Refining the Application Rates of Onsite Surface Application

Clifford B. Fedler, Jordan Littlejohn,
Runbin Duan, and Li Feng

Texas Tech University
Department of Civil and Environmental Engineering
Texas Tech University
Lubbock, TX 799409

Texas On-Site Wastewater Treatment Research Council
TCEQ
Project No. 582-9-90350
15 December 2012

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Final Report to the Texas Commission on Environmental Quality:

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Executive Summary

In the rural and residential areas in the U.S., onsite wastewater treatment systems are prevalent systems used to treat and dispose of wastewater from individual homes or from a cluster of households. These onsite systems draw public attention because they can lead to wastewater runoff and transport contaminants to nearby surface or subsurface freshwater resources that are often used for drinking water. Thus, this project is aimed to control runoff and pollution by collecting soil infiltration information via the methods of 1) testing different soil infiltration rates using a double-ring infiltrometer at different locations in Texas; 2) collecting and analyzing soil samples in order to calculate saturated hydraulic conductivity using published equations; 3) obtaining and comparing collected data with the saturated hydraulic conductivity information from the NRCS Web Soil Survey website; 4) evaluating if the percentage of sand, clay and silt affect infiltration rates; and 5) comparing the predictive capability among the various models considered.

There are several phases in this project. First, four cities, Lubbock, Houston, Austin and Dallas were chosen for testing soil infiltration rates using a double-ring infiltrometer recommended by American Society for Testing and Materials (ASTM Standard D3385-09). Soil samples were taken by a soil probe at each test location for textural analysis. The NRCS Web Soil Survey website was examined because it is an internet web-based version of the local county soil survey that can provide saturated hydraulic conductivity data for all soils. Second, the data was used to compare the model developed by Saxton and the Web Soil Survey with the field collected data. Next, the data from the Lubbock location only to examine the predictive capability of several models specifically for turf systems. This was done in order to determine the level of predictability from a limited set of data. Last, entire data set was examined from the standpoint of two simplistic models and one more complicated model along with two adaptations of both types of models. These models were examined to determine if they can provide a convenient method for engineers to predict soil infiltration given minimal soils data for a specific site.

The results showed that the double-ring infiltrometer test is a time-consuming method to test soil infiltration rates. The base intake rate ranged from 0.04 in/hr when the clay content is high to 9.93 in/hr when sand content is high. The percentage of sand, silt and clay of soils vary based on different locations. For instance, the sand content changes from 95% to 30% from Lubbock to Austin, respectively. The various models tested have their applicability to predict the soil infiltration rate. The Web Soil Survey data may not be applicable for small-scale sites such as those used for onsite surface application system since those data ranges are quite large and they are also collected from areas several orders of magnitude larger than the site of a typical onsite or clustered home system.

The infiltration curve becomes asymptotic to an infiltration rate approximately equal to the saturated permeability rate (also called the saturated hydraulic conductivity) of the soil. Normally the sprinkler irrigation application rate is set to this value as a conservative approach to a design. At this application rate no surface runoff should occur. However, the design objective is not to apply water at a given rate but to apply a given depth of water.

The depth of water needing to be applied from an onsite system is relatively small (approximately 0.4 inches) because effluent storage of effluent in these systems is limited. Furthermore, the effluent is applied to a vegetated field that has a detention depth that the field can hold without surface runoff, which is approximately 0.2 inches.

More data needs to be obtained in order to develop a relationship between the soil characteristics and the coefficients in the models tested. Since the SCS (NRCS) model proved to be insufficient for the data from this research, the Kastiakov model or the TTU equation could be used where similar soil characteristics are available and the model coefficients can be used as provided. At this point, the Horton and TTU2 Equations are the only two that fit the boundary conditions and could be used also, if the soils characteristics are similar to those collected for this research, but both models are more complicated to use at this time.

In order to more completely utilize the Horton and TTU2 Equations, the recommended next step is to gather a larger set of data and include these data (Appendix D), but from a much tighter set of soil conditions. Of course these added data should come from at least three different soil texture profiles from the soil texture triangle of the USDA.

Acknowledgements

Many people made great contribution to the completion of this study and I would like to express my appreciation to then. Without the help of Dr. Runbin Duan, Li Feng, Richard Francis, Emre Guven, Nick Kalos, Bahar Amoli, Samir Blanchet, and Dhiraj Parekh, this project would not have had the same conclusions. Special thanks are extended to Dr. John Borrelli who served as the outside consultant on this project, assisted with the development of the field test procedures, and finally reviewed this report for completeness.

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Introduction

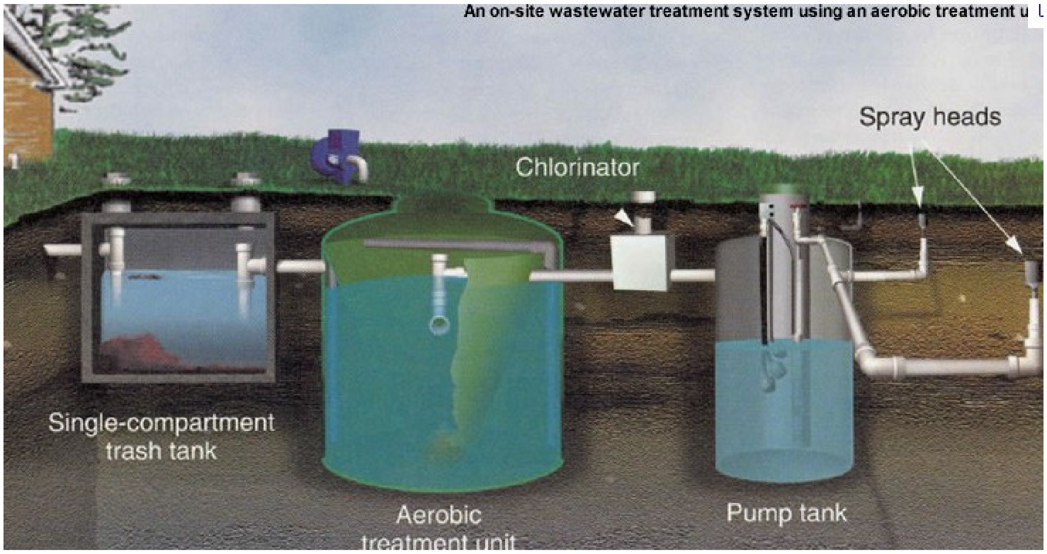
Water is vital for all known forms of life and plays an essential role on the earth. Most human activities are related to water, such as drinking, bathing, irrigation, industrial processing and fire protection. Although 70% of the earth's surface is covered by water bodies, only a small amount of that water can be utilized for human consumption. Furthermore, the various forms of water are connected to each other in terms of "water circulation." Water in the ocean is evaporated by solar radiation, transported via cloud movement, falls back to earth in various forms of precipitation, converges on brooks to rivers and finally back to oceans. Thus, it is important to prevent contaminants from entering any water body to protect the health of all forms of life.

Wastewater treatment is a process including physical, chemical, and biological methods to remove contaminants. The main objective is to remove pollutants in the wastewater and eliminate the risks of discharging the treated effluent into natural water bodies. With the development of the modern technologies, more and more precise devices can detect extremely small amounts of pollutants in the water. However, the basic mechanisms and approaches of wastewater treatment have not changed as much as devices during the past 100 years (Metcalf & Eddy, 2003).

Onsite wastewater treatment is defined as a system composed of septic tank or aerobic tank and a soil absorption field to eliminate most settleable and floatable materials, nutrients and pathogens producing an effluent with good quality. In the early days, the first known water closet with a flushing device in Crete was designed and installed by King Minos (Robert and Oppelt, 2002). With the development of society, governments have developed rules used to reduce threats to human health and ecological resources through improving the removal of human wastes from indoor areas and the treatment of the waste. By the late 1800s, direct links between poorly treated sewage and diseases were found out by the Massachusetts State Board Health. Septic tank or aerobic tank for primary treatment of wastewater and discharge of tank effluent into gravel-lined subsurface drains became common in the middle of 20^{th} century.

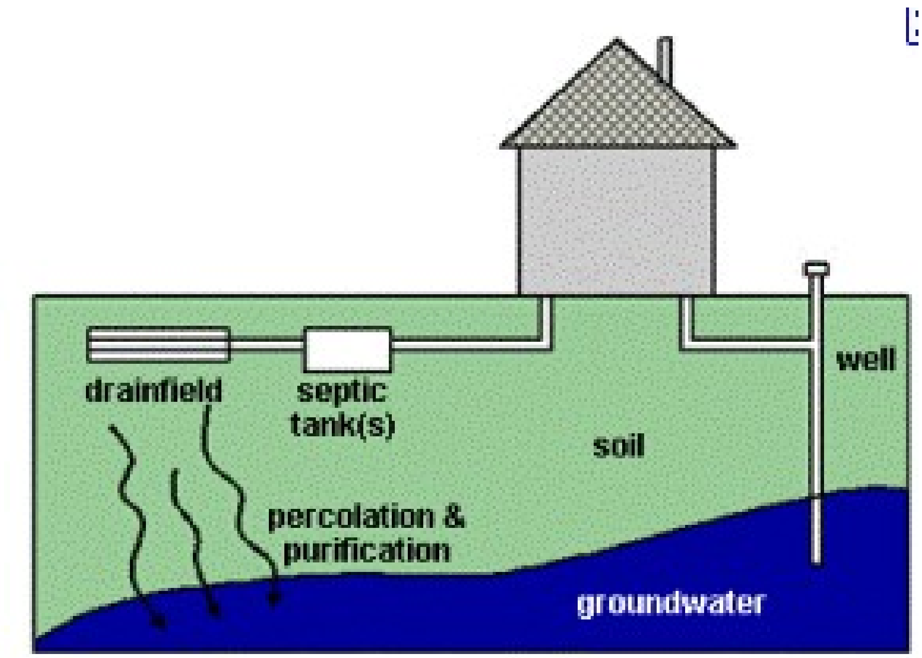
The onsite wastewater treatment system is one kind of treatment system for individual household wastewater with the capacity to produce a good quality of effluent that, when designed properly, meets the requirements of secondary treatment. There are two kinds of treatment systems--aerobic and anaerobic. Generally speaking, the system is composed of an aerobic tank or a septic tank, pipes, and drainage field or sprinkler system. Whatever the choice, organic and inorganic material and microorganisms would be removed by the soil-water matrix. However, if more wastewater is applied to the system than the intended design, it would not only produce runoff transporting pollutants to other water bodies. In addition, the soil matrix will not have sufficient capacity to treat those pollutants, and thus, result in the potential contamination of the underlying groundwater.

These two systems have different components and each component has its own functions. Briefly speaking, the aerobic system is composed of aerobic tank, pipes, disinfection devices and sprinkler system (Figure 1). The aerobic tank can equalize the influent water, retain oils, grease and remove solids by gravity. The soil-plant field plays an important role of removing solids and pathogens. Also, extra expenses on disinfection devices are required for distribution technologies to prevent adverse effect of wastewater on human beings.



(Taken from http://www.flower-mound.com/env_health/envhelth_ossf.php).
Figure 1. Example of a typical aerobic onsite treatment system.

As for the anaerobic system, it consists of septic tank, pipes and drainage system (Figure 2). The drainage system releases wastewater to the subsurface and eventually to the groundwater. The one important issue for both of the methods is to understand and figure out the soil permeability which affect the amount of wastewater applied.



(Taken from http://www.ewashtenaw.org).
Figure 2. Example of a typical septic onsite treatment system.

Objectives

A large portion (24%) of household wastewater in rural America is treated by onsite wastewater treatment systems. As mentioned, there are two types of treatment systems, aerobic system and anaerobic system. Whatever method is used, one of the mechanisms to remove pollutants from the effluent is through soil filtration and the soil absorption process. Thus, it is pivotal to determine the amount of water that can be properly applied on the soil-water matrix to prevent discharge to either surface water or groundwater resources. The overall objective of this project was to collect soil infiltration data at various locations in Texas where surface applied system are prevalent and to examine those data using various published equations to determine the predictability of the infiltration and determine if appropriate data can be obtained for designing onsite systems without the need to run the standard double ring infiltration tests in-situ. The sub-objectives of the project include:

1) to measure different soil infiltration rates at different locations in four regions in TX using the standard ASTM double ring infiltrometer,

2) to collect soil samples and analyze the physical properties of the soils for the purpose of using published equations to predict a soil's infiltration rate,

3) to compare measured infiltration rates with that calculated using published equations and procedures,

4) to determine if the tested model coefficients are a function of the percentage of sand, clay and silt, and

5) to compare measured and calculate infiltration rates with that obtained from the national NRCS Web Soil Survey website.

Soil Infiltration Rate Models

Turf and agricultural crops consume large amounts of water resources by irrigation in addition to natural precipitation, especially in arid and semi-arid areas in the summer time. Therefore, there is a great need to appropriately design and mange irrigation systems in order to effectively and efficiently utilize the limited water resources. This is especially important when the recycling of wastewater is considered. If too much water is applied the general result is runoff, which needs to be avoided when wastewater is the source of irrigation water since it can negatively impact fresh water resources.

Infiltration of water through the soil is an important process that is studied by many disciplines including soil science, hydrology, and others (Valiantzas, 2010). Infiltration not only controls the division of water into soils, water redistribution within soils, and even water deep percolation down to groundwater, but also the occurrence time and amount of runoff (Moore et al., 1981). In irrigation engineering, infiltration is the primary process that controls the surface irrigation uniformity and efficiency (Rashidi and Seyfi, 2007; Walker et al., 2006). Infiltration is a key dynamic process during irrigation events to be considered for irrigation system design, irrigation scheduling, and irrigation system optimization and management (Cuenca, 1989; Rao et al., 2006).

For onsite systems, typically a turf grass is irrigated with treated wastewater in order to save fresh water resources (Fedler and Borrelli, 2001). In wastewater land application systems, the amount of water infiltrated is one of the processes used in controlling the salt accumulation in the soil (Duan et al., 2010) and nitrogen leaching from the system (Duan et al., 2010). Infiltration is one of the important processes for engineers to properly estimate or measure to control potential contamination within nearby surface water bodies from the application of wastewater to land and to control potential contaminants from moving down to the groundwater (Williams et al., 1998).

Water infiltration into soil is a function of the soils physical properties, primarily initial soil water holding capacity and soil saturated hydraulic conductivity (Williams et al., 1998), soil texture and structure, vegetation, and plant root density. Generally, cumulative soil infiltration rates are higher with lower initial soil water content and higher with higher soil saturated hydraulic conductivity. Sandy soils have a higher infiltration rate than clay soil under identical conditions. Vegetation covered soil has a relatively higher infiltration than bared soil because plant roots tend to increase infiltration by making the soil more porous. Therefore, turf soil infiltration will behave differently when compared with agricultural fields due to the difference in vegetation and plant root density as well as the difference in management between lawns and most agricultural fields.

A number of infiltration models have been developed to describe this hydrological process since about 1911 (Green and Ampt, 1911; Cuenca, 1989; Williams et al. 1998). During the past few decades, the research question has been to determine a relationship between time and infiltration. Many useful models and empirical equations were established to describe how infiltration changes with time. However, considering the infinite combinations of soil and other factors existing in nature, no perfectly quantifiable general relationship exists. Models and equations have their significance because they can reduce costs, see how one parameter changes when changing other parameters, and predict the result for a longer period of time. Some of those soil infiltration models were systematically and extensively reviewed, presented, and summarized by Ravi and Williams (1998) and Williams et al. (1998). Although researchers have tried to successfully compare soil infiltration models in different scenarios under varying field conditions (Al-Azawi, 1985; Chahinian et al., 2005; Dashtaki et al., 2009; Davidoff and Selim, 1986; Mbagwu, 1995; Mishra el al., 2003; Rashidi and Seyfi, 2007; Sadegh et al., 2007; Shukla et al., 2003; Valiantzas, 2010), most of that research was conducted in agricultural fields and only few have evaluated the performance of those models in turf soils under field conditions. Some of the more classical infiltration models are reviewed below.

Infiltration Models

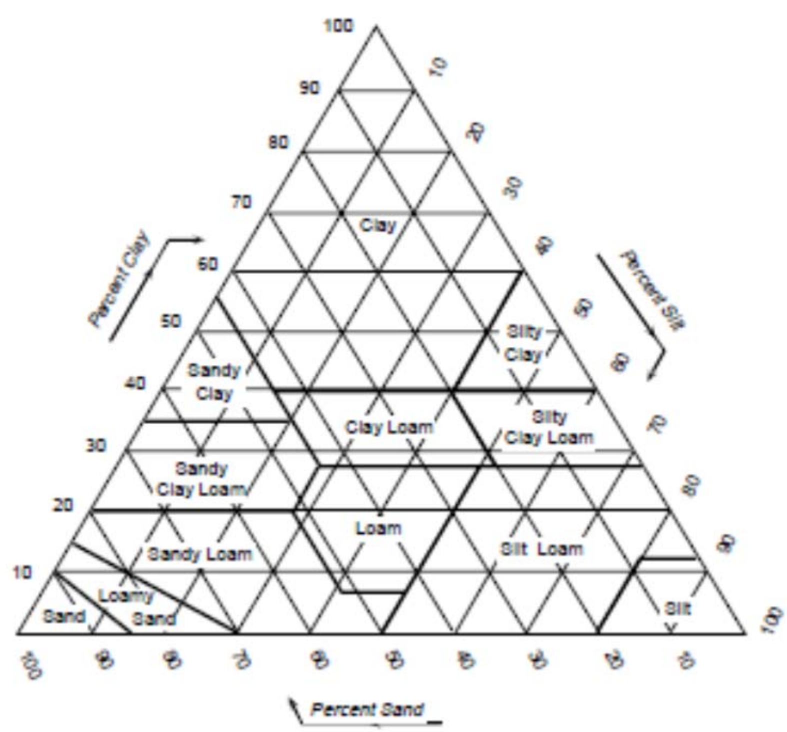
The infiltration rate of the soil is an extremely important parameter needed to design efficient irrigation systems and it is especially important when designing surface application system for the disposal of wastewater effluents from either onsite treatment system or large-scaled municipal wastewater treatment systems. Consequently, irrigation and hydrology literature contains the results of many attempts to model infiltration rates. Presented below are several popular infiltration models, several of which were evaluated using the infiltration data collected in this study.

Soil Texture and Types

Although there are many factors that can affect soil infiltration such as initial soil moisture content, evapotranspiration rate, solar radiation and so forth, the main factors considered in this project are soil texture and its physical properties. Soil physical properties are those related to the size and arrangement of solid particles such as the percentage of sand, silt and clay. Also, specific gravity, bulk density and soil types are some additional information related to soil characteristics. Soil texture can be classified and defined as the distribution of mineral particles within certain size ranges. Also, it is an intrinsic property of a soil, which may be influenced by geologic processes, but generally does not change considerably as a result of human activities.

A commonly used scheme is that of the U.S. Department of Agriculture (USDA). The assumption of soil classification is that the shapes of particles are round rather than irregular shapes by the USDA classification system. The USDA classification system defines gravel as being between 2 and 75 millimeters, cobbles between 75 to 254 millimeters, and stones are greater than 254 millimeters. Soil consists of particles less than 2.0 millimeters in diameter. Sand-sized particles will have diameters between 0.05 and 2 millimeters while silt-sized particles range between 0.002 and 0.05 millimeters and clay-sized particles are less than 0.002 millimeters in diameter (Braja, 2002).

In the soil analysis, the proportion of sand, silt, and clay in a soil always adds up to 100 percent. Twelve soil textural classes are defined by the percentages of these size groups as shown in the soil textural triangle (Figure 3) that was used to determine a soil's texture.



(Taken from http://www.usda.gov/wps/portal/usda/usdahome).
Figure 3. USDA Soil Textual Triangle used to classify soils based upon the percentage of sand, silt and clay content.

Infiltration Models Considered

The Green-Ampt model was originally based upon Darcy's law (Green and Ampt, 1911). This model can be used under the condition of steady and unsteady rainfall. Note, the saturated hydraulic conductivity is the infiltration rate of the soil after the system has reached steady state conditions.

$$\mathbf{Fp = Ks\left(1 + \frac{S * IMD}{F}\right)}$$

F_p=infiltration capacity, ft/sec
Ks=saturated hydraulic conductivity of soil, ft/sec
S=average capillary suction at the wetting front, ft of water
IMD=initial moisture deficit for the event, ft/ft
F=cumulative infiltration volume in the event, ft

$$\boldsymbol{IMD = \theta_s - \theta_i}$$

IMD=initial moisture deficit for the event, ft/ft
θ_i = initial moisture content (dimensionless) and
θ_s = saturated moisture content (dimensionless).

The Huggins-Monke model was created on time dependency problem by introducing soil moisture as the dependent variable (Viessman, 2003).

$$\mathbf{F = fc + A\left(1 + \frac{S - F}{Tp}\right)\boldsymbol{P}}$$

S=the storage potential of a soil overlying the impeding layer
F=total volume of water that infiltrates, ft
T_p=the total porosity of soil lying over the impeding stratum
f_c=a final capacity, ft/sec
A and P are coefficients from field tested data

Another important infiltration model has been developed by Holan and it is shown as follows (Viessman, 2003).

$$\mathbf{F = a\boldsymbol{S_a}1.4 + fc}$$

F= the infiltration capacity, ft/sec
a = the infiltration capacity of the available storage, ft/sec
S_a = available storage in the surface layer
f_c = the constant rate of infiltration after long wetting, ft/sec

Web Soil Survey (WSS) provides soil data and information produced by the National Cooperative Soil Survey (NRCS, 2012). It is operated by the USDA Natural Resources Conservation Service and provides access to the natural resource information system. NRCS has soil maps and data available online for more than 95 percent of the nation's counties. The concern about using the data from this national web site is that it is collected on a relatively large-scale aerial basis whereas the data needed for designing onsite systems is much more specific and on a small scale in comparison.

While the infiltration of water is a function of soil structure, chemistry of the water and soil, temperature of the water, and soil texture, the base intake rate is related to the saturated hydraulic conductivity of the soil (Karmeli et al., 1978). The equation is (Saxton et al., 1986):

$$\boldsymbol{K = 0.3939\left\{\exp\left[A + \left[\frac{B}{\Phi}\right]\right]\right\}}$$

$$\boldsymbol{A = 12.012 - 0.0755(\%sand)}$$

$$\boldsymbol{B = -3.8950 + 0.03671(\%sand) - 0.1103(\%clay) + 8.754E10^{-4}(\%clay)^2}$$

$$\boldsymbol{\Phi = 0.332 - 7.25E^{-4}(\%sand) + 0.1276log_{10}(\%clay)}$$

K = saturated hydraulic conductivity, inches/hr
Φ=soil moisture content, ft^3/ft^3

In addition to the Saxton equation and the national Web Soil Survey data, three additional published models were developed to estimate soil infiltration. One of the basic models examined was developed by Kostiakov (Cuenca, 1989).

$$\boldsymbol{I(t) = at^b}$$

I(t)=infiltration, cm

a and b are coefficients developed from the field data.

The Kostiakov model was later modified by SCS (Cuenca, 1989) to include a baseline infiltration.

$$\boldsymbol{I(t) = at^b + 0.6985}$$

To make sure there is no confusion, the constant of 0.6985 in the SCS Equation has units of cm. If the user is calculating the SCS Equation in inches, then the coefficient is 0.275. The third, and much more in-depth equation, was developed by Horton (Horton, 1940; Cuenca, 1989) and takes the following form:

$$I(t) = at + \left[\frac{b-a}{c}\right][1 - e^{-ct}]$$

Where:

a = the saturated hydraulic conductivity,cm/hr

b = the initial infiltration rate, cm, and

c = a constant indicating the rate of change in infiltration, 1/time.

Field Test for Infiltration Rate

The double ring infiltrometer (Figure 4) is the standard for field measurement of the infiltration rate of soils. The purpose of the double ring is to insure the vertically downward flow of water from the inner ring of the unit (Tech-Turf International, 2010). Mariotte siphons are used to maintain a constant head pressure while running the tests in the field. The Turf-Tec rings used in these tests have diameters of 12 and 24 inches for the inner and outer rings, respectively, and an overall height of 20 inches (Figure 4). This method is suitable for standard testing of soils with a hydraulic conductivity of 0.01 cm/s or it can be used for sandy type soils with high infiltration rates.

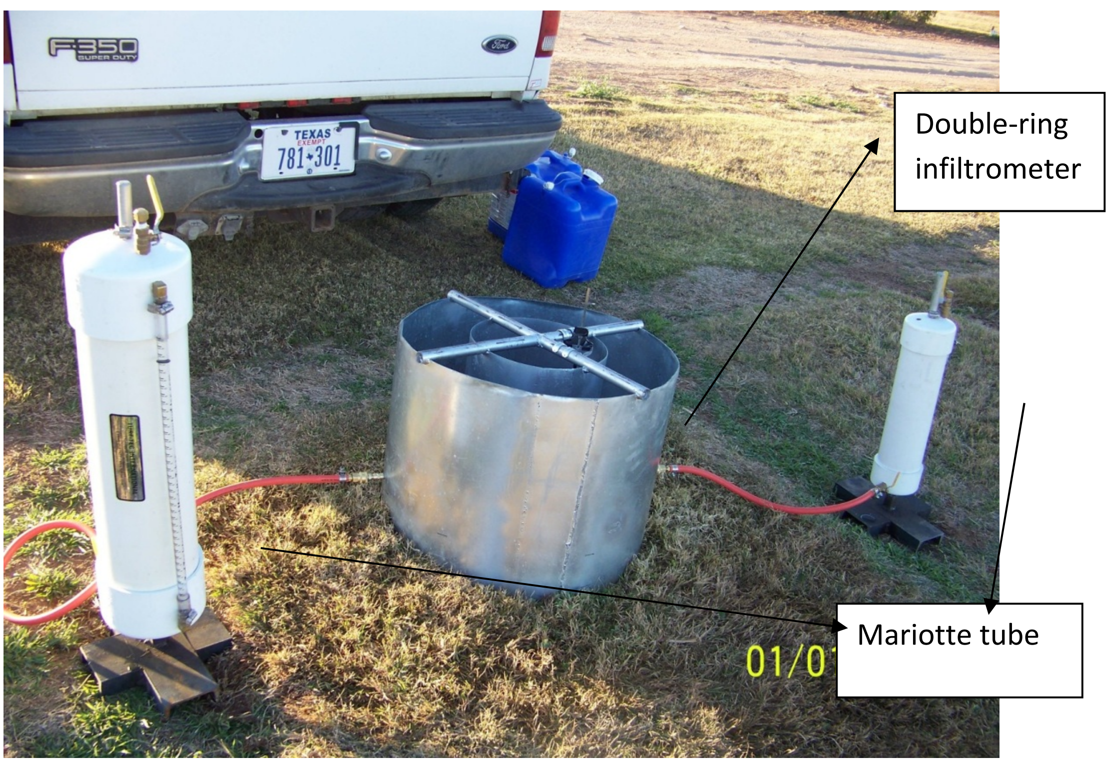


Figure 4. Double-ring infiltrometer and Mariotte tubes used in the standard ASTM infiltration tests.

Methods and Materials

This research consists of two main experiments and that includes the testing of measured infiltration rates in the field using an ASTM Standard D3385-09 double-ring infiltrometer (ASTM, 2012) and analyzing the physical characteristics (percent sand, silt, and clay) of the soils. The initial step was to determine the locations around the state where the tests should be conducted. Using data from the TCEQ database on the number of onsite surface application systems that exists throughout the state, the top ten counties using these systems were identified in Figure 5.

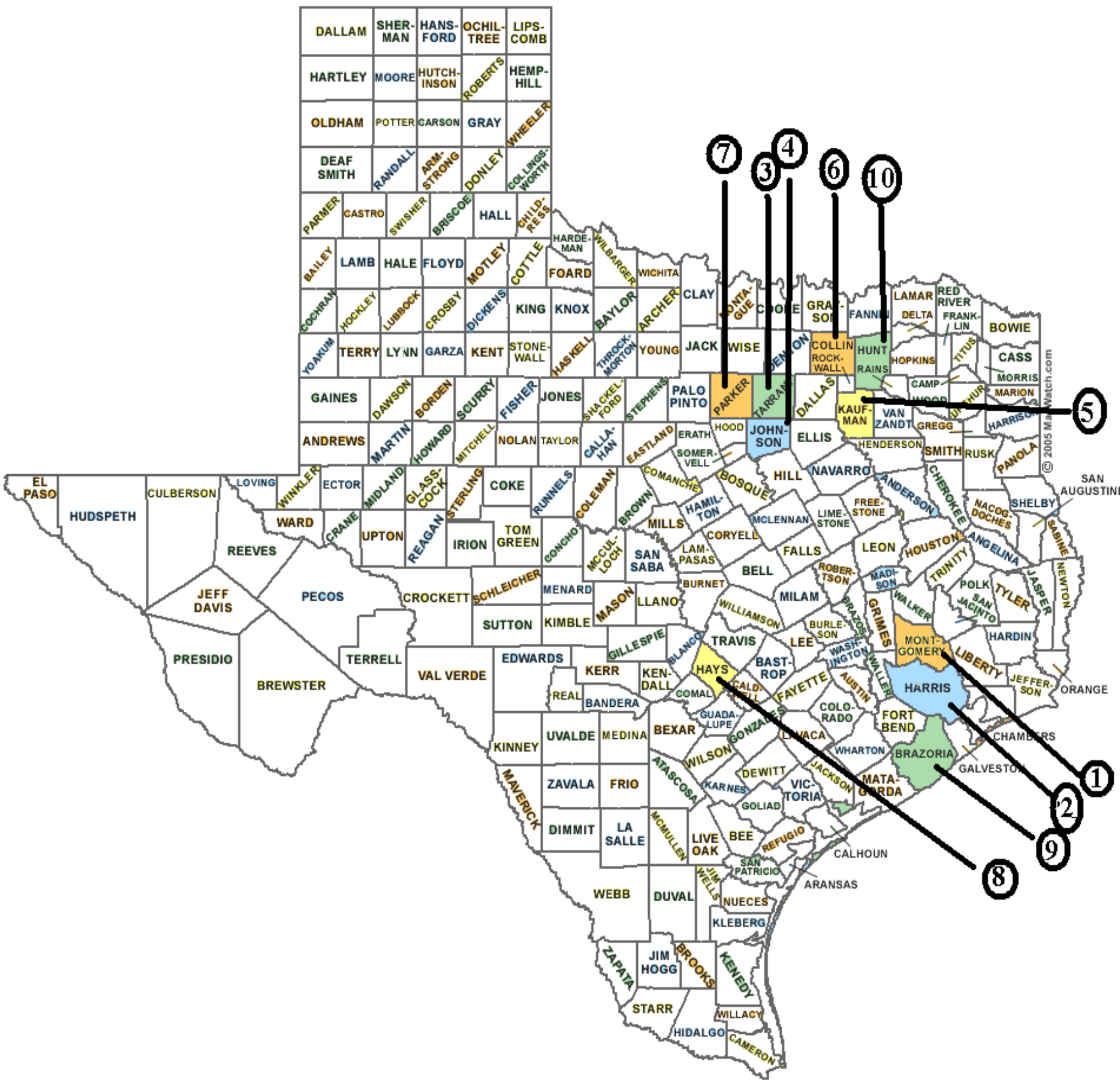


Figure 5. Top ten counties using onsite wastewater treatment systems in Texas.

From these data along with recommendations from the Texas Onsite Wastewater Treatment Research Council (part of the TCEQ until 2012), the four locations chosen for the tests are listed in Table 1 and shown in Figure 6. The four locations were chosen as representative test locations based on the distribution of onsite wastewater treatment systems and soil classifications along with convenience of the Lubbock location to the researchers.

Table 1. Locations (city) and identification code for the four test locations for the field testing of infiltration.

Cities	Location 1	Location 2	Location 3
Lubbock	Greenhouse	Plant Soil & Science	Plant Soil & Science
Houston	Hou-9225	Hou-9527	Hou-Sugarland
Austin	Austin-A1	Austin-A2	Austin-A3
Dallas	Dallas-A1	Dallas-A2	Dallas-A3

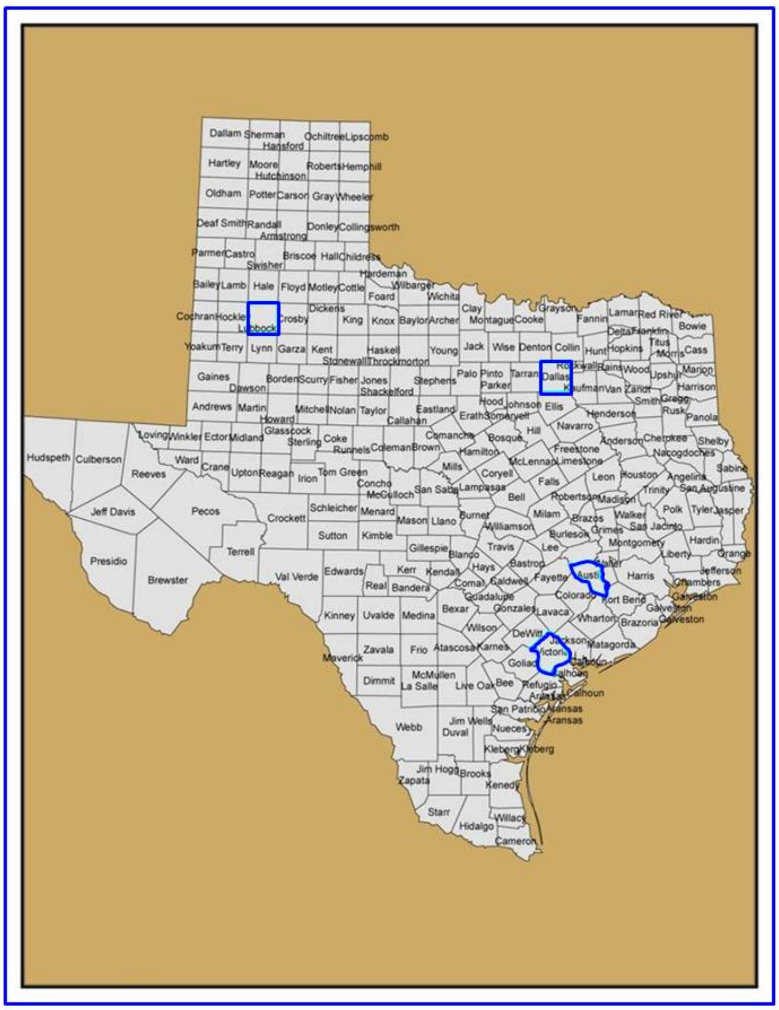


Figure 6. Map of the four test locations used in this research.

Test Equipment

In order to collect the field data for this research, several different tools were required. When arriving at the test location, the first data collected were the GPS coordinates collected from a Garmin etrex vista hand-held GPS unit (Garmin.com, 2012). The device used to measure the ambient air temperature and wind speed was the Model 45158 Mini Hygro Thermo-Anemometer by Extech Instruments (2012). A standard soil temperature probe was used to measure the soil temperature. A TDR soil moisture probe (Envco, 2012) was used to determine the soil moisture (Figure 7) while on site, but soil samples were collected and the soil moisture was determined in the lab as well. Since using the ASTM standard double ring infiltrometer is a time consuming data collection process, a study was conducted to determine if a smaller and more automated system could be used to collect meaningful data on soil infiltration. The Turf-Tec mini soil infiltrometer shown in Figure 8 (http://www.turf-tec.com/IN2lit.html) was tested along with the standard ASTM device.

Figure 7. The TDR soil moisture probe used to collect onsite soil moisture data.

(Taken from http://www.turf-tec.com/IN2lit.html).
Figure 8. Double-ring infiltrometer device tested at each location for comparison and evaluation of its potential for field use.

Double-ring Infiltrometer Tests

When selecting the test sites, one goal was to run in-situ tests at locations that would represent sites where an onsite surface application system would be installed and the location be relatively undisturbed or in near natural conditions. Once on the site for each test, the double-ring infiltrometer was hammered into the soil to a depth of 15 cm. When the double-ring infiltrometer was installed to the required depth, water was quickly placed in both the inner and outer rings of the infiltrometer simultaneously until a constant depth was obtained, which was considered time zero for the test.

The Mariotte tubes are used to maintain a constant water head throughout the test. The volume of water added for each time period was recorded. Additional information on the installation procedures for the infiltrometer can be found in Appendix A. Triplicate samples at each location were collected from both the portable infiltrometer and the ASTM Standard infiltrometer and the typical layout for the sample collection is shown in Figure 9. At least five soil sample cores were collected around the location of the infiltrometer tests in order to obtain a representative soil sample.

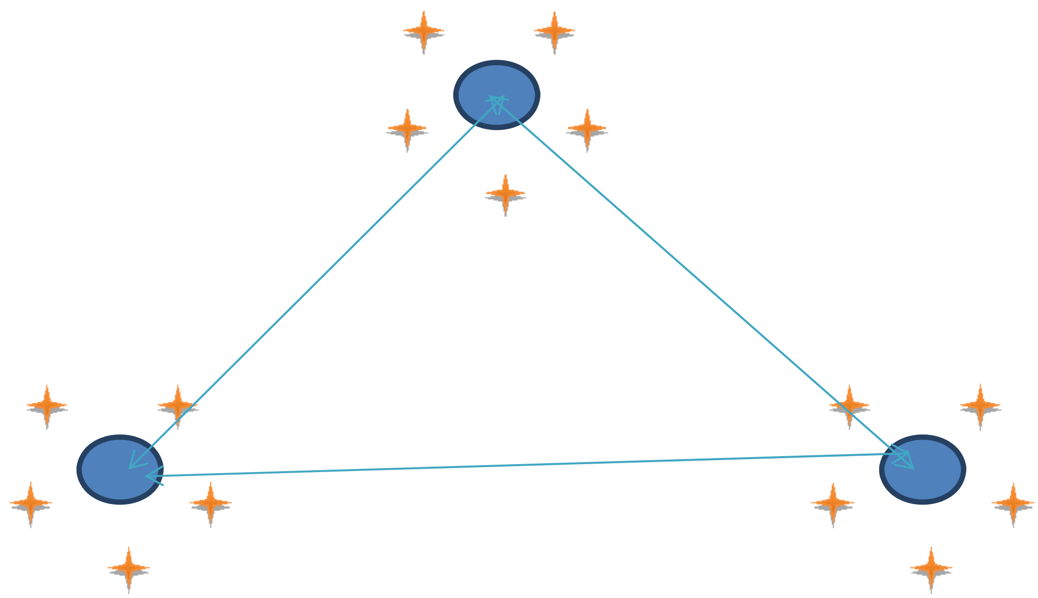


Figure 9. Layout of soil samples collected at each location. Circles represent the infiltrometer while the + represents the location of soil samples.

Physical Characteristics of the Soil

The necessary supplies and tools needed to complete the soil analysis are hydrometer, electrical stirrer, plunger, amyl alcohol, oven, vacuum and other items as shown in Figure 10. There are three experiments necessary to analyze soil samples. The first is to obtain the soil moisture content. This was accomplished by placing a 10 g sample of soil into one container, obtaining the original weight of soil then obtaining the weight after drying the sample in an oven at 105 C for 24 hours. Second, the specific gravity is determined by placing a 100 g sample of soil into a container and soaking it with distilled water for two hours. Then all the water and soil is poured into a glass vacuum jar where all of the air bubbles from spaces among the soil particles are removed. The third test was to obtain the percentage of sand, silt and clay within the soil samples. For this test, soil samples were passed through sieves (No.1000) to remove grass or other foreign material and then it was soak with a sodium heametaphosphate (SHMP) solution overnight. After mixing the solution with an electrical stirrer for 5 minutes, the mixture was poured it into sedimentation cylinder. Readings from the hydrometer were collected over a period of time based on the ASTM standard procedures. The moisture content, specific gravity and percentage of sand, silt and clay were then calculated. Details of this standard procedure can be found in Appendix B and the calculation procedures for the tests are provided in Appendix C.

Figure 10. Required supplies used to complete the soil analyses.

Results

Most infiltration models assume that soils are homogenous (no spatial variability in soil texture) and isotropic (the same permeability in every direction). However, soils are heterogeneous and anisotropic. Furthermore, the driving forces of water through the air-soil interface and through the soil consist of more than just gravitational forces. The capillary force caused by surface tension is an example of a force that also affects infiltration rates. For these reasons, infiltration rates vary spatially as well as temporal. The field data collected demonstrated the spatial variability of soils that may be used for OSSF systems. Regardless, the many efficient irrigation systems demonstrate that with a reasonable assessment of infiltration rates, irrigation systems can be designed to minimize surface runoff and percolation of water to the groundwater system.

Initial Analysis

Before all of the data were collected at the Lubbock location, some initial analyzes were made to get some understanding of the comparisons among the Saxton et al. (1986) procedures and the NRCS Web Soil Survey data. The results of this initial analysis are shown in Table 2. The base infiltration rate ranged from 0.04 in/hr when the clay content was high and up to 9.93 in/hr when sand content was high.

The NRCS Web Soil Survey website provides a range of hydraulic conductivity data for the selected sites where the measured infiltration rates were taken. The results show that in most cases, the site specific data collected from the field do not correlate with the broad-based data available from the NRCS Web Soil

Survey. This is contrary to what Jarrett (2012) reports when he states that the soil surveys are considered reliable. He goes on to say that these data better than field measured data. The soil survey data are averages from large areas, therefore one could mistakenly take this for a good "average" for small-scale systems such as onsite systems. Considering the very large range (often greater than 200%) from the soil survey data, choosing the "correct" value could become a product of chance. Choosing the lowest value and saying that the most conservative design is followed could cause systems to be largely over designed, thus causing much greater expenses to the user.

Similar results were obtained from the predictive equation of Saxton et al. (1986). Based on the percentage of sand, silt and clay tested from soil samples (Table 2), the Saxton et al. (1986) model was used to calculate saturated soil hydraulic conductivity. About half of the predictions were below the measured data while the other half were above the measured data. Another way to consider the data within Table 3 is to examine the measured versus predicted plot as is shown in Figure 10. As can be seen, there is a large cluster of data at the low end of the graph, yet a large portion of the data do not fit the 1:1 line that is expected from a measured versus predicted plot. In viewing Figure 11, it can be seen that not many of the data from the soil survey are predicted by the Saxton equation.

Some of the misalignment could be a result of data collected from a bare soil versus that containing turf where you would expect a higher infiltration rate. It would appear that is not the case for these data since about half of the data are on the over predicting the infiltration rate while the other half under predicts. If the turf was the principle difference in these data compared to the published or predicted data, the data in Figure 11 would be expected to be principally on the bottom side of the line, which is clearly not the case.

Evaluation of Infiltration Models

The next step in the analysis of the data was to compare other existing infiltration models. Five classic infiltration models were compared using the field test data from the Lubbock sites only in order to determine which models will be evaluated using the entire data collected. The investigated models were originally proposed by Philip (Philip, 1957), Kostiakov, Mezencev (Parhi, 2007), the United States Department of Agriculture Natural Resources Conservation Service (NRCS) (originally the United States Soil Conservation Service, SCS), and Horton (1940). These models were compared by investigating the sum of squared error (SSE), root mean square error (RMSE), coefficient of determination (R^2), adjusted coefficient of determination (Adj. R^2), mean error (ME), absolute value of mean error (AME), model efficiency (EF), and Willmott's index of agreement (W). The results (Table 4) showed that the Mezencev model and the Horton model performed better than the other three infiltration models. The soil at two of the Lubbock sites is a sandy clay loamy soil while the other one is an extreme sandy soil. The statistical analysis illustrated that the Mezencev model performed best in the extreme sandy soil while the Horton model performed better in the sandy clay loamy soils. Detailed results can be found in Duan et al. (2011).

Table 2. Percent sand, silt, and clay in the soil samples collected for the various locations tested along with the standard deviation of replicated samples.

Locations		%Clay +/- St. Dev.	%Sand +/- St. Dev.	%Silt +/- St. Dev.
Houston SL-A		**44.55 ± 0.898**	**30.07 ± 1.060**	**25.38 ± 1.538**
Houston SL-B		**45.42 ± 1.102**	**29.93 ± 0.242**	**24.65 ± 1.328**
Houston SL-C		**48.79 ± 2.933**	**24.16 ± 4.188**	**27.05 ± 1.895**
Houston 9225-A		**9.89 ± 1.115**	**53.68 ± 4.440**	**36.43 ± 5.372**
Houston 9225-B		**10.75 ± 1.552**	**57.15 ± 3.139**	**32.10 ± 1.628**
Houston 9225-C		**16.80 ± 3.962**	**52.85 ± 4.504**	**30.35 ± 0.788**
Houston 9527-A		**23.60 ± 1.210**	**51.94 ± 0.558**	**24.46 ± 1.728**
Houston 9527-B		**23.20 ± 0.819**	**52.53 ± 1.214**	**24.27 ± 0.573**
Dallas A1-1		**9.12 ± 0.460**	**77.97 ± 1.796**	**12.91 ± 1.957**
Dallas A1-2		**9.28 ± 0.600**	**75.69 ± 1.345**	**15.03 ± 1.943**
Dallas A1-3		**10.60 ± 0.185**	**77.03 ± 0.658**	**12.37 ± 0.588**
Dallas A2-1		**6.91 ± 0.987**	**78.54 ± 6.267**	**14.54 ± 5.292**
Dallas A2-2		**40.32 ± 12.419**	**38.50 ± .092**	**21.18 ± 12.514**
Dallas A2-3		**38.24 ± 3.572**	**38.55 ± 0.000**	**23.21 ± 3.570**
Dallas A3-1		**37.58 ± 1.796**	**38.55 ± 0.000**	**23.87 ± 1.796**
Dallas A3-2		**30.30 ± 4.260**	**45.33 ± 6.780**	**24.37 ± 2.520**
Austin A1-1		**45.32 ± 2.726**	**26.71 ± 2.802**	**27.97 ± 0.242**
Austin A1-2		**19.81 ± 2.827**	**27.59 ± 3.947**	**52.60 ± 1.267**
Austin A1-3		**18.23 ± 0.854**	**43.21 ± 0.973**	**38.55 ± 0.783**
Austin A2-1		**64.54 ± 0.294**	**2.73 ± 1.041**	**32.74 ± 1.068**
Austin A2-2		**66.12 ± 2.176**	**2.34 ± 2.019**	**31.54 ± 0.888**
Austin A2-3		**67.03 ± 1.012**	**1.83 ± 0.000**	**31.14 ± 1.012**
Austin A3-1		**64.95 ± 3.636**	**3.88 ± 3.514**	**31.17 ± 2.512**
Austin A3-2		**65.37 ± 1.689**	**2.73 ± 1.651**	**31.90 ± 0.283**
Austin A3-3		**57.40 ± 2.168**	**4.28 ± 2.350**	**38.32 ± 1.657**
TTU Greenhouse-1		**21.30 ± 4.160**	**64.52 ± 4.008**	**14.18 ± 3.383**
TTU Greenhouse-2		**21.55 ± 4.236**	**64.75 ± 3.682**	**13.70 ± 2.729**
TTU Greenhouse-3		**24.44 ± 1.565**	**61.59 ± 2.512**	**13.97 ± 2.880**
TTU PSS-1		**26.97 ± 2.391**	**54.93 ± 4.274**	**18.10 ± 2.618**
TTU PSS-2		**26.74 ± 2.192**	**56.64 ± 1.912**	**16.62 ± 0.344**
TTU PSS-3		**29.38 ± 2.391**	**54.53 ± 1.739**	**16.09 ± 0.680**
TTU PSS Sandy Soil-1		**4.04 ± 0.069**	**94.46 ± 0.985**	**1.50 ± 1.046**
TTU PSS Sandy Soil-2		**4.45 ± 0.774**	**93.12 ± 1.539**	**2.43 ± 0.838**
TTU PSS Sandy Soil-3		**4.45 ± 0.774**	**93.12 ± 1.539**	**2.43 ± 0.838**
TTU PSS101-505-Avg-1		**19.07 ± 2.822**	**63.08 ± 3.305**	**17.94 ± 6.034**
TTU PSS101-505-Avg-2		**17.88 ± 1.525**	**64.13 ± 4.429**	**18.08 ± 5.875**
TTU PSS101-505-Avg-3		**18.01 ± 1.707**	**64.32 ± 4.507**	**17.75 ± 6.103**

Table 3. Comparison of Saxton et al.(1986) model predicted soil saturated hydraulic conductivity (SSHC), the NRCS predicted SSHC, and field measured final infiltration rate (FIR).

ID	Saxton predicted SSHC, in/hr	NRCS predicted SSHC, in/hr (Adapted from NRCS web)	Field measured FIR, in/hr
LBB090101-090105	0.23	1.984-5.953(Amarillo)	0.19,2.27,4.57
LBB090201-090205	0.13	0.5669-1.984(Acuff)	0.16,0.27,0.49
LBB090112001090112005	3.93	0.57-1.98(sand**)	9.93,4.17,4.10
Hou-sugarland-A	0.07	0.0014-0.0595(Brazoria)	0.08
Hou-sugarland-B	0.07	0.0014-0.0595(Brazoria)	2.02
Hou-sugarland-C	0.07	0.0014-0.0595(Brazoria)	0.12
Hou-9225-A	1.06	0.57-1.98(Aris)	0.43
Hou-9225-B	0.96	0.57-1.98(Gessner)	0.04
Hou-9225-C	0.48	0.57-1.98(Aris)	0.10
Hou-9527-A	1.06	0.0595-0.1984(Bernard)	0.70
Hou-9527-B	0.21	0.0014-0.0595(Lake charles)	0.78
Austin-A1-1	0.08	0.0595-1.984(Comfort)	23.56
Austin-A1-2	0.42	0.57-1.98(Brackett)	2.59
Austin-A1-3	0.40	0.57-1.98(Brackett)	3.83
Austin-A2-1	0.12	0.57-1.98(Sunev)	0.04
Austin-A2-2	0.13	0.57-1.98(Sunev)	0.09
Austin-A2-3	0.14	0.57-1.98(Sunev)	0.44
Austin-A3-1	0.13	0.1984-0.5669(Doss)	0.62
Austin-A3-2	0.13	0.1984-0.5669 (Doss)	1.40
Austin-A3-3	0.11	0.1984-0.5669 (Doss)	2.67
Dallas- D1-1	1.21	1.98-5.95(Gasil)	0.22
Dallas- D1-2	1.24	1.98-5.95(Gasil)	0.32
Dallas- D1-3	1.01	1.98-5.95(Gasil)	5.78
Dallas- D2-1	1.60	1.984-5.9527(Aubrey)	0.76
Dallas- D2-2	0.10	0.57-1.98(Rayex)	0.03
Dallas- D2-3	1.01	0.57-1.98(Rayex)	0.03
Dallas- D3-1	0.08	0.0014-0.0595(Houston black)	0.35
Dallas- D3-2	0.11	0.0014-0.0595(Houston black)	0.64

Table 4. Overall ranking of the evaluated soil infiltration models at the studied lawn soil.

Models	Philip	Kostiakov	Mezencev	NRCS	Horton
Scores	34	26	12	35	13
Final ranking	4	3	1	5	2

Note: NRCS means the model developed by the United States Department of Agriculture Natural Resources Conservation Service (originally the United States Soil Conservation Service)

One of the objectives for irrigation and drainage engineers, soil physicists, and hydrologists is to develop effective methods to estimate soil saturated hydraulic conductivity based on readily available soil survey data. Although a few models have been derived from large ranges of soil texture data and successfully applied to many kinds of hydrologic analysis of agricultural lands and watersheds, there are few efforts to specifically investigate those models in soils with healthy grass growing. This field study was conducted to investigate and compare the performance of three readily-applied models including the Campbell model, the Saxton model, and the Smettem and Bristow model in the tested soils with established grass from the Lubbock location. The results (Table 5) showed that the two-parameter models of Campbell and Saxton et al. had better performance than the one-parameter model by Smettem and Bristow. The downside of all three models is that they need to be calibrated with local data for improved accuracy if they are applied in other Texas grassed soils, or even some new methods or models need to be developed with acceptable accuracy and the same simplicity level as these investigated models. Again, more detailed results can be found in Duan et al. (2011).

Based upon the results obtained from the initial tests conducted comparing the data collected at the Lubbock area location with various published models, the next was to analyze the entire data set from the standpoint of some of the more widely used models (Cuenca, 1989), the Kostiakov, the SCS (now called NRCS), the Horton, along with a variation of the SCS and Horton equations called the TTU and TTU2 equations, respectively (Table 6). The first thing to notice is that the Kostiakov, SCS, and the TTU equations do not meet the rules of achieving the boundary conditions of the infiltration process. They are all three quite simplistic, curve-fit models and they also require calibration with field data since the coefficients are all calibration coefficients. This does not necessarily mean that they are of no value, which can be understood when examining the results shown in Tables 6 through 10.

The infiltration rate begins with a positive value (the ‘B’ coefficient), which is estimated to be dependent on initial soil moisture and decays (the ‘C’ coefficient) to a final, constant value (the ‘A’ coefficient), which represents the final saturated hydraulic conductivity.

As is shown in Table 6, the SCS equation is a slight modification to the Kostiakov equation in that it contains an extra coefficient that sets the final infiltration as a constant. After analyzing some of the initially collected data using the SCS equation, the poor results indicated that the constant of 0.6985 may not be valid and could be allowed to vary to increase it predictability. Thus, the SCS equation was modified to the TTU equation where the constant was changed to a variable. As you can see from Tables 7 through 9, the Kostiakov equation predicts the measured data fairly well and better than the SCS equation, but the TTU equation is even a slightly better predictor overall. The anomaly with the TTU equation is that the c coefficient falls below zero for a few of the sites, which is physically impossible considering that it represents the saturated hydraulic conductivity.

The biggest issue concerning the use of any of these equations is the fact that none of them adhere to both boundary conditions of the physical processes that occur during the infiltration process. Therefore, since the Horton equation showed that it was rated as the number 2 model (Table 4) and the fact that it fits the boundary conditions of the infiltration process, it was determined that further evaluation should be considered. The reason the model rated as number one from the previous analysis was not considered was because it is similar to the TTU model and that also means that it does not adhere to the boundary conditions of the process.

Table 5. The performance of three soil saturated hydraulic conductivity models for several different turf plots in Texas.

Site	Campbell model			Smettem and Bristow model			Saxton et al. model		
	Error	Squared Error	Relative Error, %	Error	Squared Error	Relative Error, %	Error	Squared Error	Relative Error, %
Lubbock A	-14.6	211.8	-45	-27.0	731.4	-84	-26.7	713.2	-83
Lubbock B	3.7	13.7	53	-3.4	11.8	-49	-3.8	14.3	-54
Lubbock C	-51.8	2685.8	-35	-126.6	16016.4	-85	-50.0	2500.6	-34
Houston A-1	-53.5	2860.6	-74	-60.4	3647.5	-83	-45.6	2081.5	-63
Houston A-2	14.3	203.3	216	4.6	20.8	69	17.3	299.5	262
Houston A-3	12.0	145.0	463	4.5	20.6	174	8.6	73.2	329
Houston B-1	-124.9	15590.5	-92	-130.5	17036.0	-97	-130.0	16890.0	-96
Houston B-2	-130.0	16910.9	-92	-137.0	18767.6	-97	-136.4	18597.4	-96
Houston C-1	-34.7	1204.9	-93	-35.8	1283.8	-96	-35.5	1260.8	-95
Houston C-2	-368.9	136061.8	-99	-370.0	136870.4	-100	-369.6	136604.9	-100
Houston C-3	-11.6	135.1	-86	-12.3	150.9	-91	-11.6	135.3	-87
Austin A-1	-302.8	91690.2	-98	-302.2	91343.0	-98	-297.7	88649.6	-97
Austin A-2	-388.3	150811.9	-98	-391.7	153427.8	-98	-388.0	150529.6	-97
Austin B-1	-1.1	1.2	-69	-1.2	1.4	-73	1.6	2.5	98
Austin B-2	-25.2	635.0	-98	-25.3	639.2	-99	-22.3	498.3	-87
Austin B-3	-34.6	1194.1	-99	-34.6	1200.0	-99	-31.5	993.3	-90
Austin C-1	-114.9	13211.7	-100	-115.0	13233.6	-100	-112.3	12622.1	-97
Austin C-2	-187.0	34953.3	-100	-187.0	34983.1	-100	-184.2	33930.9	-98
Austin C-3	-402.7	162200.2	-100	-402.7	162179.8	-100	-400.7	160535.5	-99
ME	-116.7			-123.9			-116.8		
SSE	630721.2			651565.0			626932.5		
MRE	-34			-69			-36		
RMSE	182.2			185.2			181.6		

Note: 1. ME = mean error (mm/h); SSE = sum of squared error (mm^2/h^2); MRE = mean relative error (%); RMSE = root of the mean square error (mm/h); 2. Unit of error: mm/h; unit of squared error: mm^2/h^2. The letter A, B, and C in the Site column represent the three separate locations in that region of the State, while the Numbers 1, 2, and 3 represent the replications taken at each site.

Table 6. List of the five models tested against the collected data.

Equation	Infiltration	Infiltration Rate
Kostiakov[1]	I(t)=a*t^b	i(t)=a*b*t^(b-1)
SCS[2]	I(t)=a*t^b+0.6985	i(t)=a*b*t^(b-1)
TTU	I(t)=a*t^b+c	i(t)=a*b*t^(b-1)
TTU2	I(t)=(a*t+b)(1-e^(-c*t))	i(t)=(e^(-c*t))(a*c*t +b*c - a) + a
Horton[3]	I(t)=a*t+((b-a)/c)(1-e^(-c*t))	i(t)=(b-a)*e^(-c*t)+a

I(t) = cumulative infiltration at time t, cm
i(t) = infiltration rate at time t, cm/min
t = time of infiltration, min
a = empirical constant, cm/min
b = empirical constant, unitless
c = empirical constant, cm

For the Horton and TTU2Equations, the coefficients are:

a = final infiltration rate (saturated hydraulic conductivity), cm/min
b = initial infiltration rate, cm/min
c = decay constant specific to soil type, 1/min

Tables 10 and 11 show that the Horton and the TTU2 equations are nearly identical in their predictive capability of the field tests sites. The primary difference between the two equations is that the infiltration rate predicted by the Horton equation (Figure 12) begins at a given value and immediately drops whereas the TTU2 equation (Figure 13) proceeds for a short period of time before the infiltration rate decreases, which appears to be more natural with what was actually observed in the field. The differences are quite small for these data sets, therefore further testing with wider variations in initial soil moisture and smaller variation is soil type need to be conducted.

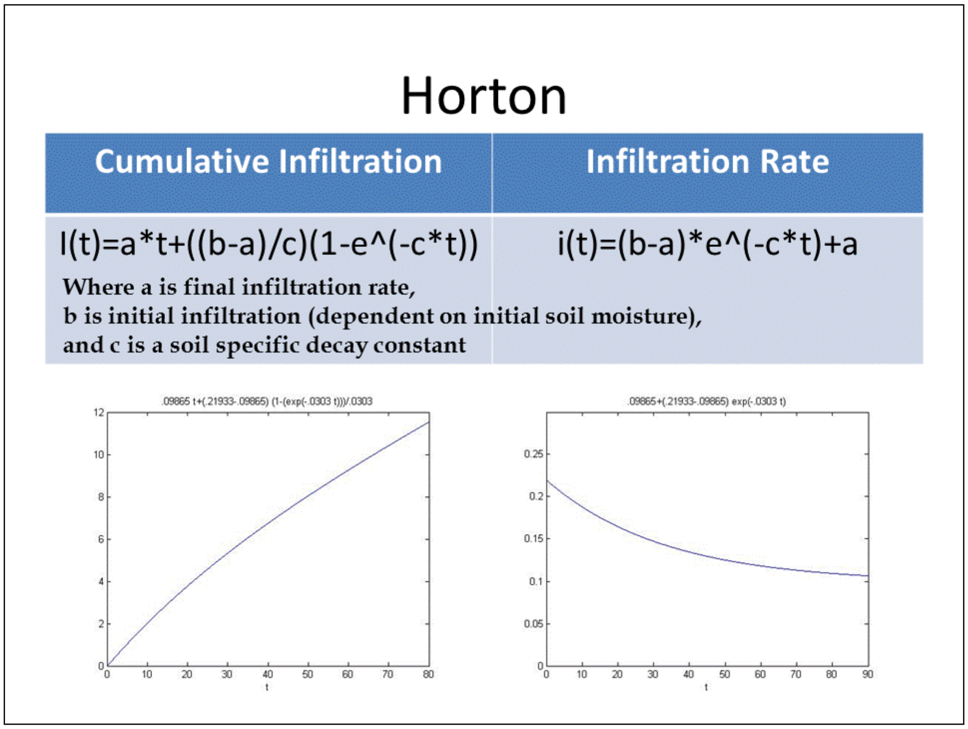


Figure 12. Boundary conditions for the Horton equation.

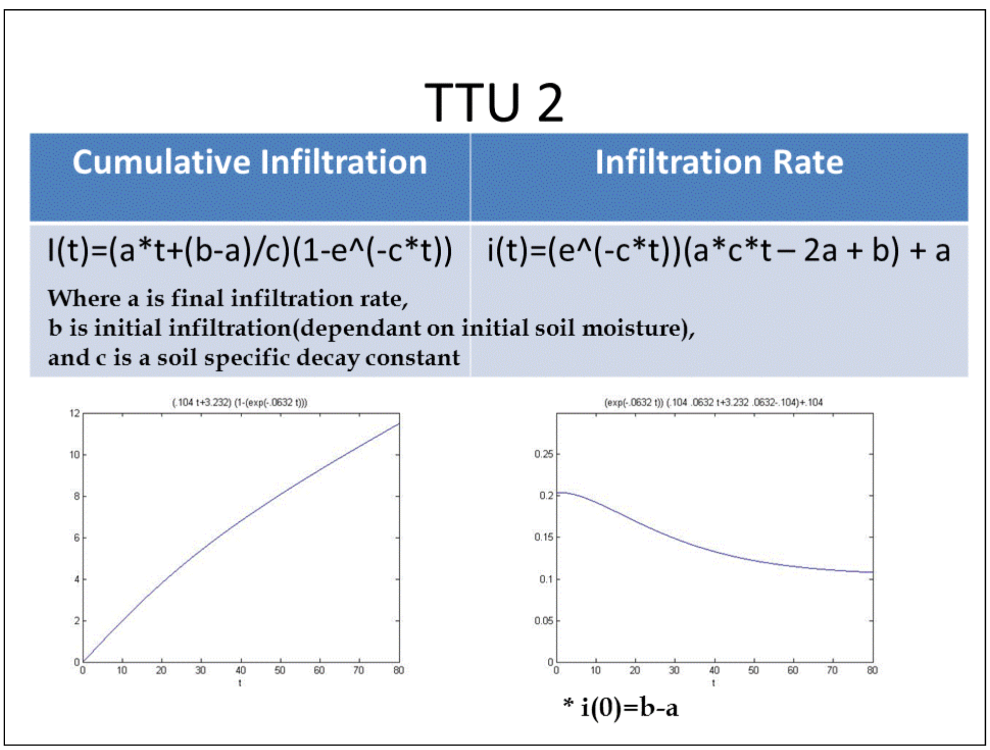


Figure 13. Boundary conditions for the TTU2 equation.

Table 7. Results of the Kastiakov model using the field data.

Site		Kostiakov: I=at^b						
		a	b	SSE	R-square	dfe	Adjusted R-square	rmse
Houston-H1, Replicate #1		0.128	0.522	0.040	0.981	8	0.979	0.071
Houston-H1, Replicate #2		0.371	0.783	0.146	1.000	8	0.999	0.135
Houston-H1, Replicate #3		0.037	0.605	0.018	0.943	7	0.935	0.051
Houston-H2, Replicate #1		0.034	0.914	0.093	0.991	8	0.989	0.108
Houston-H2, Replicate #2		0.066	0.390	0.010	0.885	7	0.868	0.038
Houston-H2, Replicate #3		0.032	0.631	0.027	0.937	8	0.929	0.058
Houston-H3, Replicate #1		0.195	0.681	0.035	0.999	9	0.999	0.062
Houston-H3, Replicate #2		0.149	0.744	0.160	0.997	9	0.996	0.133
Dallas-D1, Replicate #1		1.330	0.197	0.027	0.990	8	0.989	0.059
Dallas-D1, Replicate #2		0.918	0.240	0.035	0.980	7	0.977	0.071
Dallas-D1, Replicate #3		1.428	0.636	8.657	0.992	10	0.991	0.930
Dallas-D2 , Replicate #1		0.011	0.728	0.004	0.910	5	0.892	0.029
Dallas-D2 , Replicate #2		1.764	0.364	6.706	0.916	9	0.907	0.863
Dallas-D2 , Replicate #3		0.162	0.330	0.012	0.949	7	0.942	0.041
Dallas-D3, Replicate #1		0.032	0.828	0.018	0.995	8	0.994	0.048
Dallas-D3, Replicate #2		0.197	0.667	0.046	0.998	8	0.998	0.075
Austin-A1, Replicate #1		1.152	0.976	2.652	1.000	11	1.000	0.491
Austin-A1, Replicate #2		0.229	0.836	0.351	0.998	8	0.998	0.209
Austin-A1, Replicate #3		0.237	0.923	0.258	0.999	7	0.999	0.192
Austin-A2, Replicate #1		0.006	0.683	0.001	0.721	1	0.443	0.024
Austin-A2, Replicate #2		0.034	0.639	0.000	1.000	5	1.000	0.006
Austin-A2, Replicate #3		0.171	0.664	0.007	0.999	8	0.999	0.029
Austin-A3, Replicate #1		0.151	0.730	0.053	0.998	8	0.998	0.082
Austin-A3, Replicate #2		0.295	0.721	0.032	0.999	7	0.999	0.068
Austin-A3, Replicate #3		0.477	0.745	0.085	1.000	8	1.000	0.103
TTU Greenhouse, Replicate #1		1.635	0.336	1.586	0.957	11	0.954	0.380
TTU Greenhouse, Replicate #2		1.095	0.537	0.253	0.998	9	0.998	0.168
TTU Greenhouse, Replicate #3		0.539	0.793	0.106	0.999	8	0.999	0.115
TTU PSS, Replicate #1		0.060	0.660	0.026	0.970	5	0.964	0.072
TTU PSS, Replicate #2		0.123	0.474	0.008	0.983	5	0.980	0.039
TTU PSS, Replicate #3		0.047	0.832	0.058	0.995	11	0.995	0.072
TTU PSS Sandy Soil, Rep #1		1.198	0.843	1.158	1.000	10	1.000	0.340
TTU PSS Sandy Soil, Rep #2		1.439	0.632	1.927	0.997	8	0.996	0.491
TTU PSS Sandy Soil, Rep #3		1.006	0.700	2.799	0.995	7	0.994	0.632
TTU PSS101-505-1 Avg		0.078	0.757	0.005	0.999	6	0.999	0.030
TTU PSS101-505-2 Avg		0.038	0.761	0.005	0.998	7	0.997	0.026
TTU PSS101-505-3 Avg		0.071	0.814	0.003	1.000	6	1.000	0.022
Avg		0.458	0.657		0.975		0.965	0.172
Stddev		0.548	0.190		0.052		0.094	0.230

Table 8. Results of the SCS (NRCS) model using the field data.

Site		SCS: I=at^b+.6985						
		a	b	SSE	R-square	dfe	Adjusted R-square	rmse
Houston-H1, Replicate #1		0.007	1.000	0.472	0.781	9	0.781	0.229
Houston-H1, Replicate #2		0.254	0.852	0.598	0.998	8	0.998	0.273
Houston-H1, Replicate #3		NA	NA	NA	NA	NA	NA	NA
Houston-H2, Replicate #1		0.016	1.000	1.296	0.868	9	0.868	0.379
Houston-H2, Replicate #2		NA	NA	NA	NA	NA	NA	NA
Houston-H2, Replicate #3		NA	NA	NA	NA	NA	NA	NA
Houston-H3, Replicate #1		0.066	0.872	0.218	0.995	9	0.994	0.156
Houston-H3, Replicate #2		0.048	0.946	0.280	0.994	9	0.993	0.176
Dallas-D1, Replicate #1		0.758	0.267	0.025	0.991	8	0.990	0.056
Dallas-D1, Replicate #2		0.402	0.358	0.031	0.982	7	0.980	0.067
Dallas-D1, Replicate #3		1.227	0.663	9.857	0.990	10	0.989	0.993
Dallas-D2 , Replicate #1		NA	NA	NA	NA	NA	NA	NA
Dallas-D2 , Replicate #2		1.378	0.400	7.593	0.905	9	0.895	0.919
Dallas-D2 , Replicate #3		NA	NA	NA	NA	NA	NA	NA
Dallas-D3, Replicate #1		0.007	1.000	1.208	0.658	9	0.658	0.366
Dallas-D3, Replicate #2		0.056	0.896	0.111	0.995	8	0.995	0.118
Austin-A1, Replicate #1		1.061	0.993	3.414	1.000	11	1.000	0.557
Austin-A1, Replicate #2		0.136	0.933	0.745	0.996	8	0.996	0.305
Austin-A1, Replicate #3		0.159	1.000	0.115	1.000	8	1.000	0.120
Austin-A2, Replicate #1		NA	NA	NA	NA	NA	NA	NA
Austin-A2, Replicate #2		NA	NA	NA	NA	NA	NA	NA
Austin-A2, Replicate #3		0.029	1.000	0.627	0.948	9	0.948	0.264
Austin-A3, Replicate #1		0.042	0.963	0.441	0.984	8	0.983	0.235
Austin-A3, Replicate #2		0.147	0.854	0.091	0.998	7	0.998	0.114
Austin-A3, Replicate #3		0.340	0.807	0.197	0.999	8	0.999	0.157
TTU Greenhouse, Replicate #1		1.175	0.388	1.952	0.948	11	0.943	0.421
TTU Greenhouse, Replicate #2		0.761	0.607	0.372	0.997	9	0.997	0.203
TTU Greenhouse, Replicate #3		0.337	0.898	0.428	0.998	8	0.997	0.231
TTU PSS, Replicate #1		NA	NA	NA	NA	NA	NA	NA
TTU PSS, Replicate #2		0.003	1.000	0.315	0.307	6	0.307	0.229
TTU PSS, Replicate #3		0.014	1.000	0.932	0.923	12	0.923	0.279
TTU PSS Sandy Soil, Rep #1		1.098	0.859	1.070	1.000	10	1.000	0.327
TTU PSS Sandy Soil, Rep #2		1.206	0.665	1.174	0.998	8	0.998	0.383
TTU PSS Sandy Soil, Rep #3		0.817	0.740	1.619	0.997	7	0.997	0.481
TTU PSS101-505-1 Avg		0.018	1.000	0.569	0.942	7	0.942	0.285
TTU PSS101-505-2 Avg		0.005	1.000	0.809	0.590	8	0.590	0.318
TTU PSS101-505-3 Avg		0.023	1.000	0.692	0.953	7	0.953	0.314
Avg		0.400	0.826		0.922		0.921	0.309
Stddev		0.474	0.224		0.156		0.156	0.215

NA means that the model coefficients could not be determined adequately for the data.

Table 9. Results of the TTU equation to field data.

Site		TTU: I=at^b+c							
		a	b	c	SSE	R-square	dfe	Adjusted R-square	rmse
Houston-H1, Replicate #1		0.128	0.522	0.000	0.040	0.981	8	0.979	0.071
Houston-H1, Replicate #2		0.371	0.783	0.000	0.146	1.000	8	0.999	0.135
Houston-H1, Replicate #3		0.037	0.605	0.000	0.018	0.943	7	0.935	0.051
Houston-H2, Replicate #1		0.022	1.000	0.136	0.064	0.994	8	0.993	0.089
Houston-H2, Replicate #2		0.014	0.658	0.105	0.009	0.899	6	0.866	0.038
Houston-H2, Replicate #3		0.010	0.836	0.089	0.023	0.946	7	0.930	0.058
Houston-H3, Replicate #1		0.160	0.715	0.146	0.025	0.999	8	0.999	0.056
Houston-H3, Replicate #2		0.101	0.812	0.264	0.115	0.998	8	0.997	0.120
Dallas-D1, Replicate #1		0.846	0.253	0.586	0.025	0.991	7	0.989	0.060
Dallas-D1, Replicate #2		0.410	0.354	0.685	0.031	0.982	6	0.977	0.072
Dallas-D1, Replicate #3		1.428	0.636	0.000	8.657	0.992	10	0.991	0.930
Dallas-D2 , Replicate #1		0.011	0.728	0.000	0.004	0.910	4	0.865	0.033
Dallas-D2 , Replicate #2		1.764	0.364	0.000	6.706	0.916	9	0.907	0.863
Dallas-D2 , Replicate #3		0.162	0.330	0.000	0.012	0.949	6	0.932	0.044
Dallas-D3, Replicate #1		0.017	0.952	0.114	0.009	0.998	7	0.997	0.035
Dallas-D3, Replicate #2		0.124	0.750	0.290	0.013	0.999	7	0.999	0.043
Austin-A1, Replicate #1		1.152	0.976	0.000	2.652	1.000	11	1.000	0.491
Austin-A1, Replicate #2		0.229	0.836	0.000	0.351	0.998	7	0.998	0.224
Austin-A1, Replicate #3		0.176	0.981	0.501	0.080	1.000	6	1.000	0.115
Austin-A2, Replicate #1		0.001	0.984	0.038	0.001	0.749	0	0.000	0.000
Austin-A2, Replicate #2		0.031	0.659	0.010	0.000	1.000	4	0.999	0.006
Austin-A2, Replicate #3		0.171	0.664	0.000	0.007	0.999	8	0.999	0.029
Austin-A3, Replicate #1		0.151	0.730	0.000	0.053	0.998	7	0.998	0.087
Austin-A3, Replicate #2		0.229	0.769	0.271	0.006	1.000	6	1.000	0.031
Austin-A3, Replicate #3		0.435	0.762	0.199	0.066	1.000	7	1.000	0.097
TTU Greenhouse, Replicate #1		1.635	0.336	0.000	1.586	0.957	11	0.954	0.380
TTU Greenhouse, Replicate #2		1.065	0.543	0.058	0.252	0.998	8	0.998	0.178
TTU Greenhouse, Replicate #3		0.537	0.793	0.004	0.106	0.999	7	0.999	0.123
TTU PSS, Replicate #1		0.060	0.660	0.000	0.026	0.970	5	0.964	0.072
TTU PSS, Replicate #2		0.045	0.662	0.165	0.006	0.988	4	0.982	0.037
TTU PSS, Replicate #3		0.021	0.973	0.224	0.010	0.999	10	0.999	0.031
TTU PSS Sandy Soil, Rep #1		1.135	0.853	0.436	1.019	1.000	9	1.000	0.336
TTU PSS Sandy Soil, Rep #2		0.762	0.752	2.292	0.346	0.999	7	0.999	0.222
TTU PSS Sandy Soil, Rep #3		0.426	0.864	2.589	0.009	1.000	6	1.000	0.039
TTU PSS101-505-1 Avg		0.061	0.801	0.079	0.002	1.000	5	1.000	0.022
TTU PSS101-505-2 Avg		0.031	0.794	0.035	0.004	0.998	6	0.997	0.027
TTU PSS101-505-3 Avg		0.065	0.828	0.030	0.002	1.000	5	1.000	0.021
Avg		0.379	0.717	0.253		0.977		0.979	0.146
Stddev		0.495	0.197	0.560		0.048		0.037	0.214

Table 10. Results of the Horton equation to field data.

Site		Horton: I=at+b(1-e^(-ct))							
		a	(b-c)/a	c	SSE	R-square	dfe	Adjusted R-square	rmse
Houston-H1, Replicate #1		0.008	0.635	0.075	0.026	0.988	7	0.985	0.060
Houston-H1, Replicate #2		0.099	3.983	0.030	0.231	0.999	7	0.999	0.182
Houston-H1, Replicate #3		0.003	0.284	0.045	0.013	0.959	6	0.945	0.047
Houston-H2, Replicate #1		0.022	0.140	0.447	0.063	0.994	7	0.992	0.095
Houston-H2, Replicate #2		0.002	0.172	0.259	0.009	0.892	6	0.856	0.039
Houston-H2, Replicate #3		0.004	0.129	1.000	0.025	0.942	7	0.925	0.060
Houston-H3, Replicate #1		0.030	1.327	0.064	0.056	0.999	8	0.998	0.084
Houston-H3, Replicate #2		0.035	0.894	0.110	0.270	0.994	8	0.993	0.184
Dallas-D1, Replicate #1		0.009	2.334	0.260	0.024	0.992	7	0.989	0.059
Dallas-D1, Replicate #2		0.010	1.782	0.201	0.055	0.969	6	0.959	0.096
Dallas-D1, Replicate #3		0.150	11.821	0.039	5.873	0.994	9	0.993	0.808
Dallas-D2 , Replicate #1		0.000	0.411	0.014	0.003	0.944	4	0.917	0.026
Dallas-D2 , Replicate #2		0.016	7.877	0.051	0.469	0.994	8	0.993	0.242
Dallas-D2 , Replicate #3		0.003	0.434	0.132	0.018	0.922	6	0.896	0.055
Dallas-D3, Replicate #1		0.013	0.160	0.228	0.008	0.998	7	0.997	0.033
Dallas-D3, Replicate #2		0.031	1.054	0.111	0.027	0.999	7	0.999	0.062
Austin-A1, Replicate #1		0.783	81.311	0.004	2.583	1.000	10	1.000	0.508
Austin-A1, Replicate #2		0.089	1.894	0.040	0.313	0.998	7	0.998	0.212
Austin-A1, Replicate #3		0.160	0.693	0.247	0.061	1.000	6	1.000	0.101
Austin-A2, Replicate #1		0.001	0.039	0.538	0.001	0.750	0	0.000	0.000
Austin-A2, Replicate #2		0.004	0.202	0.069	0.001	0.998	4	0.996	0.016
Austin-A2, Replicate #3		0.026	0.972	0.079	0.008	0.999	7	0.999	0.033
Austin-A3, Replicate #1		0.030	1.296	0.041	0.066	0.998	7	0.997	0.097
Austin-A3, Replicate #2		0.065	1.610	0.094	0.041	0.999	6	0.999	0.083
Austin-A3, Replicate #3		0.113	3.321	0.061	0.127	1.000	7	1.000	0.135
TTU Greenhouse, Replicate #1		0.024	5.028	0.105	0.156	0.996	10	0.995	0.125
TTU Greenhouse, Replicate #2		0.097	3.877	0.173	0.087	0.999	8	0.999	0.104
TTU Greenhouse, Replicate #3		0.192	2.363	0.095	0.189	0.999	7	0.999	0.164
TTU PSS, Replicate #1		0.005	0.738	0.033	0.015	0.983	4	0.974	0.061
TTU PSS, Replicate #2		0.008	0.373	0.205	0.002	0.996	4	0.994	0.022
TTU PSS, Replicate #3		0.018	0.273	0.254	0.007	0.999	10	0.999	0.026
TTU PSS Sandy Soil, Rep #1		0.472	11.151	0.033	3.641	1.000	9	0.999	0.636
TTU PSS Sandy Soil, Rep #2		0.203	6.289	0.138	2.325	0.996	7	0.995	0.576
TTU PSS Sandy Soil, Rep #3		0.210	4.397	0.229	0.481	0.999	6	0.999	0.283
TTU PSS101-505-1 Avg		0.020	0.529	0.063	0.013	0.999	5	0.998	0.052
TTU PSS101-505-2 Avg		0.010	0.255	0.065	0.004	0.998	6	0.997	0.026
TTU PSS101-505-3 Avg		0.025	0.517	0.053	0.005	1.000	5	1.000	0.030
Avg		0.081	4.340	0.154		0.981		0.983	0.151
Stddev		0.151	13.330	0.185		0.046		0.034	0.188

Table11. Results of the TTU2 equation to field data.

Site		TTU2: I=(at+b)(1-e^(-ct))							
		a	**b**	**c**	**SSE**	**R-square**	**dfe**	**Adjusted R-square**	**rmse**
Houston-H1, Replicate #1		0.008	0.632	0.087	0.025	0.988	7	0.985	0.060
Houston-H1, Replicate #2		0.104	3.230	0.063	0.334	0.999	7	0.999	0.218
Houston-H1, Replicate #3		0.003	0.277	0.056	0.013	0.959	6	0.945	0.046
Houston-H2, Replicate #1		0.005	9.647	0.003	0.109	0.989	7	0.986	0.125
Houston-H2, Replicate #2		0.002	0.172	0.269	0.009	0.892	6	0.856	0.039
Houston-H2, Replicate #3		0.004	0.129	1.000	0.025	0.942	7	0.925	0.060
Houston-H3, Replicate #1		0.031	1.298	0.087	0.062	0.998	8	0.998	0.088
Houston-H3, Replicate #2		0.036	0.850	0.176	0.276	0.994	8	0.993	0.186
Dallas-D1, Replicate #1		0.009	2.334	0.264	0.024	0.991	7	0.989	0.059
Dallas-D1, Replicate #2		0.010	1.782	0.207	0.055	0.969	6	0.959	0.096
Dallas-D1, Replicate #3		0.152	11.489	0.052	5.820	0.994	9	0.993	0.804
Dallas-D2 , Replicate #1		0.000	0.387	0.015	0.003	0.945	4	0.918	0.026
Dallas-D2 , Replicate #2		0.016	7.872	0.053	0.468	0.994	8	0.993	0.242
Dallas-D2 , Replicate #3		0.003	0.434	0.139	0.018	0.922	6	0.895	0.055
Dallas-D3, Replicate #1		0.004	2.324	0.008	0.036	0.990	7	0.987	0.072
Dallas-D3, Replicate #2		0.031	1.046	0.140	0.029	0.999	7	0.998	0.064
Austin-A1, Replicate #1		1.023	1.031	0.465	3.052	1.000	10	1.000	0.552
Austin-A1, Replicate #2		0.090	1.678	0.084	0.330	0.998	7	0.998	0.217
Austin-A1, Replicate #3		0.160	0.690	0.391	0.059	1.000	6	1.000	0.099
Austin-A2, Replicate #1		0.001	0.039	0.443	0.001	0.750	0	0.000	0.000
Austin-A2, Replicate #2		0.004	0.198	0.091	0.001	0.997	4	0.996	0.017
Austin-A2, Replicate #3		0.026	0.954	0.106	0.009	0.999	7	0.999	0.035
Austin-A3, Replicate #1		0.031	1.163	0.070	0.074	0.997	7	0.997	0.103
Austin-A3, Replicate #2		0.066	1.572	0.134	0.049	0.999	6	0.999	0.091
Austin-A3, Replicate #3		0.114	3.174	0.095	0.176	0.999	7	0.999	0.159
TTU Greenhouse, Replicate #1		0.024	5.025	0.110	0.156	0.996	10	0.995	0.125
TTU Greenhouse, Replicate #2		0.097	3.866	0.197	0.092	0.999	8	0.999	0.107
TTU Greenhouse, Replicate #3		0.198	2.029	0.191	0.252	0.999	7	0.998	0.190
TTU PSS, Replicate #1		0.005	0.686	0.042	0.015	0.983	4	0.974	0.061
TTU PSS, Replicate #2		0.008	0.372	0.225	0.002	0.996	4	0.994	0.022
TTU PSS, Replicate #3		0.018	0.272	0.312	0.007	0.999	10	0.999	0.026
TTU PSS Sandy Soil, Rep #1		0.492	8.362	0.091	6.269	0.999	9	0.999	0.835
TTU PSS Sandy Soil, Rep #2		0.203	6.217	0.172	2.424	0.996	7	0.995	0.588
TTU PSS Sandy Soil, Rep #3		0.210	4.383	0.274	0.496	0.999	6	0.999	0.287
TTU PSS101-505-1 Avg		0.020	0.493	0.105	0.016	0.998	5	0.998	0.056
TTU PSS101-505-2 Avg		0.010	0.246	0.101	0.004	0.998	6	0.997	0.026
TTU PSS101-505-3 Avg		0.025	0.469	0.102	0.007	1.000	5	0.999	0.036
Avg		0.088	2.347	0.173		0.980		0.982	0.163
Stddev		0.185	2.909	0.181		0.046		0.033	0.207

When investigating the relationships between sand, silt, and clay and the various coefficients of the Horton and TTU2 Equations, no relationship could be derived. Figure 14 is an example of the relationship between the percent clay content of the soil and the "a" coefficient of the TTU2 Equation and even if you take out the outlier data point (Figure 15) no relationship exists. This was true for all coefficients when compared to the percent sand, silt, and clay. A similar result was found for the Horton Equation (not shown).

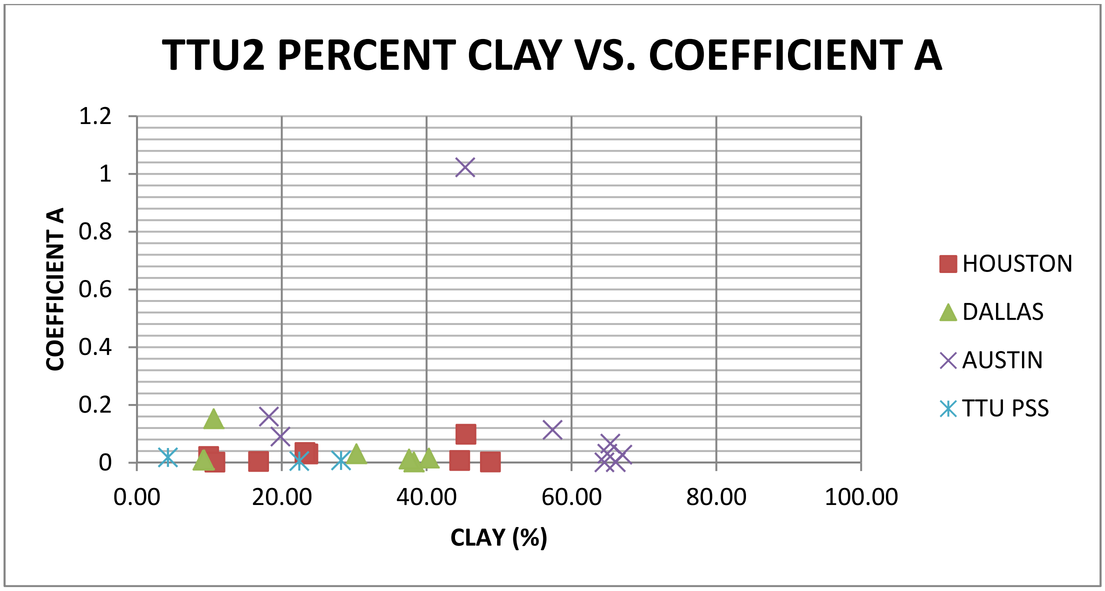


Figure 14. Relationship between the "A" coefficient from the TTU2 Equation and the percent clay content of the soil for all site locations.

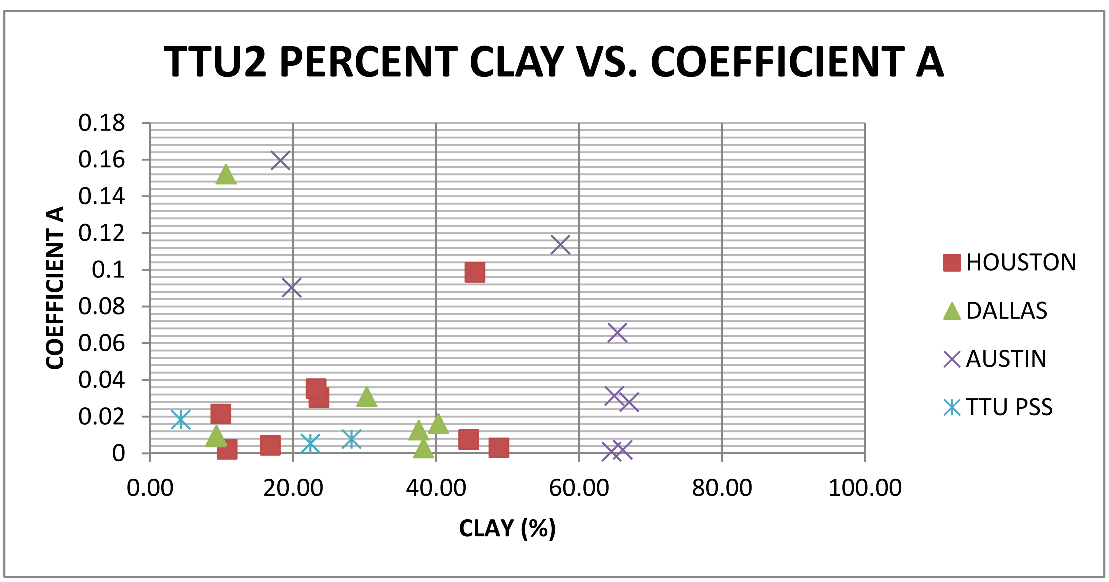


Figure 15. Relationship between the "A" coefficient from the TTU2 Equation and the percent clay content of the soil for all site locations with the outlier data removed.

Conclusions

Infiltration rate is the infiltration rate achieved when the rate changes by less than 10 percent over a one hour period. The infiltration curve becomes asymptotic to an infiltration rate approximately equal to the saturated permeability rate (also called the saturated hydraulic conductivity) of the soil. Normally the sprinkler irrigation application rate is set to this value as a conservative approach to a design. At this application rate no surface runoff should occur. However, the objective is not to apply water at a given rate but to apply a given depth of water.

The depth of water needing to be applied from an onsite system is relatively small (approximately 0.4 inches) because effluent storage of effluent in these systems is limited. Furthermore, the effluent is applied to a vegetated field that has a detention depth that the field can hold without surface runoff. This depth is approximately 0.2 inches.

If one plots the depth of application and the infiltration rate on the same graph, the minimum infiltration rate for the needed depth of application can be determined. This minimum infiltration rate can be used as the sprinkler application rate without any danger of surface runoff and with a margin of safety equal to the 0.2 inch detention depth for a vegetated field. For the depth of application generally used for onsite systems, the sprinkler application rate will be larger than a design infiltration rate determined by setting it equal to the saturated permeability rate.

More data needs to be obtained in order to develop a relationship between the soil characteristics and the coefficients in the models tested. Since the SCS (NRCS) model proved to be insufficient for the data from this research, the Kastiakov model or the TTU equation could be used where similar soil characteristics are available and the model coefficients can be used as provided. At this point, the Horton and TTU2 Equations are the only two that fit the boundary conditions and could be used also, if the soils characteristics are similar to those collected for this research, but both models are much more complicated to use at this time.

In order to more completely utilize the Horton and TTU2 Equations, the recommended next step is to gather a larger set of data to include these data (Appendix D), but from a much tighter set of soil conditions. Of course these added data should come from at least three different soil texture profiles from the soil texture triangle of the USDA.

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Appendix A

Detailed Double-ring Infiltrometer Installation Procedures

Record GPS coordinates, temperature and wind speed by corresponding devices
Data table should be prepared and printed out before infiltration test
The test site should be nearly level with grass, or a level surface should be prepared.
The test requires a distance of 12 ft away from each test spot
Driving Infiltration Rings into the ground with a hammer and wood blocks
If soil is hard, pour small amount of water around outer ring, and if the ground is too hard, driving rings with a jack is preferred
Place the driving cap on outer ring and center it. Place the wood block on the driving cap.
Drive the outer ring into the soil with blows of a heavy sledge on the wood block to a depth until 6 inches. Move wood block around the edge of the driving cap every one or two blows so that the ring will penetrate the soil uniformly. A second person standing on the wood block and driving cap will usually facilitate driving the ring, and reduce vibrations and disturbance.
At this time, one person will pour water into outer ring and the other will pour water into inner ring. Stopwatch will begin to record time when the water in the inner and outer ring has the same level.
The Mariette tubes are used to maintain a constant water head within the inner ring and annular space between the two rings
The appropriate schedule of readings may be determined only through experience. The time table will show in the following section.
Upon completion of the test, remove the rings from the soil, assisted by light hammering on the sides with a rubber hammer.
Soil samples were taken from an adjacent auger hole after the test. Label them well and put them in a container while transportation.

Appendix B

Hydrometer Test Procedures

Add 100ml of the HMP solution to a cylinder and make the volume to 1L with room temperature distilled water. Record time and mix completely. Lower the hydrometer into the solution and determine R_L. Periodically recheck R_L during the course of the hydrometer tests.

Weigh 100.0g of soil into a 600ml beaker, add 250ml of distilled water and 100ml of HMP solution, and allow the sample to soak overnight. For fine-textured soils-silts or clays, 10 to 20g may be adequate. For coarse sands, 60 to 100g will be needed in order to obtain reproducible results. Weigh another sample of the soil (10g) for determination of oven-dry weight. Dry overnight at 105^{o}c, cool and weigh. Transfer the HMP-treated sample to a dispersing cup and mix for 5 min with the electric mixer, or transfer the suspension to shaker bottles and shake overnight on horizontal shaker. Transfer the suspension to a sedimentation cylinder and add distilled water to bring the volume to 1L.

Allow time for the suspension to equilibrate thermally and record temperature. Insert plunger into cylinder and mix the contents thoroughly. Hold bottom of cylinder to prevent tipping. Dislodge sediment from the bottom using strong upward strokes of plunger. Finishing stirring with two or more slow, smooth strokes. Add a drop of amyl alcohol if the surface of the suspension is covered with foam.

As soon as mixing is completed, lower the hydrometer into the suspension and take readings after 30s and again at the end of 1min. Remove the hydrometer, rinse and wipe it dry. Reinsert the hydrometer carefully about 10s before each reading can be modified according to need. Remove and clean the hydrometer after placing it in the blank solution and record the blank reading as RL and the temperature at each time.

Quantitatively transfer the sediment and suspension from the 1L sedimentation cylinder through a 270-mesh sieve. A 20-cm-diameter sieve is placed over a sink. The sediment is washed onto the 53- screen using a wash bottle or gentle stream of water. The 53- screen can be dipped in a soap solution to improve the wettability of the screen and speed the flow. Transfer the sand to a tared beaker or AL weighing dish, dry and weigh. Transfer the dried sand to the nest of sieves arranged from top to bottom in the following order: 1000, 500, 250, 106 and 53. Shake on a sieve shaker for 3min. Weigh each sand fraction and the residual silt and clay that has passed through the 53 sieve.

Appendix C

Soil Characteristic Data Calculations Required

Soil moisture content

$$Mc = \frac{Wo - Wd}{Ww} * 100\ percent$$

Where Mc=moisture content, %

W_o=weight of original soil samples, g

W_d=weight of dry soil samples, g

W_w=weight of water, g

Specific gravity

$$Sp = \frac{(Wbd - Wb)}{(Wbd - Wb + Wfd - Wswf)} * 100$$

Where Sp=Specific gravity,

W_{bd}=Weight of bowl+ dry soil, g

W_b=Weight of bowl, g

W_{fd}=Weight of flask+ dry soil, g

W_{swf}=Weight of bowl+ soil+ flask, g

W_{bd}=Weight of bowl+ dry soil, g

Percentage of sand, silt and clay

The first step is to determine C, which is the concentration of soil in suspension in g/L.

$$\mathrm{C = R - RL}$$

R = the uncorrected hydrometer reading in g/L.

RL = the hydrometer reading of a bland solution.

The second step is to determine P, which is the summation percentage for the given interval.

$$P = \frac{C}{C0} * 100$$

C0= oven-dry weight of the soil sample.

The next step is to determine X, which is the mean particle diameter in suspension in µm at time t.

$$X=\theta t^{-1/2}$$

The unit of X and t are reported in µm and min, respectively.

Next is to determine θ, which is the sedimentation parameter.

$$\Theta=1000(Bh')^{1/2}$$

$$B = \frac{30\eta}{g(\rho s - \rho l)}$$

$$h'=-0.164R+16.3$$

h'=effective hydrometer depth,cm

η=fluid viscosity in poise, g/cm*s

ρs=soil particle density

ρl=solution density/cm^3

Lastly, from the hydrometer readings taken at 1.5 and 24 h the percentage of clay was determined. To do this, it is necessary to determine effective particle diameter X and summation percentage P for the 1.5 and 24 h readings. Then from the following equation, the percentage of clay can be computed.

$$P_{2\mu m}=m\ln(2/X24)+P24$$

The procedure of calculating the fraction of sand in the soil is similar to that for clay. Using the 30 and 60-s hydrometer readings instead and subtracting the computed P50µm value from 100, the percent of sand in the soil sample is determined.

$$P_{50\mu m}=m\ln(50/X60)+P60$$

Appendix D

Original Infiltration data

Project Identification	**Houston-H1**		
Date	3/17/2010	**Air Temperature**	60.2 F
Test Location	Houston-Sugarland	**Soil Sample ID**	Hou-SL-A,B,C
Wind velocity	3MPH	**Soil Moisture**	tested in the lab
Soil temperature	58 F	**Tested By**	Li, Fedler, Borrolli

Replicate #1		Replicate #2		Replicate #3	
Latitude	Longitude	Latitude	Longitude	Latitude	Longitude
N29°34.408'	W95°39.004'	N29°34.395'	W95°3.'005'	N29°34.378'	W95°39.015'
Time, min	Cumulative volume, ml	Time, min	Cumulative volume, ml	Time, min	Cumulative volume, ml
0	0	0	0	0	0
5	170	5	950	5	50
10	270	10	1525	10	50
20	490	20	2815	20	200
30	600	30	3895	30	200
40	690	40	4885	40	305
50	690	50	5715	50	305
60	800	60	6715	60	305
90	900	90	9245	90	380
120	1200	120	11665	120	490
150	1270	150	13540		

Project Identification	**Houston-H2**		
Date	3/18/2010	**Air Temperature**	56.5 F
Test Location	Houston-9225	**Soil Sample ID**	Hou-9225-A,B,C
Wind velocity	0.29MPH	**Soil Moisture**	tested in the lab
Soil temperature	58.5 F	**Tested By**	Li, Fedler, Borrolli

Replicate #1		Replicate #2		Replicate #3	
Latitude	Longitude	Latitude	Longitude	Latitude	Longitude
N29^{o}46.854'	W95^{o}27.996'	N29^{o}46.852'	W95^{o}27.998'	N29^{o}46.829'	W95^{o}28.094'
Time, min	Cumulative volume, ml	Time, min	Cumulative volume, ml	Time, min	Cumulative volume, ml
0	0	0	0	0	0
5	150	5	110	5	115
10	350	10	110	10	115
20	420	20	175	20	115
30	550	30	175	30	215
40	750	40	175	40	215
50	750	50	175	50	215
60	1075	60	275	60	380
90	1495	90	275	90	380
120	2045	127	325	120	470
150	2445			150	560

Project Identification	**Houston-H3**		
Date	3/19/2010	**Air Temperature**	54.6 F
Test Location	9527 Wickinbury	**Soil Sample ID**	Hou-9527-A,B,C
Wind velocity	3MPH	**Soil Moisture**	tested in the lab
Soil temperature	54 F	**Tested By**	Li, Fedler, Borrolli

Replicate #1		Replicate #2		3rd replicate not taken: Unobtainable	
Latitude	Longitude	Latitude	Longitude		
N29°38.516'	W95°32.783'	N29°38.516'	W95°32.786'		
Time, min	Cumulative volume, ml	Time, min	Cumulative volume, ml		
0	0	0	0		
5	490	5	510		
10	650	10	745		
20	1150	20	945		
30	1480	30	1290		
40	1690	40	1640		
50	2040	50	1965		
60	2290	60	2210		
90	3015	90	3150		
120	3685	120	3950		
150	4275	150	4450		
180	4925	180	5170		

Project Identification	**Dallas-D1**		
Date	10/9/2010	**Air Temperature**	61.7 F
Test Location	1055 Paigs St. Aubrey TX	**Soil Sample ID**	Da-A1-1,2,3
Wind velocity	3MPH	**Soil Moisture**	tested in the lab
Soil temperature		**Tested By**	Li, Fedler, Richard

Replicate #1		Replicate #2		Replicate #3	
Latitude	Longitude	Latitude	Longitude	Latitude	Longitude
N33^{o}17'249"	W96^{o}59.512'	N33^{o}17.252'	W96^{o}59.508'	N33^{o}17.246'	W96^{o}59.516'
Time, min	Cumulative volume, ml	Time, min	Cumulative volume, ml	Time, min	Cumulative volume, ml
0	0	0	0	0	0
5	1300	8	1125	5	2500
10	1600	10	1175	10	4075
20	1775	20	1400	15	5500
30	1875	30	1475	20	6700
40	2000	40	1575	25	7950
50	2060	50	1675	30	8950
60	2140	60	1775	35	10100
90	2340	90	2075	45	12225
120	2465	120	2075	55	13975
150	2665			65	15725
				125	20975
				155	26325

Project Identification	Dallas-D2		
Date	10/10/2010	**Air Temperature**	69.8 F
Test Location	Sprinkler Site	**Soil Sample ID**	Da-A2-1,2,3
Wind velocity	2.2	**Soil Moisture**	tested in the lab
Soil temperature		**Tested By**	Li, Fedler, Richard

Replicate #1		Replicate #2		Replicate #3	
Latitude	Longitude	Latitude	Longitude	Latitude	Longitude
N33^{o}15.217'	W97^{o}0.935'	N33^{o}15.221'	W97^{o}0.949'	N33^{o}15.220'	W97^{o}0.943'
Time, min	Cumulative volume, ml	Time, min	Cumulative volume, ml	Time, min	Cumulative volume, ml
0	0	0	0	0	0
10	25	5	1100	6	200
20	50	10	2250	10	275
30	100	15	3335	20	275
40	150	20	3975	30	375
50	150	25	4525	40	375
60	175	30	5025	50	475
90	200	40	5500	60	475
120	200	50	5875	90	525
		80	6325	120	550
		110	7225		
		184	7925		

Project Identification	Dallas-D3		
Date	10/11/2010	**Air Temperature**	61.5 F
Test Location	805 Melinda Drive	**Soil Sample ID**	Da-A2-1,2,3
Wind velocity	3MPH	**Soil Moisture**	tested in the lab
Soil temperature		**Tested By**	Li, Fedler, Richard

Replicate #1		Replicate #2		3rd replicate not taken: very little infiltration	
Latitude	Longitude	Latitude	Longitude		
N33°05.249'	W96°38.280'	N33°05.110'	W96°38.279'		
Time, min	Cumulative volume, ml	Time, min	Cumulative volume, ml		
0	0	0	0		
5	125	5	480		
10	200	10	750		
20	300	20	1075		
30	400	30	1425		
40	500	40	1650		
50	575	50	1875		
60	650	60	2150		
90	1000	90	2860		
120	1200	120	3510		
150	1525	150	4100		

Project Identification	**Austin-A1**		
Date	5/18/2010	**Air Temperature**	78F
Test Location	4161 E. Hwy. 290	**Soil Sample ID**	Austin-A1-1,2,3
Wind velocity	3MPH	**Soil Moisture**	
Soil temperature	54 F	**Tested By**	Fedler, Borrolli,Jordan

Replicate #1		Replicate #2		Replicate #3	
Latitude	Longitude	Latitude	Longitude	Latitude	Longitude
N30^{o}11.857'	W98^{o}0.966'	N30^{o}11.868'	W98^{o}1.013'	N30^{o}11.895'	W98^{o}1.103'
Time, min	Cumulative volume, ml	Time, min	Cumulative volume, ml	Time, min	Cumulative volume, ml
0	0	0	0	0	0
3	2300	5	625	5	910
6	4900	10	1125	10	1690
10	8050	20	1975	20	2770
15	11850	30	2950	30	3970
20	15700	40	3700	40	5220
30	23000	50	4420	50	6420
40	30350	60	5150	60	7420
50	37850	90	7375	90	10920
60	46650	120	8835	120	14520
70	53250	150	11235		
80	60500				
90	67750				
100	75025				

Project Identification	**Austin-A2**		
Date	5/19/2010	**Air Temperature**	73F
Test Location	Hays Country Acres Bd.	**Soil Sample ID**	Austin-A2-1,2,3
Wind velocity	3MPH	**Soil Moisture**	
Soil temperature	54 F	**Tested By**	Fedler, Borrolli,Jordan

Replicate #1		Replicate #2		Replicate #3	
Latitude	Longitude	Latitude	Longitude	Latitude	Longitude
N30°10.936'	W98°2.720'	N30°10.940'	W98°2.720'	N30°10.939'	W98°2.718'
Time, min	Cumulative volume, ml	Time, min	Cumulative volume, ml	Time, min	Cumulative volume, ml
60	75	0	0	0	0
90	75	5	75	2	175
120	115	13	125	4	300
		30	215	7	445
		49	415	10	575
		86	435	13	675
		105	485	20	925
		113	510	30	1225
		131	560	40	1465
				50	1640
				64	1715
				90	2615
				120	2995

Project Identification	**Austin-A3**		
Date	5/20/2010	**Air Temperature**	75F
Test Location	Deerfield Rd.	**Soil Sample ID**	Austin-A3-1,2,3
Wind velocity	3MPH	**Soil Moisture**	
Soil temperature	54 F	**Tested By**	Fedler, Borrolli,Jordan

Replicate #1		Replicate #2		Replicate #3	
Latitude	Longitude	Latitude	Longitude	Latitude	Longitude
N30°10.738'	W98°2.388'	N30°10.700'	W98°2.394'	N30°10.518'	W98°2.341'
Time, min	Cumulative volume, ml	Time, min	Cumulative volume, ml	Time, min	Cumulative volume, ml
0	0	0	0	0	0
5	320	5	750	5	1175
10	540	10	1200	10	2000
20	1020	20	1900	20	3300
30	1380	30	2480	30	4420
40	1540	40	3055	40	5420
50	1930	50	3555	50	6410
60	2130	60	4085	60	7335
90	3010	90	5535	90	9960
120	3640	120	6835	120	12210
150	4210			150	14710

Project Identification	**TTU Greenhouse**		
Date	10/13/2009	**Air Temperature**	85.5 F
Test Location	Greenhouse on campus	**Soil Sample ID**	090101-090105
Wind velocity	3MPH	**Soil Moisture**	tested in the lab
Soil temperature	84 F	**Tested By**	Li, Fedler, Duan

Replicate #1		Replicate #2		Replicate #3	
Latitude	Longitude	Latitude	Longitude	Latitude	Longitude
N33.58887^{o}	W101.88091^{o}	N33.58885^{o}	W101.88105^{o}	N33.58888^{o}	W101.88093^{o}
Time, min	Cumulative volume, ml	Time, min	Cumulative volume, ml	Time, min	Cumulative volume, ml
0	0	0	0	0	0
3	1100	2	1000	2	680
8	2100	4	1780	4	1220
10	2700	10	2940	6	1660
13	3000	20	4070	10	2380
20	3450	30	4930	15	3230
25	3850	40	5680	20	4330
35	4155	50	6480	30	5800
45	4375	60	7100	40	7450
55	4650	70	7800	50	8675
65	4875	80	8430	60	10085
75	5050	90	9130		
85	5150				
95	5210				

Project Identification	**TTU PSS**		
Date	11/6/2009	**Air Temperature**	85.5 F
Test Location	PSS: 090201-090205	**Soil Sample ID**	090201-090205
Wind velocity	3MPH	**Soil Moisture**	tested in the lab
Soil temperature	84 F	**Tested By**	Li, Fedler, Duan

Replicate #1		Replicate #2		Replicate #3	
Latitude	Longitude	Latitude	Longitude	Latitude	Longitude
N33°35.963'	W101°54.516'	N33°35.895'	W101°54.516'	N33°35.963'	W101°54.516'
Time, min	Cumulative volume, ml	Time, min	Cumulative volume, ml	Time, min	Cumulative volume, ml
0	0	0	0	0	0
5	40	5	200	5	210
10	180	15	350	10	320
15	280	35	475	20	450
20	380	45	525	30	625
30	405	60	600	40	750
60	680	75	675	50	875
90	830	90	800	60	995
				70	1125
				80	1275
				90	1385
				120	1835
				150	2185
				180	2635

Project Identification	**TTU PSS Sandy Soil**		
Date	11/20/2009	**Air Temperature**	85.5 F
Test Location	PSS sand	**Soil Sample ID**	09112001-09112005
Wind velocity	3MPH	**Soil Moisture**	tested in the lab
Soil temperature	84 F	**Tested By**	Li, Fedler, Duan

Replicate #1		Replicate #2		Replicate #3	
Latitude	Longitude	Latitude	Longitude	Latitude	Longitude
N33°35.863'	W101°54.499'	N33°35.795'	W101°54.499'	N33°35.863'	W101°54.431'
Time, min	Cumulative volume, ml	Time, min	Cumulative volume, ml	Time, min	Cumulative volume, ml
0	0	0	0	0	0
5	3800	5	3630	5	3120
10	6170	10	4850	10	4190
20	10970	15	5800	20	6040
30	15200	20	6880	30	7740
40	19400	30	8700	40	9390
50	23500	40	10660	50	11070
60	27470	50	12340	60	12590
80	35070	60	13960	90	17070
100	42570	90	17820	120	21370
120	49810	120	22080		
140	56500	150	26140		
160	62630	180	30000		

Project Identification	TTU PSS101-505-1		
Date	10/1/2010	**Air Temperature**	84 F
Test Location	PSS	**Soil Sample ID**	PSS101-505
Wind velocity	3MPH	**Soil Moisture**	tested in the lab
Soil temperature	84 F	**Tested By**	Li, Fedler, Duan

Replicate #1		Replicate #2		Replicate #3	
Latitude	Longitude	Latitude	Longitude	Latitude	Longitude
N33°63.05'	W101°90.85'	N33°36.169'	W101°54.591'	N33°36.237'	W101°54.510'
Time, min	volume, ml	Time, min	volume, ml	Time, min	volume, ml
0	0	0	0	0	0
5	400	5	100	5	200
10	675	10	100	10	200
15	975	20	100	20	310
20	1250	30	175	30	360
30	1640	40	175	40	420
60	2990	50	175	50	500
90	4190	60	175	60	550
120	5320	90	250	90	660
150	6320	120	300	120	800
		150	300	150	900
		180	350		

Project Identification	TTU PSS101-505-2		
Date	10/6/2010	**Air Temperature**	84 F
Test Location	PSS	**Soil Sample ID**	PSS101-505
Wind velocity	3MPH	**Soil Moisture**	tested in the lab
Soil temperature	84 F	**Tested By**	Li, Fedler, Duan

Replicate #1		Replicate #2		Replicate #3	
Latitude	Longitude	Latitude	Longitude	Latitude	Longitude
N33°36.295'	W101°54.621'	N33°36.170'	W101°54.510'	N33°36.238'	W101°54.509'
Time, min	volume, ml	Time, min	volume, ml	Time, min	volume, ml
0	0	0	0	0	0
5	200	5	100	10	50
10	310	10	100	20	80
20	660	20	150	30	100
30	760	30	200	40	140
40	1040	40	260	50	140
50	1110	50	300	60	240
60	1270	60	300	90	290
90	1820	90	400	120	340
120	2330	120	500	150	390
150	2740	150	600		

Project Identification	TTU PSS101-505-3		
Date		**Air Temperature**	84 F
Test Location	PSS	**Soil Sample ID**	PSS101-505
Wind velocity	3MPH	**Soil Moisture**	tested in the lab
Soil temperature	84 F	**Tested By**	Li, Fedler, Duan

Replicate #1		Replicate #2		Replicate #3	
Latitude	Longitude	Latitude	Longitude	Latitude	Longitude
N33°36.305'	W101°54.51'	N33°36.168'	W101°54.512'	N33°36.237'	W101°54.507'
Time, min	volume, ml	Time, min	volume, ml	Time, min	volume, ml
0	0	0	0	0	0
5	200	5	300	5	100
10	450	10	300	10	250
20	800	20	430	20	600
30	1050	30	430	30	1000
40	1270	40	520	60	1950
50	1570	50	570	90	3100
60	1670	60	620	120	4100
90	2195	90	750	150	5125
120	2645	120	870		
150	3045	150	970		
180	3420				