Monitoring the Dynamics of Field-Saturated Soil Hydraulic Conductivity in a Wastewater Irrigated Cropland

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Abstract: The maintenance of adequate hydraulic conductivity is a basic priority for the function and sustainability of long-term wastewater irrigated lands. An effective procedure to measure in situ hydraulic conductivity quickly, easily, and reliably is still elusive. This study aims to compare the performance of DualHead Infiltrometers, a novel instrument designed to measure field-saturated hydraulic conductivity ($K_{fs}$) quickly and in an automated fashion, with different parameters and old infiltrometer designs; and to investigate the dynamics of $K_{fs}$ in a cropland that has been spray-irrigated with treated wastewater for fifty years. Our results showed that a modified procedure with a longer, single pressure cycle yielded results with lower coefficients of variation (CVs) for both pressures and infiltration rates, and performed better than the original procedure with two short pressure recycles. $K_{fs}$ values measured by DualHead Infiltrometers were similar to those measured by double-ring infiltrometers in most conditions. Viscosity-corrected $K_{fs}$ on irrigated croplands was $123.8\pm94.0$ mm h$^{-1}$, insignificantly higher than that on the non-irrigated croplands, $103.2\pm94.6$ mm h$^{-1}$. We observed...
seasonal variations in $K_f$ values between winter and summer conditions, but infiltration rates during all seasons remained much higher than the spray irrigation rate (4.25 mm h$^{-1}$). Nevertheless, with CVs greater than 67%, caution must be exercised to ensure that hydraulic conductivity remains high enough to prevent runoff at all times, especially during winter frozen conditions.

**Keywords:** infiltration rates; field saturated hydraulic conductivity; soil moisture; temperature; wastewater irrigation; DualHead Infiltrometer

1. Introduction

Soil hydraulic conductivity is a metric that represents how easily water can move through soil. Understanding the dynamics of soil hydraulic conductivity over time, and its variation across a land surface, is an important step toward addressing many pedologic, hydrologic, and eco-environmental issues. These issues often require a fine understanding of soil water distribution and the partitioning of precipitation into infiltration and runoff (Nimmo et al. 2009).

Many soil physical, chemical, and biological factors have impacts on hydraulic conductivity, which can cause dramatic spatiotemporal dynamics (Rawls *et al.*, 2004; Tejedor *et al.*, 2013). Porosity and pore size distribution are the major determining factors of hydraulic conductivity (Kumar, 2015), with higher infiltration rates in soils with greater macroporosity (Lin *et al.*, 1998). High temperatures can increase infiltration rates, due to its effects on the viscosity and surface tension of infiltrating water (Briggs, 1897; Hopmans and Dane, 1986; Kumar, 2015), while antecedent soil moisture has an inverse relationship with
hydraulic conductivities, especially at sites with fine structure (Turner and Sumner, 1978; Ruggenthaler et al., 2016). Vegetation and land use can alter soil characteristic, such as aggregation, organic matter abundance, compaction, tillage, and pore size distributions, all of which impact hydraulic conductivity (Kumar, 2015; Wu et al., 2016). For example, vegetation canopies and leaf litter can protect the soil surface from the impact of raindrops and prevent the formation of crusts which could reduce infiltration capacity, while root systems can create new macropores and improve soil porosity and infiltration capacity through bioturbation (Thompson et al., 2010; Wu et al., 2017). Since all of these relevant factors have temporal and spatial heterogeneity, hydraulic conductivity is also dynamic across time and space. One common observation is that hydraulic conductivity is higher in the dry season than in the wet season (Cerdà, 1997; Hardie et al., 2012) and higher in summer than in winter (Emerson and Traver, 2008; Cerdà et al., 2016). Soil infiltration at high latitudes or elevations may be affected by frequent freeze-thaw cycles (Fouli et al., 2013), while in winter, the ice-rich layer could impede infiltration (Iwata et al., 2011).

Wastewater irrigation is a cost-effective and sustainable wastewater management solution (Bdour et al., 2009). One basic priority of long-term wastewater irrigation operations is to maintain an adequate hydraulic conductivity, because it has various impacts on soil physical, chemical, and biological properties, which vary with soil type, water quality, and overall management (Coppola et al., 2003; Hati et al., 2007). While some researchers have identified benefits of applying treated wastewater irrigation on soil properties, such as reductions in bulk density, greater aggregate stability, and increases in organic
matter content (Hati et al., 2007; Vogeler, 2009), other studies have found no such improvements, or even observed negative effects (Sparling et al., 1999; Menneer et al., 2001; Wang et al., 2003; Bhardwaj et al., 2007). In terms of hydraulic conductivity, both positive and negative influences have been reported. Hati et al. (2007) and Vogeler (2009) reported increases in hydraulic conductivity after treated wastewater applications, while Wang et al. (2003), Coppola et al. (2004), and Gharibeh et al. (2007) found that hydraulic conductivity declined with effluent application. Increases in total porosity, more aggregation, and lower bulk density could increase hydraulic conductivity, whereas increases in retention parameters and bulk density, and pore occlusion by migrated clayey material, could decrease hydraulic conductivity (Gharibeh et al., 2007; Hati et al., 2007; Vogeler, 2009; Lado and Benhur, 2010). The balance of effects like these will determine the net change in hydraulic conductivity, which is likely to be highly dependent on location and management practices.

Many methods and infiltrometer designs have been used to measure hydraulic conductivity field measurements (Angulo-Jaramillo et al., 2000; Reynolds et al., 2002; Latorre et al., 2015). To alleviate some of the difficulty of collecting such data, DualHead Infiltrometers (Decagon Devices, 2015) were developed based on falling-head measurements (Nimmo et al., 2009). This novel, highly automated tool has been used successfully by other researchers (e.g., Ravi et al., 2017). Previous researchers typically applied the instrument using the settings recommended in the instructions (Demirtas, 2017; Gonzales et al., 2018), but, as a new device, its performance, measurement procedures, and parameterization have not been tested under all conditions.
The Pennsylvania State University has used a spray irrigation system called the “Living Filter” for tertiary wastewater treatment since 1962. Currently, an annual average of 974 mm of effluent is sprayed, with irrigation continuing during the winter. Final tertiary treatment of the wastewater occurs as it penetrates through the soil and replenishes the groundwater. This wastewater irrigation dramatically decreased the nutrient load in local streams and provides the region with a sustainable buffer against drought. However, the Pennsylvania Department of Environmental Protection requires that no overland flow can leave the premises, so the infiltration capacity of the Living Filter must be monitored to ensure that it will always exceeds the effluent application rate.

The objectives of this study are to 1) compare the performance of DualHead Infiltrometers using original and modified parameters; 2) compare the results from DualHead Infiltrometers with measurements from classic double-ring infiltrometers; 3) investigate the dynamics of hydraulic conductivity across seasons, especially during winter conditions, when cold and wet weather could have great impacts on infiltration; and 4) determine if, and to what extent, the long-term irrigation of wastewater has influenced hydraulic conductivity and the sustainability of the Living Filter.

2. Materials and Methods

2.1 Study sites

The study areas are located in the Pennsylvania State University’s Living Filter (Figure 1), at an elevation of about 335 m. The climate is a composite of the relatively dry midwestern continental climate and the more humid conditions
found near the eastern seaboard. Minimum temperatures generally remain below freezing from mid-November through March, with mean monthly temperatures peaking in July (22.2 °C) and bottoming out in January (−2.8 °C). Mean annual precipitation is 932.4 mm; May is the wettest month (101.6 mm) and January is the driest (59.4 mm). The Living Filter is situated on a thick (up to 100 m) residual limestone-derived Hagerstown silt loam soil. It is well-drained with a moderate permeability (Walker and Lin, 2008). The regional water table is roughly 60 meters below the surface (Ferguson, 1983).

The Living Filter irrigation system is configured on a 24.4 m × 36.6 m grid. Any given location may be spray-irrigated with a maximum of 4.25 mm of effluent per hour over a 12-h period once per week, with irrigation continuing throughout year (Dadio, 1998). Chemical properties of the treated wastewater are shown in Table 1. The cropped land is planted periodically with corn (Zea mays L.) and wheat (Triticum aestivum L.) without tillage. Three sites in the agricultural field of the Astronomy Site at the Living Filter were used to measure hydraulic conductivity across space and time (Figure 1). The control site, K2, was located on the northwest margin of the cultivated land but outside the range of the irrigation. The other two sites, K3 and K4, were located within the irrigated and cultivated field. The distance between neighboring sites was approximately 100 m.
2.2 Field-saturated hydraulic conductivity measurements by DualHead Infiltrometer

2.2.1 Field measurements

Field-saturated hydraulic conductivity ($K_{fs}$) was measured intermittently from February 2016 until June 2017 using DualHead Infiltrometers (Decagon Devices, USA). Prior to measurement, ground surface conditions were recorded and antecedent soil volumetric water content (VWC) was measured at 10 cm depth using ECH2O 5TE sensors (Meter Group, USA). Surface soil temperature and air temperature were measured and recorded at regular intervals throughout the measurements. The exact locations of the infiltrations varied weekly to avoid soil disturbance, but all infiltrations at each site were conducted within a 10 m² area on the flattest topography available. Any leaves, large vegetative litter, or snow was carefully removed during preparation of the site.

The DualHead Infiltrometer measures $K_{fs}$ using two pressure heads, which are controlled by air pressure rather than ponding depth. The 5-cm deep, 7.5-cm radius insertion ring was gently hammered into the soil to ensure good contact with the soil and minimal disturbance, and was then checked to ensure that it was level in all orthogonal directions. A thermometer was secured inside the ring before the infiltrometer head was clamped into place, so that the water temperature could be read through the glass.

The original measurement parameters and program were compared with modified settings during the winter of 2016. Subsequent tests used only the modified parameters. The original procedure suggested by Decagon Devices (2015) for wet, loamy sand included a 15-minute soaking and two cycles with 15-
minute holding times at the high and low pressure heads. To ensure that the infiltration had time to reach a steady state, the modified procedure replaced the two short cycles with a single 35-minute long cycle at each pressure head (Table 2). The DualHead Infiltrometer recorded the water depth, pressure head, and water flux per minute (Figure 2). During testing, the infiltrometer head was checked periodically to ensure that the seal was intact. If signs of leakage or near-surface lateral flow were observed (for example, due to topography or frozen soil), the test was canceled and reset in a new position.

2.2.2 Quality control

All data collected by the DualHead Infiltrometers were examined carefully to ensure quality. The coefficients of variation (CVs) of the pressure head and water level were calculated. If either CV exceeded 0.1, the measurement was considered not to have reached steady state, probably due to a bad seal, and the measurement was rejected. The CVs of infiltration rates at high and low pressure heads were also calculated. If the CV of the infiltration rate at either pressure head was larger than 0.5, it was also deemed non-steady-state and the measurement was disqualified. Only measurements that passed these checks were used in further analysis.

2.2.3 Calculation of $K_{fs}$

The $K_{fs}$ of a soil can be computed as (Nimmo et al., 2009)

$$K_{fs} = \frac{i}{F},$$

where $i$ is the steady-state infiltration rate (mm h$^{-1}$) and $F$ is a function that
corrects for soil sorptivity and the geometric effects of the infiltrometer. $F$ can be calculated following the method of Reynolds and Elrick (1990):

$$F = 1 + \frac{\lambda + D}{C_1d + C_2b} = 1 + \frac{\lambda + D}{\Delta}, \quad (2)$$

where $D$ is the ponding depth (mm), $d$ is the insertion depth of the infiltrometer (cm), $b$ is the infiltrometer radius (mm), $\Delta$ is $C_1d + C_2b$ (mm), $C_1$ is 0.993, $C_2$ is 0.578, and $\lambda$ is the macroscopic capillary length of the soil (mm). Since $K_{fs}$ should be identical for both ponding depths (pressure heads),

$$K_{fs} = \frac{i\Delta}{\Delta + \lambda + D_1} = \frac{i\Delta}{\Delta + \lambda + D_2}, \quad (3)$$

the value of $K_{fs}$ can be solved as

$$K_{fs} = \frac{\Delta(i_1 - i_2)}{D_1 - D_2}, \quad (4)$$

where $\Delta$ is a constant for a given infiltrometer geometry. For the DualHead Infiltrometer, $d = 50$ mm and $b = 75$ mm, so $\Delta = 93$ mm. As recommended by Decagon Devices (2015), only the data from the last cycle was used in $K_{fs}$ calculation and the first two minutes of raw data after the pressure head was changed were not used for calculating $K_{fs}$ from the original procedure. To ensure comparability, a similar subset of pressure and infiltration records at each pressure head were used to calculate the $K_{fs}$ for the modified measurements, even though the cycles were longer.

2.2.4 Viscosity correction of $K_{fs}$

All $K_{fs}$ values were viscosity-corrected to a standard temperature (25 °C) before comparing among different sites to avoid the influences of water effluent viscosity changes caused by temperature variation. $K_{fs}$ may be split into two factors (Hillel, 1998),
where \( k \) is the intrinsic permeability of soil (m\(^2\)) and \( f \) is the fluidity of water (m\(^{-2}\) s\(^{-1}\)). \( f \) is inversely proportional to viscosity, and is given by

\[
f = \frac{\rho_w g}{\eta} = \frac{g}{\eta'},
\]

where \( \rho_w \) is the density of the water (kg m\(^{-3}\)), \( g \) is gravitational acceleration (m s\(^{-2}\)), \( \eta \) is the dynamic water viscosity (Pa s), and \( \eta' \) is the water’s kinematic viscosity (m\(^2\) s\(^{-1}\)). The corrected \( K_{fs} \) could be calculated as

\[
K_{fs_{\text{STD}}} = K_{fs_{\text{OB}}} \frac{\eta'_{\text{OB}}}{\eta'_{\text{STD}}},
\]

where \( K_{fs_{\text{OB}}} \) is an observed \( K_{fs} \) value and \( K_{fs_{\text{STD}}} \) is the \( K_{fs} \) value corrected to the standard temperature (25 °C). The \( \eta'_{\text{OB}} \) and \( \eta'_{\text{STD}} \) parameters are the kinematic viscosity at the temperature when \( K_{fs_{\text{OB}}} \) was measured and at 25 °C, respectively, and each can be calculated as (Clancy and Alba, 2011)

\[
\eta' = 1.98404 \times 10^{-6} \cdot e^{\frac{1825.85}{273 + T}},
\]

where \( \eta' \) is the kinematic viscosity (m\(^2\) s\(^{-1}\)) at temperature \( T \) (°C).

### 2.3 Measurement of \( K_{fs} \) by double-ring infiltrometer

The double-ring infiltrometer devices used for this study have an inner ring radius of 3.02 cm and an outer ring radius of 5.40 cm. Each measurement was conducted for 85 min, to match the DualHead Infiltrometer tests. The device was carefully pushed into the surface soil to minimize disturbance. After a soaking period, the water was poured manually into the device and then the change of the water level was recorded every minute. The \( K_{fs} \) values were calculated from double-ring infiltrometer data according to Philip’s infiltration equation (Philip,
where \( i(t) \) is the cumulative infiltration at time \( t \), \( S \) is the sorptivity of the soil, and \( A \) is a hydraulic conductivity parameter. Subsequent researchers (e.g., Youngs, 1968; Brutsaert, 1976) suggested that the value of \( A \) is between \( 2/3 K_{fs} \) and \( 1/3 K_{fs} \), but usually closer to \( 1/3 K_{fs} \). For our study, the \( K_{fs} \) measured by the double-ring infiltrometer was calculated as three times \( A \).

### 2.4 Statistical analysis

Independent samples \( t \)-tests were used to compare the data measured at different sites and times using log-transformed data with \( \alpha \) set to 0.05. This analysis was completed using SPSS 17.0 (SPSS Inc., 2008).

### 3. Results and Discussion

#### 3.1 The influence of hold time

Different measurement parameters and programs used by the DualHead Infiltrometers resulted in different infiltration processes (Figure 3). Our results showed that the pressure head was not steady during the high-head cycles, even during the second cycle (Figure 2a), and the CV of the high pressure head was significantly higher for the original procedure than for the modified procedure (Table 2). Increasing the pressure led to higher infiltration rates, which resulted in higher CVs and less stable infiltration rates using the original procedure than the modified approach (Table 2). This might be because that the high pressure head was controlled by air pressure, rather than water level (Decagon Devices,
2015), which depends on complete air tightness of the infiltrometer head and the entire installation. By contrast, the pressure and infiltration rates during the low pressure head periods of the two programs were not significantly different (Table 2). This pressure was set equal to the nominal ponding depth, so it was achieved primarily with actual water-level head, rather than air pressure.

The duration of the original procedure afforded 15 measurements, but the first two records of pressure head and infiltration rate at each pressure head were not used in $K_{fs}$ calculation, as recommended. However, the third and fourth records were also often unsteady and were sometimes lower or higher than the subsequent 11 records in the low-to-high or high-to-low pressure head transitions, respectively (Figure 3). What is more, infiltration rates might fluctuate in response to changes in the physical conditions of the soil, such as the release of trapped air bubbles or the breakthrough of water into a connected macropore system (Figure 5b and c). These processes could distort the data for several minutes at a time, making steady-state infiltration rates difficult to determine in the short time window available. Such time-steps were excluded from $K_{fs}$ calculations, sometimes reducing a test to fewer than 10 available records for $K_{fs}$ calculation and decreasing the reliability of the measurement.

We found that the modified procedure, based on a single long cycle, yielded better results at our site than two short cycles. A long cycle generally reached a steadier pressure head and infiltration rate, and it provided more of a buffer against fluctuations caused by temporary changes in soil conditions. Our recommendations for field application of DualHead Infiltrometers would be a 15-minute soak time followed by 35 minutes held at a high pressure head and then
35 minutes held at a low pressure head. The infiltration rates measured during the final 15 to 20 minutes of the hold time at each pressure head were generally usable for the $K_{fs}$ calculation.

### 3.2 Comparison of $K_{fs}$ measured by DualHead Infiltrometer and double-ring infiltrometer

Field-saturated hydraulic conductivities measured by DualHead Infiltrometers ($K_{fs\_DH}$) and by double-ring infiltrometers ($K_{fs\_DR}$) on the same days are shown in Figure 4. Nine of the $K_{fs}$ results were similar between the two methods, but five of the $K_{fs\_DH}$ results were much higher than $K_{fs\_DR}$ (Figure 4). The regression line of all measurements had a slope of 1.15 mm h$^{-1}$ and an intercept of 13.45 mm h$^{-1}$, showing that, on the whole, the DualHead Infiltrometers measured higher $K_{fs}$ values than did the double-ring infiltrometers.

This difference may be caused by the larger footprint of the DualHead Infiltrometer. Kumar (2015) also found that infiltration rates were lower when using smaller double-ring infiltrometers. Lai and Ren (2007) observed that smaller inner rings resulted in greater variability in hydraulic conductivity measurements. The infiltration area of the DualHead Infiltrometer is 13.8 times of inner ring area of the double-ring infiltrometer used in this study. This makes it less sensitive to the spatial heterogeneity of soil and probably closer to the representative elementary volume of the experimental site, which reduces the measurement scale effect (Schulze Makuch et al., 1999; Lai and Ren, 2007). Another possible confound is disturbance of the structure of the soil and crushed
macropores, which are more likely with the closely spaced double rings of the smaller infiltrometer.

On the other hand, smaller rings require a smaller area of flat topography and are more easily operated in sloped regions. The DualHead Infiltrometer uses a peristaltic pump and a water level sensor to maintain the water level and measure the water flux. This is operator-friendly, but it also uses an air pump to control the pressure head, which adds to the complexity and uncertainty of the equipment. While conducting this study, about 40% of all measurement attempts failed, usually as a result of an insufficient seal between the ring and the infiltrometer head.

3.3 Dynamics of infiltration rates and $K_f$, and their influencing factors

Under most conditions, infiltration rates decreased over time during the 15-minute soaking period, with the notable exception of dry, winter conditions, when soil VWC was below 0.25 m$^3$ m$^{-3}$, when most measurements showed gradual increases in infiltration rates (Figure 5). The increasing infiltration rates during the soaking step in cold, dry soil could be explained by an initial period of hydrophobicity caused by low temperatures and dry soil aggregates (Farrick et al., 2018; Filipovic et al., 2018). This effect would deteriorate as soil moisture rose during the soaking. Under high pressure heads, the behavior of infiltration rates depended on antecedent conditions: when the soil was wet, infiltration was more likely to decline over time; when the soil was dry, infiltration rates tended to increase.

During winter, when the soil was wet (VWC above 0.25 m$^3$ m$^{-3}$), two groups
of infiltration rates were identified (Figure 5a). One group had higher infiltration rates of 236.5±34.6 and 126.5±23.7 mm h⁻¹ at the high and the low pressure heads, respectively. The other group had lower infiltration rates of 83.0±21.1 and 49.2±15.39 mm h⁻¹ infiltration rates at the high and the low pressure heads, respectively. These pronounced differences may have been caused by the spatial heterogeneity of the soil, as the exact location of the experiment had to change weekly, or it could be attributed to some unidentified systematic error. As reported by Gamie and De Smedt (2018), great variation in hydraulic conductivity, spanning four orders of magnitude, was observed within an area of just 120 m × 120 m. They attributed this to some combination of sampling and measurement errors, randomness, and soil heterogeneity. When the soil was dry and cold, we measured infiltration rates that varied from 37.3 to 298.3 mm h⁻¹ at the high pressure head and from 16.1 to 142.3 mm h⁻¹ at the low pressure head (Figure 5b).

During summer, when the soil was wet, the infiltration rates at high and low pressure heads were 160.3±119.4 and 74.7±61.3 mm h⁻¹, respectively (Figure 5c). When the soil was dry during summer, the infiltration rates at high and low pressure heads were 423.0±286.2 and 207.1±122.1 mm h⁻¹, respectively (Figure 5d). Three of the measurements made under dry summer conditions were much higher than the other measurements.

During special winter conditions, such as snow cover with air temperature ($T_a$) slightly lower than 0 °C (-2.6 °C < $T_a$ < 0 °C) and soil temperature ($T_s$) slightly lower than 0 °C (-0.6 °C < $T_s$ < 0 °C), infiltration rates were 181.1±95.5, 193.3±87.6 and 207.7±79.8 mm h⁻¹ at high pressure head and 99.2±54.4, 96.7±44.3, and 109.4±37.9 mm h⁻¹ at low pressure head, respectively (Figure 5e).
These infiltration rates were not significantly different from other winter results (Table 3). A measurement on February 3, 2017, detected the highest infiltration rates in winter, despite snow-cover and cold and dry conditions, with $T_a = -0.05 \,$°C, $T_s = -0.3 \,$°C, and VWC = 0.20 m$^3$ m$^{-3}$ (Figures 5b and c). The results here showed that low air temperature, slightly frozen soil, and snow cover did not impede infiltration.

During winter, the mean $K_{fs\_OB}$ was 70.7±46.3 mm h$^{-1}$ when the VWC was lower than 0.25 m$^3$ m$^{-3}$ and 62.2±45 mm h$^{-1}$ when VWC was higher than 0.25 m$^3$ m$^{-3}$. During summer, the mean $K_{fs\_OB}$ was 184.8±141.0 mm h$^{-1}$ when the soil was dry and 77.5±57.4 mm h$^{-1}$ when the soil was wet (Table 3). After viscosity correction, the winter mean $K_{fs\_STP}$ values were 88.3±60.3 and 88.0±57 mm h$^{-1}$ when the soil was wet and dry, respectively; while in summer, the mean $K_{fs\_STP}$ values were 206.8±147.7 and 90.1±63.9 mm h$^{-1}$ when the soil was dry and wet, respectively (Table 3). In special weather in winter, with snow cover $T_a < 0$ °C and $T_s < 0$ °C, $K_{fs\_OB}$ values were 75.1±45.2, 88.5±47.3, and 88.5±47.4 mm h$^{-1}$, respectively; and $K_{fs\_STP}$ values were 111.8±62.8, 123.3±63.3, and 135.6±60.9, respectively (Table 3). Independent samples $t$-tests showed that the $K_{fs\_OB}$ and $K_{fs\_STP}$ of summer dry soil were significant higher than the others, whereas other $K_{fs\_OB}$ and $K_{fs\_STP}$ values had no significant differences (Table 3).

There were significant linear relationships between observed $K_{fs}$ and water temperature at both the irrigated and non-irrigated sites, K2 and K3 (Figure 7). However, the viscosity-corrected $K_{fs}$ had no significant relationship with water temperature, suggesting that the correction was effective. Additionally, no significant relationships were found between $K_{fs\_OB}$, $K_{fs\_STP}$, and soil temperature.
at K2 or K3.  

The relationships between $K_{fs}$ and water temperature are consistent with other published results (Hopmans and Dane, 1986; Levy et al., 1989; Duke, 1992; Emerson and Traver, 2008), but the relationships between $K_{fs}$ and soil temperature were inconsistent with the finding of Clancy and Alba (2011), who found a significant linear relationship between them. It was proposed that soil temperature had effect on air viscosity and permeability, as the pore spaces of field saturated soil are still between 5% and 20% occupied by air (Bond and Collisgeorge, 1981; Constantz et al., 1988). Air permeability is related to air viscosity, so it was thought that hydraulic conductivity would correlate with soil temperature. We did not observe this association in this study. Levy et al. (1989) revealed that the effects of temperature on hydraulic conductivity were dependent on soil type, so the results of this study suggest that the differences we observed in $K_{fs}$ at different temperatures are mainly controlled by the kinematic viscosity of water.

We were unable to effectively address one probably mechanism by which soil temperature could affect infiltration: frozen soil. The operating internal temperature range of the DualHead Infiltrometer was limited to 0 °C, and the water tubes easily froze when exposed under such conditions, as well. The result was that conditions conducive to an ice-rich layer near the surface tended to prevent successful infiltration measurements (Iwata et al., 2011).

We observed a significant negative linear relationships between $K_{fs,STP}$ and antecedent VWC during winter, and across the whole experimental period, while
such linear relationships were insignificant during summer (Figure 8). Similar
linear relationships between $K_{fs}$ and antecedent VWC have been found in many
studies and can be explained by the tendency of wet soils to have reduced soil
sorptivity and restricted subsoil drainage (Philip, 1957b; Hardie et al., 2012). In
addition, high soil VWC tends to cause clay-rich soils to swell, constricting soil
cracks, decreasing soil macroporosity, and reducing macropore flow (Lin et al.,
1998; Hardie et al., 2012).

Two $K_{fs}$ measurements from June 12, 2017, were extremely low. The surface
soil was reported to be extremely dry, though the recorded VWC at 10 cm was
not especially low at 0.18 m$^3$ m$^{-3}$. A similar result was observed on July 5, 2016,
when the lowest soil moisture, 0.18 m$^3$ m$^{-3}$, was recorded in the experimental
period, and a relatively low $K_{fs}$ value was observed (Figure 8c). These may be
attributable to water repellency of the soil and reduced water infiltration (Doerr
and Thomas, 2000; Wang et al., 2000), but it’s also possible that an antecedent
heavy storm that fell on freshly harvested land during the summer formed soil
crusts which reduced the surface soil infiltration capacities (Vandervaere et al.,
1997).

The soil at the Living Filter tends to be cold and wet during winters (Hopkins,
2016a), and this combined effect could explain the lower $K_{fs}$ in winter than in
summer. Similar seasonal variations of $K_{fs}$ have been observed in other regions
and should be considered when planning wastewater treatment management, best
management practices, or water resources management (Cerdà, 1997; Emerson
and Traver, 2008; Cerdà et al., 2016).
3.4 Long-term treated wastewater irrigation effects on field-saturated hydraulic conductivity

In the irrigated cropland, at site K3, the observed minimum $K_{fs}$ was 13.2 mm h$^{-1}$ and the maximum $K_{fs}$ was 311.4 mm h$^{-1}$, with a mean and standard deviation (SD) of 97.9±78.4 mm h$^{-1}$ and a CV of 80.1%. There were only six valid measurements at K4, with a minimum and maximum $K_{fs}$ of 37.4 and 174.3 mm h$^{-1}$, respectively, and a CV of 61.0%. Measurements at K4 were carried out in June 2017 and had a mean $K_{fs}$ of 95.0±57.9 mm h$^{-1}$, without significant differences from the results of K3 during the same period. In the non-irrigated cropland, K2, we observed minimum and maximum $K_{fs}$ values of 14.8 and 367.2 mm h$^{-1}$, respectively, with a mean and SD of 85.1±87.4 mm h$^{-1}$ and a CV of 102.7%. The minimum of all results at all three sites was higher than the nominal application rate of the treated wastewater irrigation (4.25 mm h$^{-1}$).

After viscosity calibration, all $K_{fs\_STP}$ values from K3 and K2 were compared and no significant differences ($p = 0.357$) were found (Figure 6). At site K2, the mean and SD of $K_{fs\_STP}$ was 103.2±94.6, while the results from site K3 were a bit higher at 123.8±94.0 mm h$^{-1}$. During winter, $K_{fs\_STP}$ values at K3 and K2 were 107.0±76.0 and 80.4±52.9 mm hr$^{-1}$, respectively, without a significant difference ($p = 0.442$). During summer, $K_{fs\_STP}$ at K3 and K2 were 122.5±101.7 and 127.1±133.9 mm hr$^{-1}$, respectively, also without a significant difference ($p = 0.737$).

These results do not contradict previous reports in the same areas. Sopper and Richenderfer (1978) measured $K_{fs}$ using double-ring infiltrometers and an
Alderfer-Robinson Rainfall Simulator and found that there was a significant increase in infiltration on the irrigated corn-cropped land. Walker (2006) also reported higher hydraulic conductivity in irrigated areas than in control areas, in the same areas, as measured by the constant head method in a laboratory setting. Larson (2010) measured hydraulic conductivity using a tension infiltrometer and showed that hydraulic conductivity was relatively higher on irrigated lands than on control lands, especially at 3 and 6 cm of tension, suggesting that the increased hydraulic conductivity was mainly attributable to an increase in the abundance of pores with radii of 0.025 to 0.050 mm.

Several explanations have been offered for the increase in hydraulic conductivity on these irrigated lands. First, the increased growth of plants due to the nutrient-rich treated wastewater should be considered. A lush crop canopy offers protection from raindrop impacts, thereby decreasing surface soil compaction, while the activity of plant roots improves soil structure, increases macropores. Macropores may contribute nearly 85% of the variation of hydraulic conductivity or total infiltration (Cameira et al., 2003; Liu et al., 2016), as suggested by the dramatic increase in the incidence of preferential flow at irrigated sites in the Living Filter (Hopkins et al., 2016b). In addition, the increase in nutrients from the effluent would also tend to improve soil physicochemical properties. Treated wastewater irrigation was found to increase organic matter content and soil pH (Walker and Lin, 2008); lower bulk densities and higher soil pH values and electrical conductivities have been found on irrigated croplands, as compared to non-irrigated croplands (Vogeler, 2009; Larson, 2010). These positive effects could result from higher organic matter inputs, increased soil
animal abundance and plant root growth, and greater freeze-thaw cycling (Oades, 1984; Frey et al., 1999; Bronick and Lal, 2005). The irrigated soils at the Living Filter have physically adapted to accommodate large volumes of water, after decades of spray irrigation.

4. Conclusions

Field-saturated hydraulic conductivity was measured at the “Living Filter” tertiary wastewater treatment system at The Pennsylvania State University. Infiltration tests were conducted during both summer and winter using DualHead Infiltrometers with original and modified procedures and using double-ring infiltrometers. We have drawn the following conclusions:

1) The modified DualHead Infiltrometer procedure, with one long cycle, achieved steadier pressure heads and infiltration rates than the original procedure, with two short cycles. Thus, the \( K_{fs} \) calculated from the modified measurements were more reasonable and credible.

2) \( K_{fs} \) values measured by DualHead Infiltrometers were similar to those measured by double-ring infiltrometers, but they were higher under some conditions due to the tendency of the double-ring infiltrometer to compact and disturb the soil. However, the small double-ring infiltrometer would be more easily operated on sloped regions.

3) \( K_{fs,STP} \) values from irrigated croplands were insignificantly higher than those from non-irrigated croplands, suggesting that the long-term application of wastewater irrigation had possibly altered hydraulic
conductivity, but indicating that additional measurements may be required
to tell for sure. Infiltration rates and $K_{fs}$ values were much higher than the
spray irrigation rate under all conditions. From this perspective, the
application of treated wastewater irrigation does not seem to be at high
risk of causing overland flow, even after decades of irrigation.

4) Infiltration rates and $K_{fs}$ were lower during winter than during summer, as
soil conditions tend to cold and wet. Infiltration processes during winter
should receive extra attention when implementing wastewater irrigation.

5) Infiltration rates and $K_{fs}$ showed great spatial and temporal variability and
uncertainty and were strongly influenced by antecedent soil moisture and
water temperature. Though snow cover, slightly cold air, and frozen soil
did not show a particular influence on winter infiltration rates and $K_{fs}$,
caution should be taken in very cold conditions with thick layers of frozen
soil to ensure no runoff generation.

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and Heather Gall for their help with the field work.

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Table 1 Average chemical characteristics of the municipal wastewater used for irrigation from Nov. 2005 until August 2006 (n = 21; Parizek et al., 2006).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total alkalinity (mg L(^{-1}) as CaCO(_3))</td>
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</tr>
<tr>
<td>Biological oxygen demand (mg L(^{-1}))</td>
<td>8</td>
</tr>
<tr>
<td>Specific conductance (μmhos cm(^{-1}))</td>
<td>1109</td>
</tr>
<tr>
<td>Total hardness (mg L(^{-1}) as CaCO(_3))</td>
<td>245</td>
</tr>
<tr>
<td>pH</td>
<td>7</td>
</tr>
<tr>
<td>Total suspended solids (mg L(^{-1}))</td>
<td>5</td>
</tr>
<tr>
<td>Nitrate (mg L(^{-1}) as N)</td>
<td>12</td>
</tr>
</tbody>
</table>
Table 2 Characteristics of infiltration processes with different measurement parameters. CV_PH and CV_PL are the coefficients of variation for high and low pressure heads, respectively. CV_IH and CV_IL are the coefficients of variation for infiltration rates at high and low pressure heads, respectively. \(|\text{Slp}_H|\) and \(|\text{Slp}_L|\) are the absolute rates of change of the infiltration rate over time at high and low pressure heads, respectively. Different letter labels indicate significance groupings at \(\alpha = 0.05\), as assessed by an independent samples \(t\)-test using log-transformed data, where all intragroup differences were not significant.

<table>
<thead>
<tr>
<th>Parameters and statistics</th>
<th>Original measurements</th>
<th>Modified measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
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<td></td>
</tr>
<tr>
<td>Soak Time (min)</td>
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<td>15</td>
</tr>
<tr>
<td>Low Pressure Head (cm)</td>
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<td>5</td>
</tr>
<tr>
<td>High Pressure Head (cm)</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>Hold Time @ Pressure Head (min)</td>
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<td>35</td>
</tr>
<tr>
<td>Pressure Cycles</td>
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<td>1</td>
</tr>
<tr>
<td>Total Run Time (min)</td>
<td>75</td>
<td>85</td>
</tr>
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<td>Statistics</td>
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<td>CV_PH (%)</td>
<td>4.0±3.2a</td>
<td>0.9±1.1b</td>
</tr>
<tr>
<td>CV_PL (%)</td>
<td>1.1±0.4a</td>
<td>1.2±0.8a</td>
</tr>
<tr>
<td>CV_IH (%)</td>
<td>7.1±4.5a</td>
<td>3.0±1.5b</td>
</tr>
<tr>
<td>CV_IL (%)</td>
<td>6.0±3.9a</td>
<td>4.5±3.8a</td>
</tr>
<tr>
<td>(</td>
<td>\text{Slp}_H</td>
<td>) (mm h(^{-2}))</td>
</tr>
<tr>
<td>(</td>
<td>\text{Slp}_L</td>
<td>) (mm h(^{-2}))</td>
</tr>
<tr>
<td>Numbers of data used</td>
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<td>8</td>
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</tbody>
</table>
Table 3 Characteristics of infiltration processes in different conditions. $T_a$ is air temperature; $T_s$ is soil temperature; VWC is soil volumetric water content. IR_H and IR_L are infiltration rates at high and low pressure heads, respectively; $K_{fs}$ and $K_{fs, STP}$ are initial and viscosity-corrected field saturated hydraulic conductivities, respectively. Different letter labels in the same column show significant groupings at $\alpha = 0.05$, as assessed by an independent samples $t$-test using log-transformed data, where all intragroup differences were not significant.

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Number of data</th>
<th>$T_a$</th>
<th>$T_s$</th>
<th>VWC</th>
<th>IR_H</th>
<th>IR_L</th>
<th>$K_{fs}$</th>
<th>$K_{fs, STP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter, dry soil</td>
<td>6</td>
<td>4.7±4.9</td>
<td>1.5±1.9</td>
<td>0.21±0.02</td>
<td>133.6±94.3</td>
<td>56.4±45.8</td>
<td>70.7±46.3</td>
<td>88.3±60.3</td>
</tr>
<tr>
<td>Winter, wet soil</td>
<td>9</td>
<td>2.7±3.3</td>
<td>2.1±1.3</td>
<td>0.31±0.01</td>
<td>151.2±85a</td>
<td>83.6±44.7</td>
<td>62.2±45.0</td>
<td>88.0±57.6</td>
</tr>
<tr>
<td>Summer, dry soil</td>
<td>7</td>
<td>17.1±10.5</td>
<td>23.8±2.3</td>
<td>0.19±0.03</td>
<td>423.0±286.2</td>
<td>207.1±122.1</td>
<td>184.8±141.0</td>
<td>206.8±147.</td>
</tr>
<tr>
<td>Summer, wet soil</td>
<td>17</td>
<td>18.9±2.7</td>
<td>19.2±1.5</td>
<td>0.30±0.01</td>
<td>160.3±119.4</td>
<td>74.7±61.3</td>
<td>77.5±57.4</td>
<td>90.1±63.9</td>
</tr>
<tr>
<td>With snow</td>
<td>6</td>
<td>1.7±5.3</td>
<td>0.2±0.4</td>
<td>0.27±0.06</td>
<td>181.1±95.5</td>
<td>99.2±54.4</td>
<td>75.1±45.2</td>
<td>111.8±62.8</td>
</tr>
<tr>
<td>$T_a&lt;0$ °C</td>
<td>4</td>
<td>-1.7±1.2</td>
<td>0.1±0.4</td>
<td>0.28±0.05</td>
<td>193.3±87.6</td>
<td>96.7±44.3</td>
<td>88.5±47.3</td>
<td>123.3±63.3</td>
</tr>
<tr>
<td>$T_s &lt; 0 , ^\circ\mathrm{C}$</td>
<td>4</td>
<td>-</td>
<td>0.2 - 0.1 ± 3.4</td>
<td>0.28 ± 0.06</td>
<td>109.4 ± 37.9</td>
<td>88.5 ± 47.4</td>
<td>135.6 ± 60.9</td>
<td></td>
</tr>
<tr>
<td>------------------------</td>
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<td>------------</td>
<td>---------</td>
<td>------------</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.2 ± 0.3</td>
<td>ab</td>
<td>ab</td>
<td>ab</td>
<td>ab</td>
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</tr>
</tbody>
</table>
Table 4 Date, site, air temperature ($T_a$), soil temperature ($T_s$), and soil volumetric water content (VWC) of measurements using the modified parameters in Table 2.

<table>
<thead>
<tr>
<th>Number</th>
<th>Date</th>
<th>Site</th>
<th>Repetition</th>
<th>$T_a$</th>
<th>$T_s$</th>
<th>VWC</th>
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<td>1</td>
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<td>K3</td>
<td>1</td>
<td>4.7</td>
<td>-0.6</td>
<td>0.33</td>
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<tr>
<td>2</td>
<td>Jan 27, 2017</td>
<td>K3</td>
<td>1</td>
<td>1.6</td>
<td>1.5</td>
<td>0.32</td>
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<tr>
<td>3</td>
<td>Jan 27, 2017</td>
<td>K3</td>
<td>2</td>
<td>1.6</td>
<td>1.5</td>
<td>0.32</td>
</tr>
<tr>
<td>4</td>
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<td>-2.6</td>
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<tr>
<td>5</td>
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<td>K3</td>
<td>2</td>
<td>-2.6</td>
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<td>0.30</td>
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<td>0.31</td>
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<td>3.0</td>
<td>0.33</td>
</tr>
<tr>
<td>8</td>
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<td>K3</td>
<td>2</td>
<td>0.9</td>
<td>3.0</td>
<td>0.33</td>
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<td>K3</td>
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</table>
Figures

Figure 1. Maps of the locations of the experimental locations at (a) Penn State’s “Living Filter” and (b) a zoomed-in view of the Astronomy site.
Figure 2. Examples of the raw data record of measurements using a DualHead Infiltrometer with (a) the original parameters and (b) the modified parameters, as given in Table 1.
Figure 3. Infiltration rates of experiments in February and March with (a) the original and (b) the modified measurement parameters, as given in Table 1.
Figure 4. Plotted relationship between field-saturated hydraulic conductivities measured concurrently by DualHead Infiltrometers ($K_{fs_{DH}}$) and by double-ring infiltrometers ($K_{fs_{DR}}$). Solid dots indicate measurements with great differences between the two infiltrometer types, while hollow dots were similar results, and are therefore near the 1:1 line. All data were included in the regression line, which is drawn as a bold, solid line, and whose equation and fit parameters are in the top left corner.
Figure 5. Infiltration rates (IR) under dry and wet soil conditions and in winter and summer. Winter spanned from November to March while summer comprised June and July. Wet soil refers to soil volumetric water contents (VWCs) higher than 0.25 m$^3$ m$^{-3}$, while dry soil had VWC lower than 0.25 m$^3$ m$^{-3}$. $T_a$ is air temperature; $T_s$ is soil temperature. Numbers in the legends refer to the measurements in Table 3.
Figure 6. Viscosity-corrected field-saturated hydraulic conductivities ($K_{fs,STP}$) in cropped land with (K3) and without (K2) irrigation. This includes with 29 and 23 valid measurements, respectively, during the whole experimental period.
Figure 7. The relationship between $K_{fs}$ and water temperature. $K_{fs}$: field saturated hydraulic conductivity; $K_{fs,OB}$: observed $K_{fs}$; $K_{fs,STP}$: $K_{fs}$ that has been viscosity-corrected to the standard temperature of 25 °C; $T_w$: water temperature.
Soil moisture ($m^{-3}$)

Kfs_STP = 444.91 - 1042.36VWC, $R^2 = 0.24$, $p < 0.001$

(a) K3, Whole period

Kfs_STP = 612.76 - 1585.47VWC, $R^2 = 0.515$, $p < 0.001$

(b) K3, Winter

Kfs_STP = 328.74 - 749.93VWC, $R^2 = 0.10$, $p = 0.119$

(c) K3, Summer

Figure 8. Plots of the relationships between antecedent soil volumetric water content (VWC) and viscosity-corrected field saturated hydraulic conductivity ($K_{fs \_STP}$) at K3 during the entire study duration (a), the winter (b), and the summer (c). The shaded region encompasses notably low $K_{fs}$ values with the low soil VWC (included in the regression).