Use of a field method for determining hydraulic conductivity in soils in the Bogue Phalia Basin in the Mississippi River alluvial plain

Claire E. Rose and Richard H. Coupe
U.S. Geological Survey, Mississippi Water Science Center
cerose@usgs.gov

Interest in the determination of hydraulic conductivity for soils in the Mississippi River Alluvial Plain is spurred by the heavy use of agricultural chemicals on these highly productive soils and the potential for offsite movement of these chemicals. Ground-water models indicate that up to 5 percent of the precipitation recharges the shallow alluvial aquifer, indicating a potential pathway for movement of these chemicals into ground water. A field method designed to rapidly measure field-saturated hydraulic conductivity (K_{fs}) on soybean and cotton fields in the Bogue Phalia Basin was used to evaluate the potential for recharge through agricultural soils. This technique uses a portable falling-head, small-diameter, single-ring infiltrometer and an analytical formula for K_{fs} that compensates both for the falling head and for subsurface radial spreading. Measured K_{fs} values generally were higher than expected and vary more than four orders of magnitude from 1×10^{-2} to 5×10^{-6} cm/s. Hydraulic conductivity was shown to vary spatially within an agricultural field and temporally due to soil moisture conditions.

Keywords: Ground Water, Geomorphological Processes, Nonpoint Source Pollution

Introduction

The Mississippi River alluvial plain (MRAP), a 7,000-square-mile area in northwestern Mississippi commonly called the Delta, is underlain by the Mississippi River alluvial aquifer (hereafter referred to as the alluvial aquifer in this report). The alluvial aquifer has the most water withdrawn from it in the state for agricultural and industrial purposes. The hydrology of the alluvial aquifer has been defined extensively by Arthur (2001), Boswell and others (1968) and Snider and Sanford (1981).

Arthur (2001) used MODFLOW, a modular 3D finite-difference ground-water flow model, to study the flow system of the alluvial aquifer. Arthur reported that up to 5 percent of annual precipitation recharges the alluvial aquifer and found that the most important source of vertical recharge to the aquifer is precipitation. The percentage of annual precipitation recharging the aquifer has not been directly measured, and the estimate is seemingly incongruent with the surficial lithology of the Delta. The estimate is a residual of all other water budget component estimates. Developing a better understanding of the infiltration capacity of MRAP soils would help to improve existing concepts regarding precipitation infiltration. The water table of the alluvial aquifer has been declining over time. To get a complete understanding of what happens, it is important to find a more direct way to measure the inputs and outputs to better manage the system. Additional study is needed in the Delta to better understand the magnitude and distribution of recharge from rainfall.

This paper demonstrates a method and apparatus for rapidly measuring field-saturated hydraulic conductivity (Kfs) of soils and presents the results from 42 infiltration tests on unconsolidated soils overlying the Mississippi River alluvial aquifer in the Bogue Phalia Basin. This report is limited to data collected from July through December 2007, using the "bottomless bucket" infiltrometer (Figure 1). Forty-two infiltration tests were completed under a variety of conditions, at 5 field sites, under 2 crop types, and different agricultural management practices. The entire study area was within the boundary of the Bogue Phalia Basin in northwestern Mississippi (Figure 2).

Background and Description of Study Area

In the early 2000s, the U.S. Geological Survey National Water-Quality Assessment (NAWQA) Program began studies in seven agricultural basins within the United States to better understand how the transport and fate of water and agricultural chemicals is affected by natural factors and agricultural management practices. The

Bogue Phalia Basin in MRAP is part of this study, and was selected because of its unique natural features (Figure 2).

The MRAP is made up of rich floodplain soils and has an ample water supply. The average rainfall for Washington County is 52 inches annually, which makes for an ideal agricultural setting (Taylor and Thompson, 1971). Land use in the study area is dominated by agriculture (cotton, soybeans, and rice); agricultural chemicals are heavily used in the study area and have been detected in surface water and rainfall since the 1990s (Coupe, 2000; Coupe and Capel, 2005). A further description can be found in Coupe (2002).

Five agricultural fields were used in this study. Two of the fields (AR2 and C-28) are non-irrigated cotton fields, located only three-fourths of a mile apart in the northern part of the Bogue Phalia Basin. Observation wells are on both fields. In the middle of the basin are two field sites, named Pace and Pace (New): both are soybean fields, one being irrigated and one non-irrigated, respectively. Installed at the Pace site are air and rain samplers, along with a rain gage. The final site, in the southern part of the basin, is a non-irrigated soybean field on which wheat is grown in the winter. Due to the array of observation wells installed across the adjacent Bogue Phalia to determine a ground-water flow path, the field is called the Flow Path site (Figure 2).

Previous Soil Infiltration Studies

Smiles (1974), did experimental studies in infiltration by ponding water on a laterally-restricted swelling soil. Smiles found that cumulative infiltration is a function of time. Bagarello and others (2004) reported a simplified falling-head technique for rapidly determining the kfs. Reynolds and others (2002) described infiltrometer tests using single and double ring infiltrometers. The equation developed for this paper is based on equations from Bagarello and others (2004) and Reynolds and others (2002).

Data Collection and Analysis

During July through December 2007, 42 infiltrometer tests were completed on 5 agricultural fields in the Bogue Phalia Basin in the MRAP. The “bottomless bucket” infiltrometer tests are described in the following section. Volume of water added, the time the water was added, and the depth to water with respect to time were collected for each test. These measurements were used in an analytical formula described in the following section to obtain the kfs.

Soil samples were collected at each infiltrometer test location from the soil surface and at a depth of 2-3 inches for texture determination. Soil samples were placed into plastic jars and were shipped to the U.S. Geological Survey in Menlo Park, California, for particle size analysis using the optical diffraction method (Gee, 2002).

Methods

Kfs was measured using a procedure based on the methods described by Reynolds and others (2002). A portable, single-ring, small diameter infiltrometer and an analytical formula were used to derive Kfs. This method uses inexpensive and common equipment. The infiltrometer used in this study was a standard 5-gallon PVC bucket, from which the bottom was removed. The infiltrometer was 35 centimeters (cm) high, and had a non-uniform diameter which tapered from 29 cm at the top to 27 cm at the bottom of the ring.

Once a suitable location was selected for the test, the infiltrometer was inserted into the ground by applying even pressure around the top rim, and twisting slightly so that the insertion depth was uniform at 5 to 8 cm. Care was used to ensure that no foreign material was caught under the lip of the infiltrometer, as this could cause a preferential flow pathway. If there was a small gap on the inside between the soil and the infiltrometer, it was sealed with soil from nearby to minimize lateral leakage.

The average depth from the top of the rim to the ground surface inside the infiltrometer was recorded. A plastic mat was placed on the ground surface inside the infiltrometer to keep the surface soil intact when the water was added, then the mat was removed during measurement. The volume of water required for each test depended on the need for an initial ponding depth of 0.03 to 0.1 meter (m) and the antecedent soil moisture conditions. The initial volume used for all tests was 4 liters (L), but when infiltration rates were high, additional water was required to obtain multiple measurements over time. Thereafter, depending upon conditions, 4 or 7 L were used.

After the water was added to the infiltrometer, the plastic mat was removed and measurements of the depth of water, with respect to the top rim of the infiltrometer, were recorded, along with the time. The measurements were recorded as quickly as possible for several minutes shortly after the start of the test, and then the intervals between measurements were increased based on how quickly the water was infiltrating (Figure 1). Measurements continued until all the water infiltrated the soil, or for as long as was practical. If there was any leakage, the test was terminated and the ring was moved to a new location.

The Kfs values reported are limited in depth and surface area, as the "bottomless bucket" infiltrometer was inserted into the ground to a depth of only 5 to 8 centimeters, and the diameter of the infiltrometer was only approximately 28 centimeters.

Analytical Formula Theory

The data-collection procedure used in this study can be classified as a falling-head single-ring ponded infiltration test, similar to those described by Reynolds and others (2002). Although the infiltrometer had a non-uniform diameter, use of the average diameter of the initially filled portion causes negligible error for a given test because of the small diameter of the ring; a more significant concern is the departure from one-dimensionality of flow, which must be compensated for in the calculations.

In some cases, the infiltration flux density (i) is considered as a first approximation of Kfs. However, this neglects the other phenomena that are known to occur. In order to calculate Kfs more accurately, an algorithm which accounts for the following factors was necessary: (1) gravity as a driving force, (2) matric suction as a driving force, (3) radial spreading of infiltrated water, (4) inhibition of radial spreading by the ring wall inserted to a finite depth, (5) positive water pressure applied at the soil surface, and (6) decline of applied water pressure with time.

Reynolds and Elrick's (1990) formula for gravity- and suction-driven angularly symmetric radial spreading below a finite insertion depth during constant-head ponding most closely approximates this design and procedure:

$$K_{fs} = \frac{i}{\left[1 + \frac{\lambda + D}{C_1 d + C_2 b}\right]} \tag{1}$$

where K_{fs} is field-saturated hydraulic conductivity, i is infiltration flux density, λ is macroscopic capillary length (White and Sully, 1987), D is the depth of ponding, b is the ring radius, d is the depth that the ring penetrates into the soil, and C1 and C2 are empirically determined constants. Reynolds and Elrick (1990) found optimal values for C1 (0.993) and C2 (0.578) by using a Richard's equation-based numerical analysis of K vs. i and indicated that the values C1 and C2 are relatively insensitive to the calculation of Kfs. The value of λ was chosen from one of four broad soil categories based on texture and structure. Elrick et al. (1989) showed that the value of λ had little sensitivity to the calculations of Kfs.

Adapting the Reynolds and Elrick (1990) formula to a falling-head test, the infiltration rate equals the rate of change of pond depth:

$$K_{fs} = \frac{-\frac{dD}{dt}}{\frac{1}{L_G}\left[L_G + \lambda + D\right]} \tag{2}$$

where the ring-installation scaling length $L_G = C_1 d + C_2 b$ is defined for convenience. Rearranging, and integrating over time t_f, during which D falls from its initial value D_o to final value D_f,

$$\int_0^{t_f} K_{fs} dt = \int_{D_f}^{D_o} \frac{L_G}{\left[L_G + \lambda + D\right]} dD \tag{3}$$

Thus, the formula accounting for matric suction, lateral spreading, and falling head is

$$K_{fs} = \frac{L_G}{t_f} \ln\left(\frac{L_G + \lambda + D_o}{L_G + \lambda + D_f}\right) \tag{4}$$

This formula can be applied whether or not the test is continued until no water remains in the ring, as long as both D_0 and D_f have been measured. If the falling head is allowed to fall to 0, the formula simplifies to

$$K_{fs} = \frac{L_G}{t_f} \ln\left(1 + \frac{D_o}{L_G + \lambda}\right) \tag{5}$$

Results and Discussion

Kfs measurements from the 42 infiltrometer tests vary over more than four orders of magnitude, from 1.6x10-1 to 9.27x10-6 centimeters per second (cm/s). The infiltrometer tests yield substantially variable values of Kfs. The Kfs varies over time, Agricultural Management Practices (AMPs), antecedent soil moisture conditions, and Kfs also varies spatially due to soil heterogeneity. Figure 3 illustrates spatial and temporal variation in Kfs, as well as variation due to crop type, and each bar represents the Kfs value for one individual "bottomless bucket" infiltrometer test. The tests completed on agricultural sites AR2, C-28, and Flow Path were all done in July 2007. The tests completed on field sites Pace and Pace (New) were completed over a period of several months, illustrating the temporal variation of infiltration capacity (Figure 3).

Figure 4 shows the averages of the infiltrometer test values for each field site and illustrates how the differences in agricultural management practices can affect the infiltration capacity. For example, Pace and Pace (New) sites are within 1 mile of each other and are both soybean fields; however, Pace is irrigated and Pace (New) is not. Infiltrometer tests were done during the same seasons, yet the average kfs for the tests run at Pace (New) is higher (1.87x10-2 cm/s) than the average of Kfs for the tests run at Pace (4.73x10-4cm/s). The Pace (New) site probably developed more substantial macropores than Pace due to the development of shrinkage cracks without irrigation to keep the soil moist.

Table 1 lists the temporally averaged Kfs values, weather conditions, and agricultural management practices at the Pace and Pace (New) sites. The average Kfs determined from tests conducted on the Pace field in July, while soybeans were still growing, was 6.82x10-4 cm/s (Table 1). However, 2 months later in September, the average Kfs was greater, at 1.53x10-4 cm/s. It is probable that this difference is due to the antecedent soil moisture conditions, as September was dryer than July 2007. After October harvest, disking, and precipitation, the average infiltration capacity was lower, 6.40x10-5cm/s. This likely is due to the rehydration of the soil which promotes the sealing of existing cracks (Table 1).

Multiple tests were conducted on the Pace (New) field on four separate occassions: early September, mid-September, early October, and mid-December. The Kfs values were averaged by date. The early September tests were conducted soon after harvest and disking. Because lateral flow throughout the disked layer is probable, the average Kfs was higher than at any other time (4.27x10-2 cm/s). This higher Kfs may also be attributed, in part, to the presence of larger or more numerous macropores under the disked layer compared to those at the Pace site due to lack of irrigation, which would limit swelling potential. In mid-September, when surface soil cracks were 1.27 cm deep, the average infiltration capacity (for all tests run on this date) was 5.59x10-3 cm/s, lower than in early September 2007. This change of Kfs likely is caused by the settling of surface soil after disking. In early October, the average Kfs was 5.41x10-3cm/s, which is within the same order of magnitude as the mid-September average Kfs. In mid-December, the average Kfs of the field was lower than in mid-September, at 5.36x10-4 cm/s, although the soil had 0.31 cm cracks at the surface, this is a result of the wet conditions of the winter season (Table 1).

The range, median, mode, and average Kfs for each agricultural field site are found in table 2. The field site with the highest average, median, and mode of Kfs in cm/s is the non-irrigated Pace (New) soybean field. Temporal variability is evident in the data collected over a 3-month period at Pace (New) (Table 2).

The soil samples collected at each infiltrometer test location were analyzed for particle size distribution; one sample was taken from the soil's surface, and one from 2-3 inch deep. The averaged USDA particle size classes (Soil Survey Staff, 1975) as determined by the optical diffraction method are listed in table 3. Averages for all five field sites are representative of a silt loam textural type (Soil Survey Staff, 1975), or a soil in which nearly 80 percent of the particles are silt sized (Table 3).

Conclusion

It is clear that equation (5) considers the factors that affect the Kfs for this unique infiltrometer method. Kfs values derived from this method and equation vary spatially and temporally. Consequently, there is potential for a substantial amount of infiltration to take place under certain conditions and in certain areas. This method is ideal for creating a rapid and far-reaching assessment of the in situ infiltration capacity of a site, with ease and with minimal monetary commitment.

The data collected in this study have provided a better understanding of the vadose zone processes occurring within soils common to the Mississippi Delta, and give direct measurements related to the infiltration of precipitation into the surface soil. The question of what happens to the precipitation that does infiltrate still cannot be answered, as the "bottomless bucket" infiltrometer tests are limited to the surface of the soil to a depth of about 2-3 inches. This adds knowledge to other studies of vadose zone processes.

Future Studies

There are several possibilities to investigate the fate of infiltrated water; (1) it could potentially flow laterally to ditches and end up as surface water, (2) it could be taken up by evapotranspiration, (3) it could take up a long-term residence in the vadose zone, or (4) it could eventually recharge the alluvial aquifer.

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Figure 1. Diagram of infiltrometer.

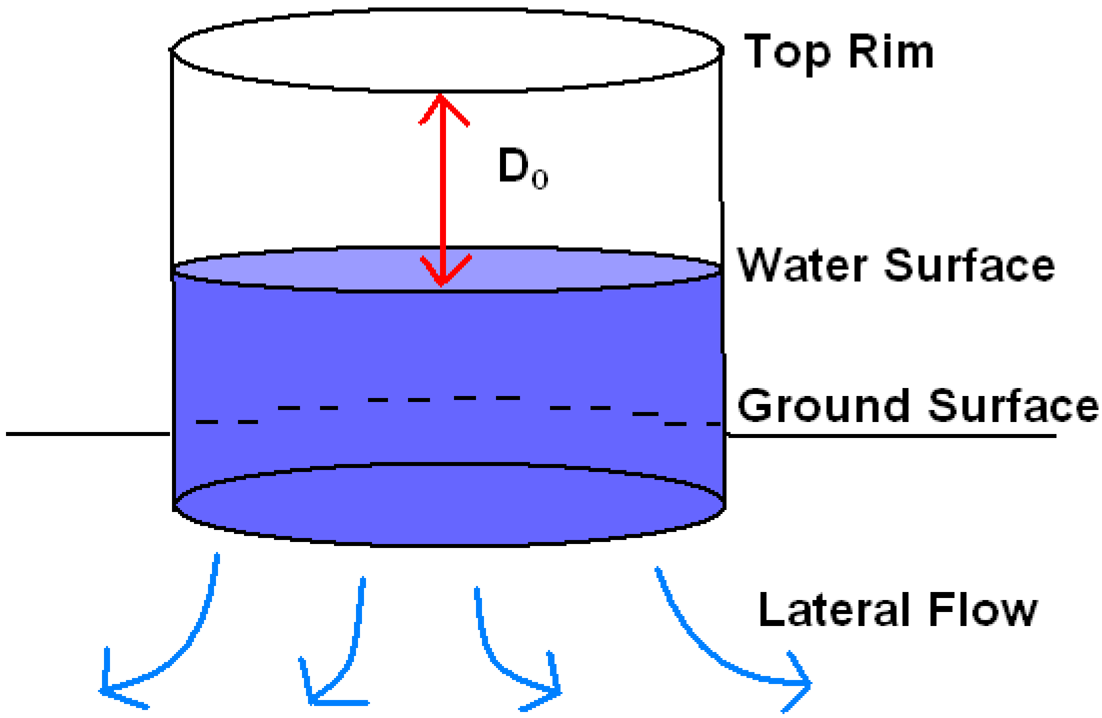

Figure 2. Study area and agricultural field locations.

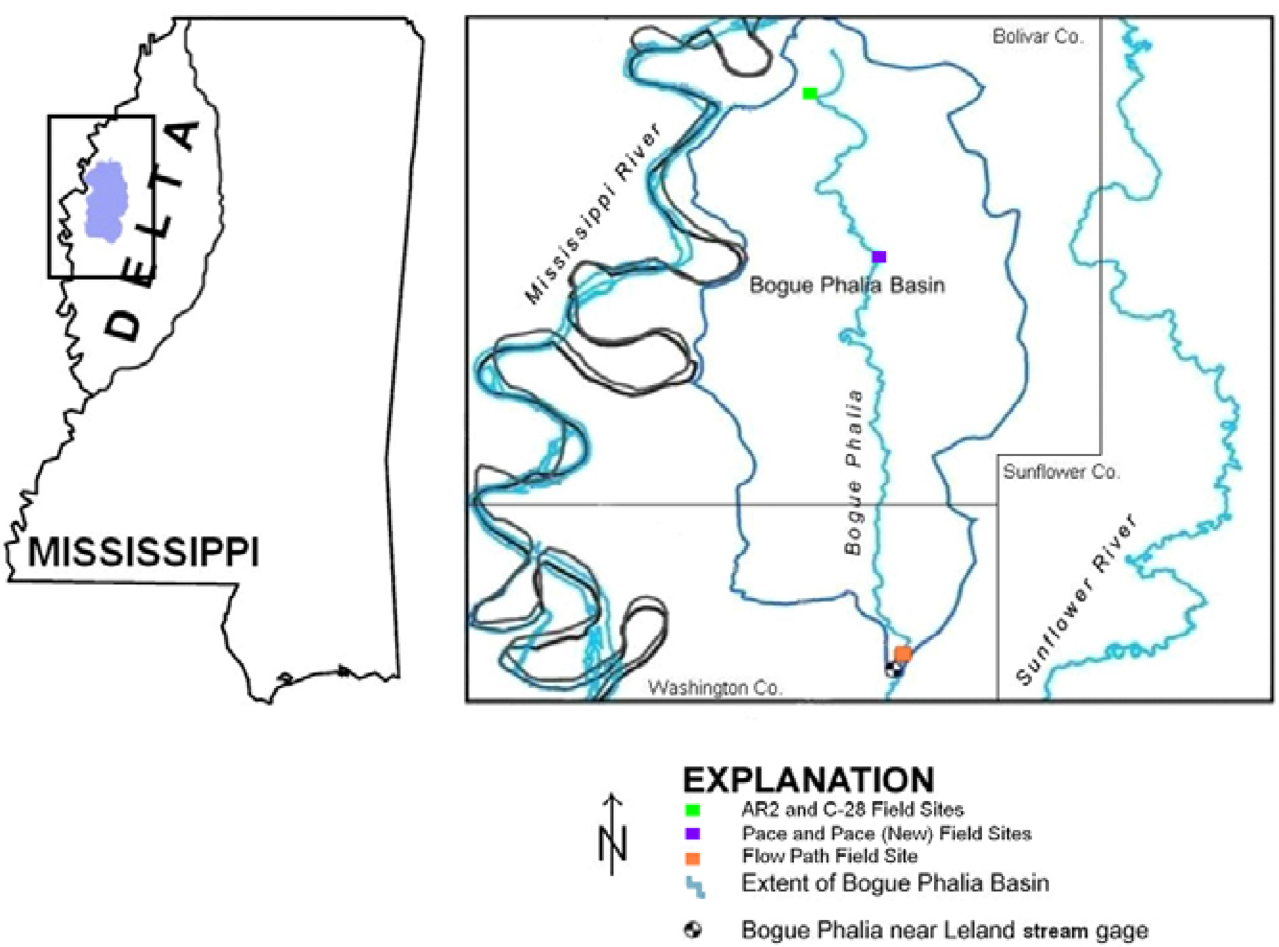

Figure 3. Kfs data for each infiltrometer test.

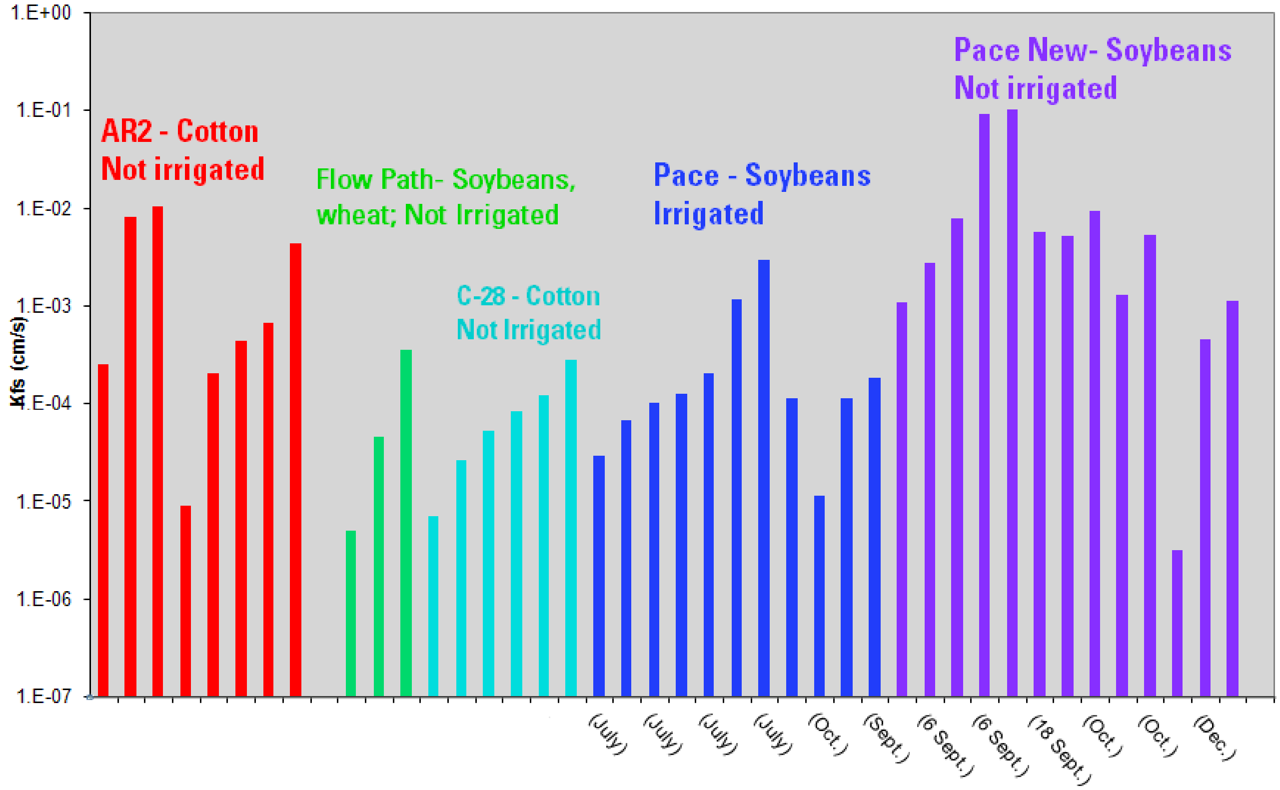

Figure 4. Average Kfs data for each agricultural field.