

## Measuring Saturated Hydraulic Conductivity in Soil

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The purpose of this document is to provide guidance on measuring water movement through in situ saturated soil (saturated hydraulic conductivity, or  $K_{sat}$ ) as it relates to dispersal and treatment of on-site sewage (wastewater) through an on-site wastewater dispersal area (drainfield) such as that in figure 1.

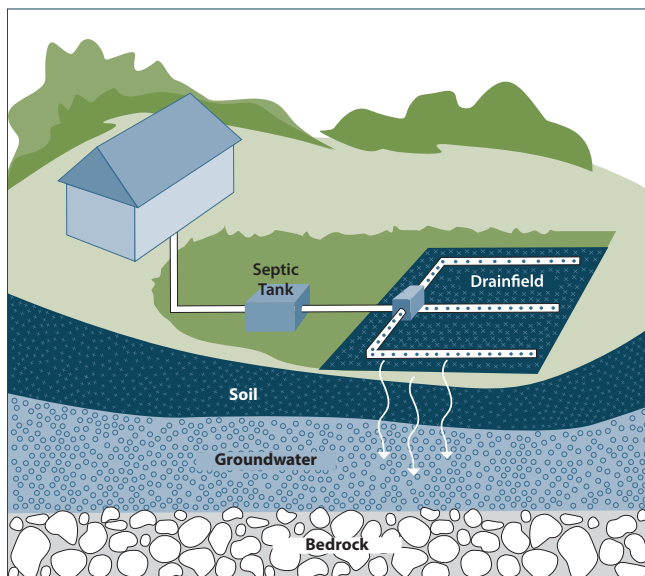


Figure 1. A conventional on-site wastewater dispersal system for a single house is typically made up of a septic tank and a drainfield installed in the soil above the water table. (Reprinted by permission from The Groundwater Foundation. "Potential Threats to Our Groundwater: On-Site Wastewater Treatment Systems." [www.groundwater.org/get-informed/groundwater/wastewater.html](http://www.groundwater.org/get-informed/groundwater/wastewater.html).)

Soil is a complex, three-dimensional material made of solids, liquids, and gasses. One of the soil's most important properties is its ability to transmit water

through pores and between particles (hydraulic conductivity, noted by "K"). Hydraulic conductivity increases with increasing soil water content until reaching a maximum rate in saturated conditions, at which time it is referred to as " $K_{sat}$ ." We refer only to field measurements of  $K_{sat}$  in this document. Figure 2 shows a zone of saturated soil under a zone of unsaturated soil. The contact between the two zones is called the "water table."

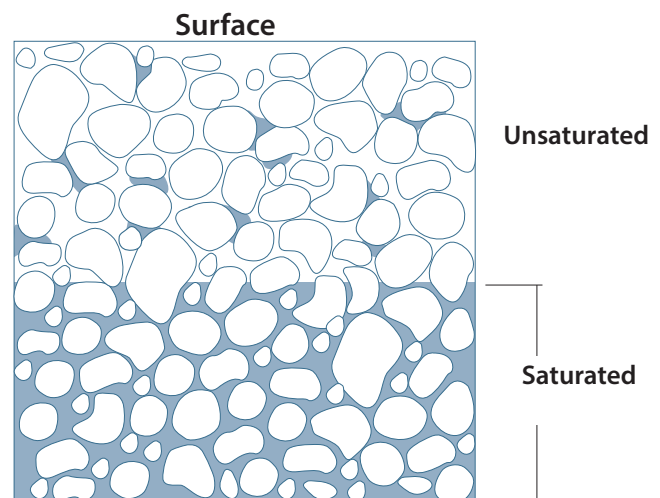


Figure 2. Contact between saturated and unsaturated zones in the soil is called the "water table." (Reprinted by permission from the Kansas Geological Survey. Saturated Thickness: Concepts and Measurement. In "An Atlas of the Kansas High Plains Aquifer," 2000. [www.kgs.ku.edu/HighPlains/atlas/apst.htm](http://www.kgs.ku.edu/HighPlains/atlas/apst.htm).)

A soil and site characterization for on-site wastewater treatment and dispersal is needed to predict the rate that wastewater will flow through the soil for an extended period of time, providing adequate treatment

to minimize the impact of the wastewater contents to the receiving groundwater (fig. 1). The acceptable soil and drainfield site footprint can include a reserve area (from 50 to 200 percent of the drainfield area) adjacent to or close to the drainfield location in case of system failures. Galbraith, Zipper, and Reneau (2015) and the U.S. Environmental Protection Agency (2012) have provided more information about owning and maintaining on-site wastewater systems.

Soil horizons with high conductivity rates are said to be highly permeable. Permeability classes were used in the past to describe the downward movement of water through soil. Horizons that do not allow water to move through them at rates of 12 inches (30 centimeters [cm]) or less per year were said to be impermeable. However, permeability classes and rates have been replaced in field use for evaluating soil for on-site wastewater disposal by Ksat values (Natural Resources Conservation Service 2004).

Restriction of water movement for long periods while microbes are actively decomposing organic matter often causes the soil to become devoid of gaseous oxygen ( $O_2$ ). Microbes reduce manganese (Mn) and iron (Fe), causing them to become soluble and mobile. The soil zone becomes depleted of oxidized Mn and Fe as they move with soil water, and it develops a gray color, called “redoximorphic depletion.” When the soil solution again encounters  $O_2$ , the Mn and Fe crystallize as oxidized compounds, called “redoximorphic concentration.” Formation of yellow, orange, and red color patterns are the result. Redoximorphic depletions and concentrations are known as “redox features.”

Physical soil properties that limit permeability are called “restrictive features.” Examples include bedrock and dense (compacted) horizons. In Virginia, several types of restrictive features can be found. The Sewage Handling and Disposal Regulations in Section 12 VAC 5-610-490 of the Virginia Administrative Code (Virginia Department of Health 2014) list fragipans, clay pans, shrink-swell soils, horizons containing concretions, or any other layers that are compacted or high in clay content as permeability-limiting features in the soil. Following are examples of restrictive features in soils:

- Redox features in soil directly above bedrock indicate that the bedrock is restricting downward water movement.

- Brittleness of a moist soil aggregate (e.g., shattering when pressed between thumb and forefinger) indicates high bulk density and disconnected porosity (Schoeneberger et al. 2012). Brittle horizons such as fragipans limit water movement and root growth and almost always have very distinct patterns of redox features (National Soil Survey Center 2015).
- Compacted horizons due to pressure applied by vehicular traffic or agricultural tools such as plow layers typically have a platy structure that limits water movement and root growth and sometimes have redox features (Schoeneberger et al. 2012).
- Soils with strongly contrasting textures in adjacent horizons create contrasting permeability rates that restrict water movement (e.g., a sandy loam texture directly over a clay texture or clay over sand). Redox features form in the horizon with a finer texture.
- Horizons with redox features and clayey textures (sandy clay, clay, silty clay) and either no structure (massive) or a weak grade of structure are known to be water-restrictive. The problem is worse if the clay type is one that expands greatly when saturated (shrink-swell clay). The restrictive nature of shrink-swell clays is indicated by smooth, shiny, shear zones called “slickensides” (Schoeneberger et al. 2012). Manganese-iron oxides that form above clayey layers might become cemented, called “concretions,” indicating that the clay weathered from a bedrock type that is rich in manganese.
- The presence of plinthite, a cemented concentration of iron oxide that is brick-red in the center, is indicative of a type of restrictive horizon found in the upper Coastal Plain.

In Virginia, percolation tests and permeability tests are the two in situ methods most commonly used to determine the conductivity of water through a soil for on-site wastewater treatment and dispersal. Both methods measure the amount of water entering the soil from a test hole made by an auger (metal tube with a cutting tip).

The percolation test measures soil conductivity with a falling head, where the height of a column of water in the test hole drops during the testing period, as described in the Soil Handling and Disposal

Regulations, Section 12 VAC 5-610, Appendix G, of the Virginia Administrative Code (Virginia Department of Health 2014).

The permeability test measures the Ksat of a soil horizon in the field with a constant head, where the height of a column of water in the test hole is maintained at the same level throughout the testing period (Amoozegar and Warrick 1986).

Both conductivity test methods can yield valuable data if performed properly. However, Ksat tests have the advantage of providing a greater degree of precision and expediency compared to the percolation test and will be the only tests described further in this document.

When applying water from above, it is difficult to achieve saturation because of trapped air and rapid water flow away from the source between soil aggregates and channels. Variability of soil saturation is due to spatial variations in soil properties, such as porosity, root density, texture, structure, consistence, bulk density, mineralogy, and temperature within the soil. These challenges make Ksat one of the most variable of all soil characteristics.

A common method for determining Ksat in a soil horizon is through the use of a constant head permeameter (Amoozegar and Wilson 1999). There are several commercially available permeameters, as shown in figure 3. The most common devices used in Virginia are the Compact Constant Head Permeameter, commonly referred to as the Amoozometer (available from Ksat Inc., P.O. Box 30818, Raleigh, NC 27622), the Johnson Precision Permeameter commonly referred to as the Johnsonmeter (*available from Johnson Permeameter LLC, 190 Whites Lake Blvd, Saluda, NC 28773*), and the Aardvark



Figure 3. From left, Amoozometer, Johnsonmeter, and Aardvark Permeameter. (Photos by Steven Thomas.)

Permeameter (available from Soil Moisture Equipment Co., 801 S. Kellogg Ave., Goleta, CA 93117). User's manuals with specific details are available from the manufacturer.

Saturated hydraulic conductivity tests, when performed, should be used in conjunction with information collected through a soil description to aid in determining the design of a drainfield or in identifying permeability-limiting features.

All Ksat tests have limitations that should be considered when determining a final on-site septic system design and drainfield footprint. A Ksat value measured in the field represents a value for a specific time and location within the tested soil, but it might not represent the hydraulic characteristics and soil properties across an entire site. The Ksat tests often confirm the soil properties in the soil profile description but should not be used exclusively to size a drainfield or increase the loading rate.

## General Ksat Testing Protocol

### Soil Investigation and Descriptions

It is important to record a detailed soil description of all horizons in the profile down to at least 20 inches (50 cm) below the Ksat testing depth. It is recommended the soil description be within 6 feet (2 meters [m]) of the Ksat test location. Detailed soil descriptions not only convey justification for the testing depth or strata but can also provide information if Ksat results vary outside of normal expectations. Table 1 lists information to record in making soil pit and soil auger descriptions that accompany Ksat tests. In particular, soil structure and boundary depths are very difficult to describe from auger samples and are best described from soil pit samples.

Soil horizon topography can vary drastically over a given site, which is one reason Ksat test results can vary widely. There are two approaches to gathering Ksat test data for any given site: (1) perform tests at a uniform depth across the proposed drainfield site or (2) recognize and document the spatial variability of the horizon(s) to be tested and then test, if possible, within the boundaries of the horizon(s) in question. If the most conservative results are used to aid in the drainfield design, this can result in the drainfield design being larger.

Table 1. Recommended data to be collected from pit and auger holes for soil descriptions accompanying saturated hydraulic conductivity tests.

Parameter	Pit description	Auger description
Horizon	X	X
Depth	X	X
Matrix color(s) (Munsell and narrative)	X	X
Texture (NOT abbreviation)	X	X
Feature color(s) (quantity, size, contrast) Redoximorphic – depletions, concentrations, concretions, nodules (size, hardness) Lithochromic - mottle (quantity, size, contrast)	X	X
Aggregate and void surface feature(s) such as clay films, slickensides, etc. (quantity, contrast, location)	X	
Rock fragments (abundance, shape, kind)	X	X
Structure (grade, size, type)	X	
Consistence (dry, moist, or wet; rupture resistance, stickiness, plasticity, brittleness w/ approx. % brittle)	X	X
Roots (quantity, size, location)	X	
Pores (quantity, size, shape)	X	
Special features (lamellae, plinthite, stone lines, mica, etc.)	X	X
Chemical response (effervescence – Mn, carbonates, etc.)	X	X
Horizon boundary (distinctness, topography)	X	
Surface morphometry (landform, elevation, aspect, gradient, slope shape, vegetation)	X	X
NRCS soil moisture content at time of test	X	X
Miscellaneous field notes not covered above	X	X

## Number and Location of Ksat Test Points

Ksat data are required by the Virginia Department of Health (2014) for large (>1,000 gallons per day [gpd]) alternative on-site wastewater systems (alternative drainfields) and for large conventional drainfields (>1,200 gpd). Ksat data are not required for small alternative systems (≤1,000 gpd) or small conventional systems (≤1,200 gpd), but they can be used by designers to verify an estimated permeability rate based on soil morphology.

A minimum of five testing points is recommended for drainfields and reserve area footprints up to 0.5 acre (approximately 2,023 square meters [m<sup>2</sup>]) in size, with three additional tests per each additional 0.5 acre and a proportional number of tests for the remaining fraction of 0.5 acre. For example, if a footprint is less than 0.5 acre, five tests would be needed. If the footprint is 1.2 acres (approximately 4,856 m<sup>2</sup>), the first 0.5 acre would need five tests, the next 0.5 acre would need three tests, and the remaining 0.2 acre would need two additional tests (0.6 test per 0.1 acre, rounded up), for a total of 10 tests. The same formula is used if the

drainfield and reserve areas are not contiguous. Soils that are uniform in depth and properties might require fewer tests, based on the best professional judgment of the field investigator. Additional tests can aid in explaining the natural variation of  $K_{sat}$  within soils and reduce the influence of unrepresentative values. For large conventional drainfields and large alternative drainfields that require greater than 5 acres (2 hectares [ha]) of drainfield area, the number of testing points to be investigated should be determined on a case-by-case basis.

All  $K_{sat}$  test points should be located as close as practical to the probable center and probable corners of the primary and reserve drainfield and within 6 feet (2 m) of soil profile description sites. The number and location of the  $K_{sat}$  test points should be sufficient to provide reasonable assurance that the range of soil variability encountered at the site can be observed, described, and tested.

### Depth/Horizon of $K_{sat}$ Testing

All  $K_{sat}$  tests using a permeameter should be performed with the bottom of the hole at a minimum depth of 12 inches (30 cm) below the ground surface and a minimum of 7 inches (18 cm) below the upper boundary of the specific soil horizon or strata that

is to be tested so long as no restrictive features are suspected within 18 inches (46 cm) below the testing depth based on the site and soil descriptions. Permeameters are not appropriate for shallow tests (<12 inches) and in horizons that are less than 7 inches thick. Other constant head measuring devices should be used in thin or shallow horizons instead. In either case, the water column within the hole should be at least 1 inch (2.5 cm) below the upper boundary of the soil horizon being tested, and the hole should extend down another 6 inches (15 cm) or more to allow for a minimum 6-inch column of water in the hole and a 1-inch separation to the top boundary of the tested horizon (minimum horizon thickness is 7 inches if a permeameter is used). The column of water in the test hole should not be allowed to rise higher than 1 inch below the top of the tested horizon, and the test borehole (hole made by auger or probe) should not penetrate the lower boundary of the tested horizon; if they do, the rate determined might not be representative of the horizon intended for study.

The  $K_{sat}$  test should be conducted at a depth relative to a slowly permeable or impermeable layer (restrictive feature). In figure 4, part A,  $K_{sat}$  is measured in the blue zone (water column) when the vertical separation distance ( $s$ ) from the bottom of the hole (and water column) to any restrictive feature

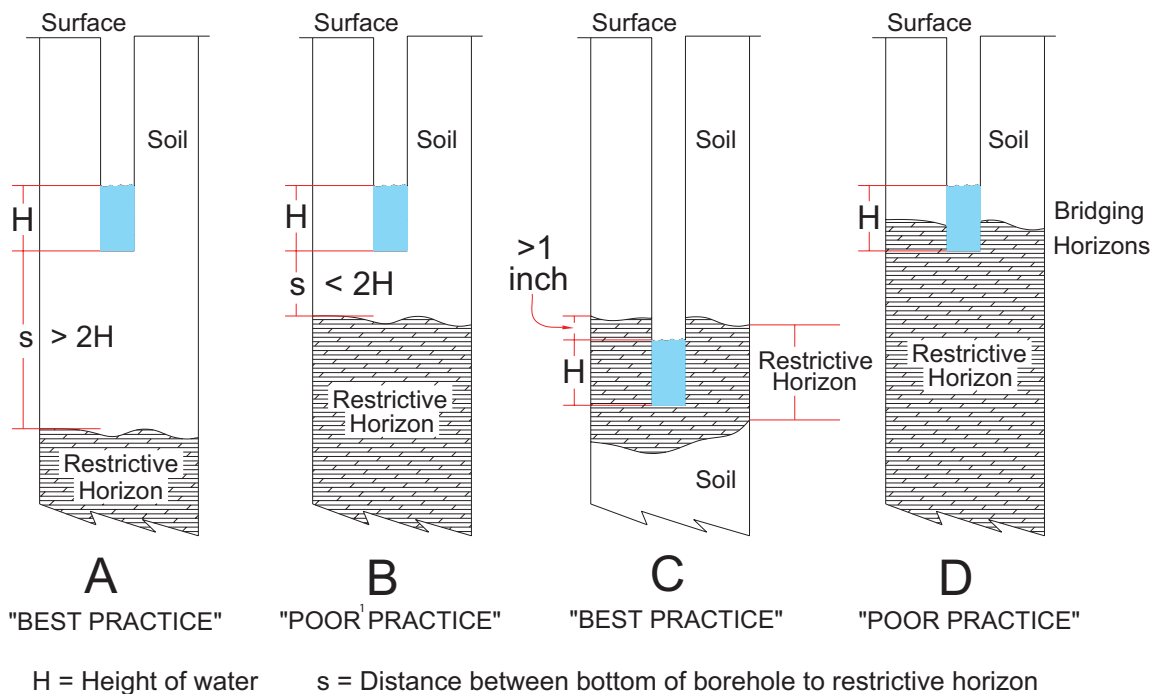


Figure 4.  $K_{sat}$  water column ( $H$ ) testing depth in relation to depth to soil restrictions.

<sup>1</sup> Acceptable with use of equations from Ammozegar and Warrick (1986).

below is at least two times the constant height of water (H) in the borehole (Zangar 1953). In figure 4, part B, where a restrictive feature is suspected or confirmed with a vertical separation distance less than two times the height of water (H) in the hole, the test water column depth should be moved down into the restrictive horizon (fig. 4, part C), or use Equation 15 from Amoozegar and Warrick (1986).

Ksat tests should not be performed where the column of water in the hole bridges two or more soil horizons (fig. 4, part D), especially if one of the soil horizons has highly contrasting properties or features where significant variability could be expected in Ksat values (fig. 5). Bridging two or more soil horizons with the column of water in the test hole can result in Ksat rates that overestimate the long-term water acceptance rate of one of the two horizons. Thin horizons with similar properties and features can be bridged. Test results can be assigned to multiple tested horizons if the soil morphological characteristics of the tested horizons are very similar.

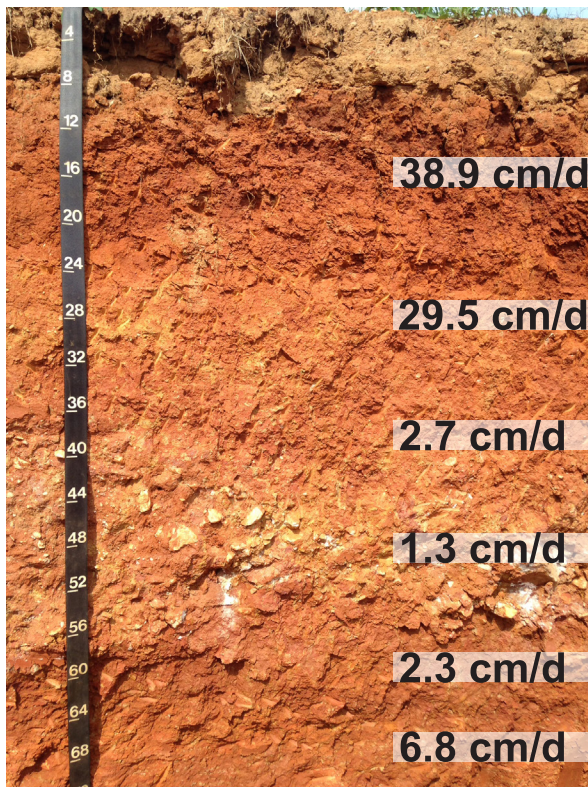


Figure 5. Results of Ksat tests in a Piedmont soil. The low rates (< 2.2 cm/d) are generally unsuitable soil horizons that form a restriction to downward water movement. Note that rates are higher below the most restrictive horizons, a common feature of Piedmont soils. (Photo by Steven Thomas.)

The Ksat test results should be considered representative of the entire thickness of the particular soil horizon being tested. When the soil profile characteristics are known and understood, it is recommended that the bottom of the hole be located in or above the most restrictive layer, based on properties observed during soil description.

In cases where it is unclear if a restrictive feature exists, Ksat tests should be performed below the proposed drainfield installation depth to properly characterize the hydraulic properties of the standoff zone. The standoff zone is the thickness of soil between the dispersal point of a drainfield and a permeability limiting feature. Testing below a restrictive horizon is not recommended where subsurface water is observed flowing laterally across a restrictive feature (the water is said to be perched) because it might enter the permeameter borehole. It is recommended that for all Ksat tests, the depth of the water in the hole (H) be measured at the start and finish of the test (see fig. 4). If H increases, water has entered the borehole, the test is invalid, and the results should be disregarded. Testing the standoff zone could be necessary to meet the minimum regulatory requirements for vertical separation distances from the bottom of the drainfield to a restriction (Sewage Handling and Disposal Regulations, Section 12 VAC 5-610-594 and 596 of the Virginia Administrative Code [Virginia Department of Health 2011], and Regulations for Alternative Onsite Sewage Systems, Section 12 VAC 5-613-80.13, table 2, of the Virginia Administrative Code [Virginia Department of Health 2011]).

## Water Drawdown Measurement Intervals

Water drawdown measurement intervals are established by the rate of water movement from the permeameter into the soil and are normally more frequent with higher permeability rates of the tested horizon. Measurements of the volume (cm<sup>3</sup>) of water released by the permeameter and time intervals from the initial filling of the hole through completion of the test should be documented. Table 2 provides water measurement intervals based on typical permeability rates for each soil texture.

Table 2. Recommended measurement intervals by soil texture.

Texture	Typical measurement interval (minutes)
Sand, loamy sand	1
Sandy loam	1-2
Loam, sandy clay loam	2-5
Clay loam, silty clay loam, silt loam, silt	5-15
Clay, silty clay, sandy clay	10-30

The flow rate into the hole might not be absolutely constant even after reaching a steady state of flow. A steady state of flow is reached when the change in volume of water entering the soil from the permeameter is insignificant or is nearly the same between interval measurements. Most soils contain varying aggregate and pore structures and voids which will cause water to move at different rates at all times. The water flow rate is often essentially constant after reaching steady-state conditions with a uniform sand, but it might show minor variation in clayey soils and saprolite (former bedrock that has the same layering and volume but none of the cementation of the original bedrock).

Evaluators must use their best professional judgment to determine that steady-state flow has been achieved and should refer to the appropriate permeameter manual for particular recommendations of each manufacturer.

Percolation rates can deviate widely depending on site and soil properties and land management practices. Using appropriate measurement intervals is crucial to determining when steady-state water flow is achieved and the test completed (fig. 6).

### Duration of Ksat Tests

The time to reach this steady state of flow will vary with the antecedent moisture state of the soil and other soil properties. The recommended minimum test duration (determined based on the first few readings) is as follows:

- Thirty minutes or more for fast rates of water movement.
- One hour or more for moderate rates of water movement.
- Two hours or more for slow rates of water movement.

Clayey Subsoil Horizon Ksat Data

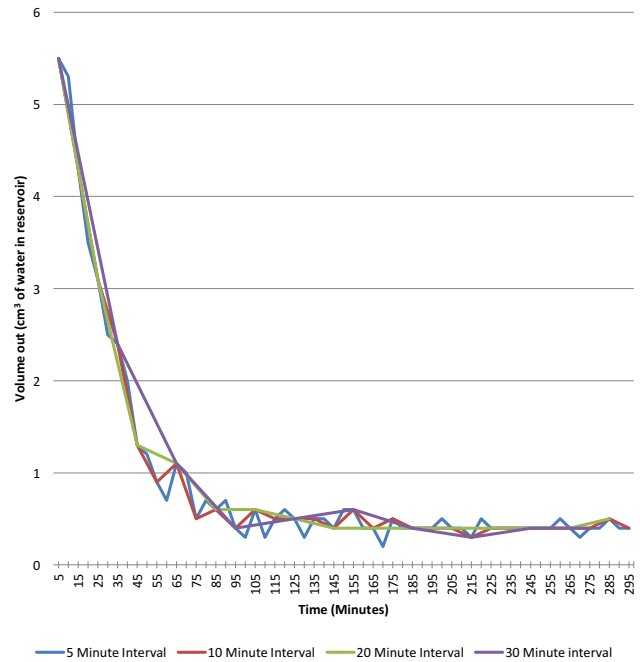


Figure 6. Ksat steady-state flow based on measurement intervals in a clayey subsoil horizon. The vertical axis represents the volume of water out of the reservoir in cm<sup>3</sup> for a given time interval. Five-, 10-, 20- and 30-minute time intervals are plotted on the graph across the time in minutes since the beginning of the test.

In general, drier soil conditions necessitate that extended tests be performed in order to achieve steady-state flow. Tests are not recommended to be conducted during drought without extended presoak periods. Results of Ksat testing during drought conditions might not be representative of the hydraulic conductivity of the soil due to the presence of soil cracks and the time necessary to moisten the soil uniformly.

The following soil properties can be found in soils that have historically shown to take longer to reach steady state (Vepraskas 1992):

- Olive, yellow, blue-green, or black weathered bedrock.
- Iron- or manganese-cemented soil.
- Manganese coatings or masses.
- Red and yellow variable color patterns.

- Redox color patterns in a darker matrix horizon color.
- Slickensides (shiny surfaces of soil aggregates).
- Pale-colored (reduced or depleted) clay coatings on soil aggregate surfaces.

## Steady State of Flow

Two examples of Ksat test data graphs are given: one for a soil with high permeability and clay that does not shrink-swell (fig. 6) and one with lower permeability and a different clay type (fig. 7).

Figure 6 represents a five-hour Ksat test in a subsoil horizon. Steady-state water flow is assumed when the rate of water infiltrating into the soil from the permeameter is nearly the same (steady) for at least three successive measurements, where the plotted lines are essentially horizontal. Steady state is reached after approximately 85 minutes. However, near the 90-minute mark, the 5- and 10-minute measurement interval graph lines are still jagged (sawtooth-like) due to minor fluctuations in the flow rate. With time, each of the graphed measurement interval lines begins to overlap as the flow of water is consistent regardless of which reading interval is chosen. This could also represent steady-state flow because the deviations in measurements above and below a line that would be their average are insignificant in value.

Figure 7 represents a three-hour Ksat test of a soil with a different clay type and lower permeability than that in figure 6. Readings were taken at 5, 10, 30, and 60 minutes. This graph does not have the smooth pattern and flattening curved lines as seen in figure 6. The 5-, 10-, and 30-minute interval lines have a sawtooth pattern for the entire three-hour test period. Based on these lines, steady state has not been achieved within the testing time. The 10- and 30-minute intervals are jagged in the first 95 minutes and flatten out somewhat after that time, with the 30-minute interval being most consistent, from 95 to 155 minutes. The 30-minute interval only provides three readings that are nearly equal (95 to 155 minutes). Based on the fluctuations of the 30-minute interval plotted line and only three readings that are nearly the same, it might be best practice to continue to run the tests for several additional readings after the recommended three equal readings to have assurance that a steady-state of flow has been reached. Notice the increase in Ksat values

at the 155-minute time period. This could be caused by water reaching soil material with greater porosity, root channels where the water flow is concentrated, or steady state not being achieved. The 60-minute interval is not a desired time interval because there are insufficient readings to determine steady state. That time interval line is essentially linear throughout the entire test.

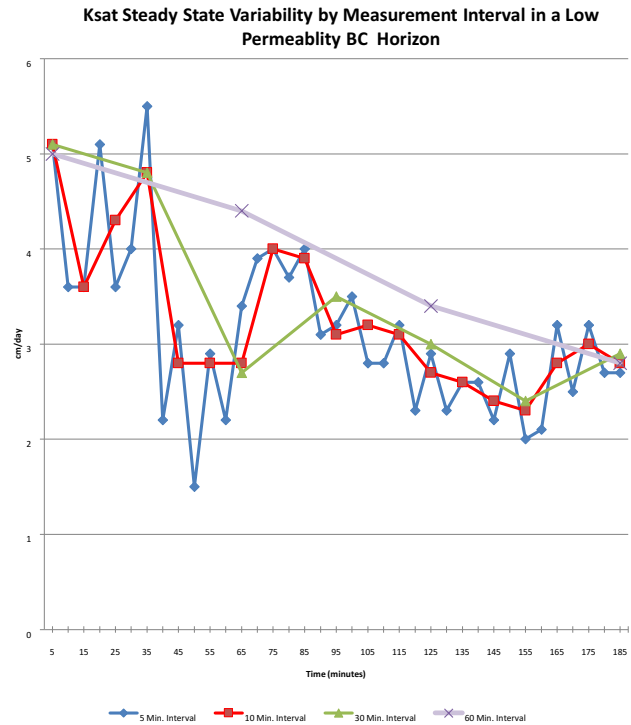


Figure 7. Ksat flow variability by measurement interval in a low-permeability subsoil horizon. The vertical axis represents the calculated Ksat rate in cm/day for a given time interval. The 5-, 10-, 30- and 60-minute time intervals are plotted on the graph across the time in minutes since the beginning of the test. Steady-state flow was not attained during the testing period. (Data from Gary Gilliam, environmental health supervisor, Virginia Department of Health.)

## Calculations

The steady-state flow ( $Q$ ) of water with a constant head ( $H$ ) at the bottom of a test hole with a radius ( $r$ ) is measured, and Ksat is calculated by the Glover solution using  $Q$ ,  $H$  and  $r$  (Zangar 1953). Calculation of Ksat values commonly involves the use of the Glover solution, which use the following equations:

For conditions where the distance from the bottom of the borehole to an impermeable layer (denoted by “ $s$ ” as in figure 4) is  $\geq 2H$ ,



$$K_{sat} = Q[\sinh^{-1}(H/r) - (r^2/H^2 + 1)^{0.5} + r/H]/(2\pi H^2). \quad (1)$$

Or, for conditions where an impermeable layer is  $<2H$ ,

$$K_{sat} = Q\{3\ln(H/r)/[\pi H(3H+2s)]\}, \quad (2)$$

where Q is the steady-state flow rate (ml/min or cm<sup>3</sup>/min), H is the constant height of water in the bottom of the test hole (cm),  $\sinh^{-1}$  is the inverse hyperbolic sine function, and r is the radius of the borehole (cm). For the purpose of this document, K<sub>sat</sub> rates are reported in cm/day. For further discussions on impermeable layers, please refer to the NRCS Field Book for Describing and Sampling Soils (Schoenberger et al. 2012).

### Example of a Calculation of K<sub>sat</sub> for $s \geq 2H$

A column of constant head (H) of water in the borehole is 15 cm, and the borehole diameter is 6 cm (radius is 3 cm). This makes an H/r value of 5 (dimensionless). The constant, steady-state flow (Q) from the permeameter is 38.33 cm<sup>3</sup>/minute. The following example uses the Glover solution (Equation 1):

$$\text{Step 1. } K_{sat} = Q[\sinh^{-1}(H/r) - (r^2/H^2 + 1)^{0.5} + r/H]/(2\pi H^2)$$

$$\text{Step 2. } K_{sat} = Q[\sinh^{-1}(15 \text{ cm}/3 \text{ cm}) - (3 \text{ cm}^2/15 \text{ cm}^2 + 1)^{0.5} + 3 \text{ cm}/15 \text{ cm}]/(2\pi 15 \text{ cm}^2)$$

$$\text{Step 3. } K_{sat} = Q[\sinh^{-1}(5) - (9/225 + 1)^{0.5} + 0.2]/2 \times (3.14159) \times (225 \text{ cm}^2)$$

$$\text{Step 4. } K_{sat} = Q[2.3124 - (1.0198) + 0.2]/1413.72 \text{ cm}^2$$

$$\text{Step 5. } K_{sat} = Q[1.4926/1413.72 \text{ cm}^2] = 38.33 \text{ cm}^3/\text{min}[0.0010558/\text{cm}^2] = 0.04047 \text{ cm}/\text{min}$$

$$\text{Step 6. } K_{sat} = 0.04047 \text{ cm}/\text{min} \times 60 \text{ min}/\text{hr} \times 24 \text{ hr}/\text{day} = 58.28 \text{ cm}/\text{day}$$

Inverse hyperbolic sine values can be calculated with a scientific calculator, found in the manufacturer's instruction manual, or automatically calculated in manufacturer-provided spreadsheets.

### K<sub>sat</sub> Test Results

K<sub>sat</sub> calculations for the last three or four measurements should be documented for each test point and then averaged. K<sub>sat</sub> of the test area should be determined by calculating the geometric mean of

the last three averaged K<sub>sat</sub> calculations from each test point. Isolated, excessively rapid test results should be discarded and not used in determining the geometric mean.

Warrick and Nielsen (1980) have shown that K<sub>sat</sub> can have a coefficient of variation (CV = 100 × standard deviation/mean) that can exceed 100 percent. Because the statistical distribution of the measured K<sub>sat</sub> values can be highly variable, there is utility in using the geometric rather than the arithmetic mean of the measured values. The geometric mean is a measure of the central tendency or typical value of a set of numbers by using the product of their values, whereas the arithmetic mean uses their sum. Following are examples of calculating the geometric mean of K<sub>sat</sub> measurements.

### Example 1

Three permeability rates are measured within a proposed drainfield: 1.8 cm/day, 2.4 cm/day, and 2.4 cm/day.

The geometric mean of these results is 2.178 cm/day, or it can be rounded to 2.2 cm/day. To calculate the geometric mean, find the log of each of the measured K<sub>sat</sub> rates (the log of 1.8 = 0.255; the log of 2.4 = 0.380) and then take the arithmetic average of the numbers (0.255 + 0.380 + 0.380 = 1.015) and 1.015/3 = 0.338. Take the antilog of 0.338 = 2.178, rounded to 2.2. A rate of 2.2 cm/day is the lowest K<sub>sat</sub> rate allowable under the Sewage Handling and Disposal Regulations for drainfields (Virginia Department of Health 2014). However, one of the results is less than 2.2 cm/day. In this case, the most conservative approach would be to report the 1.8 cm/day. This is probably caused by an impervious layer. Whether or not this conservative approach is prudent depends on multiple observations made during the site and soil evaluation of the area investigated. More testing could be needed to demonstrate the suitability of the area.

### Example 2

Six K<sub>sat</sub> rates are obtained from a proposed large drainfield area: 28 cm/day, 3 cm/day, 54 cm/day, 88 cm/day, 43 cm/day, and 121 cm/day.

The slowest and fastest K<sub>sat</sub> rates should be disregarded, and the geometric mean of the remaining rates should be used. The long-term acceptance rate

would be reduced if the faster Ksat values were incorporated into the design (i.e., the loading rate will be too high for the soil at the faster design rate, and the long-term function of the drainfield will be compromised). The authors do not recommend using fast Ksat rates that appear to be outliers (well outside of the average cluster of values).

## Effects of Soil/Water Temperature on Ksat Results

The temperature of water entering the soil at the bottom of the hole can affect the Ksat results. As temperature changes, the viscosity of water also changes. Generally, water has a viscosity of 1 at 68 degrees Fahrenheit (°F). As water cools below 68°F, it will have a higher viscosity and a slightly reduced ability to move through the soil. Conversely, as water gets warmer, it will have a lower viscosity and will move through the soil more quickly. To correct for differences in the temperature of the water used in testing, multiply the final steady-state Ksat rate by a viscosity ratio (the viscosity at the temperature of water used during the test divided by the viscosity of water at the 68°F reference/standard temperature). Table 3 contains viscosity values of water at various temperatures.

For example, to correct a Ksat value to 68°F during a test using 55°F water and a final Ksat rate of 6 cm/day, use the following procedure and the centipoise (cps) values from table 3:

$$\text{Ksat rate (cm/day)} \times \text{cps (at temperature of test water)} / 1.002 \text{ (cps of water at 68°F)} = \text{temperature-corrected Ksat rate.}$$

For example, the field-measured Ksat was 6 cm/day, but the temperature-corrected Ksat rate equals 7.2 cm/day:

$$6 \text{ cm/day} \times 1.201 / 1.002 = 7.192 \text{ cm/day.}$$

With slower Ksat rates or where the temperature of water used is hotter or colder than 68°F, correcting to a temperature standard can alter the “measured” Ksat rate and thus affect the area requirements for the drainfield footprint. Conversely, using the same water temperatures as in the example above and a field-measured Ksat of 2 cm/day, the temperature-corrected Ksat would be 2.4 cm/day. The temperature-corrected Ksat rate in this example is now within the acceptable rates for conventional drainfield design.

Avoid extreme soil/water temperatures when performing Ksat tests. For Ksat devices using a large water reservoir, the water in the reservoir

Table 3. Viscosity of water in centipoise (cps) at various temperatures. (Data from International Association for the Properties of Water and Steam [2008].)

Temperature C°	Temperature F°	Viscosity cps	Temperature C°	Temperature F°	Viscosity cps	Temperature C°	Temperature F°	Viscosity cps	Temperature C°	Temperature F°	Viscosity cps
2	36	1.674	12	54	1.234	22	72	0.9544	32	90	0.7644
3	37	1.619	13	55	1.201	23	73	0.9321	33	91	0.7488
4	39	1.567	14	57	1.168	24	75	0.9107	34	93	0.7337
5	41	1.518	15	59	1.138	25	77	0.89	35	95	0.7191
6	43	1.472	16	61	1.108	26	79	0.8701	36	97	0.7050
7	45	1.427	17	63	1.080	27	81	0.8509	37	99	0.6913
8	46	1.385	18	64	1.053	28	82	0.8324	38	100	0.678
9	48	1.344	19	66	1.027	29	84	0.8145	39	102	0.6652
10	50	1.306	20	68	1.002	30	86	0.7972	40	104	0.6527
11	52	1.269	21	70	0.9775	31	88	0.7805			

might maintain a constant temperature long enough that running Ksat tests for a few hours should not significantly impact Ksat results, depending on daily air temperature variations. When performing Ksat tests for long periods of time in extremely hot or cold temperatures, recording the temperature of the water as an adjustment to the results could be necessary. For deep borings, it might be easier to measure the water temperature in the water reservoir of the Ksat device rather than in the Ksat borehole, even though the measurements of the water temperature in the bottom of the test hole will more closely match the actual soil temperature at time of testing. On extremely hot, sunny days, it would be prudent to shade or protect the Ksat device from direct sunlight in order to moderate water temperature fluctuations. Ksat tests should not be performed when the air temperature is approaching freezing due to the potential for equipment damage.

Septic systems must function satisfactorily throughout yearly temperature ranges. Shallow-placed drainfields are of special concern. The variation in soil temperatures at shallow depths could necessitate temperature correction of Ksat results to the lowest soil/effluent temperature expected during the winter months. If temperature correction is made to the lowest temperatures expected, the design will be conservatively modified, as opposed to using a design where the viscosity of water is 1, (i.e., 68°F) or higher. For conventional drainfield designs, correcting the temperature will not likely be necessary in the winter except possibly at high elevations. It would be prudent to correct viscosity when performing Ksat tests during lengthy periods of hot weather — the measured Ksat rates might be artificially biased toward a faster rate than the soil can accept during cold periods. The best practice is to correct to a soil/water temperature where the soil and drainfield effluent would be at or near the lower limit of yearly soil temperatures.

### **Effects of Windy Weather and Barometric Pressure Change on Ksat Results**

Strong winds and changes in barometric pressure could affect equipment performance, resulting in equipment malfunction and, ultimately, unreliable determination of Ksat value. Large barometric pressure changes while performing Ksats with the Amoozometer can cause the water level within the instrument and/or borehole to vary (Amoozegar and

Wilson 1999). In some cases, it can appear that the water level in the Amoozometer has actually risen instead of the water level drop normally observed. Running the Amoozometer during very windy days or when there will be a sharp change in the barometric pressure is discouraged. If there is a mild or slight breeze, shield the top of the adjustable bubble tube to prevent direct airflow across the top of the tube, which could create suction.

The Aardvark Permeameter uses a sensitive scale to measure the weight of water leaving the water reservoir, so strong winds can vibrate the device and result in reading errors. In some cases, the Aardvark device might need to be protected inside a tent or vehicle (Soilmoisture Equipment Corporation 2011).

The Johnson Permeameter is insensitive to shifts in barometric pressure. The water control unit is entirely below the ground surface and is not usually subject to atmospheric conditions such as strong winds. However, windy or hot periods can cause evaporation from the water reservoir. To minimize water loss by evaporation, cap off the top of the water-containing reservoir (Johnson Permeameter 2016).

### **Effects of Saturated Soil on Ksat Results**

Soil wetness is one of the factors that can prevent valid Ksat testing regardless of the device used. Please refer to the guide “Estimating Soil Moisture by Feel and Appearance” for information about estimating moisture content by feel (U.S. Department of Agriculture 1998). The three devices mentioned in this guide measure Ksat above a water table (fig. 8). The easiest way to determine if a soil is saturated is to determine if free water is observed either at or



Figure 8. Saturated soil. Photo used by permission from Gary Gilliam, Virginia Department of Health.

above the testing depth. If free water is present, the Ksat test cannot be performed. Perched and seasonal water tables are a primary concern. If groundwater is encountered below the borehole at depths less than two times the height of the water column in the borehole, the test could be invalid. Also, a recent rainfall event can result in the presence of temporary free water in the soil as a wetting front advances downward, thus creating the same conditions, albeit temporarily, as high groundwater.

## Summary

The following are key concepts to running a valid Ksat test above the water table. Specific information about each concept is located in the text.

- Soil and site characterization within 6 feet (2 m) of Ksat test borehole locations.
- Number and location of Ksat test points: minimum five tests.
- Test depths: minimum depth of 12 inches (30 cm) below the ground surface and a minimum of 7 inches (18 cm) in the horizon to be tested.
- Duration of Ksat tests: run test to steady-state.
- Calculate Ksat by using the Glover solution.
- Avoid running tests during temperature and weather extremes.
- Maintain adequate separation distance to groundwater.

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