OPERATING INSTRUCTIONS
09.11 Ksat constant head pemeameter

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All it takes for environmental research

COMPACT CONSTANT HEAD PERMEAMETER

USER'S MANUAL

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INTRODUCTION

The Compact Constant Head Permeameter (also known as Amoozemeter) is an advanced field instrument for in situ measurement of the saturated hydraulic conductivity (K_{sat}) of the unsaturated (vadose) zone. the Compact Constant Head Permeameter (hereafter referred to as CCHP) is designed and manufactured to last through many years of rugged field use. This permeameter allows convenient and easy collection of field data for determination of in situ K_{sat} of many porous media. The procedure for measuring K_{sat} using the CCHP is called the constant-head well permeameter technique, which is also known as shallow well pump-in technique, borehole permeameter, or borehole infiltration test (see Amoozegar and Warrick, 1986; Philip, 1985; Stephen et al., 1987). Detailed description of this procedure can be found in a number of publications (e.g., Amoozegar and Warrick, 1986; Boersma, 1965; Bouwer and Jackson, 1974).

The CCHP can measure K_{sat} of the vadose zone from the surface to 2 m depth. Measurement depth can be increased to 4 m by using an available accessory set of constant-head tubes. Measurement of K_{sat} below 4 m depth requires a special flow measuring reservoir and a portable pressure measuring device which are also available as accessories. For information about the accessories and measurements at depths greater than 2 m contact

In this manual, the CCHP unit without the above mentioned accessories is discussed. The first chapter discusses various components of the equipment and their functions. The second and third chapters present in detail the procedure to collect field data and some of the equations for calculating K_{sat}. The last chapter of the manual is devoted to maintenance, transportation and storage of the CCHP. The Appendix includes a sample data sheet, tables for calculating K_{sat} for some cases, and a list of references for some of the available equations and approaches for calculating K_{sat}. The user is encouraged to become familiar with the permeameter and functions of each part to better understand the procedures to measure K_{sat}. Please take a few moments to examine the permeameter, and have it handy when studying this manual. It would be advantageous to refer to the permeameter for comparison with the figures presented in the manual.

In this manual, the term "soil" does not specifically conform to the traditional definition of soil which may terminate at 2 m depth or where plant roots are scarce. Instead, the term "soil" will refer to any porous medium composed of unconsolidated materials that can be dug with hand tools and extend from the land surface to bedrock.

CHAPTER I

THE COMPACT CONSTANT HEAD PERMEAMETER

The CCHP is a single unit comprised of five sections: four constant-head tubes, a four-liter (4-L) main water reservoir, a one-liter (1-L) flow measuring reservoir, a water dissipating unit, and a base with a three-way valve (Figure 1). The constant-head tubes and the two water reservoirs are permanently mounted on a 19- by 29.5-cm base. The water dissipating unit is permanently attached to both the 4-L main and 1-L flow measuring reservoirs through the three-way valve. A carrying strap, designed for easy transportation to and from field sites, is also permanently attached to the permeameter. Field assembly is not required for the CCHP.

Constant-Head Tubes

The four constant-head tubes (Figures 1 and 2) can provide up to -200 cm of water pressure (i.e., vacuum), and thus the CCHP can maintain a constant head of water in the bottom of an auger hole down to approximately 200 cm below the device. The "WATER LEVEL" mark on each constant-head tube indicates the amount of water that must be added to the tube for optimal operation.

The base of each constant-head tube has an air tight seal, and the tube is permanently attached to the base of the permeameter. Two small diameter air tubes are installed in each constant-head tube through a rubber stopper (Figure 2). One small diameter air tube (referred to as "bubble tube") extends to approximately 5 mm above the bottom of the constant-head tube. The other tube (referred to as "air tube") only extends into the air void above the water level in the constant-head tube. For proper operation, the rubber stopper on top of each constant-head tube must be tightly fitted to form an air tight seal. Each air tube is connected through flexible plastic tubing (flexible air tube) to a quick-release connector that can be easily connected to an adjacent bubble tube to serially connect the constant-head tubes to one another (Figure 3) and to the flow measuring reservoir as needed.

The bubble tubes inside constant-head tubes two, three and four are fixed. The bubble tube inside constant-head tube number one is adjustable. When connected, the pressure differential at the bottom tip of each fixed bubble tube and the air above the water level in the corresponding constant-head tube is approximately equivalent to -50 (minus 50) cm of water pressure (i.e., equivalent to 50 cm of vacuum). The adjustable bubble tube inside the first constant-head tube can be moved up or down, and can be used to make adjustment in the depth of water at the bottom an auger hole. By moving the bottom tip of the adjustable bubble tube

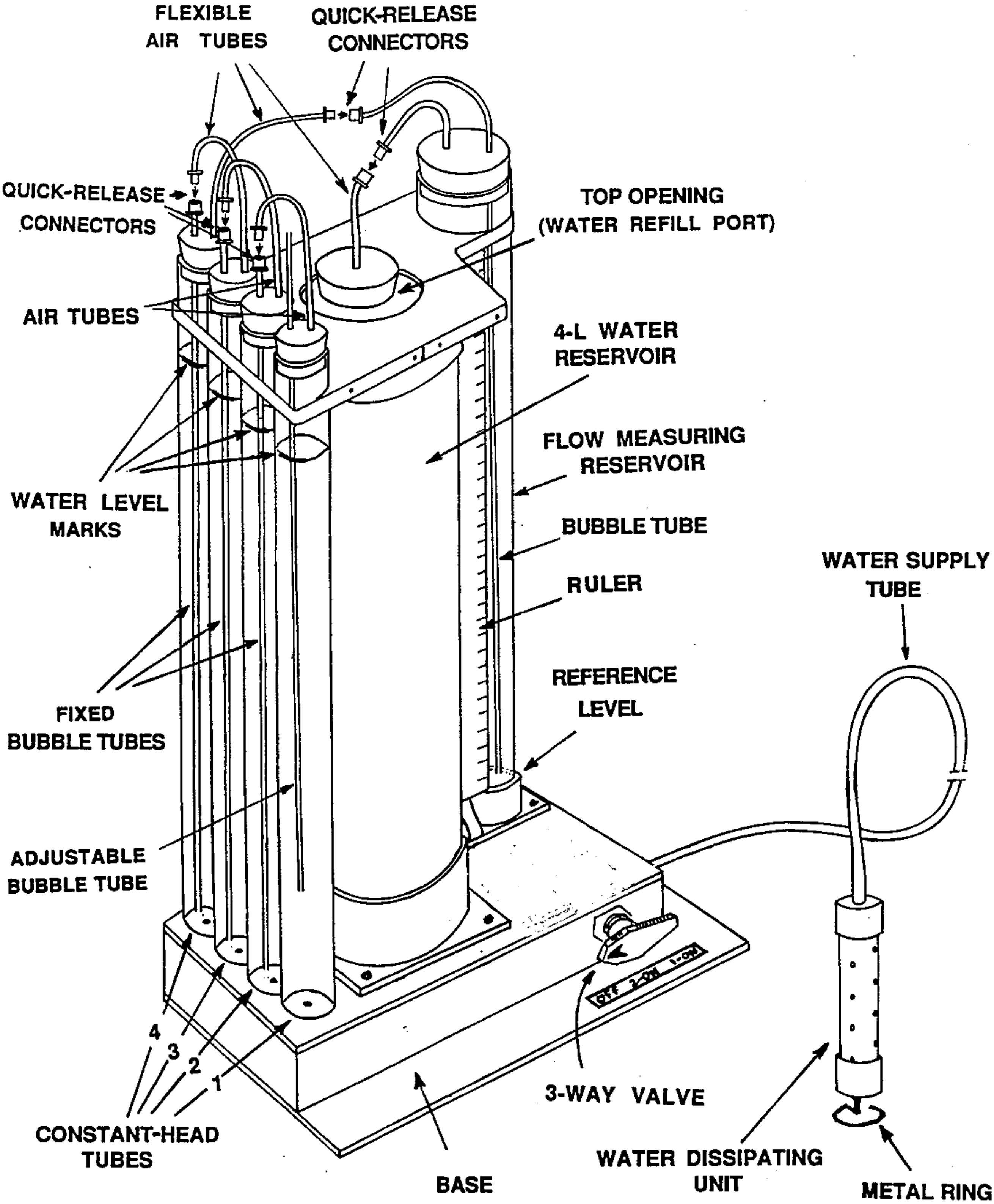


Figure 1. Schematic diagram of the CCHP showing various components of the device.

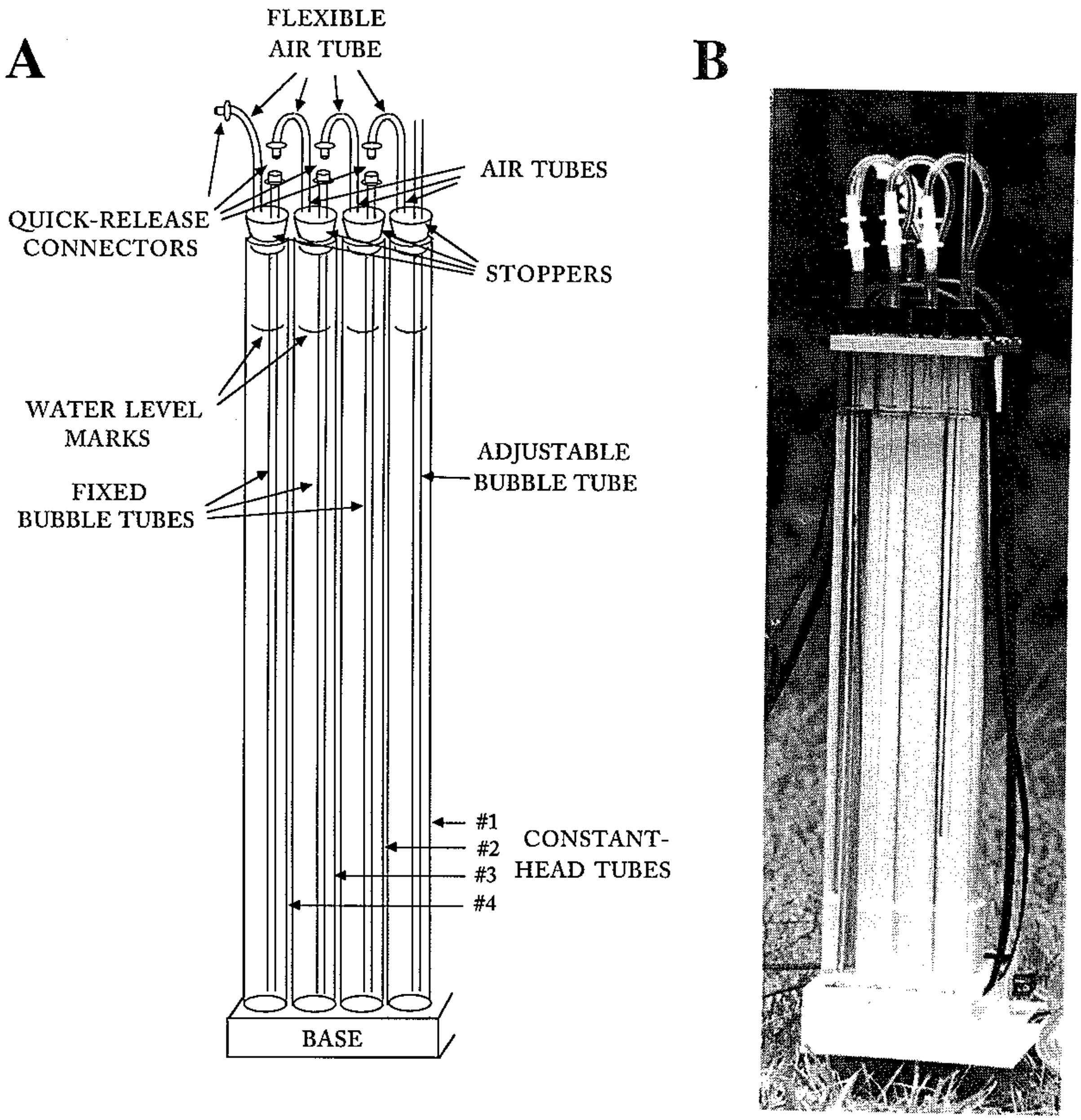


Figure 2. A schematic diagram (A) and a photograph (B) of the four constant-head tubes.

through the range from the level of water in the constant-head tube (i.e., constant-head tube #1, see Figure 2A) to 5 mm above its base, the pressure on top of the water in constant-head tube #1 can be varied from 0 to -50 cm of water pressure. This variable constant-head tube allows the operator to adjust the head of water (i.e., depth of water) at the bottom of the auger hole to a desired level. The proper connection series of the adjustable and fixed bubble tubes to the air tubes (using the quick-release connectors) for measuring K_{sat} at various depths up to 2-m below the soil surface will be presented later.

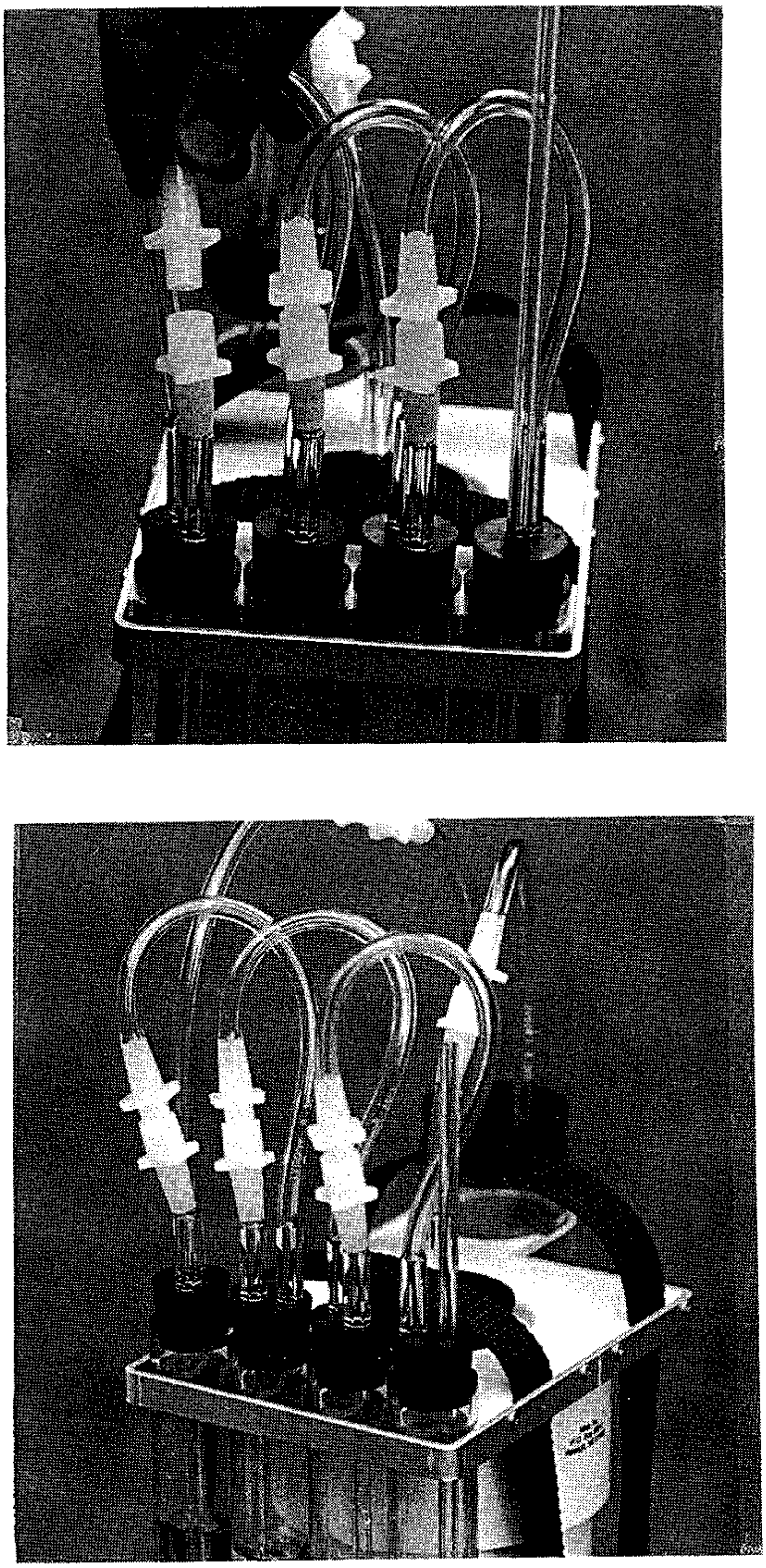
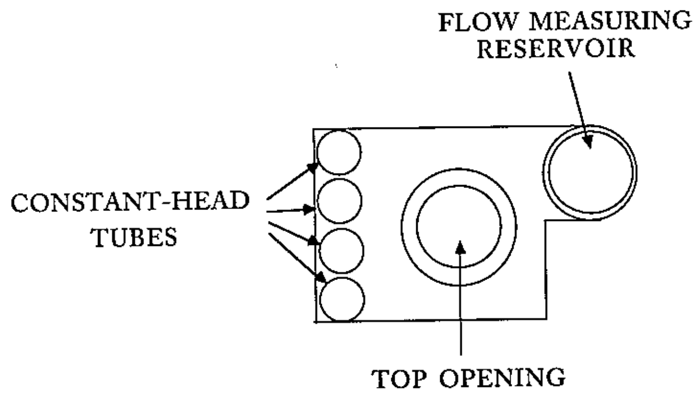


Figure 3. Photographs of the top of the constant-head tubes showing the connection of the air and bubble tubes.

Four-Liter Water Reservoir

The 4-L water reservoir (hereafter referred to as the main reservoir) in the center of the CCHP (Figure 1) has over 4 L water capacity. Constructed of durable white polyvinyl chloride (PVC), it is designed to maintain the CCHP's center of gravity in the middle of the base of the unit. The large opening on top of this reservoir (Figure 4), shown as "top opening (water refill port)" in Figure 1, allows the operator to quickly fill or refill the permeameter. In fact, the

A



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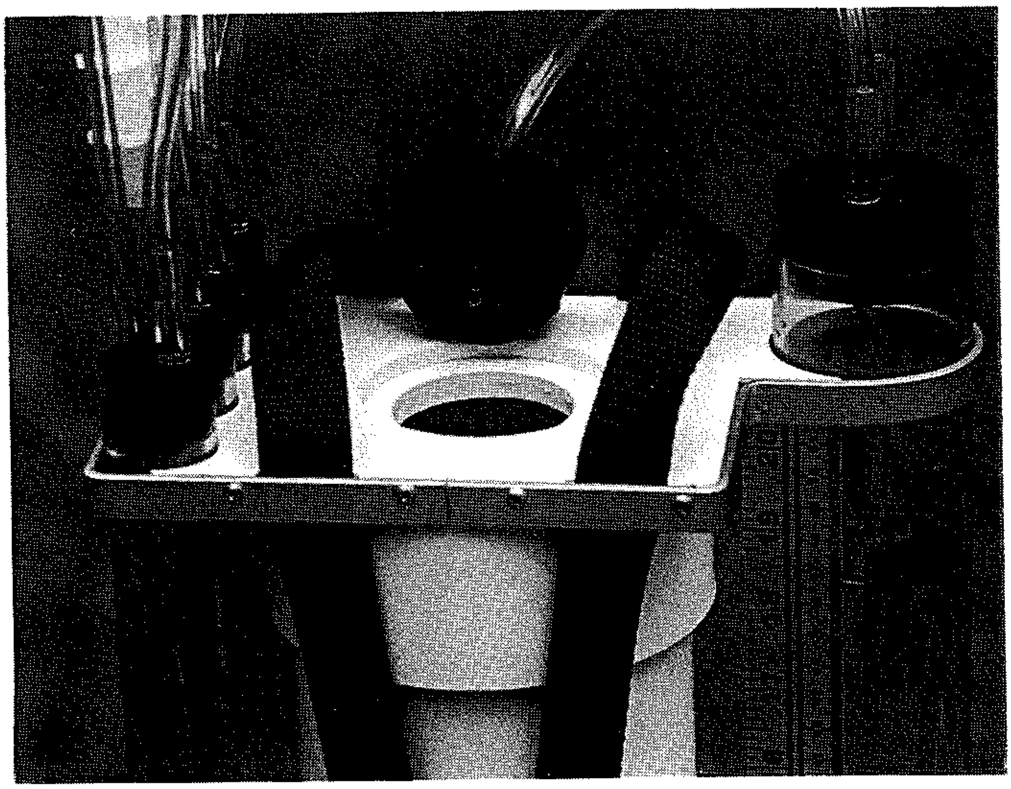


Figure 4. Schematic diagram of the top view of the CCHP (A) and a photograph of the upper part of the CCHP (B) showing the top opening.

reservoir can even be refilled while permeameter is being operated with minimal disturbance to hydraulic conductivity measurement. A flexible air tube, equipped with a quick-release connector, is attached to a rigid air tube through the rubber stopper that seals the top opening.

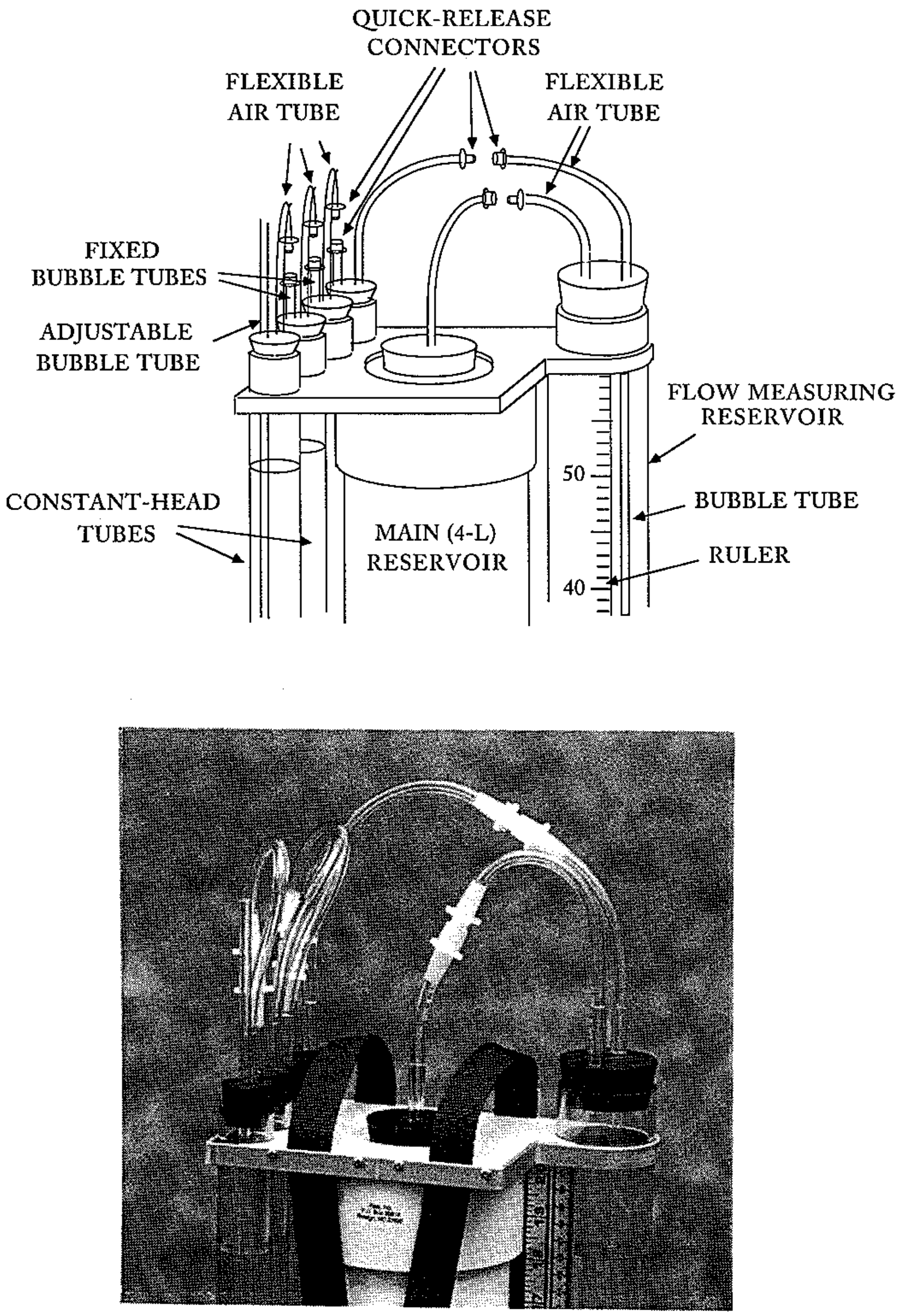
Flow Measuring Reservoir

The flow measuring reservoir (Figure 1) is made from clear polycarbonate tube and has over one L water capacity. This reservoir allows observation of water movement from the CCHP into the bottom of the auger hole, and thus is used for the measurement of the flow rate from the auger hole into the surrounding soil material. The flexible tube attached to the rigid bubble tube that extends to the reference level at the bottom of this reservoir is equipped with a quick-release connector that must be attached to one of the constant-head tubes (see Figures 1 and 5). The shorter air tube on the flow measuring reservoir is also connected to a piece of flexible tube equipped with a quick-release connector for connecting the air void above water in this reservoir to the corresponding air void in the 4-L main reservoir (Figures 1 and 5).

The CCHP's reference level is set at the top of the white PVC coupling where the clear polycarbonate flow measuring reservoir is attached to the CCHP's base (Figures 1 and 6). This level is identified by a black "**O**" ring. This reference datum level (zero or base level) is used to set the desired constant depth of water for measuring K_{sat}. The metal ruler mounted next to the flow measuring reservoir (see Figures 1 and 6) is for measuring the drop in the water level in the flow measuring reservoir as water discharges out of the CCHP through the water dissipating unit and into the soil material at the bottom of the auger hole. The ruler is marked in both mm increments for metric system (SI units) and in 1/8-inch increments for English system. Zero on the ruler corresponds with the reference level of the flow measuring reservoir.

Water Dissipating Unit

The water dissipating unit (Figures 1 and 7) allows uniform distribution of the water flow from the permeameter into the auger hole while causing minimum disturbance to the hole. The water dissipating unit is connected to both the main reservoir and flow measuring reservoir through a 2.5-m long water supply tube and a special three-way valve (Figure 1). The metal ring at the bottom of the water dissipating unit (Figure 7) is designed to minimize blockage of the surface area at the bottom of the auger hole. The flexible water supply tube allows placement of the water dissipating unit at the bottom of the auger hole (less than 2.5-m deep), and also allows for compact storage without disassembly of the CCHP.



A

B

Figure 5. Schematic diagram (A) and a photograph (B) of the upper part of the CCHP showing various components.

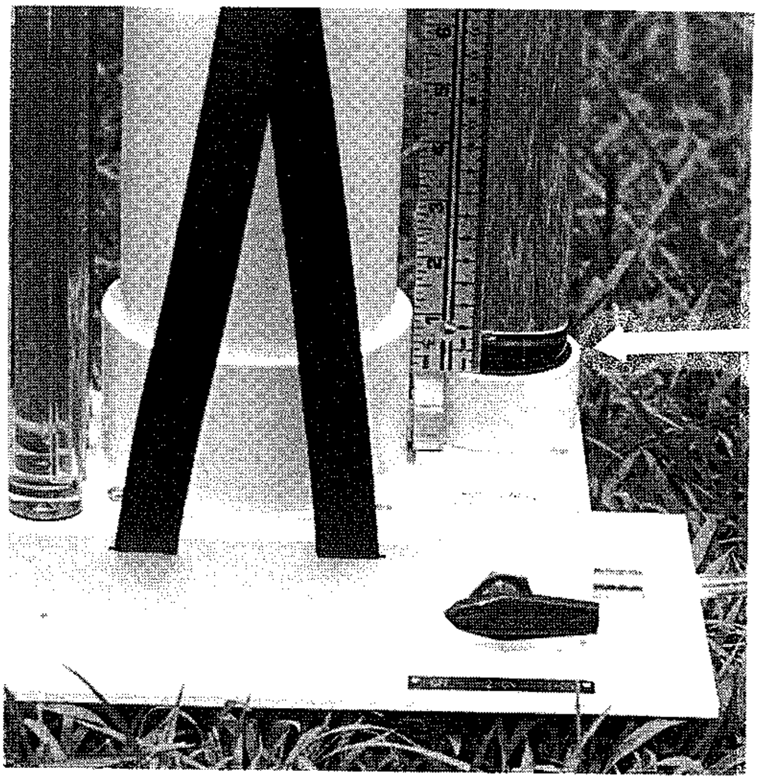


Figure 6. A photograph of the lower part of the CCHP. The reference level is at the zero mark on the ruler.

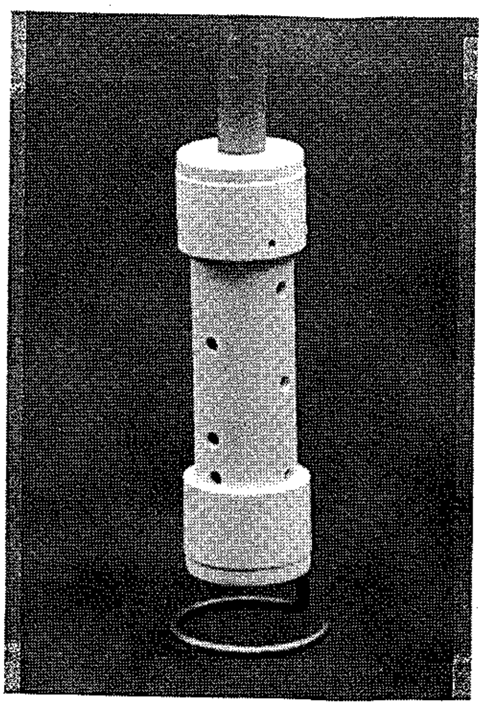


Figure 7. A photograph of the water dissipating unit.

Three-Way Valve

The three-way valve (Figure 1) is a high quality brass valve and has three different positions (Figure 8). In the "**OFF**" position (Figure 8A), this valve halts flow to the water dissipating unit while keeping the flow measuring reservoir connected to the main reservoir. When the valve is set on the "**2-ON**" position (Figure 8B), the volume of both the main reservoir (4 L water capacity) and the flow measuring reservoir (1 L water capacity) are connected to the water dissipating unit (i.e., a total of 5 L water capacity). In the "**1-ON**" position (Figure 8C), only the flow measuring reservoir is connected to the water dissipating unit. All plumbing connections are housed inside a PVC base assembled on a 19- by 29.5-cm base plate.

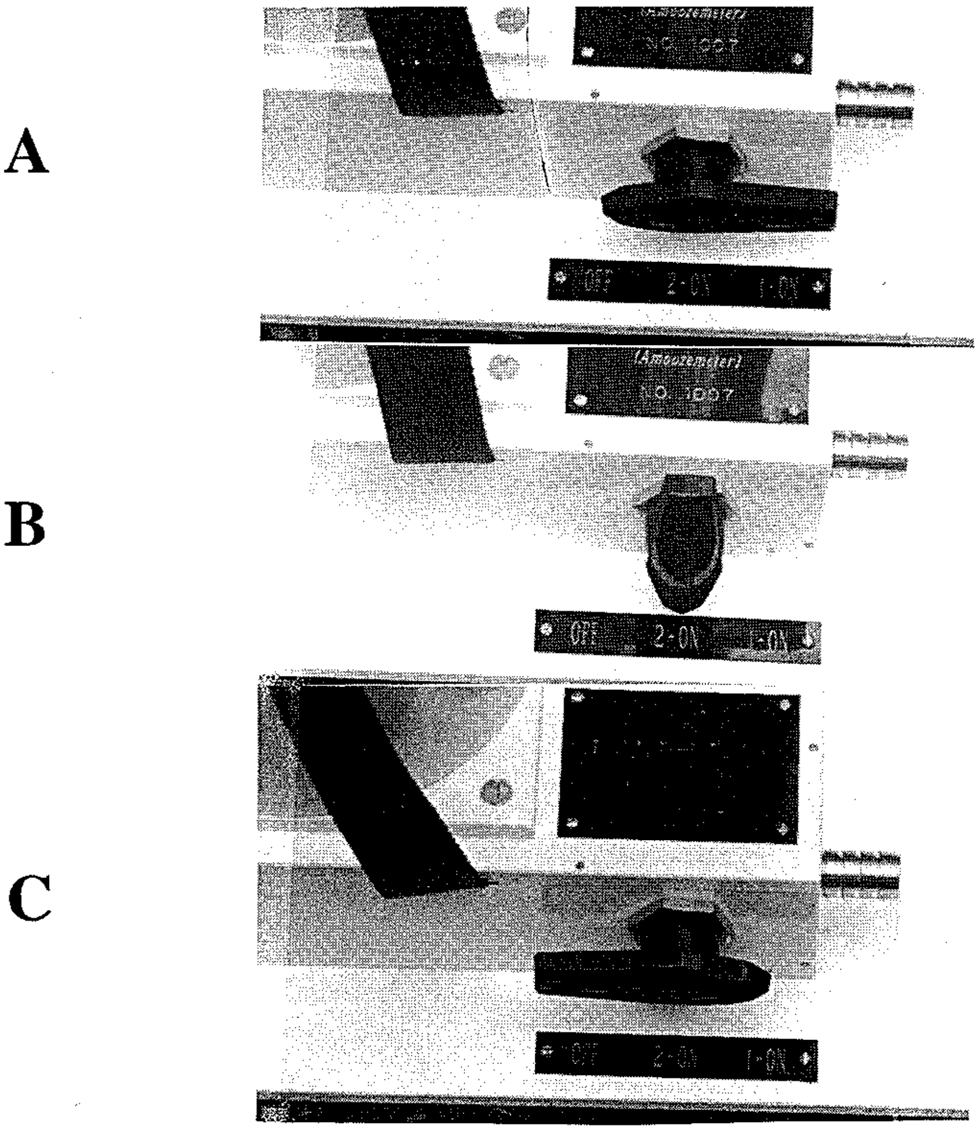


Figure 8. Photographs showing the positions of the three-way valve on "**OFF**" (A), on "**2-ON**" (B), and on "**1-ON**" (C).

Carrying Strap and Transportation

The carrying strap allows easy and convenient transportation of the CCHP either by hand or as a back pack for use in remote sites. The strap is adjustable and does not interfere with the operation of the permeameter. During transportation, water can remain inside the constant-head tubes and the two reservoirs. Water may also be left inside the permeameter during short storage. However, water should be removed from the CCHP for long distance land transport, air shipment, and long-term storage to avoid microorganism growth in the reservoirs, constant-head tubes, and air or bubble tubes.

CHAPTER II

COLLECTION OF FIELD DATA FOR MEASURING K_{sat}

Measurement of the saturated hydraulic conductivity of the vadose zone by the constant-head well permeameter technique is a two-step process. First, the steady-state rate of water flow from a cylindrical hole under a constant head of water is determined in the field. Then, using the data, K_{sat} is calculated by an appropriate equation that will be discussed in CHAPTER III.

[NOTE: It is the responsibility of the user of the CCHP to determine the location and depth of the auger hole for measuring K_{sat}. Also, it is the responsibility of the user to use his/her best judgement to determine if the soil conditions, climatic conditions, and other circumstances are suitable for measuring K_{sat} using the CCHP. Like other procedures, the constant-head well permeameter technique has a number of limitations. For example, this technique is not suitable for measurement in the zone immediately above a water table (i.e., capillary fringe) where water movement from the hole may be restricted due to the near saturated conditions. Another example is that this technique cannot be directly used to specifically determine K_{sat} of a relatively thin (e.g., 10 cm thick) layer or horizon. In general, the measured K_{sat} by this technique represents the overall saturated hydraulic conductivity of the soil around the wetted perimeter of the hole.]

Materials and Equipment

Following materials and equipment are needed for determining the steady-state water flow rate from a cylindrical hole under a constant head in the field.

1. Compact Constant Head Permeameter [NOTE: If the porous medium under consideration has a very high K_{sat}, more than one CCHP unit may be required for supplying water to the hole.]

2. Auger set (quick-release auger set is highly recommended):
   - 2-inch (6-cm diameter cutting head) auger
   - 2-inch planer auger or hole cleaner
   - brush
   - auger extension(s)

[NOTE: The above items are commercially available from a number of outlets. A 2-inch auger capable of boring a 6-cm diameter auger hole is highly recommended. The use of other size augers (and holes) for measuring K_{sat} will be discussed later. Regardless of the nominal size of the auger used for boring the final stages of the hole, the user of the CCHP is responsible for determining the size of the hole that is dug by the auger. In fact, the auger used for boring the bottom part of the hole should be checked periodically as the shape of the auger may change with use.]

3. Locking tape measure (metric system is highly recommended)

4. Stop watch or a watch capable of reading seconds accurately

5. Adequate water for each measurement (approximately one L for filling the constant-head tubes and 5 L to fill the two reservoirs)

6. Data sheet (see the sample data sheet in the Appendix) or data book and pen

7. A copy of this manual or a "how to do" list for reference

The following is a suggested list of additional materials and equipment that facilitate field operation and data collection. You may, however, find other materials and equipment that can assist in collecting field data. Prepare a complete list to ensure that all materials and equipment are available at the field site.

1. A device (such as a hand-held battery operated water level indicator) for determining and verifying the depth to water level in the auger hole accurately

2. Small (30 cm long) and 1-m long rulers

3. Hand vacuum pump (available from boat supply stores), over 2 m of plastic tube, and a trap for removing excess water from the hole if needed

4. Vacuum grease or vaseline to lubricate the adjustable bubble tube

5. Laboratory marking tape (avoid using masking tape, duct tape or other kinds of tape that may not peel off easily, or leave a residue on the polycarbonate tube)

6. Water proof marking pen

7. A clip board

8. Soil knife to aid cleaning out the auger if necessary

9. Programmable pocket calculator for calculating K_{sat} in the field

10. A 2.5-gallon water container (collapsible bottle if available)

11. A section of perforated 2-inch PVC pipe (2-inch PVC well casing is recommended)

12. Small tent, large blanket or sheet, or other suitable materials for protecting the CCHP from solar radiation, wind, and other climatic conditions

Site Characterization and Auger Hole Preparation

Following are general steps that are recommended for collecting reliable field data.

Site Characterization:

1. Select a small, uniform area within the landscape where measurement of K_{sat} is desired.

2. Describe the soil profile using pit(s) or auger boring(s), and determine the depth of any impermeable layer that may exist within at least 60 cm below the maximum depth where K_{sat} will be measured.

Auger Hole Preparation:

1. Choose the location of the auger hole where K_{sat} measurement will be conducted. Clear the area of trash, plant material, and other objects that may interfere with auger boring, placement of the permeameter next to the hole, operation of the permeameter, or data collection. Prepare a small area next to the hole for the level placement of the permeameter. On side-slopes, a small area can be cut and leveled next to the auger hole. As a less disruptive alternative, the permeameter may be leveled by placing fillers (rocks, wooden blocks, etc.) under the front of the base of the unit.

2. Determine the soil depth interval where K_{sat} measurement is desired. This depth interval will correspond with the depth of water under the constant head at the bottom of the auger hole. To determine K_{sat} of a horizon you may choose the midpoint of the horizon as the center of the height of water in the hole (e.g., for a 16 cm constant head, the bottom of the hole to be 8 cm below the middle of the horizon). Bore a 6-cm diameter hole (i.e., radius of the hole r = 3 cm) to within one cm of the desired depth for the auger hole in which K_{sat} must be measured. Use your professional judgement in determining if the bottom of the hole is at the desired depth. To facilitate preparation of the auger hole, a larger diameter auger may be used to bore the upper part of the hole, but the lower 30 to 40 cm of the hole must be bored using the 6-cm diameter auger. Bore the final 30 to 40 cm of the hole carefully, and do not apply excessive downward force to "speed-up" the auger hole boring process at the bottom of the hole. [NOTE: This distance can be reduced if soil conditions (e.g., presence of high coarse fragments) do not allow boring of a hole by the 2-inch auger. The bottom of the hole to within at least 10 cm above the desired level of water in the hole must be 6 cm in diameter.] Care must also be taken to minimize smearing of the hole's sidewall at the bottom of the hole where measurement will be conducted. Note any possible smearing by examining the soil water content and smearing on any material removed from the auger hole. [NOTE: A different size hole may be used for measuring K_{sat}. Holes larger than 6-cm diameter, however, are not recommended for the CCHP because the

volume of water required to fill the hole to the desired depth and to measure the steady-state flow rate may exceed 5 L (the capacity of the CCHP). A larger diameter hole may also require a higher head (i.e., depth of water in the hole) than the head required for a 6-cm diameter hole. The only exception is when the soil under consideration is relatively thick and has a relatively low K_{sat} such that the CCHP can be refilled after establishing the desired constant head at the bottom of the auger hole. Although not recommended, holes as small as 4 cm in diameter can also be used, but their use should be limited to specific applications. The user of the permeameter should determine if using a hole smaller than 6 cm in diameter is justified. For most practical applications, a 6-cm diameter hole is the best size hole for measuring K_{sat} using the CCHP.]

3. Use the planer auger (hole cleaner) to cut and clean the bottom of the auger hole to form a cylindrical hole. **Do not push the planer into the bottom of the auger hole during this processes.** Excessive downward force will result in compaction and/or smearing of the bottom surface of the hole. Apply a minimal downward force and turn the handle on the planer to clean and square the bottom of the hole. **The planer should not be used to deepen the hole.**

4. Inspect the inside of the auger hole for possible smearing. Sometimes, the effect of smearing can be reduced by brushing the auger hole side wall using a plastic brush that easily fits inside the auger hole (available commercially). Attach the brush to the auger extension, place the brush in the bottom of the auger hole, move the brush gently up and down, and turn it once or twice to reduce auger smearing on the auger hole wall. After removing the brush, carefully insert the planer auger into the hole to remove the loose materials that may have fallen to the bottom of the hole during smearing removal process. [NOTE: Some suggested methods for removing the smearing from the auger hole side wall may result in enlargement of the hole due to the removal of a layer of soil material from the hole side wall. Measure the inside diameter of the hole if you suspect that the inside diameter is enlarged as a result of removing the smearing.]

5. Measure and record the finished depth of the hole on the data sheet or in the data book for your record. A sample data sheet is presented in the Appendix. [HINT: In some soils (e.g., sandy texture soils) the hole wall may collapse after addition of water to the hole. To minimize collapse of the hole wall, insert a section of commercially available 2-in PVC well screen in the

hole. Cut the perforated PVC pipe a few cm above the ground level, and place the water dissipating unit inside the well screen.]

Permeameter Preparation

The general permeameter settings for measurements between the soil surface and 200 cm depth are shown in Figures 9 to 12. Familiarize yourself with various components marked on these figures.

1. Fill each of the four constant-head tubes such that the top of water is at the "WATER LEVEL" mark with the bubble tube fully inserted inside the constant-head tube. **Only use clean water**. [HINT: Lift up the rubber stopper and hang it on top of the constant-head tube with the bubble tube inside the constant-head tube. Fill the constant-head tube to just below the WATER LEVEL mark. Water can be added or removed from the constant-head tube if needed.] Install the rubber stopper on the constant-head tube and press it firmly in place to create an air tight seal. [NOTE: Do not use any lubricating agent on the stoppers or the top edge of the constant-head tubes. Lubrication may cause a stopper to pop out of its respective constant-head tube.] During actual measurement operation, the water level in each constant-head tube that is used in measurement will rise slightly above the WATER LEVEL mark because of air bubbles moving through the water inside the constant-head tube. Make sure water is not sucked through the air tubes, because water can block the air tube(s) and adversely affect the head height.

2. Place the three-way valve on the "**OFF**" position (Figure 8A). Remove the rubber stopper from the refill opening on top of the main reservoir and fill the reservoir with clean water to the top. Simultaneously the flow measuring reservoir will be filled from the bottom during this process. To speed up the filling process, water can also be added from top of the flow measuring reservoir. Tightly secure the rubber stoppers on top of the main and flow measuring reservoirs. [NOTE: Do not use any lubricating grease on the stoppers.]

3. Place the permeameter on the previously prepared flat area besides the hole.

4. Measure and record the distance from the bottom of the hole to the REFERENCE LEVEL on the permeameter (i.e., distance D in Figures 9 to 12).

5. The radius of the hole (r) must be determined prior to measurement. [As indicated earlier, the user of the CCHP is responsible for determining the exact size of the hole dug by the auger. Information about the size of the hole may be obtained from the manufacturer or supplier of the auger set. The auger and the hole dug with the auger should be checked when the auger is used

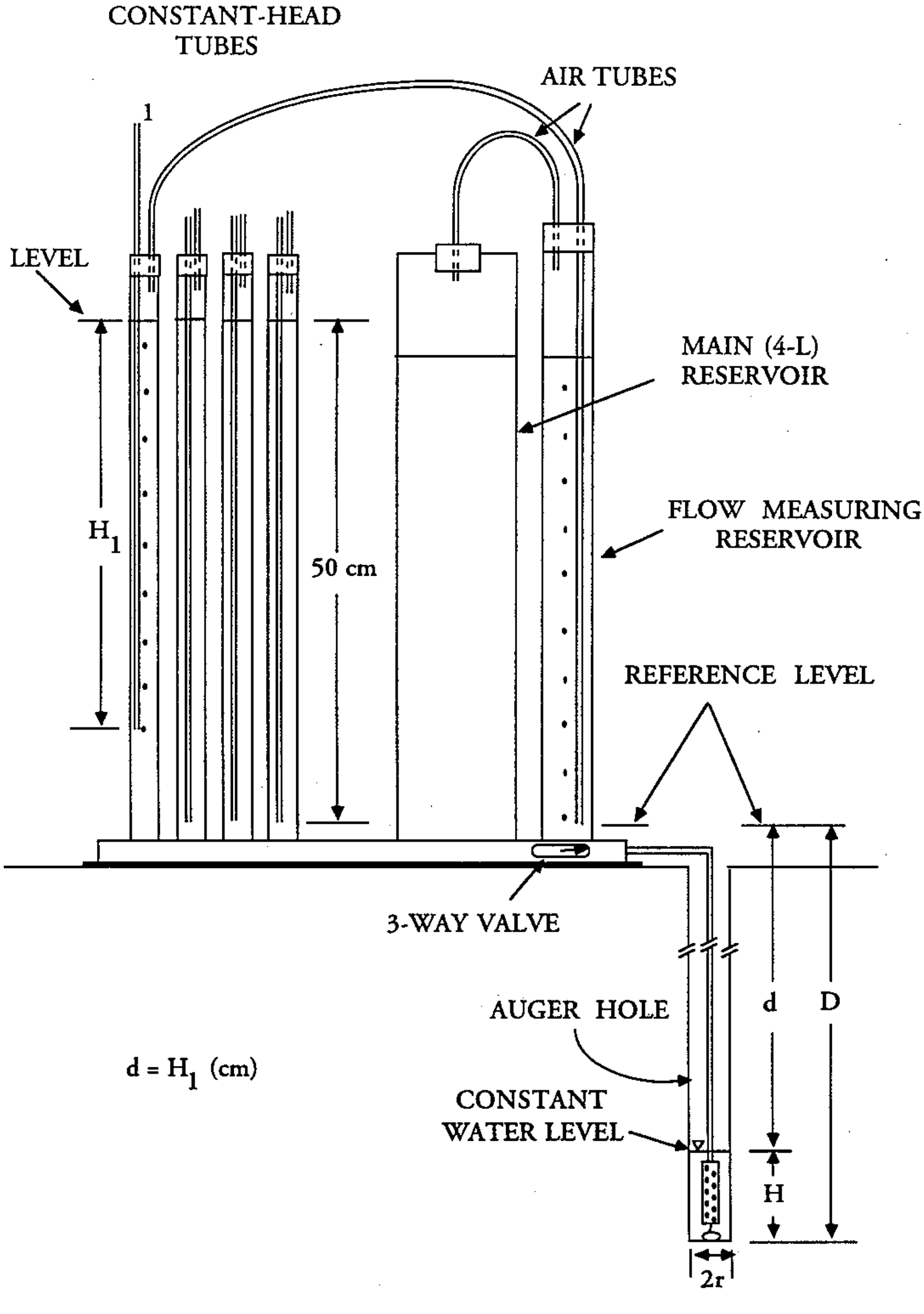


Figure 9. Schematic diagram of the CCHP showing the proper connection of constant-head tube #1 to the flow measuring reservoir for measuring K_{sat} between 0 and 50 cm depths.

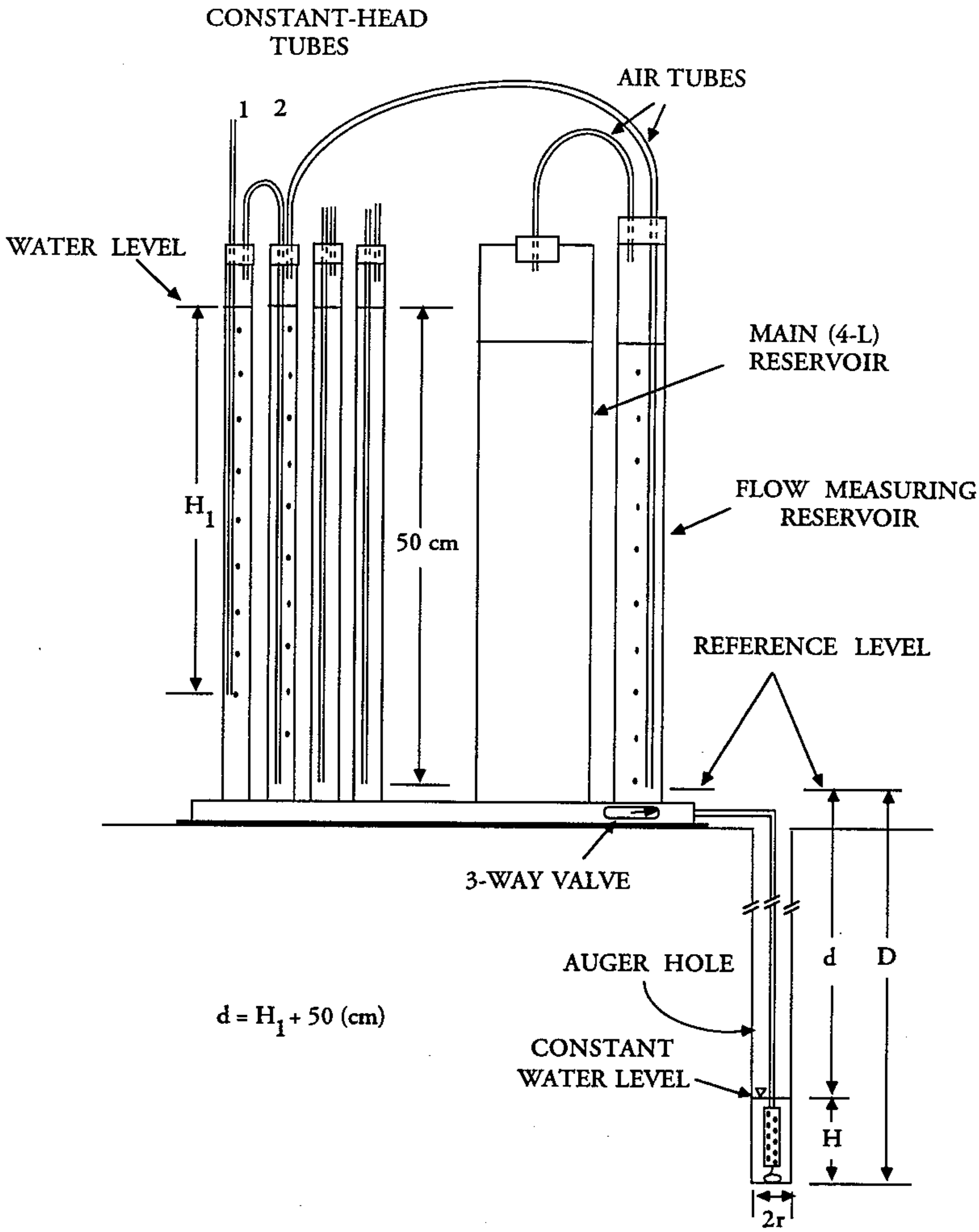


Figure 10. Schematic diagram of the CCHP showing the proper connection of constant-head tubes #1 and #2 to the flow measuring reservoir for measuring K_{sat} between 50 and 100 cm depths.

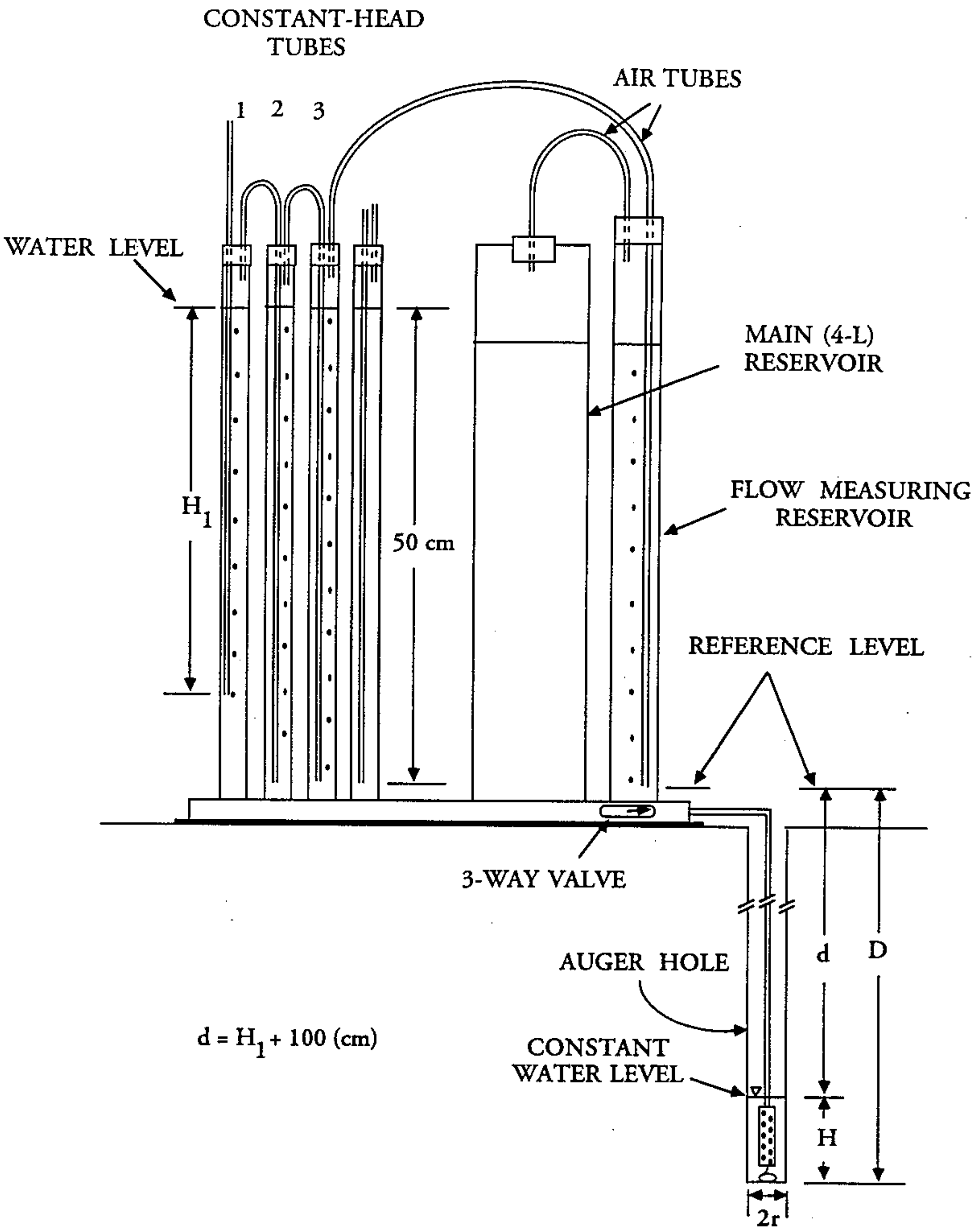


Figure 11. Schematic diagram of the CCHP showing the proper connection of constant-head tubes #1, #2 and #3 to the flow measuring reservoir for measuring K_{sat} between 100 and 150 cm depths.

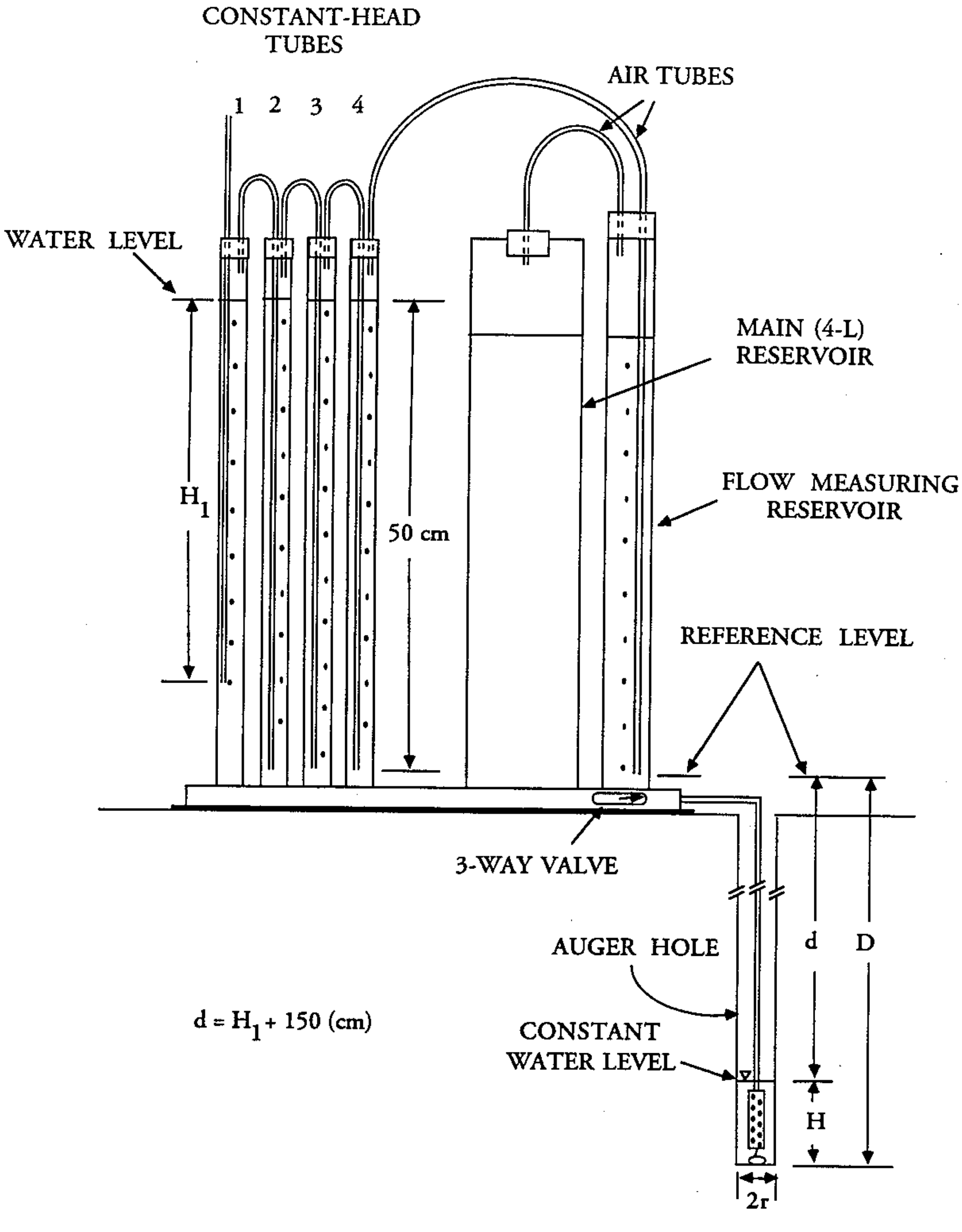


Figure 12. Schematic diagram of the CCHP showing the proper connection of constant-head tubes #1, #2, #3 and #4 to the flow measuring reservoir for measuring K_{sat} between 150 and 200 cm depths.

for the first time and then periodically because the shape of the auger may change with use. To check the auger, measure the widest distance between the edges of the opposite teeth on the auger. The diameter of the hole will be approximately equal to this distance. To determine the size of the hole more accurately, bore a hole with the auger to at least 50 cm depth below the soil surface, fill the hole with concrete, extract the concrete column after it is dried, and measure the diameter of the bottom part of the column.] Choose the desired depth of water in the hole (H) such that the H/r ratio is at least 5 (i.e., $H/r \geq 5$). A 15-cm constant-head of water is desirable for most measurements using a 6-cm diameter auger hole. At this time, we do not recommend using less than a 15-cm head for a 6-cm diameter hole. [NOTE: Based on the available information, the suggested equation for calculating K_{sat} (the Glover solution) requires high H/r ratios. Smaller than 15 cm head (5 to 15 cm) in a 6-cm diameter hole can be used to obtain field data. However, the calculated K_{sat} may contain some error. This limitation of the Glover solution and a possible alternative for using a smaller water head will be discussed later.] To prepare the permeameter for maintaining the desired head H, calculate the distance from the top of the desired water level in the hole to the reference level (distance d in Figures 9 to 12) by subtracting the desired head H from distance D. Record this distance on the data sheet as calculated distance d. [NOTE: For initial setup, H does not need to be predetermined exactly. However, H should be measured exactly for calculating K_{sat} when steady-state flow rate is achieved.]

6a. If $d \leq 50$ cm, connect the air tube on top of the adjustable constant-head tube (constant-head tube #1) to the bubble tube of the flow measuring reservoir as shown in Figure 9. Move the adjustable bubble tube in the first constant-head tube up or down until the distance from the tip of the bubble tube to the water level in the constant-head tube (distance H_1 in Figure 9) is slightly (about 1 cm) more than the calculated distance d.

6b. If $50 < d \leq 100$ cm, connect the air tube on top of the adjustable constant-head tube (tube #1) to the bubble tube of constant-head tube #2, and connect the air tube of constant-head tube #2 to the bubble tube of the flow measuring reservoir as shown in Figure 10. Move the adjustable bubble tube in constant-head tube #1 up or down so that $H_1 + 50$ (cm) is slightly (1 or 2 cm) more than the calculated distance d.

6c. If $100 < d \leq 150$ cm, connect the air tube on top of the adjustable constant-head tube (tube #1) to the bubble tube of constant-head tube #2, connect the air tube of constant-head tube #2 to the bubble tube of constant-head tube #3, and connect the air tube of constant-head tube

#3 to the bubble tube of the flow measuring reservoir as shown in Figure 11. Adjust the adjustable bubble tube in constant-head tube #1 such that H_1 + 100 (cm) is slightly (1 or 2 cm) more than the calculated distance d.

6d. If 150 < d ≤ 200 cm, connect the air tube on top of the adjustable constant-head tube (tube #1) to the bubble tube of constant-head tube #2, connect the air tube of constant-head tube #2 to the bubble tube of constant-head tube #3, connect the air tube of constant-head tube #3 to the bubble tube of constant head tube #4, and finally, connect the air tube of constant-head tube #4 to the bubble tube of the flow measuring reservoir as shown in Fig. 12. Adjust the adjustable bubble tube in constant-head tube #1 such that H_1 + 150 cm is slightly (1 or 2 cm) more than the calculated distance d.

7. Connect the air tube on top of the main reservoir to the remaining air tube on the flow measuring reservoir. Check all the connections for positive seal and to make sure that they correspond with the depth of the hole and the desired depth of water in the hole for measuring K_{sat}. [NOTE: If more fixed tubes are connected than is required, water will not flow from the CCHP to maintain a constant head at the bottom of the auger hole. If fewer fixed tubes are connected than is required, then the hole will be overfilled.]

8. To prime the water supply tube and water dissipating unit, disconnect the air tube on top of the main reservoir from the air tube on top of the flow measuring reservoir. Stretch out the water supply tube and the water dissipating unit on the ground and away from the auger hole. Open the three-way valve to the **2-ON** position so both reservoirs are connected to the water dissipating unit. Allow water to flow out of the water supply tube through the water dissipating unit to purge all the air from the water supply line. [HINT: You may hold the water dissipating unit above the water level in the flow measuring reservoir and allow water to displace the entrapped air inside the water supply tube. When the flexible plastic tube is full of water, lower the water dissipating unit below the water level in the flow measuring reservoir and allow water to move out of the water dissipating unit to assure that no air bubble is present in the line.] When all the entrapped air is removed from the water supply tube, close the three-way valve (**OFF** position).

9. Connect the air tube on top of the main reservoir to the air tube on top of the flow measuring reservoir. Lower the water dissipating unit to the bottom of the hole. Open the three-way valve to the **2-ON** position and allow water to move out of the unit into the auger hole. Air bubbles must appear in the flow measuring reservoir and all the constant-head tubes connected to it. When water level in the auger hole reaches the level corresponding with the distance setting of the permeameter, air bubbles through the constant-head tube(s) and flow measuring reservoir will slow down and become more uniform. At this point, a constant head (level) of water is established in the hole.

Note that water moves very rapidly from the permeameter during the initial filling of the auger hole. Consequently, large bubbles in the constant-head tube(s) may result in water being carried up into the flexible air tubes. This may cause improper operation of the entire unit. If water remains in the flexible air tubes, or if water is moved from one constant-head tube to the next, turn the three-way valve to **OFF** position, disconnect all the air tubes on top, blow the water droplets out of the tubes, refill the main and the flow measuring reservoirs to the top, and check and readjust the water levels in the constant-head tubes if needed. Reconnect the air tubes and begin again. If the hole is overfilled, remove the excess water from the hole, or allow it to infiltrate the soil if possible.

To reduce the time required to fill the hole to the desired depth and to minimize the possibility of large bubbles forcing water into the air tubes, the initial filling of the hole can be accomplished through the following procedure. [Please see the NOTE at the end of this section.] At the end of step number 8, do not connect main reservoir and the flow measuring reservoir air tubes. Lower the water dissipating unit to the bottom of the hole. Note the level of water in the flow measuring reservoir and open the three-way valve to the **1-ON** position (i.e., only the flow measuring reservoir is open to the water dissipating unit)., Allow water to move from the flow measuring reservoir to the hole while the top of water in the reservoir is open to the atmosphere. When the water level in the flow measuring reservoir drops about 5 to 7 cm for H = 15 cm and about 20 cm for H = 30 cm, connect the air tube on top of the main reservoir to the air tube on top of the flow measuring reservoir, and open the three-way valve to the **2-ON** position to allow water from both reservoirs to move into the hole. This must be accomplished quickly to eliminate the possibility of over filling the hole. At this time, air bubbles start to appear in the constant-head tube(s) and flow measuring reservoir. This indicates that water is moving from the permeameter into the hole. Note that water also moves from the 4-L reservoir to fill the 1-L flow measuring reservoir so that the water levels inside the two reservoirs will be at equilibrium. When the water level in the hole reaches the level corresponding to the setting of the permeameter (i.e., when the cumulative lengths of the fixed and adjustable bubble tubes below the water level in the constant-head tubes being employed for measurement corresponds with the distance d), bubbling through the tubes becomes more uniform, and a constant head is established more quickly in the auger hole. [NOTE: Do not try this procedure before you are totally familiar with the operation of the device. You may overfill the auger hole beyond the desired depth of water, and may be required to remove the excess water from the hole, wait for a long time to allow excess water to infiltrate the soil, or even abandon the measurement and start at another location. Also, do not try this method if the depth of measurement exceeds 150 cm.]

10. A constant head of water is achieved when air bubbling through the constant-head tube(s) and the flow measuring reservoir is stable and uniform. At this point, determine the exact depth of water in the hole by measuring the distance "d" exactly and subtracting it from the distance "D" (see Figures 9 through 12). As noted earlier, to measure K_{sat}, the depth of water in the hole (H) does not have to be predetermined exactly. However, to calculate K_{sat}, H must be measured accurately. It would be advantageous to have a range of acceptable H (e.g., 15 to 20 cm) for each measurement. For most practical purposes, choose a desired depth of water (e.g., 18 cm) and proceed with measurements if the depth of water in the hole is within an acceptable range of the desired depth (e.g., between 17.5 and 18.5 for 18 cm head). If H at this point is different from the desired depth of water, then continue with step #11. Otherwise, record the distance d and the depth of water in the hole H on the data sheet and go to step #12. [NOTE: It is advisable to periodically check the water level in the hole to assure that the depth of water remains constant during the entire measurement period. If the water level in the auger hole drops with no bubbling through the air tubes, move the adjustable bubble tube (constant-head tube #1) up in small increments until bubbling resumes. Then go back to the beginning of this step (i.e., step #10) and check the depth of water in the hole. If water level in the hole continuously increases beyond the level set by the permeameter with or without bubbling through the bubble tubes, then there may be a leak in the system. Check all the connections (i.e., quick-release connectors) and stoppers to assure the system is air tight. If the problem continues, check the permeameter for possible leaks.]

11. If the depth of water in the hole is less than the desired depth of water, move the adjustable bubble tube in constant-head tube #1 up a distance equivalent to the difference between the desired depth and measured depth of water in the hole. This will allow additional water to move out of the permeameter into the hole to increase the depth of water. Note that the rate of bubbling increases immediately after moving up the adjustable bubble tube. Return to step #10 to assure that the desired constant head of water is achieved.

If the depth of water in the hole (H) is greater than the desired depth of water, the adjustable bubble tube in constant-head tube #1 should be lowered a distance equivalent to the difference between the measured (i.e., actual) depth of water and desired depth of water in the hole. Then, water must be removed from the hole to achieve the desired depth. Use a small hand pump (preferably with a trap) to remove the excess water from the auger hole. When the water level in the hole is lowered sufficiently, bubbling through the tubes will resume and water moves into the hole from the permeameter. Return to step #10 for determining the depth of water in the hole. [NOTE: If the soil material around the bottom of the hole has a relatively high conductivity, you may allow water to simply move out of the hole into the surrounding material instead of pumping the water out of the hole. As the water moves from the hole into the surrounding material, water level in the hole will decrease until it reaches a level corresponding with the set up of the constant-head tubes. Bubbling resumes as soon as water level in the hole reaches its preset level. In slowly permeable soils, hand pumping will probably be required if the hole is inadvertently overfilled.]

12. When the desired depth of water is established in the hole, keep the three-way valve on the **2-ON** position and allow time for the steady-state condition to be reached. Measure the depth of water at the bottom of the hole and record the value as soon as the desired depth of water (i.e., the constant head) is established. Depending on the physical properties of the soil under consideration, this time to steady-state may vary from a few minutes to a few hours. For most practical cases, measurements can be completed in 2 h using < 5 L of water. In general, for high conductivity soils, start the measurements immediately after the constant head is established. For low conductivity soils, a period of up to a few hours may be allowed if desired. Measure the depth of water in the hole a few times before and after steady-state flow rate to assure a constant head is maintained at the bottom of the hole.

To reach the steady-state, three consecutive measurements of the flow rate (i.e., volume of outflow per unit time such as cm^3/h) must be equal. Determining the steady-state conditions can be accomplished in the filed without actually calculating K_{sat} by measuring the level of water in the flow measuring reservoir at constant time intervals. If a constant time interval (e.g., 15 min) is used between readings, the steady-state is reached when the changes in the water level in the flow measuring reservoir are equal for the three consecutive measurements. By doing this, no calculation of the actual flow rate is needed. **When the three-way valve is on 1-ON (i.e., only the flow measuring reservoir is used), one cm drop in water level in the flow measuring reservoir is equivalent to 20 cm^3 of water (Conversion Factor = 20). When the 3-way valve is on 2-ON (i.e., both the main and the flow measuring reservoirs are used), one cm drop in the water level in the flow measuring reservoir is equivalent to 105 cm^3 of water flow from the permeameter (Conversion Factor = 105).** To determine the amount of water flowing into the hole during a given time period measure the change in the level of water in the flow measuring reservoir during the time period and multiply it by the appropriate conversion factor given above.

The measurement time interval should be based on the flow from the permeameter. High conductivity soils may require 1 to 5 min intervals. Low conductivity soils may require more than 30 min intervals. In general, the greater the time interval between measurements, the more accurate is the estimation of K_{sat}. To increase accuracy of measurement, the time interval for measuring the steady-state flow rate should correspond with at least one cm drop in the water level in the flow measuring reservoir. However, for soils with conductivity < 1 cm/d or 1.2 x 10^{-7} m/s (steady-state flow rate of < 40 cm^3/h under 15 cm head in a 6-cm diameter hole), the time interval can be selected as 30 min even though the water level in the flow measuring reservoir (with three-way valve on the **1-ON** position) may drop less than 1 cm.

For soils with conductivity < 5 cm/d (6 x 10^{-7} m/s) it is necessary to switch the 3-way valve to the **1-ON** position (water flowing out of the flow measuring reservoir only) to allow a more accurate measurement of water flow from the flow measuring reservoir in a < 30-min time interval. Make sure that adequate water is available in the flow measuring reservoir before switching from the **2-ON** (i.e., flow from both reservoir) to the **1-ON** (i.e., flow from the flow measuring reservoir only) for determination of the steady-state flow rate. Record which reservoirs are being used by noting the position of the three-way valve during the steady-state flow measurements.

After determining the three consecutive steady-state flow rates, measure and record the depth of water in the hole exactly (by measuring the distance d). At this point, field data collection is completed and you are ready to calculate K_{sat}.

Refilling the Permeameter

Always start with both the main reservoir and the flow measuring reservoir full of water (a total of 5 L). Only measurement of K_{sat} in a high conductivity soil may require refilling of the permeameter before field measurements are completed. To refill the permeameter before steady-state is reached you may either (i) stop the permeameter by turning the three-way valve to the **OFF** position, or (ii) refill the permeameter while it runs.

i. To refill the main and flow measuring reservoir, turn the 3-way valve to **OFF** position. Carefully release the vacuum from the reservoir and the constant-head tubes. Open the top of the main reservoir and fill the reservoirs to the top. Leave as little air space as possible on top of the water in the reservoirs. Tightly secure the stoppers on top of both reservoirs and reconnect all the air tubes as before. Turn the 3-way valve to the **2-ON** position and continue with measurement. If the permeameter is stopped and the top opening is opened to atmosphere, then the pressure above the water level in the main and the flow measuring reservoirs will become atmospheric. As a result, after restarting, water must move from the permeameter immediately before the pressure above the water in the flow measuring reservoir comes back to equilibrium with the depth of water in the hole. For high conductivity soils the water level in the hole may drop substantially while the water supply to the hole is cut off (i.e., three-way valve is on **OFF** position). Therefore, after restarting, water may initially move very rapidly from the permeameter until the water level in the hole rises back up to its pre-refilling level. [NOTE: Opening the top of the reservoirs to atmosphere when the system contains vacuum will result in the movement of air into the constant-head tube(s) in a reverse direction. As a result, water may move into the air tubes and from one constant-head tube to the next. One way to remove the vacuum is by clamping the individual air tubes and undoing the quick-release connectors.]

ii. To refill the main reservoir while running the permeameter you must have some water in the flow measuring reservoir. Switch the three-way valve to the **1-ON** position. Close the air tube that connects the top of the flow measuring reservoir to the top of the main reservoir by bending and holding (i.e., crimping) the plastic (flexible) air tube between the flow measuring reservoir and the quick-release connector. Disconnect the quick-release connector that connects to the top of the main reservoir while keeping the air tube on top of the flow measuring reservoir tightly closed. Remove the stopper from the top opening on top of the main reservoir, and fill the reservoir to the top (leave as little air space as possible) with clean water . Tightly secure the stopper on the top opening of the main reservoir and reconnect the air tube attached to the stopper to the clamped air tube of the flow measuring reservoir. Release (i.e., unbend) the air tube on top of the flow measuring reservoir, and turn the three-way valve to the **2-ON** position. Water will start to rise inside the flow measuring reservoir. Refilling the permeameter while running must be accomplished quickly so that the flow measuring reservoir will not run out of water. Note that water level in the hole may rise slightly above its preset level immediately after reconnecting the air tubes on top of the two reservoirs. As a result, bubbling through the constant-head tube(s) and the flow measuring reservoir may cease temporarily. As soon as water level in the auger hole reaches its previously established level, bubbling will resume through the permeameter.

Water Composition and Temperature

Always use clean water. Use of dirty water may result in unwanted microbial growth in the permeameter. Dirt and other objects in water may also cause blockage in the tubes and/or the 3-way valve connecting the two reservoirs to each other and to the water dissipating unit.

Any types of clean water can be used in the permeameter. For more realistic measurement of K_{sat}, however, it is best to use water with chemical composition comparable to the natural soil or ground water in the area. For most purposes, tap water may be adequate. However, freshly drawn tap water may contain a high level of dissolved air. Try to collect tap water from outlets with no aerator and make sure air does not mix with water during filling the water container. In general, distilled or deionized water should not be used for K_{sat} measurements. As an alternative to tap, well, or local stream water, a 0.005*M* $CaSO_4$ or 0.005 to 0.01*M* $CaCl_2$ solution can be used. This solution may be made prior to the trip to the site. Make sure the container is full of solution and tightly sealed for transportation.

The temperature of water entering soil at the bottom of the auger hole may alter the hydraulic conductivity of the soil. The steady-state flow rate, and hence the K_{sat}, can be corrected for any desirable temperature. Multiply the final steady-state flow rate by the ratio of the viscosity of water at the temperature during measurement and the desired (reference) temperature. The viscosity of water for selected temperatures are given in the Appendix. A reference temperature may be chosen as the mean annual soil temperature at the depth of interest. Do not use the ambient temperature if temperature correction is desired. It is best to measure the water temperature at the bottom of the auger hole. As an alternative, measure the temperature of the water inside the main reservoir and the flow measuring reservoir before starting water application to the auger hole and immediately after completing steady-state measurement. For correction, use the average of these temperature values. Also, to minimize the effect of direct sunshine, the permeameter can be shaded or placed in an open ended tent. If possible, measurement of K_{sat} in extreme cold or hot weather should be avoided.

Determination of the Steady-State Flow Rate

For practical purposes, the steady-state flow rate is reached when three consecutive measurements of the flow rate from the permeameter (i.e., volume of outflow per unit time such as cm^3/h) are the same.

For an ideal situation (hypothetical condition of a homogeneous and isotropic soil with no change in soil characteristics with time), the rate of water flow from an auger hole in the unsaturated zone under a constant head will gradually decrease with time and asymptotically approach a final value (Figure 13) considered to be the steady-state flow rate Q. Because of temporal and spacial variabilities (i.e., variations with time and space, respectively) of soil properties, water flow from an auger hole dug to a given depth may not behave similar to the theoretical curve shown in Figure 13. Depending on the soil characteristics, the steady-state flow rate from a small diameter auger hole (4 to 10 cm in diameter) under a constant head of water may be achieved in a few minutes to a few hours. For some cases (e.g., heavy clay with smeared auger hole sidewall, wet expanding clay) no water flow may occur after the constant head is established in the hole. In some other soils, on the other hand, steady-state may be reached very quickly. In relatively dry soils with expanding clay mineralogy around the bottom of the hole, the flow rate may gradually decrease as the soil around the auger hole expands and eventually become sealed. In rare occasions, some users may experience an increase in the flow rate after an initial decline. Although this situation is unlikely, two explanations can be offered here. (i) There may be an initial sealing of the pores as a result of smearing the sidewall or clogging of the pores during the hole construction. The pores may open with time after water application to the hole, and allow more water to move into the surrounding soil. If this is the case, the flow rate should decline again and reach a steady-state value. (ii) The hole sidewall may collapse and increase the size of the hole below the level of water. If an increase in the flow rate is encountered, check the auger hole and the level of water in the hole to assure that the hole integrity is intact. Regardless of the type of soil or conditions under which K_{sat} measurements are conducted, determination of the steady-state flow rate is the sole responsibility of the individual conducting the measurement.

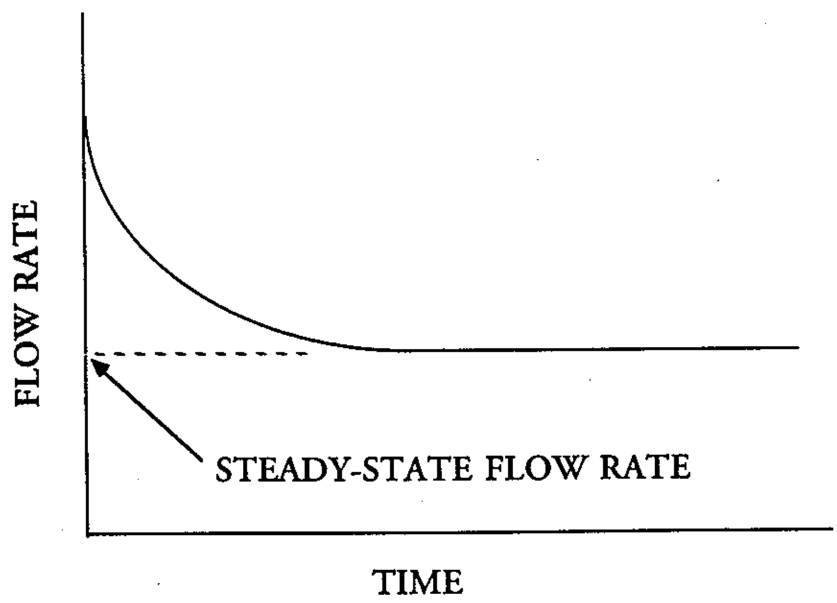


Figure 13. A hypothetical curve depicting the reduction in the flow rate with time and the final or steady-state flow rate.

CHAPTER IV

CALCULATING K_{sat}

The CCHP allows collection of field data easily and conveniently. Saturated hydraulic conductivity must then be calculated from the field data using an appropriate equation. A number of mathematical and statistical (regression) models are available for calculating K_{sat}. Each one of these models has physical and mathematical limitations. Discussion of these models is beyond the scope of this manual. For a more comprehensive discussion of some of the models, the interested users are referred to the articles listed in the BIBLIOGRAPHY section of this manual.

One of the available equations for calculating K_{sat} is the Glover solution. This solution is recommended for calculating K_{sat} when the distance between the bottom of the auger hole and any impermeable layer (distance s in Figure 14) is ≥ 2H. The Glover solution was developed over 40 years ago and has a number of advantages over some of the other models and

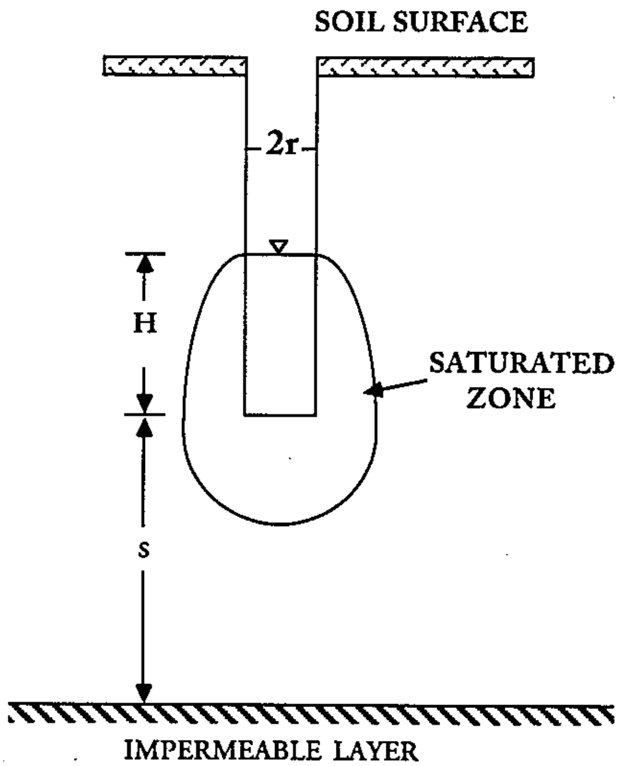


Figure 14. Schematic diagram of the cross sectional area of an auger hole showing H and r, the saturated zone (referred to as the saturated bulb) around the bottom of the hole, and the distance between the bottom of the hole and an impermeable layer .

approaches. (i) The only unknown parameter in the Glover solution is K_{sat}. Therefore, there is no need to estimate or use an independent method to obtain a second parameter related to the unsaturated flow around the auger hole. (ii) The Glover solution is independent of the soil texture and structure. Therefore, there is no need to estimate or determine the soil texture and structure to obtain a coefficient (a constant factor) for determining K_{sat}. (iii) Only one steady-state flow rate value under one constant head of water is required, and no negative values are obtained by the Glover solution. For these and other reasons, in this manual, the Glover solution is recommended for calculating K_{sat}. **Although the Glover solution for calculating K_{sat} is recommended and presented in this manual, it is the responsibility of the user of the CCHP to choose the model(s) or approach(s) for calculating K_{sat}.** The users of the CCHP are encouraged to study other models and approaches, and choose one (or more) that will fit their needs for calculating K_{sat}. For a brief discussion of the Glover solution see Amoozegar (1992).

The Glover solution is given by:

$$K_{sat} = AQ \qquad [1]$$

where

$$A = \{\sinh^{-1}(H/r) - [(r/H)^2 + 1]^{1/2} + r/H\}/(2\pi H^2) \qquad [2]$$

and Q is the steady-state rate of water flow from the permeameter into the auger hole. In the above equation, $\sinh^{-1}$ is the inverse hyperbolic sine function, and r and H are as defined earlier.

If the distance between the bottom of the auger hole and an impermeable layer (i.e., s) is < 2H, K_{sat} can be calculated by

$$K_{sat} = BQ \qquad [3]$$

where

$$B = \{3\ln(H/r)/[\pi H(3H + 2s)]\}. \qquad [4]$$

In these equations Q, r, H, and s (measured or estimated distance between the bottom of the hole and the impermeable layer below the hole, see Figure 14) are as before, and ln(H/r) is the natural logarithm of H/r.

The Glover solution can be evaluated very easily because it depends only on the depth of water in the hole (H), the radius of the hole (r), and one measurement of the steady-state flow rate (Q). Most scientific calculators have the $\sinh^{-1}$ function. For those who do not have access to a scientific calculator (or wish to calculate K_{sat} without computing Eq. [2]), or those who are unfamiliar with the above function, Tables 1 to 3 in the Appendix present the coefficient A (Equation [2]) for three different r values (r = 2.5, 3, and 3.5 cm, respectively) under various H values (H/r between 5 and 10). Table 4 gives the values of $\{\sinh^{-1}(H/r) - [(r/H)^2 + 1]^{1/2} + r/H\}$

for H/r values between 5 and 10. To calculate K_{sat}, when the radius of the hole is 2.5, 3 or 3.5 cm, multiply the steady-state flow rate Q in units of cm^3/unit time (e.g., cm^3/h) by the coefficient A obtained for the desired H value from the appropriate table for the r value. Using the coefficient A from Table 1, 2 or 3, the units for K_{sat} are cm/unit time, where the unit time is the same as the unit time used for obtaining Q. Interpolate between the appropriate A values for H values not given in the tables. The value of A for a r value that is different from 2.5, 3 or 3.5 cm cannot be obtained by interpolation between the tables. If you have an auger that creates a different size hole than 5, 6 or 7 cm in diameter, a table similar to Table 1, 2, or 3 can be created for easy calculation, or the coefficient A can be calculated by Eq. [2] using the appropriate value of its numerator obtained from Table 4.

For all calculations, the units for H, r, Q, and K_{sat} should be consistent. For example, if H and r are in cm and Q is in cm^3/d, then the units for K_{sat} are cm/d. If H and r are measured in inches and Q is in cubic inches per hour then K_{sat} is in inch/h.

Originally, it was determined that the Glover solution results are valid for H/r values > 10 (Zangar, 1953). This was based on comparison of an abbreviated version of the Glover solution (not suggested in this manual) and the results of electrical analog analysis. Using equation [1] with the A factor obtained by Eq. [2], however, lower H/r ratios between 5 and 10 can be used with confidence while keeping the limitations of the Glover solution in mind. At this time, ratios of H/r < 5 are not recommended for measuring K_{sat}. For a 6 cm diameter hole, a H/r ratio of 5 requires a minimum of 15-cm depth of water in the hole. If a smaller than 15 cm depth of water is desired, then the size of the auger hole can be decreased (e.g., r = 2.5 cm, H = 12.5 cm).

CHAPTER IV

MAINTENANCE, TRANSPORTATION, AND STORAGE

Maintenance

The CCHP is designed and constructed for many years of rugged field use. No special maintenance, other than cleaning the constant-head tubes, the two water reservoirs, and the water supply tube is needed. Also, it is necessary to occasionally lubricate the adjustable bubble tube in constant-head tube number 1. Extensive field use, especially under hot summer sun, however, may cause some of the plastic tubes or rubber stoppers to become loose or brittle. If necessary, the rubber stoppers, the 1/4-in rigid air tubes, and the flexible plastic tubes can be replaced easily.

Under normal operation, no air bubble should enter the constant-head tubes and the two measuring reservoirs except through the air and bubble tubes. Appearance of air bubbles other than the ones associated with the air and bubble tubes may be due to leakage. Leakage may also occur around the rubber stoppers if they are not properly secured. As a result, water level in the flow measuring reservoir may drop while no air bubble moves through the constant-head tubes(s). If leakage occurs, the CCHP may not be able to maintain a constant head, and water level in the hole may rise above the level set by the permeameter. **Measurement of H before and after steady-state flow measurements will assure that the CCHP unit is working properly.** To eliminate leakage from around the stoppers make sure that all stoppers on top of the constant-head tubes and the two water reservoirs are tightly sealed and are not defective. Also, make sure all the quick-release connectors used in K_{sat} measurement are tightly connected and are not defective. To avoid popping up of the rubber stoppers, do not use any grease or other lubricating agents on the stoppers or the edge of the corresponding tube opening.

The plumbing that connects the main reservoir and the flow measuring reservoir to the three-way valve is tightly sealed. Any leaks in the plumbing inside the box, however, may result in improper operation of the permeameter. If a leak is developed in the plumbing inside the base box, the water level in the reservoir should drop with water accumulating under the base box during storage. During operation, however, air bubbles may enter the reservoir or the water supply tube if there is a leak in the plumbing under the reservoir or at the connection point between water supply tube and the three-way valve. Any leaks in the body of the two reservoirs will result in water seeping out of the cavity or fracture during storage and air entering the reservoir during operation.

The leaks in the permeameter should be easily detected. The signs for leakage and improper operation are (i) observation of air bubbles entering the water in the clear flow measuring reservoir or the water supply tube through the connection joints or the outflow port at the base of the flow measuring reservoir, and (ii) water moving out of the permeameter into the hole while no air bubble moves through one or all of the bubble tubes. Water level in the auger hole may also rise beyond the level set by the permeameter if the leakage is large. This is especially true if the soil has a low saturated hydraulic conductivity. Note that if the K_{sat} of the depth (or horizon) where measurement is conducted is very low, bubbling through the air tube(s) will be infrequent. An increase in the air temperature around the permeameter may result in an increase in the air pressure above the water in the flow measuring reservoir and air tubes. This will force water to move out of the reservoir into the hole without bubbling and will eventually result in an increase in the depth of water at the bottom of auger hole. If K_{sat} is high enough that the permeameter bubbles to supply water to the hole, then an increase in air temperature around the permeameter should have a minimal effect on the constant depth of water in the auger hole.

The fixed and adjustable bubble tubes and the rigid part of the air tubes may ultimately become brittle after extensive use or aging. These tubes can be replaced by 1/4-in diameter clear tubing that are available from most commercial plastics vendors . The rubber stoppers and the flexible plastic tubes used for the air tubes and water supply tube can also be replaced, and are available from many plastic vendors, scientific supply companies,

Transportation

The strap attached to the CCHP allows transportation of the permeameter by lifting it like a hand bag or as a back pack (see Fig. 9). Water can be left in the permeameter for transportation by hand or a vehicle providing that the permeameter is secured in an upright position. For long distance transportation and air transportation, always empty and dry the permeameter. For long distance travel and air shipment, the CCHP unit and the associated accessories will readily fit inside an inexpensive plastic footlocker which are available in most discount stores. Unless it is properly secured, do not lay the CCHP on its side during transportation.

Storage

Water can be left in the constant-head tubes and the two water reservoirs during short storage. For long term storage, however, empty and dry the constant-head tubes, the main reservoir, the flow measuring reservoir, the water supply tube, and the water dissipating unit. Also, dry the bubble and air tubes with their rubber stoppers and store them separately or in their respective constant-head tubes or reservoirs. Although the CCHP is constructed of durable PVC and polycarbonate tubes, it may not withstand lengthy exposure to excessive heat. Do not store the permeameter under direct sun light or in places where temperature may rise above 50 °C (120 °F). Specifically, do not leave the permeameter for an extended period of time in a vehicle under the sun because excessive heat might damage the permeameter (particularly rubber stoppers, flexible plastic tubes, and rigid bubble tubes).

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APPENDIX

SAMPLE DATA SHEET

Measurement No. _____ Conducted by ______________________________

Location ______________________________ date __________

Weather Condition ______________________________ Temperature __________

Horizon ______________ Source of Water ______________________________

Hole depth	_______ cm	Measured (Actual) water level in hole	
Distance between reference level and soil surface	+ _______ cm	Initial _______ cm	
		Final _______ cm	
Distance from the hole bottom to the reference level (D)	= _______ cm	Clock time	
Desired water depth in hole (H)	- _______ cm	Start saturation	_______
Constant-head tube setting (d)	= _______ cm	Steady-state reading	_______

Reservoirs Used for Measurement of the Steady-State Flow Rate

Flow Measuring Reservoir Only _____ Conversion Factor (C.F.) = 20 cm^2

Both Flow Measuring and Main Reservoirs _______ Conversion Factor (C.F.) = 105 cm^2

(To obtain flow volume multiply change in water level by the appropriate C.F. from above)

Clock Time h:min	Reservoir Reading cm	Δt min	Change in Water Level cm	Flow Volume cm^3	Q cm^3/min	Q cm^3/h	K_{sat} cm/h
____	____	____	____	____	____	____	____
____	____	____	____	____	____	____	____
____	____	____	____	____	____	____	____
____	____	____	____	____	____	____	____
____	____	____	____	____	____	____	____
____	____	____	____	____	____	____	____
____	____	____	____	____	____	____	____

Average of last three measurements: K_{sat} = _______ cm/h _______ (other units)

COMMENTS: ____

____

____

Table 1. Coefficient A (Eq. [2]) in the Glover solution and the corresponding H and H/r values for a 5-cm diamater auger hole.

H	H/r	A
cm	cm/cm	$1/cm^2$
12.5	5.00	0.001520
13.0	5.20	0.001436
13.5	5.40	0.001359
14.0	5.60	0.001288
14.5	5.80	0.001223
15.0	6.00	0.001163
15.5	6.20	0.001108
16.0	6.40	0.001057
16.5	6.60	0.001009
17.0	6.80	0.000965
17.5	7.00	0.000923
18.0	7.20	0.000885
18.5	7.40	0.000849
19.0	7.60	0.000815
19.5	7.80	0.000783
20.0	8.00	0.000753
20.5	8.20	0.000725
21.0	8.40	0.000699
21.5	8.60	0.000674
22.0	8.80	0.000651
22.5	9.00	0.000628
23.0	9.20	0.000607
23.5	9.40	0.000587
24.0	9.60	0.000568
24.5	9.80	0.000550
25.0	10.00	0.000533

Table 2. Coefficient A (Eq. [2]) in the Glover solution and the corresponding H and H/r values for a 6-cm diamater auger hole.

H	H/r	A
cm	cm/cm	1/cm^2
15.0	5.00	0.001056
15.5	5.17	0.001007
16.0	5.33	0.000961
16.5	5.50	0.000919
17.0	5.67	0.000879
17.5	5.83	0.000842
18.0	6.00	0.000808
18.5	6.17	0.000776
19.0	6.33	0.000745
19.5	6.50	0.000717
20.0	6.67	0.000690
20.5	6.83	0.000665
21.0	7.00	0.000641
21.5	7.17	0.000619
22.0	7.33	0.000598
22.5	7.50	0.000578
23.0	7.67	0.000558
23.5	7.83	0.000540
24.0	8.00	0.000523
24.5	8.17	0.000507
25.0	8.33	0.000491
25.5	8.50	0.000477
26.0	8.67	0.000463
26.5	8.83	0.000449
27.0	9.00	0.000436
27.5	9.17	0.000424
28.0	9.33	0.000412
28.5	9.50	0.000401
29.0	9.67	0.000390
29.5	9.83	0.000380
30.0	10.00	0.000370

Table 3. Coefficient A (Eq. [2]) in the Glover solution and the corresponding H and H/r values for a 7-cm diamater auger hole.

H	H/r	A
cm	cm/cm	1/cm^2
17.5	5.00	0.000776
18.0	5.14	0.000745
18.5	5.29	0.000715
19.0	5.43	0.000688
19.5	5.57	0.000662
20.0	5.71	0.000638
20.5	5.86	0.000615
21.0	6.00	0.000594
21.5	6.14	0.000573
22.0	6.29	0.000554
22.5	6.43	0.000536
23.0	6.57	0.000518
23.5	6.71	0.000502
24.0	6.86	0.000486
24.5	7.00	0.000471
25.0	7.14	0.000457
25.5	7.29	0.000443
26.0	7.43	0.000431
26.5	7.57	0.000418
27.0	7.71	0.000406
27.5	7.86	0.000395
28.0	8.00	0.000384
28.5	8.14	0.000374
29.0	8.29	0.000364
29.5	8.43	0.000355
30.0	8.57	0.000346
30.5	8.71	0.000337
31.0	8.86	0.000329
31.5	9.00	0.000321
32.0	9.14	0.000313
32.5	9.29	0.000305
33.0	9.43	0.000298
33.5	9.57	0.000291
34.0	9.71	0.000285
34.5	9.86	0.000278
35.0	10.00	0.000272

Table 4. Values of $\{\sinh^{-1}(H/r) - [(r/H)^2 + 1]^{1/2} + r/H\}$ for various H/r ratios between 5 and 10.

H/r	$\{\sinh^{-1}(H/r) - [(r/H)^2 + 1]^{1/2} + r/H\}$
cm/cm	Dimensionless
5.00	1.492635
5.20	1.524910
5.40	1.556194
5.60	1.586545
5.80	1.616015
6.00	1.644653
6.20	1.672504
6.40	1.699610
6.60	1.726009
6.80	1.751736
7.00	1.776825
7.20	1.801306
7.40	1.825207
7.60	1.848555
7.80	1.871375
8.00	1.893690
8.20	1.915522
8.40	1.936890
8.60	1.957814
8.80	1.978312
9.00	1.998401
9.20	2.018097
9.40	2.037414
9.60	2.056368
9.80	2.074971
10.00	2.093236

Table 5. Viscosity of water between 10° and 50°C .
Source: Handbook of Chemistry and Physics.

Temperature		Viscosity
°C	°F	centipoises
10	50	1.307
11	52	1.271
12	54	1.235
13	55	1.202
14	57	1.169
15	59	1.139
16	61	1.109
17	63	1.081
18	64	1.053
19	66	1.027
20	68	1.002
21	70	0.9779
22	72	0.9548
23	73	0.9325
24	75	0.9111
25	77	0.8904
26	79	0.8705
27	81	0.8513
28	82	0.8327
29	84	0.8148
30	86	0.7975
31	88	0.7808
32	90	0.7647
33	91	0.7491
34	93	0.7340
35	95	0.7194
36	97	0.7052
37	99	0.6915
38	100	0.6783
39	102	0.6654
40	104	0.6529
41	106	0.6408
42	108	0.6291
43	109	0.6178
44	111	0.6067
45	113	0.5960
46	115	0.5856
47	117	0.5755
48	118	0.5656
49	120	0.5561
50	122	0.5468

EQUATIONS AND APPROACHES FOR CALCULATING K_{sat}

Glover Solution	Zangar (1953) Amoozegar (1989b)
Simultaneous Equations Approach and Laplace Approach	Reynolds and Elrick (1985) Reynolds and Elrick (1986)
Fixed α Approach	Elrick et al. (1989)
Philip's Solution	Philip (1985)
Regression Equations	Stephens et al. (1987)