 mg L^{-1} KCl (correlating to 48 to 95 mg L^{-1} 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^{-1}. 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. The P (highly sorbing) concentrations of 3 to 10 mg L^{-1}(corresponding to 10 to 32 mg L^{-1} 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} (1 to 3 ton $acre^{-1}$). The P 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.

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

Floodplain Site	Date	Plot	Area (m^2)	Treatment	Duration (hr)	"Steady State" Infiltration (*q*) (cm hr^{-1})	Limiting Layer Depth (*d*) (cm)	Average Head (*h*) (cm)	Hydraulic Gradient (*i*) (cm cm^{-1})	Hydraulic Conductivity (K_{eff}) (cm hr^{-1})
Pumpkin Hollow	5/4/11	1x1α	1	Control	32	5.3	99	6.8	1.07	5.0
Pumpkin Hollow	5/5/11	3x3α	9	Gravel Outcrop	2.8	18	46	5.4	1.12	16
Pumpkin Hollow	6/1/11	1x1β	1	Gravel Outcrop	4.3	74	36	3.2	1.09	68
Pumpkin Hollow	6/2/11	3x3β	9	Control	24	6.3	58	6.5	1.11	5.7
Barren Fork	6/30/11	1x1α	1	Shallow gravel	22	10	92	5.8	1.06	9.6
Barren Fork	6/30/11	3x3α	9	Shallow gravel	22	13	110	3.1	1.03	12
Barren Fork	7/13/11	1x1β	1	Deep gravel	46	6.8	134	4.7	1.04	6.6
Barren Fork	7/13/11	3x3β	9	Deep gravel	48	3.0	145	6.4	1.04	2.9
Barren Fork	5/7/12	10x10	60*	Shallow gravel	4	13	107	3.0	1.03	13
Barren Fork	6/6/12	1x1γ	1	Shallow gravel	86	14	113	9.0	1.08	13
Clear Creek	4/12/11	1x1α	1	Formation A	41	5.6	57	1.8	1.03	5.4
Clear Creek	4/12/11	3x3α	9	Formation A	41	3.3	76	1.8	1.02	3.2
Clear Creek	7/27/11	1x1β	1	Formation B	48	1.3	137	6.3	1.05	1.2
Clear Creek	7/27/11	3x3β	9	Formation B	45	0.8	210	7.2	1.03	0.7
Clear Creek	5/21/12	10x10	100	Formation A	52	0.6	84	6.0	1.07	0.6

*Pump capacity was not sufficient to keep the entire infiltration gallery inundated.

Soil Cores and Particle Size Analysis

During the installation of the observation wells with a Geoprobe Systems (Salina, KS) 6200 TMP (Trailer-mounted Probe) direct-push drilling machine, which has been shown to be effective in coarse gravel aquifers (Miller et al., 2011), soil core samples were collected at known depths 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. Direct push cores were recovered from one to four wells per plot.

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).

A complete textural analysis was desired for surface soil samples from one soil core per plot. Following the procedure developed by Miller (2012), the particle size distribution (PSD) of the mass retained on the finest sieve (2 mm) “was determined using a Cilas 1180 Particle Size Analyzer (Cilas USA, Madison, WI), which calculated the ratio of particle sizes based on the obscurance of a laser beam. The Cilas 1180 measured the relative volume for particle size ranges of a representative sample. The PSD of the fine fraction was calculated by multiplying the percent distribution from the sample by the total volume of the fine dry-sieved fraction.”

Double Ring Infiltrometer Soil Hydraulic Conductivity

While this research was driven by infiltration and leaching, the best way to compare data across scales was to convert infiltration data to effective saturated hydraulic conductivity (K_{eff}) of the top soil layer. In most cases (at the Ozark floodplain sites) this was a layer of silt loam which was overlying coarse gravel.

In order to represent a scale in between the plot scale and the point scale, a double ring infiltrometer (ELE 25-0660, ELE International, Loveland, CO), with an outer ring diameter of 60 cm and an inner ring diameter of 30.5 cm (infiltration area of 0.07 m^2), was used at the Barren Fork Creek site. Tests were performed at two locations: near the “shallow gravel” plots and near the “deep gravel” plots. The shallow gravel location was an area where a high hydraulic conductivity zone (a buried gravel bar) came close to the soil surface, with only 0.3 to 1 m of silt loam. At the deep gravel location, 1 to 1.3 m of silt loam capped the coarse gravel layer.

During the constant head double ring experiments (12 to 55 min), the wetting front (total infiltration of 0.6 cm) did not proceed past the top silt loam layer of soil. With the double ring infiltrometer, flow from the inner ring was assumed to be one dimensional. Therefore, the data was fit to the following well known one dimensional transient solution (Philip 1957; Lai & Ren, 2007):

$$I = St^{\frac{1}{2}} + At \tag{1}$$

where I is cumulative infiltration (L), S is sorptivity (L T$^{-1/2}$), t is the elapsed time from initiation of infiltration (T), and A is a constant (L T^{-1}).The A term was taken to be the effective saturated hydraulic conductivity (K_{eff}). Water depth (around 10 cm) is not included in this equation, but its effect is accounted for in the sorptivity term along with matric potential effects. For the experiment at the deep gravel location, the first three points were treated as outliers and it was assumed that the experiment started on the 4th data point (seven minutes after initiation).

Plot Scale Soil Hydraulic Conductivity

A brief survey of the literature was performed to determine the best method to determine K_{eff} from plot scale constant head infiltration rate data. Transient solutions are available for early time infiltration data (e.g. Philip, 1957; equation 1) for one dimensional infiltration. A quadratic equation can be fit to the data in order to determine two parameters: K_{eff} and sorptivity, the latter of which accounts for both capillary action and depth of the water above the soil surface (head). This approach worked well for double ring infiltrometer experiments at the Barren Fork Creek site with a high level of precision at the beginning of infiltration and a limited depth of total infiltration, since the equation assumes a homogenous semi-infinite medium. For the longer duration (3 to 52 hr) plot scale experiments, though, the depth of infiltration often exceeded the top layer of soil, violating the homogeneous assumption in these equations. Also, it was difficult to get precise transient early time data when accounting for measurement error and the change in storage of water above the soil surface during plot scale experiments.

The second major category of equations for predicting K_{eff} from infiltration data is steady state equations (Bodhinayake et al., 2004). Most of the plots were run long enough to achieve quasi-steady state conditions, with total infiltration often greatly exceeding the depth of the top layer of soil. Without transient data, more parameters are needed for these solutions (ponded depth, geometry to account for two dimensional (radial) effects, etc.). However, a good solution for our situation, with two distinct soil layers, was not found.

Therefore, we developed our own solution applying Darcy’s law specifically to the top layer of soil for steady state infiltration under a constant head. Since edge effects were considered small compared to the large area of infiltration at the plot scale, one dimensional vertical flow was assumed at the plot scale. Equation 2 is for infiltration into a lower conductivity layer underlain by a higher conductivity layer:

$$q = K_{eff}i = K_{eff}(1 + \frac{h}{d}) \tag{2}$$

where q is the steady state infiltration rate (L T^{-1}), K_{eff} is the effective saturated hydraulic conductivity (L T^{-1}), i is the hydraulic gradient (L L^{-1}), *h* is the spatial and temporal average depth of water in the infiltration gallery (L), and *d* is the depth of the top layer of soil. The first term in the parentheses represents the hydraulic gradient due to gravity, which is unigradient. The second term is the gradient due to the change in pressure head over the length of flow. Water pressure at the soil surface is the hydrostatic pressure head associated with the spatially and temporally averaged depth of water in the plot. As water flows from a restrictive layer of soil into a more conductive layer, an inverted water table will form at the bottom of the restrictive layer, indicating a pressure head of zero at the bottom of the top layer of soil. It is acknowledged that the one dimensional flow assumption is a limitation of this approach when considering the heterogeneity and anisotropy of these complex alluvial deposits (Fox et al., 2011; Freiberger et al., 2013).

For 1 m by 1 m and 3 m by 3 m plots, *q* was determined based on flow rates from the mixing tanks. The tanks were instrumented with automated water level data loggers with an accuracy of 0.5 cm (HoboWare U20, Onset Computer Corp., Cape Cod, MA) to monitor water depth (pressure) and temperature at one minute intervals. An additional water level data logger was used to monitor the atmospheric pressure. Logger data were processed with HoboWare Pro software, which adjusted for changes in atmospheric pressure and water density. Measured tank water depth over time was used to calculate the flow rate using a volumetric rating curve. For the 10 m by 10 m plots, flow was estimated based on the frequency of cycles in the Dosatron® injectors (D8R, Dosatron®, Clearwater, FL). The *h* was determined from automated water level data loggers (HoboWare U20, Onset Computer Corp., Cape Cod, MA) placed in the plots along with manual measurements of water depth.

The *d* of the silt loam layer was determined from soil cores within and near the plots. The Barren Fork Creek site had a distinct layer change from silt loam to coarse gravel. The Pumpkin Hollow site was highly heterogeneous, and it was sometimes difficult to identify the bottom of a restrictive layer. In some cases (e.g. gravel outcrops), the majority of the flow would have been lateral flow above a restrictive layer. With these limitations in mind, the results were termed *effective* saturated hydraulic conductivity (K_{eff}).

Point Scale Soil Hydraulic Conductivity

Point scale K_{eff} were estimated based on a topsoil sample from one soil core per plot, as described above. Using the PSD determined by sieving and the Cilas Particle Size Analyzer, K_{eff} was estimated by Retention Curve (RETC) with the van Genuchten equation using the Mualem assumption (van Genuchten et al., 1991). RETC requires the percent sand, silt, and clay according to the USDA soil classification, which defines clay as particles less than 2 μm. Since the Cilas Particle Size Analyzer only measured down to 3.9 μm, a minor amount of extrapolation was required to extend the PSD to 2 μm. In order to best account for this source of uncertainty, both a low and high clay content were estimated for each sample. RETC was utilized for both clay contents, and the average of the two K_{eff} was taken to be the K_{eff} for that sample. Since RETC only utilized sand, silt and clay percentages, one the limits of this method is that it does not account for the gravel content of a soil sample.

Results and Discussion

Barren Fork Creek

Calculated K_{eff} varied widely across sites and within sites, ranging from 0.5 to 68 cm hr^{-1}. At the Barren Fork Creek site, estimated K_{eff} of the top layer of soil based on double ring infiltrometer experiments were 1.5 cm hr^{-1} and 0.5 cm hr^{-1} for the shallow gravel and deep gravel, respectively (Figures 1 and 4). While the shallow gravel location had a smaller layer of silt loam soil, the thickness of the limiting layer should not have an effect on short duration (12 to 55 min) double ring infiltrometer experiments. In effect, the double ring infiltrometer not only measures a smaller horizontal area than plot scale infiltration experiments, it also measures the effective hydraulic conductivity for a shallower depth of soil.

During plot scale infiltration experiments at the Barren Fork Creek site, hydraulic gradients ranged from 1.03 to 1.08 cm cm^{-1} (Figure 1, Table 1). Infiltration rates ranged from 3.0 to 6.8 cm hr^{-1} for the deep gravel plots and from 10 to 14 cm hr^{-1} for the plots with shallow gravel. The calculated K_{eff} data were similar, ranging from 2.9 to 6.6 cm hr^{-1} for the deep gravel plots and from 9.6 to 13 cm hr^{-1} for the shallow gravel plots. The pattern of higher K_{eff} in the shallow gravel location compared to the deep gravel location held for both double ring infiltrometer data and plot scale data, although the magnitude of the K_{eff} measured plot scale was an order of magnitude greater than K_{eff} measured by the double ring infiltrometer. This may be due to 1) measuring at a different scale (area as well as depth of soil), 2) differences in procedure (short v. long duration), 3) using a different equation (transient v. steady-state), or 4) the double ring infiltrometer being more faithful to the one dimensional flow assumption.

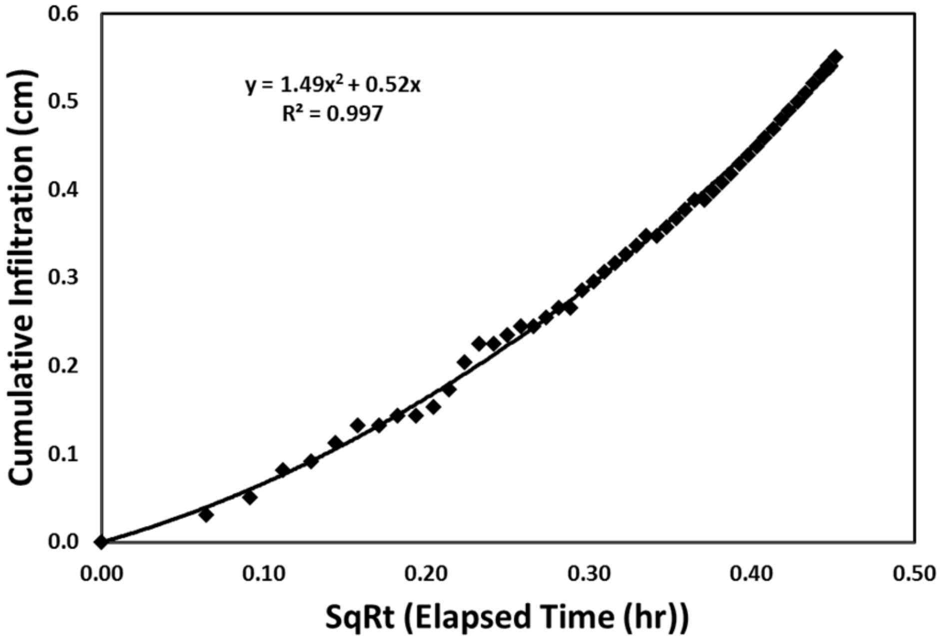

Figure 4. Double ring infiltrometer data from the shallow gravel location at the Barren Fork Creek site, resulting in an effective saturated hydraulic conductivity of 1.5 cm hr^{-1} and a sorptivity of 0.52 cm hr$^{-1/2}$.

Data from the plot scale and double ring experiments were compared to point scale estimates of K_{eff} and 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^{-1} for the Razort gravelly loam soils at the floodplain sites (Figure 5). Five out of the six plot scale data were higher than the maximum predicted by the NRCS soil survey, as well as the point scale estimates. It is also noted that the point scale estimates do not capture the variability in K_{eff} shown in the plot scale data. Within the plot scale, increasing plot size did not seem to have a strong impact on K_{eff} or reduce spatial variability in K_{eff}.

Pumpkin Hollow

Plots at the Pumpkin Hollow field site were located in gravel outcrops and control locations (Figure 2). Gravel outcrops in the floodplain appeared to be gravel splays from a recent high flow event (on the order of a 50 year recurrence interval) rather than an exposed buried gravel bar. A 10 m by 10 m plot was not performed at the Pumpkin Hollow site because of insufficient water supply in the small ephemeral creek.

During the plot scale infiltration experiments, estimated hydraulic gradients ranged from 1.07 to 1.12 cm cm^{-1} with calculated K_{eff} ranging from 5.0 to 5.7 cm hr^{-1} for the control plots and from 16 to 68 cm hr^{-1} for the gravel outcrop plots (Table 1). This wide range indicates considerable heterogeneity in infiltration processes at the Pumpkin Hollow floodplain due to the occurrence of gravel outcrops. The very high conductivity gravel outcrops achieved quasi-stead state flow quickly, resulting in relatively short (less than 5 hr) plot infiltration experiments.

Plot scale data were analyzed along with point scale calculations of K_{eff} and estimates from NRCS (NRCS 2012) (Figure 6). Both point scale data and NRCS soil survey data severely underestimated the capacity of the gravel outcrops to infiltrate water. This difference indicates the need for larger scale field measurements of infiltration rate and K_{eff}. 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. The agreement between the point scale data and the NRCS estimates (for both the Pumpkin Hollow and the Barren Fork Creek sites) supports the idea that the NRCS data may be more representative of hydrological processes at a small scale rather than a plot or field scale.

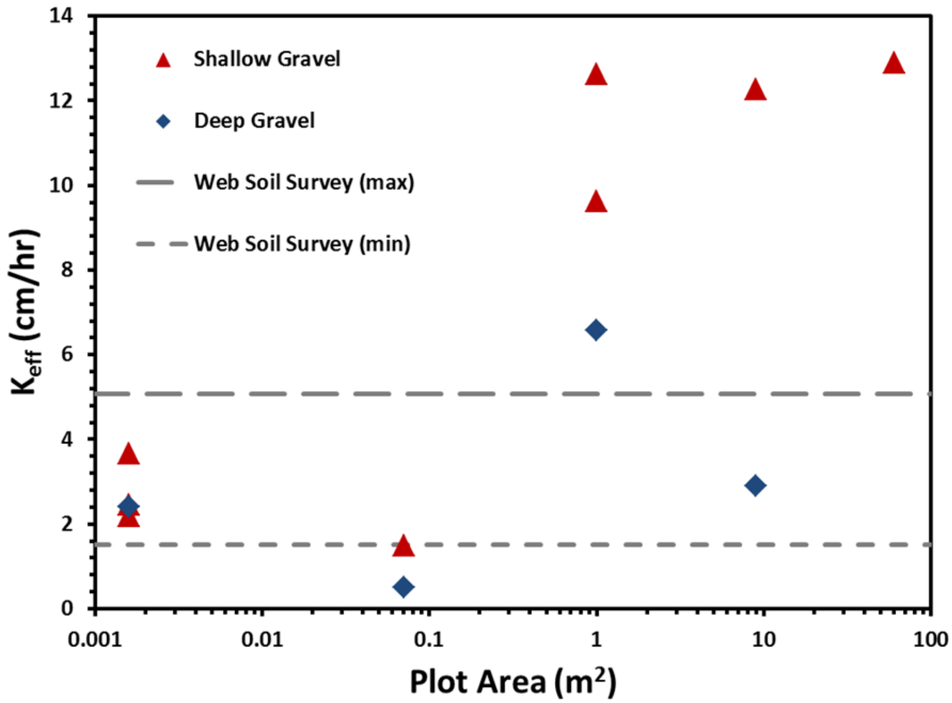

Figure 5. Effective saturated hydraulic conductivity (K_{eff}) data for the Barren Fork Creek floodplain site, including both point scale estimates and plot scale infiltration experiments. Double ring infiltrometer data is also included (infiltration area of 0.07 m^2). The expected range of infiltration rates based on the permeability of the limiting layer reported in the Natural Resources Conservation Service Soil Survey (NRCS, 2012) is shown by the dashed lines.

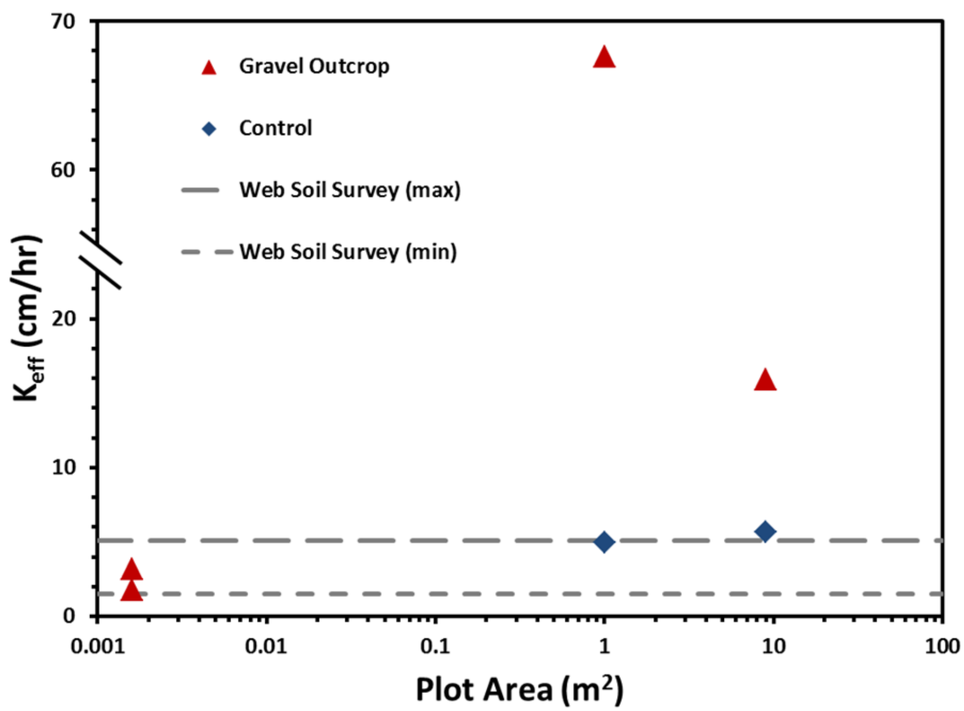

Figure 6. Effective saturated hydraulic conductivity (K_{eff}) data for the Pumpkin Hollow floodplain site, including both point scale estimates and plot scale infiltration experiments. The expected range of infiltration rates based on the permeability of the limiting layer reported in the Natural Resources Conservation Service Soil Survey (NRCS, 2012) is shown by the dashed lines.

Clear Creek

Infiltration plots at the Clear Creek floodplain site were located in two unique geomorphic formations (Figure 3). "Formation A," located on the west side of the creek, was very similar to the alluvial deposits at the Barren Fork Creek site with an apparently uniform layer of silt loam (0.5 to 1.0 m) above the gravel. Unlike the Barren Fork Creek site, the gravel in Formation A did contain a buried soil horizon with potential for a perched water table. "Formation B," located on the east side of the creek, was very gravelly at the surface but had enough fines mixed in to result in low infiltration rates. The streambank profile at Formation B is 3.5 m tall, with a very thick limiting layer ranging from 2.4 to 2.1 m (Table 1). At this location Clear Creek is a bedrock stream, with the water table in the alluvial aquifer being essentially at bedrock (determined by auger refusal with the Geoprobe drilling machine) during baseflow conditions.

Plot scale infiltration rates were lower than the other sites, ranging from 0.7 to 5.6 cm hr^{-1} (Table 1). The correlating K_{eff} data (0.6 to 5.4 cm hr^{-1}) were compared to the point scale data and estimates from NRCS (NRCS 2012) (Figure 7). At the Clear Creek site, K_{eff} from all three data sources were comparable. However, similar to the other sites, the point scale estimates failed to capture the spatial variability in K_{eff} present in these floodplains. There was a negative correlation between K_{eff} and plot size at the Clear Creek site (similar to the gravel outcrop plots at the Pumpkin Hollow site). It could be that smaller plots had larger edge effects (violating the one dimensional flow assumption), resulting in inflated estimates of K_{eff}. It could also be due to the large variability in the data, making it difficult to discern the significance of the trend with limited data points. Additional infiltration plots would have enabled more rigorous statistics, but the effort required for plot scale infiltration experiments made a large sample size prohibitive.

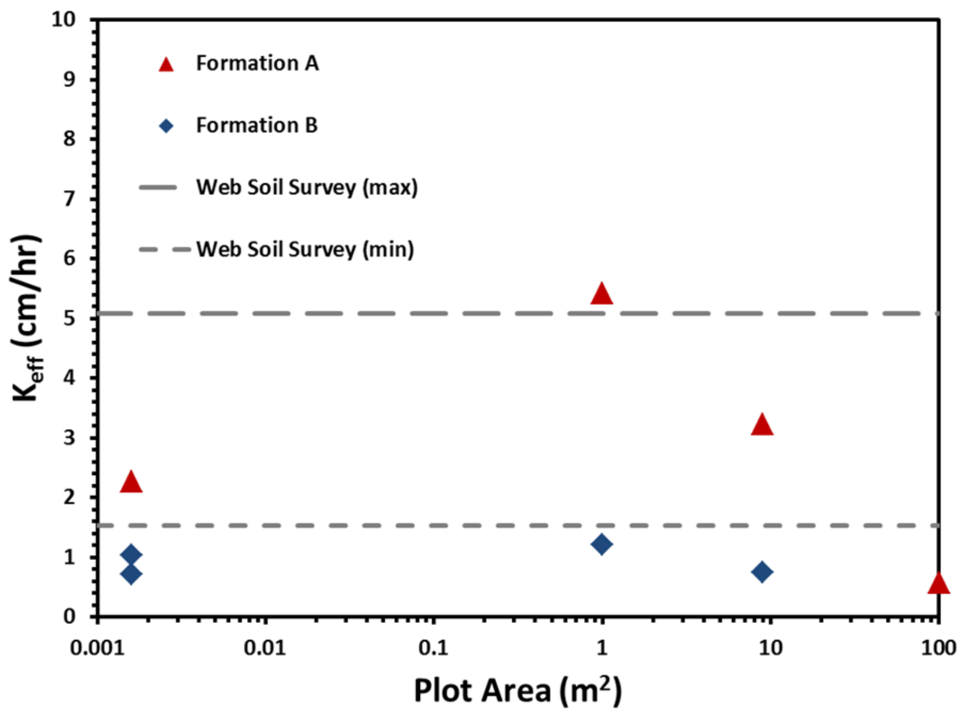

Figure 7. Effective saturated hydraulic conductivity (K_{eff}) data for the Clear Creek floodplain site, including both point scale estimates and plot scale infiltration experiments. The expected range of infiltration rates based on the permeability of the limiting layer reported in the Natural Resources Conservation Service Soil Survey (NRCS, 2012) is shown by the dashed lines.

Research Implications

It was hypothesized that as the scale of measurement increases, measured infiltration rate and hydraulic conductivity of the topsoil will increase due to an increased likelihood of having a very large but infrequent macropore in a large plot size, and that the spatial variability will decrease, until an REV is attained (Brown et al., 2000). At all sites the K_{eff} did increase until the plot scale was reached (1 m by 1 m), but K_{eff} did not consistently increase or decrease as the plot scale increased from 1 m by 1 m to 10 m by 10 m. While spatial variability in K_{eff} decreased as the scale increased from 1 m by 1 m to 3 m by 3 m at the Pumpkin Hollow and Clear Creek sites, the spatial variability actually increased at the Barren Fork site as the scale of measurement increased from 1 m by 1 m to 3 m by 3 m. Therefore, it was concluded that the plot scale (1 m^2 to 100 m^2) is within the REV.

Observed large macropores (greater than 1 cm) did not have as much impact on infiltration as expected. For example, a 4 to 5 cm diameter macropore was observed in the 10 m by 10 m plot at the Barren Fork Creek site. Subsequent excavation revealed that the macropore descended vertically to a depth of 1.0 m, into the gravel layer, before proceeding laterally 15 cm. Infiltration into this single macropore was quantified to be 27.4 L min^{-1} with head of 3.4 cm (the maximum achieved during the plot scale infiltration test), and up to 56.2 L min^{-1} with a head of 20 cm. However, a head of 0.4 cm, designed to better simulate natural rainfall conditions, resulted in a flow of only 1.3 L min^{-1}. As the diameter of a macropore increases, it has a larger capacity to transport water, but at some critical diameter this capacity surpasses typical rainfall rates and flow into the macropore becomes supply limited. Macropores larger than this critical diameter do not have a larger flow rate and, assuming a typical soil pore size distribution, are less frequent. It is hypothesized that there is a dominant diameter, less than the critical diameter, which is the pore size responsible for the most infiltration, because it is large enough to have significant flow but small enough to occur frequently. In fact, this pore size range occurs frequently enough that it can be characterized sufficiently by 1 m by 1 m plots, explaining in part why they are included in the REV.

In order to best characterize infiltration processes at the field scale, plot scale infiltration tests are recommended over double ring infiltrometer tests or point scale estimates. Also, since the 1 m by 1 m plot size is already within the REV, 1 m by 1 m plots are recommended. While a slight decrease in spatial variability can be observed for larger plot sizes, the level of difficulty in doing plot scale infiltration measurements increases significantly at the 3 m by 3 m and especially the 10 m by 10 m scales. Instead of investing in larger plot sizes, more will be gained from investing in a higher number of 1 m by 1 m plots in order to accurately determine the mean K_{eff} for a field. In order to evaluate the number of plots necessary, the standard error of the mean was calculated (Equation 3) according to Steel and Torrie (1980) for each floodplain site:

$$SE = \frac{s}{\sqrt{n}} \tag{3}$$

where *SE* is the standard error of the mean, *s* is the standard deviation, and *n* is the number of plots. The *SE* is a measure of how close a sample mean is to the population mean. While K_{eff} data tend to be more lognormally distributed, parametric statistics can give an indication of the level of site characterization achieved for a range of sample sizes (Table 2). For example, if three plot scale infiltration experiments were performed at each site, the standard error of the mean would be 25% of the mean at the Barren Fork Creek site, 73% of the mean at the Pumpkin Hollow site, and 53% of the mean at the Clear Creek site. The Pumpkin Hollow site would be the most difficult to characterize with a low number of plots due to the high level of heterogeneity present.

Table 2. Statistics for effective saturated hydraulic conductivity (K_{eff}) derived from plot scale infiltration experiments, including mean, standard deviation, and coefficient of variation, for each floodplain site. Hypothetical standard errors were calculated to evaluate the level of site characterization achieved for a range of sample sizes.

	Barren Fork Creek	Pumpkin Hollow	Clear Creek
n	6	4	5
Mean (cm hr^{-1})	9.5	24	2.2
Standard Deviation (cm hr^{-1})	4.0	30	2.1
Coefficient of Variation (cm hr^{-1})	0.4	1.3	0.9
n		Standard Error of the Mean (cm hr^{-1})	
1	4.0	30	2.1
2	2.9	21	1.5
3	2.3	17	1.2
4	2.0	15	1.0
5	1.8	13	0.9
6	1.6	12	0.8

Conclusion

Point scale estimates of K_{eff} were significantly lower than plot scale K_{eff}, and also failed to capture the variability of K_{eff} within a field site. The estimated permeability of the limiting layer reported by the U.S. Natural Resources Conservation Service (NRCS) Soil Survey was consistent with point scale estimates of K_{eff}, but was lower than plot scale K_{eff} at most sites. Plot scale infiltration tests are recommended over double ring infiltrometer tests or point scale estimates, although only small plots (1 m by 1 m) are necessary. Concurrent research is modeling infiltration and P leaching of these infiltration plots and will estimate long term P loads to the alluvial aquifers (Freiberger et al., 2013).

Acknowledgements

The authors gratefully acknowledge the support of the U.S. Geological Survey with a 104(g) grant. 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. David A. Correll, David T. Criswell, Devon Ketchum, Taber L. Midgley, Ronald B. Miller, Qualla J. Parman, Peter Q. Storm, Oklahoma State University, and Jason Corral and Chad Walker, University of Arkansas, are acknowledged for their assistance with field and laboratory research. Finally, Qualla J. Parman and Ryan P. Freiberger are acknowledged for their assistance with data analysis.

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