Determination of Soil Hydraulic Conductivity in Nurseries and Plantations

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Introduction

Water management is one of the most important aspects of the nursery growing technology. At the same time, studies of soil water balance in forest stands require accurate description of the soil water transport, which is dependent on the physical characteristics of soils and influences water availability. A plethora of soil water movement models, mostly from agriculture, that could be adapted to nursery crops are now available for the estimation of the soil water balance of crops with various physical characteristics and irrigated and fertilized or not (De Jong and Hayhoe 1984, De Jong and Bootsma 1996). There are several benefits of these models; the most important being:

- Avoidance of hydric stress during the growing season,
- Improvement of irrigation activity (only as much water as necessary),
- Avoidance of fertilizers waste (prevention of situations when fertilizers are washed due to excessive irrigation), and
- Prevention of groundwater contamination.

The soil's hydraulic conductivity, K, measures the speed with which water progresses downwards into the soil. It influences the time residence of water in soils and determines to a large extent its usefulness for seedlings and trees. There are several empirical methods for the measuring of hydraulic conductivity (Dorsey et al. 1990).

One of these methods uses a relatively new device, Guelph Permeameter, largely adopted in agricultural practice, especially for irrigation and drainage design. This simple device should also be adopted in forest nurseries, where the permeability changes often due to soil manipulations, especially peat moss additions, of various qualities and in different proportions. This light, relatively simple and robust field instrument, manufactured by Soil Moisture Company in California, USA, uses a new embodiment of the Mariotte principle. In use, it needs only water and can be manned by only one operator. It is available as a kit with a series of attachments, making it fully operational within a few minutes. In this paper, we attempt to give a brief review of the method, a description of the device, and an illustration of its ecological usefulness.

The Hydraulic Conductivity

Ontario has a great site diversity; from desertic, bare landscapes to forested wetlands. The 800 to 900 mm of annual precipitation in southern Ontario, with about an equal amount supplied each month of the year, results in very different water availability conditions due to soil's permeability. Soils given this amount of moisture can be well or poorly drained, depending upon how fast the water will move downward.

Simply speaking, hydraulic conductivity, K, is the measure of the ease with which water moves gravitationally through the soil. Generally, the higher the K value of a certain soil layer, the greater the flow rate. Since in a forest nursery irrigation and drainage are very important activities, which depend critically on the rate of water flow through the soil, measurement of the soil K is an essential component in the design and functioning of these utilities. At the same time, the additions of peat moss improve the soil water-related properties. However, the decomposition of peat moss causes a slight increase of K during a growing season and the soil has to be reamended with peat moss after a few years.

In the past 50 to 70 years, a number of field methods have been developed to measure the soil K. These include ring and cylinder infiltrometer methods, the air-entry permeameter method, the double tube method, and various well methods. All of these techniques, described in detail in irrigation and drainage handbooks published by the

American Society of Agronomy or by the American Society of Agricultural Engineers, have been used with varying degrees of success and suffer from various theoretic and practical limitations. The limitations include low accuracy, complex and unreliable equipment, large time and water requirements per measurement and the need for at least two skilled operators.

The development of an "in-hole," permeameter has removed many of the practical limitations of one well method, known as the constant-head well permeameter or the dry auger hole method. This is based on the observed fact that around of a nucleus of wetting, after a short while, a sphere of wetting develops in the soil. Initially, in the soil, the absorption of water is fast, filling quickly the empty pores. After the sphere has developed, the absorption stabilizes to a constant rate. In this sphere, soil is at its maximum capacity for water. The standard conditions for the K measurement begin when this constant rate of absorption stabilizes. Hence, it will need more water and more time to a dry soil and less water/time to a soil close to field capacity, at the time of measurement. The formation of the sphere of influence depends critically on the texture. In sands, the sphere is small and forms quickly, while in clays it is much larger and may take more than a day to form. The K-value measured is in fact the conductivity when the soil is saturated with moisture, Ksat.

This new permeameter, made of plexiglas, is inexpensive, simple, and can be operated by one person after very little training—described in instructions that accompany the device. Usually, only small quantities of water, about 0.5 to 2 litres, are required per measurement, and in most cases, in typical nursery conditions, measurements can be made within 5 to 30 minutes.

In spite of these practical advances, which provide considerable advantages over many of the other techniques, the constant-head well permeameter method still has not seen widespread use in forestry.

The Permeameter

The constant well permeameter method estimates Ks. by measuring the steady-state rate of waterflow out of a shallow well in which a constant depth of water, H, is maintained. Its principle is illustrated in figure 1. The well is constructed using a 1 1/2-inch soil auger to give a well radius, a, of approximately 4 cm. It uses a plastic storage tank and a float-valve system to maintain the constant depth of water in the well. The air-inlet maintains sufficient vacuum above the water in the permeameter such that water flows out of the permeameter, in the well, at a rate sufficient to keep the level of water in the well at the base of the air-inlet tube. With this system, the rate of flow of water out the well is obtained readily by measuring the rate of fall of the water level in the permeameter vs. time. The water **in** the well can, theoretically, be kept at any height, although 10 or 20 cm appear to be the most convenient.

The K-value of the soil has traditionally been calculated using the relationship—

$$K_{sat} = \frac{C \times Q}{2 \times \pi \times H^2} \quad (1)$$

where

Q = Steady flow rate out of the permeameter and, therefore, out of the well (volume of water per unit time).

H = Depth of water in the well (length). C = Proportionality constant equal to 2 for H/a = 10 and equal to 1.3 for H/a = 5.

The theory represented by equation (1) neglects the influence of gravity and estimates the values of C by approximate analytical means. The inclusion of gravity and estimation of the C-values by more accurate numerical procedures have resulted in the relationship:

$$K_{sat} = \frac{C \times Q}{2 \times \pi \times H^2 \times [1 + \frac{C}{2} \times (\frac{a}{H})^2]} \quad (2)$$

Where: C=3.3 for H/a=10, and C=2.2 for H/a=5. Equation (2) results in a 77-percent increase in the estimate of K over equation (1), when H/a=5 and a 68-percent increase when H/a=10 (Elrick and Reynolds 1985). These increases effectively eliminate the previously observed underestimation of Ksat relative to the values obtained using other methods.

For the field, the principle shown in figure 1 has been modified to the more useable form in figure 2. The sliding seal in the reservoir cap allows the operator to change the depth of water in the well, H, easily by adjusting the height of the air-inlet tube. The interchangeable reservoir tube makes it possible to use one permeameter for several soil types, since sandy soils generally require a larger reservoir than those with high clay content. The removable cap and shutoff valve make it easier to fill and start

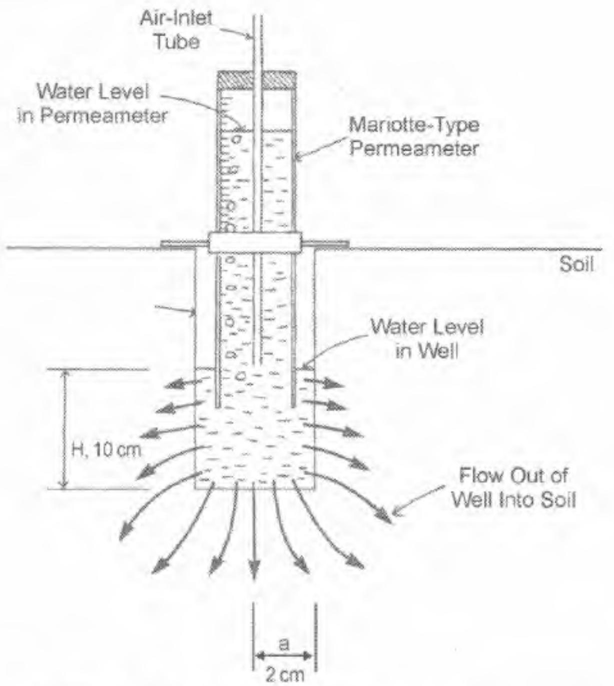

Figure 1. *The head of the in-hole Mariotte-type pereameter.*

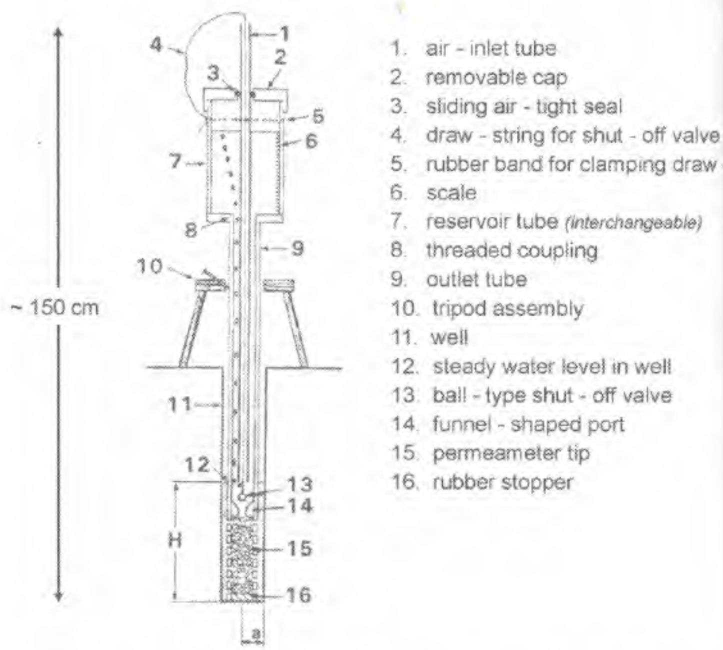

Figure 2. *The constant-head well pereameter in position.*

the permeameter. The tip of the permeameter, which consists of a perforated section of outlet tube, filled with coarse sand, serves to reduce erosion of the sides of the well while it is being filled to the steady-water level. Finally, by extending the length of the outlet tube, vertical profiles of K_{sat} of more than 1-meter depth can be obtained readily in deep soils.

Usually, by choice, the soils of forest nurseries are sandy, noncrust forming, and easy to work. Normally they are conditioned with minced peat moss to improve their water time residence and reduce the percolation. The time and volume of water required to complete a Ksat measurement were found to depend on the soil moisture content at the beginning of the procedure. On sandy soils at moisture content close to field capacity, a K. measurement requires less than 5 minutes and only 0.3 to 0.5 liters of water. Conversely, at the other extreme, dry, sandy soils, required measurement times of about 15 to 30 minutes and up to 2 or even more liters of water. Measurement times can be reduced by prewetting the well and surrounding soil to increase the initial moisture content. This might be important for the clay soils, where times of about 20 to 60 minutes and 0.5 to 1.0 liters of water are required.

Three different methods for measuring K were compared on a structureless, Fox loamy sand soil at the Cambridge Agricultural Research Station; namely, the constant head well permeameter, the air entry permeameter, and soil cores. The first two procedures are field methods and the third is a laboratory method. Statistical analysis revealed that the measurements with the constant well and the air entry devices were not significantly different, but that the soil core measurements were significantly lower (Elrick and Reynolds 1986). These differences are, however, not large enough to be of practical importance. For highly structured soils, such as well-aggregated clay loam[y], a much larger variation in K,at amount was found among the methods. This is believed to reflect the differing degrees to which the methods respond to soil macropores such as cracks, worm holes, and root channels. The Guelph permeameter was also independently tested with good results (Gallichand et al. 1990; Kanwar et al. 1989), and is now in use on large scale in Ontario's agriculture.

In soils containing a significant amount of clay, both the soil probe and the soil auger tend to smear the walls of the well as it is being dug. Since all the water must flow out of the wall and bottom of the well, it is critical that this region not be partially sealed by smearing as this would result in an underestimation of the K., value. There can also be a gradual sealing of the inside surfaces of the well in soils high in silt and clay which also results in an underestimation of the Ksat value.

Applications in Nurseries and Plantations

On the base of Ks., theoretical equations allow the calculation of some very important and useful characteristics:

- Relation between the soil suction (or hydraulic head) and soil moisture and
- Relation between hydraulic conductivity and soil moisture.

These relations are determined from a simple physical model described by Campbell (1974). This model links the soil matric head and the volumetric water content through a power function of saturated water content. On this base, it is possible to determine the suction head of the soil, at every level where soil moisture is measured, and implicitly, the stress level under which the roots operate at that depth. This is then expressed in terms of suction, cm or MPa, that the seedling or the tree have to exert in order to snatch water from the soil. In figure 3, we presented the suction heads developed in by "typical" sand, loam, and clay, having a certain Ks., corresponding to typical sandy, loam, and clay soils (soils 1, 6, and 11 from Clapp and Hornberger, 1978), respectively. It is easily noticeable that the same soil moisture content results in very different suction heads in soil of various textures. Thus, if we have in soil a suction head of 15,000 cm (equivalent to wilting point), we notice that this suction is achieved at less than 5-percent soil moisture in sand, 12 percent in loam and 22 percent in clay.

The second relation, conductivity versus soil moisture, allows to know the speed with which water percolates through soil. In a fine textured soil, with a low Ks., this time is very long. Conversely, water passes quickly through a coarse soil, where the particles of soil matrix don't develop large attraction forces, and Ksa, is large. This is the typical situation of the washed sands, where water is available only for a short interval after a rain event. The water-related properties of such soils will improve only through lowering of Ks.. In figure 4, using the same soils, a comparison is given amongst the soil hydraulic conductivities at various levels of soil moisture. It can be observed that, in sand, water is very slowly mobile under 12 percent of soil moisture. Its mobility increases gradually up to 40 percent, when it is completely mobile (at maximum soil capacity). Here, the values of K allows also to calculate the amount of percolation vs. time.

In real life, the lowering of Ksat is achieved in nurseries through peat moss addition—which inflates soil mixture and retains water; while in a forest stand it is the result of the evolution under vegetation from unstructured material to a soil—adding continuously small amounts of humus that lower the Ks. in time.

At the next level of sophistication, when operational irrigation policies will be expressed by models, a computer will control the irrigation activity, triggering the re-supply of a certain area when a certain level of stress, in respect to the wilting point, has been attained. In a forest stand, the knowledge of local hydraulic conductivity may be an important factor in selecting the species to be planted. Thus, on sites with high Ksat , implying that frequent alternatives of soil water suction occur, the most appropriate species to plant would be, for instance, red pine, European larch or oaks, due to their proven ability to grow in these conditions, while the sites with lower Ks. would

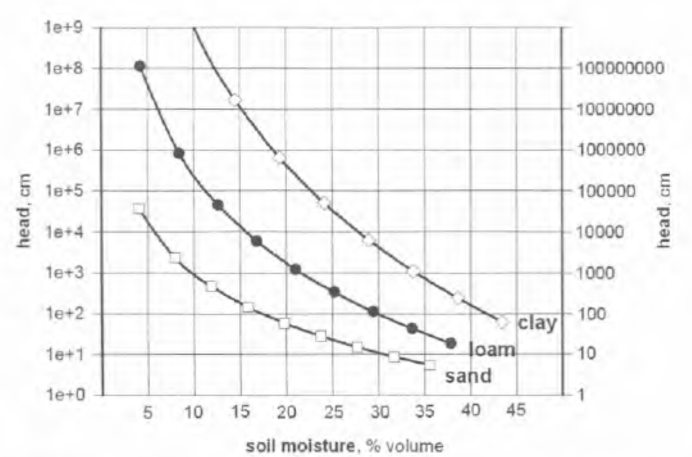

Figure 3. *Suction head vs. soil moisture for sand, loam, and clay.*

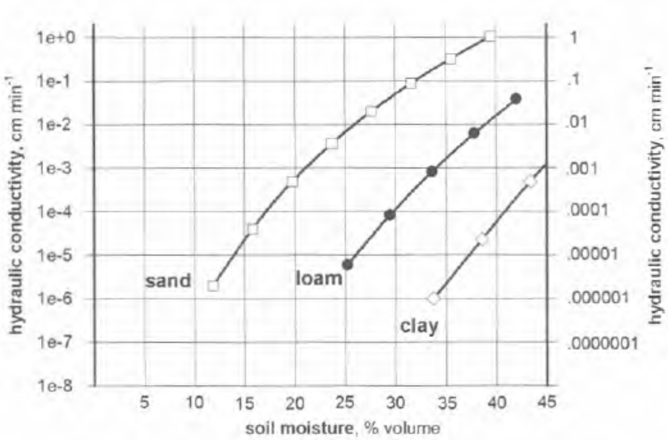

Figure 4. *Hydraulic conductivity vs. soil moisture for sand, loam, and clay.*

not have such limitations. Also, based on these relations, in a forest stand in which both the soil moisture and the diameter growth are periodically recorded, for instance in spacing/density treatments, it is possible to represent, in retrospect, the stress evolution, suggesting optimal times for silvicultural interventions.

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