Coarse Fragments Affect Soil Properties in a Mantled-Karst Landscape of the Ozark Highlands

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Abstract: The Ozark Highlands region of the mid-southern United States is characterized in many areas by thin stony soils overlying highly fractured and dissolution-prone carbonate bedrock that are highly susceptible to groundwater contamination. The objective of this study was to evaluate the effect of coarse fragments on soil physical and hydraulic properties within a typical mantled-karst landscape in northwest Arkansas. In 2002, three representative soil series (i.e., Clarksville, Captina, and Razort) that vary taxonomically in coarse fragment content were selected for investigation. The alluvial Razort soil had the largest coarse fragment content, ranging between 15% in the top 10 cm and 80% in the 90- to 100-cm depth, which strongly affected the soil’s hydraulic properties. With increasing coarse fragment contents with depth (P < 0.05) in all three soils, total bulk density increased with depth to approximately 1,400 kg m⁻³, whereas the soil bulk density markedly decreased to less than 500 kg m⁻³ across all three soils in the 90- to 100-cm depth. Ponded infiltration measurements, which did not differ among the three soils, demonstrated that coarse fragments reduced the vertical one-dimensional volume available for water flow, increased the tortuosity, and reduced the hydraulic conductivity of the soil pore system. However, ponded intake measurements demonstrated that the soil surface properties of the alluvial soil generated greater two-dimensional water flow below the land surface once infiltration occurred. Transmissivity was roughly 35 times greater in the alluvial Razort compared with the residual Captina and Clarkville soils, resulting in greater estimated saturation hydraulic conductivity at the surface for the alluvial soil. The combination of results from this study shows that careful consideration of the coarse fragment content of the soil is necessary when managing land use in mantled-karst landscapes.

Key Words: Coarse fragments, soil hydraulic properties, infiltration, Ozark Highlands

The Ozark Highlands comprise a unique physiographic region that occupies approximately 2.1 million ha across south-central and southwestern Missouri through northwest and north-central Arkansas and into extreme eastern Oklahoma.

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The Ozark Highlands are represented by Major Land Resource Area 116A (USDA, NRCS, 2005), where the landscape consists of low dissected mountains with broadleaf forest vegetation (Brye et al., 2004). The soils are generally thin and shallow to bedrock, which consists of soluble carbonate rocks that have resulted in karst development (Brye et al., 2013). Land use in the Ozark Highlands is somewhat limited by the steep topography, thus, pasturelands and hardwood timber production are prevalent (Brye et al., 2013). However, the Ozark Highlands have also become an area with a large occurrence of confined animal feeding operations, namely, for poultry production.

The concentration and expansion of the poultry industry in the Ozark Highlands in recent decades have resulted in a marked intensification of agricultural land use (Slaton et al., 2004; Sharpley et al., 2007). The availability of poultry litter as a nutrient source for pasturelands has led to increased forage production and stocking rates of grazing livestock (Steele and McCallister, 1991; Sharpley et al., 2009). This concentration of animal agriculture and subsequent land application of poultry litter, which typically has a large phosphorus (P) concentration, have increased environmental concerns regarding nutrient loads in runoff and potential percolation to groundwater. Thin soils and fractures of dissolutionally enlarged openings in the Boone–St. Joe aquifers are major factors that make groundwater in the Ozark Highlands highly susceptible to contamination (Steele et al., 1990). Better understanding of surface soil-water relationships in the Ozark Highlands is needed to develop best management practices for surface applications of animal manure, particularly poultry litter (Gburek and Sharpley, 1998; Gburek et al., 2007). Furthermore, identifying and quantifying relationships among near-surface soil physical and hydraulic properties and processes in regions where surface applications of organic amendments are common (Khaleel et al., 1981; Lindsay and Logan, 1998) can help extend the understanding of the fate of water and solutes in the unique surface topography and underlying geologic combination present in the Ozark Highlands.

Easily measureable soil physical properties, such as particle size distribution, organic carbon (C), and bulk density, have been used to predict soil hydraulic properties and water retention as pedotransfer functions (Gupta and Larson, 1979; Arya and Paris, 1981; Cassel et al., 1983; Naney and Ahuja, 1985; Tietje and Tapkenhinrichs, 1993; Kravchenko and Zhang, 1998). However, one of the most dynamic processes of soil water movement, and one that is of particular concern in regions with mantled karst such as the Ozark Highlands, is infiltration and/or intake. Infiltration is generally considered the one-dimensional vertical movement of water into the soil at the surface, whereas intake is generally considered the two-dimensional vertical movement of water into the soil and laterally away from the land surface. Soil permeability during infiltration is mainly controlled by large-diameter soil pores in which the water is not greatly influenced by capillary forces. Therefore, water flow in any particular soil void is related to the size of that void and its geometry (i.e., connectivity with and conductivity of the soil pore system).
Once water is in the soil, preferential flow (i.e., macropore flow or bypass flow) may lead to rapid transport of water and the solutes or contaminants it contains from near the surface to deeper into the soil profile and ultimately to groundwater. Rapid movement of water within the soil is associated with large pores of undisturbed and/or well-structured soil, fractured rocks, water-repellent soils, and fine-over-coarse layered sandy soils. Pasture or forestland cover frequently dominate these situations, where vegetation and associated biological activity often generate additional preferential flow pathways (Kanchanasut and Scotter, 1982). Continuous macropores are developed by soil fauna, drying cracks and fissures, earthworm channels, small-mammal burrows, decayed root channels, or natural soil pipes caused by erosive actions of subsurface flows (Quisenberry and Phillips, 1976; Beven and Germann, 1982; Muyanskii et al., 1994; Scott, 2000).

Predicting preferential flow of water and/or solutes is difficult but can be greatly complicated in soils with large coarse fragment contents, which typifies a large proportion of the soils in the Ozark Highlands. Many of the soils within the Ozark Highlands were developed in place from weathering impure limestone and sandstone that contain as much as 70% chert, which is insoluble and thus large amounts of coarse fragments (Brye et al., 2013). These coarse fragments (i.e., >2 mm in diameter) are composed of silica that has geochemically replaced the limestone and thus are hard and angular. By natural erosion, the coarse chert fragments are transported downslope and accumulate at the base of uplands as colluvium; ultimately, they are water transported, slightly rounded, and deposited in floodplains as stony alluvium. Consequently, coarse fragments can affect infiltration and water storage and, thus, land use and site productivity. For example, the chert fragments in the Ozark Highlands have rendered the topsoil virtually unusable for cultivated row crops because the chert is harder than the steel in plows, thus managed grasslands and animal agriculture presently dominate the nonforested land use in the Ozark Highlands.

Coarse fragments influence water flow by affecting total soil porosity and the tortuosity of water flow paths. By increasing the impermeable coarse fragment content, the volume available for water flow decreases, the flow path tortuosity increases, and overall water movement can become restricted (Ravina and Magier, 1984; Brakensiek and Rawls, 1994). However, if sufficient fine material (i.e., <2 mm in diameter) is not present to plug macropores, then soil-water flow may not become restricted, but rather may increase. Furthermore, these general soil physical-hydraulic property relationships may not hold true in karst landscapes, such as in the Ozark Highlands.

The presence of rock fragments in soil layers, particularly at the surface, can also have a profound impact on hydraulic properties. Variation of surface soil hydraulic properties may influence the amount, distribution, and routing of overland flow. Consequently, the effects of coarse fragments on surface hydraulic properties may have a large influence on potential surface erosion in landscapes with steep topography. These coarse fragments can also influence potential groundwater contamination in areas with thin soils overlying fractured bedrock where the hydraulic connectivity between surface water and groundwater can be rapid. To complicate management, both characteristics are present in the Ozark Highlands. Sauer and Logsdon (2002) investigated the effects of coarse fragments on infiltration, hydraulic conductivity, and related soil physical properties in the Ozark Highlands region of northwest Arkansas and reported that Clarksville soils (i.e., Paleudults formed in residuum) had fewer coarse fragments and, thus, lower infiltration rates and hydraulic conductivities at saturation compared with Razort soils (i.e., Hapludalfs formed in alluvium). At saturation, hydraulic properties tended to vary directly with coarse fragment content, whereas below saturation, the inverse relationship was observed (Sauer and Logsdon, 2002). Therefore, it appears that the source of coarse fragments (i.e., residual or water transported) and nature of the contact with surrounding soil horizons can influence water flow by affecting hydraulic continuity at or near saturation at soil surfaces with large coarse fragment contents.

Considering the fact that highly fractured aquifers (Brahana, 2011) underlie Ozark Highland soils with highly variable coarse fragment contents, the potential for groundwater contamination is high. Groundwater recharge within karst terrains is associated with point or line source surface features, such as sinkholes, estuaries, losing streams, and variably in-filled dissolutionally enlarged joints or faults. Less effective, more diffuse, non-point source recharge occurs through the soil-regolith-epikarst system. Although flow through the soil in karstlands is generally considered slow, it provides continuous long-term recharge of groundwater to the base flow of springs and streams. Therefore, contamination of groundwater is highly related to characteristics of the soil system. As a result, land management practices can become a critical long-term source of non-point contamination if they have not been managed properly (Jarvie et al., 2014). In contrast to sinkholes and losing streams within the Ozark Highlands and elsewhere, water movement within soils over mantled-karst landscapes has not been extensively studied (Leh et al., 2008). Therefore, the objective of this study was to evaluate the effects of coarse fragment content on soil physical and hydraulic properties and infiltration into three soils representative of the mantled-karst landscape in the Ozark Highlands. It was hypothesized that coarse fragment content would have a large influence on select soil physical properties, namely, bulk density and porosity, throughout the top 1 m and that infiltration would be restricted in soils as the coarse fragment content increased.

**MATERIALS AND METHODS**

**Site Description**

This study was conducted at the Savoy Experimental Watershed (SEW) at the University of Arkansas, Division of Agriculture Systems’ Savoy Research Unit in Washington and Benton Counties, northwest Arkansas, approximately 20 km west of Fayetteville. The SEW is composed of six basins or subwatersheds, with a total area of 1,250 ha within the Springfield Plateau of the Ozark Highlands (Fig. 1). The surrounding landscape is characterized by steep ridges and valley topography of highly dissected plateaus. The Illinois River serves as the western boundary for a portion of the research unit and the SEW and as the major hydraulic drain from the site is one of the few continuously flowing streams in the area. The elevation ranges from approximately 310 m at the river to almost 400 m above sea level on the ridge tops.

The land encompassing the study area, in pasture at the time this study was conducted, was cleared from forestlands and cultivated in small private tracts until the 1930s when the tract came under control of the federal government and was subsequently converted to grazinglands. Since acquisition of the property by the University of Arkansas in 1952, most of the research unit has been grazed by beef cattle (Sauer et al., 1998). Currently, the SEW is a collaborative research site among the University of Arkansas, Arkansas Department of Environmental Quality, Agriculture Research Service, US Department of Agriculture, and US Geological Survey for the study of the effects of animal waste on water quality.
The dominant geological formations underlying the SEW are limestones of variable purity that have been uplifted with considerable fracturing and faulting. Considering that the underlying geologic impurities are dominated by chert, with as much as 70% by weight in the Boone Formation, the rock unit has significantly lower overall solubility than that of the other carbonate lithologies, such as the underlying St. Joe Formation (Brahana, 2011). The purity of the rock units controls the coarse fragment content in the overlying soil. Therefore, the coarse fragments present are made up almost exclusively (i.e., >98% by weight) of chert.

Soils within the SEW differ according to the depth of the underlying carbonate-rock formation (NRCS, 2013). Sauer et al. (1998) presented a conceptual cross section of SEW according to the elevation relevant to the Illinois River. The greatest thickness of the impure Boone Formation (i.e., ~45 m) is associated with the Nixa series (loamy-skeletal, siliceous, active, mesic Glossic Fragiudults) that is most frequently present at the highest elevations on the landscape (NRCS, 2013). The Nixa series is followed at successively lower elevations by Waben (loamy-skeletal, siliceous, active, mesic Ultic Hapludalfs), Pickwick (fine-silty, mixed, semiactive, thermic Typic Paleudults), Captina (fine-silty, siliceous, active, mesic Typic Fragiudults), and Clarksville (loamy-skeletal, siliceous, semiactive, mesic Typic Paleudults) series in the catena (NRCS, 2013). A gravelly phase of the Razort series (fine-loamy, mixed, active, mesic Mollic Hapludalfs), present on old terraces of the Illinois River, is underlined directly by high-permeability pure carbonate formations or old alluvium, depending on distance from the present river channel (NRCS, 2013). A cherty phase of the Razort series exists closer to the present river channel and is characterized by chert contents that typically reach 60% by volume at the surface. Although the immediate study area was limited in scope, the processes and controls identified herein are thought to have widespread applicability to mantled-karst areas in similar settings in the Ozark Highlands and elsewhere (Brahana et al., 1988).

The long-term average annual precipitation is 1,120 mm, with an average monthly minimum of 47 mm in January and maximum of 128 mm in May (NOAA, 2002). Winters are relatively short and mild, with brief periods of snow cover and frost with a mean January temperature of 1.1°C (NOAA, 2002). Summers are long, warm, and humid, with a mean July temperature of 25.9°C (NOAA, 2002).

FIG. 1. The Savoy Experimental Watershed (SEW) is located on the boundary between Benton and Washington Counties in the Ozark Highlands region of northwest Arkansas. Six basins or subwatersheds and numerous springs have been identified within the SEW and are labeled on the image. This study was conducted in Basin 1. The western boundary of Basin 1 is the Illinois River, which is continuously flowing, whereas all other streams indicated are ephemeral.
General Characteristics of the Selected Soils

In 2002, three soil series were selected for investigation within Basin 1 of the SEW (Fig. 1): Clarksville, Razort, and Captina. The Clarksville series, which represents approximately 49% of the basin area, consists of a well-drained, moderately permeable, silt mantle formed from limestone residuum (NRCS, 2013). The Razort series, representing approximately 10% of the basin area, consists of a well-drained, moderately permeable soil developed on the floodplain of the Illinois River in alluvium with a thin silt-loam–textured A horizon and variable coarse fragment content and lithology (NRCS, 2013). The Captina series, which represents approximately 2% of the basin area, consists of moderately well-drained slowly permeable soil that is nearly level to moderately sloping with a silty mantle underlain by colluvial residuum weathered from limestone and chert with a firm brittle fragipan beginning at approximately 50 cm (NRCS, 2013). According to soil taxonomy, the Captina series has the finest family particle size class and the Clarksville series has the coarsest family particle size class (NRCS, 2013).

Soil Sampling

Both core and disturbed soil samples were collected from each soil series using soil core and auger samplers, respectively. Sampling was conducted in 10-cm increments to a 1-m depth at three randomly selected locations within a 20-m radius in each soil series. Samples were oven dried at 105°C for 24 hours for total bulk density determination (Blake and Hartge, 1986), then crushed and sieved through a 2-mm mesh screen to determine the fractional mass of both soil and coarse fragments. Soil bulk density was calculated by subtracting the coarse fragment mass and volume assuming a particle density of 2,650 kg m\(^{-3}\). Particle size distributions were determined on the fine-earth fraction using a 12-h hydrometer method (Gee and Bauder, 1986). Total and fine-earth porosities were also calculated for all samples. Total C (TC; Nelson and Sommers, 1996) and nitrogen (TN; Bremner, 1996) concentrations were determined by high-temperature dry combustion using a LECO CN2000 analyzer (LECO Corp., St. Joseph, MI).

Water Infiltration

Replicated ponded infiltration and intake rates were measured on each soil using double- and single-ring infiltrometers, respectively (Bouwer, 1986). Double (30-cm outer-diameter ring, 15-cm inner-diameter ring, and 20 cm in height) and single-ring infiltrometers (30-cm-diameter ring and 20 cm in height) were carefully inserted approximately 1 cm on a leveled soil surface at three randomly selected representative locations within a 20-m radius in each soil series. Infiltration and intake rates were recorded until a steady-state flow rate was achieved, which took approximately 4 h.

Although this approach could technically be considered pseudoreplication, the alternative approach of conducting replicate measurements in multiple fields was an unavailable option. However, considering that soil hydraulic properties are known to be inherently variable even within short distances and at small spatial scales, it was considered reasonable to assume measurement independence with a 20-m radius. Similar assumptions have been made concerning near-surface soil properties in the Ozark Highlands region of northwest Arkansas (Brye and West, 2005; Brye, 2009).

Data Analyses

Assuming a completely random experimental design and independent replicates, analysis of variance was conducted to evaluate differences in coarse fragment content in the top 10 cm and final infiltration and intake rates among soil series using JMP 5.01 (SAS Institute Inc., Cary, NC). Analysis of covariance (ANCOVA) was performed to evaluate the relationship between coarse fragment content, total and soil bulk density, TC and TN concentration, and soil depth among soil series using JMP. In addition to the linear model used in the ANCOVA, a logistic model (Eq. (1)) was also fit using the nonlinear fit function within JMP to characterize the relationship between coarse fragment content and soil depth because the coarse fragment content cannot exceed 100%:

\[ dW/dz = kW(W - M) = W = M/(1 + ce^{-Wc}) \]  

where \( W \) represents the gravimetric coarse fragment content, \( z \) is soil depth, \( k \) is the growth rate factor, \( M \) is the maximum coarse fragment content, and \( c \) is a statistically determined constant. Therefore, \( W \) at \( z = 0 \) represents the intercept and is equal to \( M/(1 + c) \).

Linear regression was performed to evaluate the relationship between sand, silt, and clay and soil bulk density and coarse fragment content using JMP. Multiple regression was performed to evaluate the relationship between soil bulk density and soil series, soil depth, and total C concentration using JMP. The Kostiakov equation (Eq. (2)) was used to characterize the intake rate coefficients for the three soil series.

\[ I = \left( \alpha/(1 - \beta) \right)^{1/\beta} = dI/dt = \alpha^{-\beta} \]  

The Philip equation (Eq. (3); Philip, 1957) was fitted to the experimental data at each site using the nonlinear module within JMP.

\[ I = S'i + At + \beta i^{1/2} = dI/dt = i = (1/2)S'i' + A + (3/2)\beta i^{1/2} \]

RESULTS AND DISCUSSION

Coarse Fragment Content

The coarse fragment content varied among the three soil series according to expectations based on their taxonomic classifications. Visual observations during sampling indicated that both the content and size of the coarse fragments were usually small at the surface, typically gravels (i.e., 2–75 mm in diameter), and generally increased with depth in the profile. The Razort soil had nearly twice \((P < 0.05)\) the coarse fragment content (15%) in the top 10 cm compared with the Captina (7%) and Clarksville (9%) soils, which did not differ. The coarse fragment content increased linearly with depth in the profile \((P < 0.001; r^2 \geq 0.97)\) for all three soil series (Fig. 2). However, ANCOVA indicated that the slope of the line characterizing the relationship between coarse fragment content and soil depth for the Razort soil was greater \((P < 0.05)\) than that for the Captina and Clarksville soils, for which the slopes did not differ. Similar to the actual calculated mean value, ANCOVA also indicated that the Razort soil had 15% coarse fragments in the top 10 cm as indicated by the \( y \) intercept test \((P < 0.001)\), whereas the \( y \) intercepts for the Captina and Clarksville soils were both nonsignificant and did not differ from...
Soil Texture

Combined across soil series and soil depth, coarse fragment content was a significant predictor for silt and clay ($P < 0.001$; data not shown) but not for sand content ($P > 0.05$; data not shown). Silt content decreased linearly with increasing coarse fragment content, which indicates that, in the upper layers, the soil had been subjected to more weathering either from the Boone layer itself or by sediment load from higher positions in the landscape. In contrast, clay content increased logarithmically with increasing coarse fragment content, indicating that clay was translocated from the upper soil layers and accumulated at a maximum of approximately 24% at lower depths just above the Boone or St. Joe Formations to form the argillie horizon recognized on all three soil series.

Bulk Density

Similar to coarse fragment content, when averaged across soil series, total ($P = 0.03$; $r^2 = 0.46$) and soil ($P < 0.001$; $r^2 = 0.85$) bulk density varied linearly with depth (Fig. 2). Total bulk density increased with depth to a mean of 1,260 kg m$^{-3}$ across soil series between the depths of 40 and 60 cm, whereas soil bulk density decreased to a mean of 375 kg m$^{-3}$ across soil series in the 90- to 100-cm depth interval (Fig. 2). Soil bulk density data were slightly more variable with depth than that for coarse fragment content, whereas total bulk density data were substantially more variable with depth than that for soil bulk density (Fig. 2). The inverse relationship between soil bulk density and depth can only be explained by increasing coarse fragment content with depth (Fig. 2).

Combined across soil series and depth and similar to silt content, coarse fragment content was a significant predictor for both total ($P = 0.03$; $r^2 = 0.46$) and soil bulk density ($P < 0.001$; $r^2 = 0.87$). Total bulk density increased, whereas soil bulk density decreased linearly with increasing coarse fragment content. The contribution of coarse fragments to the total bulk density was less than 13% in the top 20 cm but increased with depth to more than 67% in the 90- to 100-cm depth interval. Based on this relationship and visual observations at the time of sampling, the fine-earth fraction appeared to fill a successively smaller proportion of macropores with depth, indicating that the macropores may not be sufficiently plugged with fine material to restrict vertical water movement. Consequently, subsoil macropores in the mantled-karst landscape of this study may be significant conduits.

![FIG. 2. Summary of the coarse fragment (CF) content and total and soil bulk density (BD) profile by depth for three soil series representative of a mantled-karst landscape in the Ozark Highlands. Horizontal bars associated with individual data points represent the standard error of the mean ($n = 3$). Regression lines characterizing the relationship between the measured soil property and depth are included separately among soil series or averaged across soil series depending on the results of statistical analyses.](image-url)
decreased sharply to an average of 9,020 mg kg$^{-1}$ in the top 10 cm did not differ among soil series and averaged 25,600 mg kg$^{-1}$ in the 20-cm depth interval, followed by a more gradual decrease to an average of 1,651 mg kg$^{-1}$ in the 90- to 100-cm depth interval.

The TC concentration subsequently decreased sharply to an average of 8,020 mg kg$^{-1}$ in the top 10 cm, but, as would be expected, were greatest near the surface and decreased exponentially with depth (Fig. 3). The TC concentration subsequently decreased sharply to an average of 8,020 mg kg$^{-1}$ in the top 10 cm, followed by a more gradual decrease to an average of 1,651 mg kg$^{-1}$ in the 90- to 100-cm depth interval, followed by a more gradual decrease to an average of 1,651 mg kg$^{-1}$ in the 90- to 100-cm depth interval.

Similar to TC concentrations, the TN concentration in the top 10 cm did not differ among soil series and averaged 2,395 mg kg$^{-1}$ (Fig. 3). The TN concentration subsequently decreased sharply to an average of 901 mg kg$^{-1}$ in the 10- to 20-cm depth interval, followed by a more gradual decrease to an average of 300 mg kg$^{-1}$ in the 90- to 100-cm depth interval. The presence of C and N at depth was likely caused by either organic matter movement in the solution phase within the soil-pore system and/or to decaying plant roots as directly observed during sampling.

Theoretically, as with organic matter, TC concentration is inversely related to soil bulk density. Soil bulk density was a function of soil series, soil depth, and total C concentration ($P < 0.001; r^2 = 0.86$). The effect of C appears to somewhat offset the effect of coarse fragments on bulk density. Based on significant regression coefficients, for each 1% increase in coarse fragment content, soil bulk density increased by 11.7 kg m$^{-3}$ regardless of soil series. In contrast, for each 1-mg kg$^{-1}$ increase in TC, soil bulk density decreased by 0.01 kg m$^{-3}$. The negative effect of the TC concentration was attributed to the lower density of the C-containing organic matter compared with inorganic material.

**TC and TN Contents**

Because of similar vegetation and land use among the three soils, TC and TN concentrations were unaffected by soil series but, as would be expected, were greatest near the surface and decreased exponentially with depth (Fig. 3). The TC concentration in the top 10 cm did not differ among soil series and averaged 25,600 mg kg$^{-1}$ (Fig. 3). The TC concentration subsequently decreased sharply to an average of 8,020 mg kg$^{-1}$ in the 10- to 20-cm depth interval, followed by a more gradual decrease to an average of 1,651 mg kg$^{-1}$ in the 90- to 100-cm depth interval.

Infiltration and Intake Rates

As expected, both infiltration and intake rates, measured using double- and single-ring infiltrometers, respectively, started high and exponentially decreased over time (Fig. 4). Assuming steady state was achieved, the final infiltration rate, as measured by the double-ring infiltrometer, between 210 and 240 min was 42, 66, and 72 mm h$^{-1}$ for the Razort, Clarksville, and Captina soils, respectively, but did not differ among soil series (Fig. 4). This result suggested that, with increasing coarse fragment contents at the surface, the volume of strictly vertically conductive material (i.e., for gravity flow into the soil) decreases, thus resulting in at least numerically lower steady state infiltration rates.

Intake rates, measured using a single-ring infiltrometer, represent two-dimensional water movement into and away from the soil surface. Theoretically, the intake rate should be greater than the infiltration rate, regardless of soil series, because of the extra matric (i.e., capillary) force exerted on the infiltrating water to pull the water away from the surface in addition to gravity. The magnitude of increase in the intake over the infiltration rate is an indication of lateral variability of the soil pore system. Assuming steady state was achieved, the final intake rate for the alluvial Razort soil (264 mm h$^{-1}$) was greater ($P = 0.04$) than that for the residual Captina (120 mm h$^{-1}$) and Clarksville (126 mm h$^{-1}$) soils, which did not differ (Fig. 4). The differences in final (i.e., steady-state) intake rates between the large-coarse-fragment-content alluvial soil and the smaller-coarse-fragment-content residual soils can be explained by the increase in lateral water movement away from the soil surface introduced by the coarse fragments. However, the final intake rate for the Razort
soil was six times greater and for Captina and Clarksville soils were roughly two times greater than their respective final infiltration rates. Therefore, an increase in coarse fragments at the surface results in greater tortuosity of the surface soil pore system, which coincides with that reported by Mehruys et al. (1975).

The use of mathematical models can provide further investigations and understanding of water infiltration into the highly weathered stony soils of the Ozark Highlands. The Kostiakov equation (Eq.(2)) is an empirical equation with two parameters with physical meaning. The empirical coefficient \( \alpha \) represents the initial infiltration rate and is a function of the soil surface texture and, in the case of this study, the coarse fragment content at the surface as well. The change in infiltration with time, which is related to soil structure, is considered to be represented by the empirical coefficient \( \beta \). The two residual soils at higher and similar elevations in the landscape, the Captina and Clarksville soils, behaved similarly according to the empirical \( \alpha \) and \( \beta \) coefficients of the Kostiakov model (Table 1). In contrast, the empirical coefficient \( \alpha \) for the alluvial floodplain Razort soil was nearly twice that of the Captina soil or Clarksville soil, with an intake rate of 301 mm h\(^{-1}\) at time \( t = 1 \) h as compared with 149 and 158 mm h\(^{-1}\) for the Captina and Clarksville soils, respectively (Table 1). The ratio of micropores to macropores (i.e., the soil structural factor) is the main controlling factor of the magnitude of the \( \beta \) coefficient. The \( \beta \) coefficient for the alluvial Razort soil was smaller than that for the residual Captina and Clarksville soils, which did not differ (Table 1). Because the Razort soil contained a greater coarse fragment content in the top 10 cm and the coarse fragment content increased with depth, the macropores created between the coarse fragments were highly conductive, particularly at saturation. The intake rate from the surface of Captina and Clarksville soils was greatly reduced during saturation because these soils had more micropores and fewer macropores compared with the Razort soil.

Some similarities and some differences to the results of fitting the Kostiakov model were observed for the fits of the Philip equation to the measured intake rates for the three soils.

In the Philip equation (Eq.(3)), the first term of the model, \( S \), represents the sorptivity, which is caused by the capillary water movement, whereas the second term, \( A \), represents steady state water movement caused by gravity or transmissivity. During the early stages of infiltration, sorptivity is the dominant parameter and a plot of the infiltration rate against the square root of time, rather than time, theoretically results in a straight line, where the slope of the resulting line is the sorptivity. As time progresses, the sorptivity term becomes negligible because the average hydraulic gradient across the wetting region is decreasing and the importance of gravitational flow (i.e., the \( A \) parameter) increases. The \( A \) parameter is not equal to the saturated hydraulic conductivity until all of the soil air is displaced and the hydraulic gradient is unity.

The ability of the three soils to absorb water (i.e., the sorptivity, \( S \)) was numerically similar for the Clarksville and Razort soils, with an average value of 200 mm h\(^{-0.5}\), whereas the average value for the Captina soil was 158.3 mm h\(^{-0.5}\) (Table 1). However, despite these apparent numeric differences, these sorptivities did not differ on account of large variability associated with this parameter, which was somewhat expected.

In contrast to the lack of difference in sorptivities among the three soils, the transmissivity of the Philip equation (i.e., \( A \) parameter) differed among the three soil series. The alluvial Razort soil had a transmissivity of 171.5 mm h\(^{-1}\), which was significantly greater than that for the Captina and Clarksville soils, which did not differ and averaged 5.2 mm h\(^{-1}\) (Table 1). These results suggested that macropores near the surface in the Razort soil were more transmissible for water than those in the Captina and Clarksville soils likely caused by larger non-fines-filled pores between coarse fragments in the Razort compared with the Captina and Clarksville soils.

Transmissivity in some cases represents the saturated hydraulic conductivity (\( K_s \)), but because a truncation error was introduced using the first three terms of the infinite series in the Philip equation Kutilek and Nielson (1994) suggested the use of Eq.(4) to overcome this error to approximate \( K_s \):

\[
K_s \approx \sqrt{\left(3 \times A_1 \times A_3\right) + A_2}
\]  

Use of Eq.(4) to predict the near-surface saturated hydraulic conductivity for the three soil series resulted in the Razort soil having the largest transmission rate of 252 mm h\(^{-1}\) compared with 204 and 203 mm h\(^{-1}\) for Captina and Clarksville soils, respectively.

The third parameter of the Philip equation (i.e., the \( \beta \) parameter) represents a porosity-related factor, in which soil porosity in the top 10 cm tended to be numerically greater for the Razort soil compared with Captina and Clarksville soils. However, similar to the sorptivities, the \( \beta \) parameter did not differ among the three soils (Table 1). Considering the Captina and Clarksville soils had similar sorptivities, transmissivities, saturated hydraulic conductivities, and \( \beta \) parameters, it was concluded that water intake into these two residual soils behaved similarly, whereas water intake into the alluvial Razort soil, with the greater near-surface coarse fragment content, behaved differently from those of the two residual soils.

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**TABLE 1. Summary of the Statistical Fits of the Kostiakov (Eq.(2)) and Philip (Eq.(3)) Models to the Intake Rate Over Time Data Generated With Single-Ring Infiltrometers**

<table>
<thead>
<tr>
<th>Model/Statistical Parameters</th>
<th>Soil Series</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Captina</td>
</tr>
<tr>
<td>Kostiakov model</td>
<td></td>
</tr>
<tr>
<td>Mean square error</td>
<td>389.7</td>
</tr>
<tr>
<td>Root mean square error</td>
<td>19.7</td>
</tr>
<tr>
<td>( \alpha ) coefficient</td>
<td>148.7</td>
</tr>
<tr>
<td>Upper 95% confidence limit</td>
<td>137.3</td>
</tr>
<tr>
<td>Lower 95% confidence limit</td>
<td>159.8</td>
</tr>
<tr>
<td>( \beta ) coefficient</td>
<td>0.22</td>
</tr>
<tr>
<td>Upper 95% confidence limit</td>
<td>0.14</td>
</tr>
<tr>
<td>Lower 95% confidence limit</td>
<td>0.28</td>
</tr>
<tr>
<td>Philip model</td>
<td></td>
</tr>
<tr>
<td>Mean square error</td>
<td>568.4</td>
</tr>
<tr>
<td>Root mean square error</td>
<td>23.8</td>
</tr>
<tr>
<td>( S ) coefficient</td>
<td>158.3</td>
</tr>
<tr>
<td>Upper 95% confidence limit</td>
<td>138.5</td>
</tr>
<tr>
<td>Lower 95% confidence limit</td>
<td>178.0</td>
</tr>
<tr>
<td>( A ) coefficient</td>
<td>6.4</td>
</tr>
<tr>
<td>Upper 95% confidence limit</td>
<td>−43.4</td>
</tr>
<tr>
<td>Lower 95% confidence limit</td>
<td>56.1</td>
</tr>
<tr>
<td>( \beta ) coefficient</td>
<td>27.4</td>
</tr>
<tr>
<td>Upper 95% confidence limit</td>
<td>5.6</td>
</tr>
<tr>
<td>Lower 95% confidence limit</td>
<td>49.3</td>
</tr>
</tbody>
</table>
Environmental Implications

The combined results of this study suggest that lower transmissivities near saturation plus lower steady-state intake rates likely contribute to greater runoff of water and potential solutes (i.e., dissolved and/or sediment-bound P from poultry litter applications) from the residual Captina and Clarksville soils at higher elevations and topographic positions in the mantled-karst landscape compared with the alluvial Razort soil at lower elevations and landscape positions (DeFauw, 2006; Leh et al., 2008). This scenario would lessen the potential for rapid transport of water and solutes from the surface directly to a relatively deep groundwater table or indirectly to the groundwater via cracks in the bedrock and/or in dissolutionally created flow paths in upper landscape positions. However, if water and solutes are not infiltrating as readily in the upper parts of the landscape, where residual soils with large coarse fragment contents at the surface dominate, and runoff occurs to lower landscape positions, where alluvial soils with large coarse fragments contents at the surface dominate, the potential is greatly increased for rapid transport from the surface to relatively shallower groundwater. Consequently, proper timing of soil amendments, particularly poultry litter, to pasture soils in the Ozark Highlands with regard to precipitation events could offset potential increased solute transport via runoff (Menjoulet et al., 2009). Therefore, at present, the amount of poultry litter additions to Ozark Highland pastures and managed grasslands are being regulated by plant uptake of P and the risk of loss in runoff as estimated by the P Index (DeLaune et al., 2004a, b; Sharpley et al., 2010).

SUMMARY AND CONCLUSIONS

Because of landscape variability, the soils of the Ozark Highlands differ in their thickness above carbonate bedrock units with differing amounts of chert inclusions. The residual Captina and Clarksville soils are underlain by 1 to 10 m of cherty limestone or, near the hydraulic drain, a pure carbonate bedrock. Captina and Clarksville soils are underlain by 1 to 10 m of cherty units with differing amounts of chert inclusions. The residual Highlands differ in their thickness above carbonate bedrock via cracks in the bedrock and/or in dissolutionally created transmissivities near saturation plus lower steady-state intake rate. For these reasons, the springs. In contrast, the alluvial Razort soil is underlined directly by highly permeable alluvial materials. For these reasons, the coarse fragment content within the profile varies among the three selected soil series. This study examined the principal effects of coarse fragments on soil-water interactions by investigating the behavior of water infiltration and redistribution within and between the soil matrix and potential susceptibility for groundwater pollution.

Coarse fragment content affected both total and soil porosity. Large voids between coarse fragments would suggest faster drainage and water movement at greater depths in the profile. However, ponded infiltration rates indicated that coarse fragments disrupted the continuity of the soil-pore system by providing a random distribution of large discontinuous voids between coarse fragments that had little direct contact with the soil fraction and were somewhat nonconductive. In contrast, ponded intake rates showed that the larger surface coarse fragment content in the alluvial soil was capable of inducing greater lateral flow of water away from the surface than in the residual soils.

According to both the empirical Kostiakov and the physically based Philip models, the residual Captina and Clarksville soils had similar surface physical and hydraulic properties and, therefore, had similar empirical coefficients, whereas the alluvial Razort soil behaved differently. Coarse fragments appear to increase vertical tortuosity in residual and alluvial soils but also appear to be able to increase the two-dimensional hydraulic conductivity of the soil-pore system in alluvial soils where there may be insufficient fines between coarse fragments to even minimally restrict water flow to the soil matrix. This combination requires careful consideration when managing land use in mantled-karst landscapes, such as in the Ozark Highlands, where the potential for groundwater contamination is high because of the presence of thin stony soils overlying fractured carbonate bedrock.

ACKNOWLEDGMENTS

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REFERENCES


