LABORATORY OUTFLOW TECHNIQUE FOR MEASUREMENT OF SOIL WATER DIFFUSIVITY AND HYDRAULIC CONDUCTIVITY

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CONTENTS

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Abstract

An implementation of the one-step outflow method for measuring soil water diffusivity and conductivity is described. The laboratory procedures are detailed, as is the working form of the calculations (following Passioura, 1976) so that they might be easily implemented by other research groups. The present method does not yield hydraulic property values near saturation and appears more difficult to apply reliably in clay soils. However, the method is a relatively low cost laboratory method for diffusivity measurement which is convenient for the processing of large numbers of samples and is an appropriate technique for many applications.

Introduction

Demand for accurate hydraulic property data for field soils has increased as soil related environmental issues have gained prominence, as the use of soil water simulation models has increased, and as the recognition grows that soil water processes are an important component of regional scale climate models. Only a very small amount of unsaturated hydraulic data presently exists for soil in Australia where few research groups have invested in collection of such data. One laboratory method for determining unsaturated soil water diffusivity and unsaturated hydraulic conductivity is the outflow method proposed by Gardner (1956). The outflow experiment consists of placing an 'undisturbed' cylindrical soil core sample in a pressure cell on top of a saturated porous ceramic plate. The sample is wetted to saturation then equilibrated at a small suction. A gas pressure is then applied to the top of the sample thereby initiating outflow of water from the sample through the ceramic plate. The volume of outflow is then recorded with time until the core equilibrates at the imposed pressure and outflow ceases. The outflow method is attractive because the laboratory measurements are of short duration, they can be carried out in controlled conditions, and they don't require the restrictive boundary conditions that make many other methods slower and more expensive (van Dam *et al.*, 1990).

Contributions to the development of the one-step outflow method have included those of Doering (1965), Gupta *et al.* (1974), Passioura (1976), Valiantzas *et al.* (1988). The analysis methods used by the above workers do not require assumption of any particular mathematical form for the soil water and unsaturated hydraulic conductivity characteristics which is an advantage. However, they do require independently measured soil water characteristic data to determine unsaturated hydraulic conductivity. Recently parameter estimation methods have been used together with laboratory outflow experiments for determining hydraulic properties (Kool *et al.*, 1985; Parker *et al.*, 1985; Kool *et al.*, 1987; Valiantzas and Kerkides, 1990; van Dam *et al.*, 1992,1994; Eching and Hopmans, 1993; Eching *et al.*, 1994). Parameter estimation techniques enable simultaneous determination of unsaturated hydraulic conductivity, diffusivity, and the soil water characteristic just from an outflow experiment given the assumption of particular mathematical forms for the hydraulic characteristics.

Difficulties with instability and parameter uniqueness have meant that multi-step outflow experiments have become necessary to determine these hydraulic properties simultaneously (van Dam *et al.*, 1990). We have applied the parameter estimation technique with our one-step outflow data and encountered the instability problem with many of our samples. Separate water characteristic measurement might be required to ensure parameter uniqueness even when multi-step outflow experiments are used.

In our laboratory we prefer to measure the soil water characteristic independently so that we do not have to rely on assuming any particular mathematical model to describe the data. We have adopted the one-step outflow method and combine outflow data with soil water characteristic data to determine unsaturated hydraulic conductivity again, independent of any particular soil hydraulic model. We use the calculation method of Passioura (1976), which was used by Jaynes and Tyler (1980) who compared it against an *in situ* crust method with satisfactory results. The method was also applied, for example, by Borcher *et al.* (1987) using undisturbed samples of a fine-textured soil, and by Parker *et al.* (1985) who used it to validate their inverse parameter estimation method. van Dam *et al.* (1990) found that combining the one-step outflow method (inverse parameter estimation) with independently measured soil water characteristic data yielded unsaturated hydraulic conductivity estimates in good agreement with other laboratory methods.

We have developed the laboratory measurement procedure and calculation procedure into a routine method. The purpose of this report is to describe the complete one-step outflow measurement procedure and subsequent 'working' calculations, in sufficient detail that they might be adopted and successfully applied by others without having to repeat the 'trial and error' development process through which we have progressed. Our aim has been to develop procedures that work on intact samples of field soil.

Theoretical background

Passioura (1976) developed a method of calculating diffusivity from one-step outflow data and his method is adopted here. The method is based on the assumption that the rate of change of water content at any given time is effectively uniform throughout the draining column of soil (i.e. $\partial\theta/\partial t$ is assumed constant throughout the soil column; θ is volumetric soil water content and t is time). This makes the solution of the diffusion equation simpler than other approaches (Gupta *et al.*, 1974).

With the one-step method, a pressure is applied at the upper end ($x = L$, where L is the length of the soil column) of a soil sample with an initial water content, θ_i . The outflow is then measured at the lower end, $x = 0$, where it is assumed that water content is reduced to the final water content (θ_f) at the onset of the outflow. The governing equation, neglecting gravity, and the initial and boundary conditions are as follows:

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial x}\left(D(\theta)\frac{\partial\theta}{\partial x}\right) \qquad (1)$$

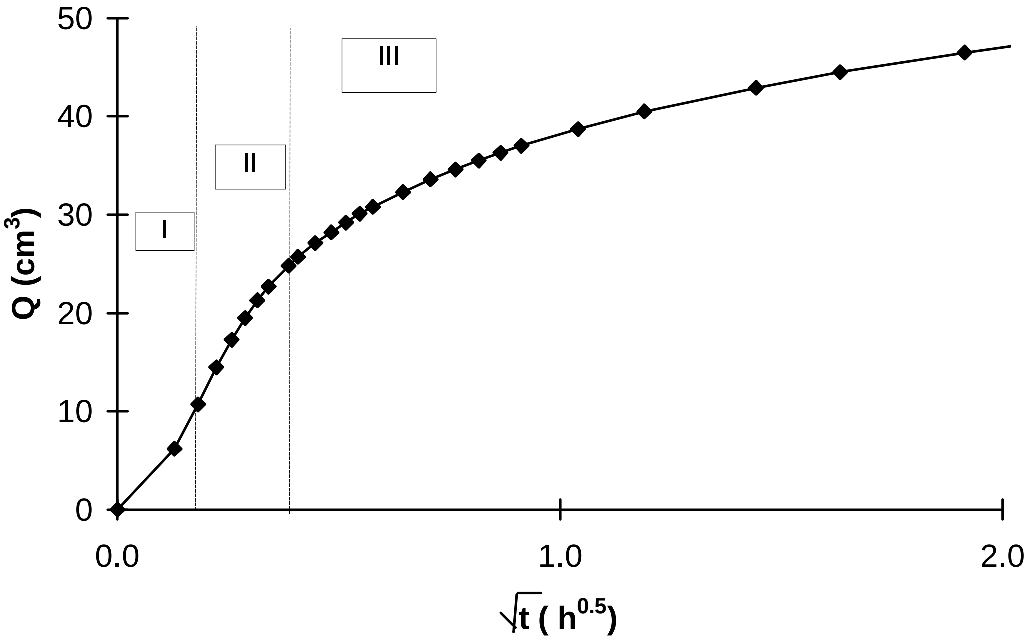
subject to the conditions:

$$\begin{aligned} &\theta = \theta_i, \quad 0 \le x \le L, \quad t = 0 \\ &\theta = \theta_f, \quad x = 0, \qquad t > 0 \\ &\frac{\partial \theta}{\partial x} = 0, \quad x = L, \qquad t > 0. \end{aligned} \tag{2}$$

where D is diffusivity, and the other terms are as defined previously.

There are three stages of outflow (Figure 1). The first stage is controlled by the membrane (ceramic plate) and its resistance to flow, so that the cumulative outflow (Q) is proportional to time, t. The flow rate decreases as the soil permeability controls the flow, the membrane resistance becomes negligible and the soil water content at the bottom end of the core reaches θ_f (stage II). During this stage the core sample behaves as a semi-infinite column, and Q is a linear function of $\sqrt{t}$. When this linear relation ceases, stage III of the outflow starts and the boundary condition at the top end of the soil, $x = L$, begins to influence the flow. This is the stage when the assumption of uniform water content over most of the soil column is used to determine $D(\theta)$.

Figure 1. Cumulative outflow vs √ t , showing the three stages of outflow.



Using the above assumption for the third stage of outflow, Passioura (1976) found the following solution to equation (1):

$$D(\theta_L) = \frac{dF}{dW} . \frac{L^2}{2} \qquad (3)$$

Where F is the rate of outflow, W is the amount of water remaining in the soil at any time, and θ_L is the water content at $x = L$. Equation (3) is obtained by assuming $\theta_L >> \theta_f$.

To find a relation between θ_L and the average water content of the soil column $\bar{\theta}$, the following relationships are used:

$$\delta \cong \theta_L - \bar{\theta} \cong \frac{0.61}{B} \qquad \text{for larger water contents, and} \qquad (4)$$

$$\frac{(\theta_L - \theta_f)}{(\bar{\theta} - \theta_f)} = \frac{\pi}{2} \qquad \text{when } q_L \text{ approaches } q_f. \qquad (5)$$

where

$$B = \frac{d(\ln D)}{d\bar{\theta}} \qquad (6)$$

For interpolation between points when determining the relation between $\bar{\theta}$ and θ_L an exponential form of $D(\theta)$ is assumed. B can be determined by equation (6) using outflow data.

The steps required to complete the calculation of diffusivity and unsaturated hydraulic conductivity following a one-step outflow experiment and determination of the soil water characteristic are detailed below following description of the outflow measurement procedure.

Equipment and materials

- Soil core sampling rings
- Tanner sampler
- Leak-proof tray and blotting paper
- Tempe pressure cell (Soil Moisture Equipment Inc. model 1450[†].)
- High flow 100 kPa (1 bar) porous ceramic plate (Soil Moisture Equipment Inc.)
- Rubber 'O' rings (1 flat, 1 round)
- Teflon® PFA tubing (Cole-Parmer Instrument Co., Chicago. IL)
- Pressurised air supply with regulator and/or mercury manometer

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[†] Mention of company names or specific products does not imply endorsement by CSIRO but is included for convenience to the reader.

- Swagelok® pressure fittings (Sydney swagelok Service Pty. Ltd.)
- Electronic weighing platform (optional)
- Burette
- Hypodermic syringe
- Knife
- PVC tubing
- Suction table apparatus*
- Pressure plate apparatus*
- Diatomaceous earth contact material*

(* indicates requirements for soil water characteristic measurement which is not detailed here, refer Cresswell, in prep.).

Modified Tempe pressure cell

The Tempe pressure cell used is a modified form of the commercial unit supplied by Soil Moisture Equipment Inc. These are essentially two perspex end caps which hold the core sample against a 100 kPa (one bar) bubbling pressure porous ceramic plate. They are suitable for core samples that are 88.9 mm (3.5”) outside diameter (O.D.), 85 mm internal diameter (I.D.), and 60-75 mm long.

The reduction in air pressure on the underside of the ceramic plate leads to the dissolution of air from the water flowing out of the cell. This leads to an accumulation of air beneath the ceramic plate where it displaces water leading to an over-estimation of outflow. To remove this air the Tempe cell is modified by drilling a small hole through the base into the cavity beneath the ceramic plate. A syringe needle is cemented into this hole and fitted with a two-way tap which allows the air to be withdrawn from the space under the ceramic plate. During measurement air is periodically withdrawn as necessary. When withdrawing air, some water is usually removed. The amount of this water is determined and used to correct the outflow measurement. The weight of water is determined by weighing the syringe before and after use.

The unmodified Tempe cells are fitted with 'O' rings to seal against the core samples. These 'O' rings are not designed for coring rings with sharpened cutting edges as are used in this laboratory. To accommodate these, and ensure a seal against the ring at the top of the Tempe cell, the upper 'O' ring is replaced with a flat ring of insertion rubber which seals against the sharpened edge of the coring ring. The use of coring rings with sharpened cutting edges is also the reason that cores are mounted upside down in the Tempe cell.

To enable the soil core to be conveniently weighed prior to, or after being subject to the air pressure, swagelok pressure couplings are used to connect the air pressure supply line to the top of the Tempe cells. A 'snap-fit' pressure coupling is used allowing fast disconnection of the cores so that the core and Tempe cell can be quickly weighed then reconnected Without loss of pressure.

The air pressure supply line used is manufactured from Teflon® PFA which has very low water vapour permeability. This tubing was selected to prevent error from vapour loss during outflow measurement.

Outflow measurement equipment

Outflow measurement is best achieved by an automatic weighing system but can also be completed using burettes. The weighing system is potentially more accurate with less outflow measurement error. This is important as such error is amplified when the derivatives of the outflow versus time data are calculated.

Electronic weighing platforms of 1 kg capacity and 0.01 g resolution are adequate. Outflow is collected in a flask located on top of the weighing platforms via a PVC tube from the Tempe cell (Figure 2). The outflow tubing connected to the base of the Tempe Cell is clamped to the supporting frame. This enables the cell to be moved without disturbing the electronic balance. A fine nylon tube is used to conduct the outflow from the clamp to a stainless steel needle inserted in to the water reservoir on the electronic balance. The needle is inserted below the water surface so that water can be drawn back into the tube as air and water are sucked out from below the plate. The water level in the reservoir is maintained at equivalent height to the bottom of the sample to ensure a constant head. A large diameter vessel should be used as a reservoir to minimise the change in back pressure on the plate. While the hole through which the needle is inserted into the reservoir should be as small as possible, care must be taken to ensure that the needle does not touch the lid as substantial weighing errors may occur if side pressure is exerted on the weighing cell of the balance. The weighing platforms are connected to a personal computer *via* an RS232 output which is read through the computer serial port. The computer software product "SoftwareWedge for Windows™" is one which can be used to facilitate recording of the mass data to file at designated time intervals. The software logs each balance at prescribed time intervals and the data are imported into an “Excel” spreadsheet. Each reading is time stamped and the data for each cell is thus easily transferred to a spreadsheet template. The time interval for logging can be set individually for each cell and increased during each run as necessary. We measure the outflow at one minute intervals initially but reduce the logging frequency to five minutes and then hourly as the rate of outflow slows.Where burettes are used (Figure 3), we find 50 ml burettes suitable, they are connected to the base of the Tempe cell by a length of PVC tubing. The burette must be lowered as it fills with water so as to maintain a constant head at the base of the ceramic plate. The Tempe cell and burette outflow collection system is illustrated in Figure 2.

In detailing the measurement procedure below we describe the use of the burette outflow measurement system for convenience, the procedures specific to the burette system and not required for the weighing system will be noted. We do however recommend direct weighing of outflow for the reasons given above.

Figure 2. Tempe pressure cell and electronic weighing platform.

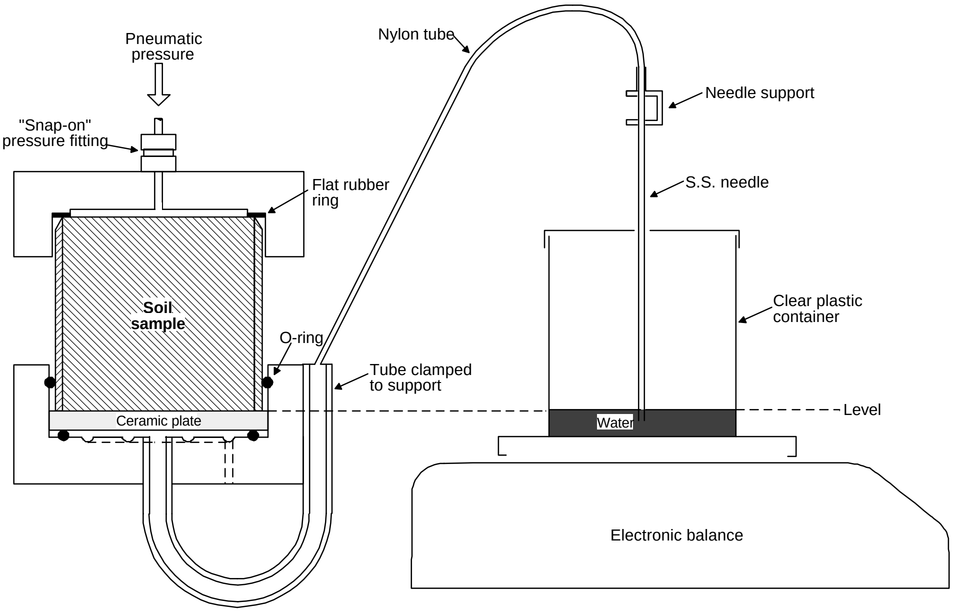
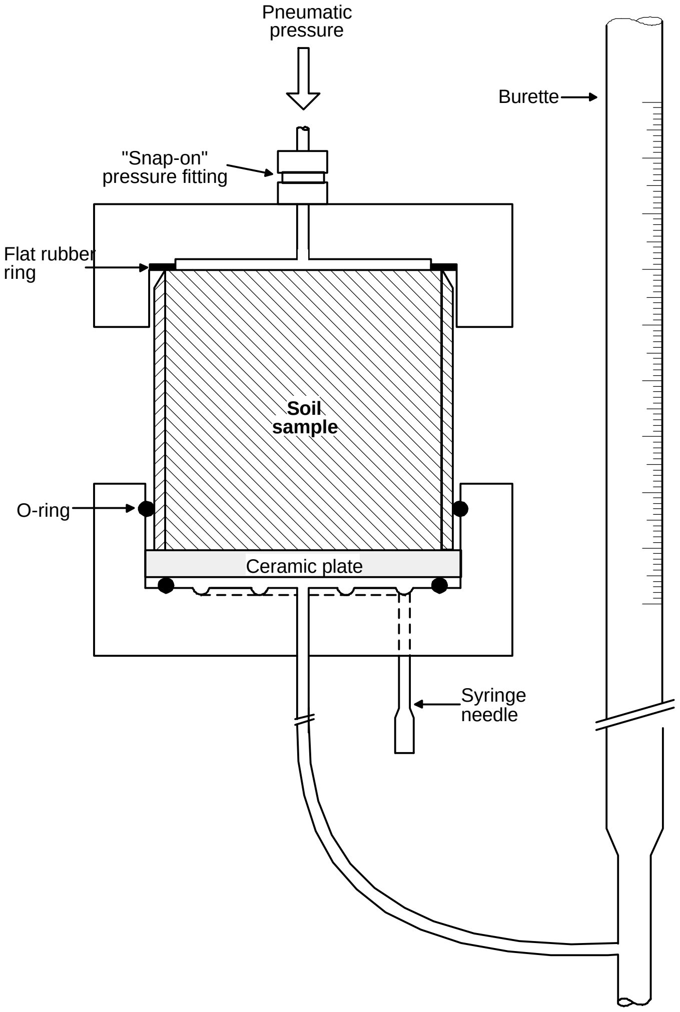


Figure 3. Tempe pressure cell and outflow collection equipment.



Sample collection and measurement procedure

The laboratory procedure used includes measurement of the soil water characteristic with suction tables and pressure plates as well as the measurement of outflow, using a single pressure step, from Tempe pressure cells. The equipment and procedure for determining the soil water characteristic are not detailed here as they are described elsewhere (Cresswell, in prep.). The sequence of the various steps in the entire measurement procedure is important however and is detailed below.

1. Undisturbed core samples collected.
2. Samples trimmed and wetted.
3. Tempe cell equipment prepared.
4. Samples wetted in Tempe cells.
5. Outflow experiment completed.
6. Samples drained on suction tables at a range of suctions (0, 1, 3, 5, 10, 33, and 60 kPa)
7. Cores sub-sampled for pressure plate measurements.
8. Disturbed soil material used on pressure plate apparatus (for 100, 500, and 1500 kPa suction).
9. All soil material oven dried, and bulk density is determined.

The outflow measurement is done first when the cores are least disturbed as it can be completed without damaging the core end surfaces. Soil water characteristic determination requires cores to be placed in contact with, and to be removed from ceramic plates a number of times. Contact material also has to be removed by brushing or scraping. These operations cause some disturbance and render the core end surfaces less suitable for attaining the very good contact required with the Tempe cell ceramic plate.

Field sampling

'Undisturbed' soil cores are collected using thin-walled brass sampling rings with a modified Tanner sampler following the procedure of McIntyre (1974a). Brass tubing of the 88.9 mm (3.5”) O.D. and 85 mm I.D. size required is not readily available within Australia and hence sampling rings had to be machined from 88.9 mm O.D. and 76.2 mm I.D. tubing using an engineers lathe. A sharpened cutting edge was also machined on one end of the sampling ring. The sampling rings are lubricated with cooking oil prior to insertion into the soil. Once extracted from the soil the ends of the soil core are trimmed level with the ends of the ring with a sharp knife. For the more plastic clays cutting the ends off with a 'cheese knife' made from 'laystraight' wire will give good results. Further description of the collection and preparation of soil core samples is given by McKenzie and Cresswell (in prep.). With this application extreme care is necessary to ensure that the top end of the core sample is as flat as possible and that removal of small aggregates from the upper core surface is minimised. Care must also be taken to avoid smearing this surface while trimming it. 'Picking' of the top of the core to unblock any occluded pores (refer McIntyre 1974b, McKenzie and Cresswell in prep.) is not practicable because the core is to be placed in the Tempe cell upside down with this top face against the ceramic plate. Good contact between the soil and ceramic plate is very important in the outflow measurement procedure.

Sample pre-treatment

Note: sample pre-treatment and laboratory measurements should be made in constant temperature conditions ($20^{\circ c}$).

The porous ceramic plate in the Tempe cell must be fully saturated with deaired water prior to commencement of measurement. This can be achieved by placing the ceramic plates in boiling water for a few minutes, then removing them once the water has been allowed to cool. Incomplete saturation of the ceramic plate can lead to measurement error.

The ceramic may block as a result of particulate material entering the pores, through chemical cementation, or through biological growth. The hydraulic conductivity of the plate should be checked and, if found unsatisfactory, the plate should be cleaned or replaced. Cresswell (in prep.) and McIntyre (1974c; p169) described procedures for cleaning porous ceramic plates. One simple approach is to soak the plates in hydrogen peroxide (H_2O_2) for 48 hours then boil in water to clean the plate and decompose any residual H_2O_2 .
A solution of 0.01M $CaCl_2$ is used to wet soil cores to minimise soil dispersion. The trimmed core is slowly wet up before it is placed in the Tempe cell. Samples are best wet by capillarity on a ceramic suction plate. Alternatively blotting paper can be used conveniently in a leak-proof tray. The blotting papers are placed in the bottom of the tray and cores placed on the paper. The blotting paper is kept wet with small, periodic additions of water. Once water has visibly risen to the top surface of the core by capillarity then the core can be wetted further by incremental immersion. That is, the water level in the bottom of the tray is raised a few mm and the cores are left to wet up. This wetting procedure minimises slaking which can occur with rapid wetting of dry soil. The final wetting to saturation is best done within the Tempe cell in order to aid establishment of contact between sample and plate. A burette connected to the base of the Tempe cell with PVC tubing is used to wet the core to saturation. Soil-plate contact is also facilitated by applying a thin film of water to the ceramic plate immediately prior to placing the sample in the Tempe cell. Care is required to maximise the contact between soil and ceramic plate as incomplete contact will cause measurement error.

Steps to complete the one-step outflow experiment

1. Wet up the cores from below by adding water to the burette until the core is saturated. Then drain by lowering the burette to establish the water level equal to the top of the ceramic plate so that the soil sample has zero cm suction at the base for commencement of the outflow experiment. The samples are not fully saturated at commencement of the outflow experiment because attaining consistency in initial water content across different core samples is very difficult and small changes in water level at the top of the core can give significant differences in initial (and total) outflow volumes. Further, it was shown by Hopmans *et al.* (1992) that non-saturated conditions at initialisation of outflow and subsequent air continuity through the core sample, results in more uniform draining of the sample.

2. Tighten the 'wing-nuts' that secure the end caps of the Tempe cell just before commencing the run to ensure minimal air leakage. Any air leakage will allow vapour loss thus inducing measurement error if not corrected. Disconnect and weigh the cell prior to starting the run.

3. Reconnect the cell to the burette (or else connect tubing and run into flask on weighing platform) and remove any air under the plate by tipping the cell on its side and withdrawing the air through the two-way tap using a syringe. Then adjust the water level in the burette to be level with the bottom of the core sample.

4. Set the gas pressure to 100 kPa (1 bar) with the air lines to the Tempe cell disconnected. We use a mercury manometer to measure the pressure. A good quality pressure regulator suitable for 'dead end applications' is required.

5. Record the water level in the burette (or else tare the weighing platform) then start the run by pressing together both parts of the swagelok pressure fitting to connect the airlines to the cells. When multiple samples are being run at once stagger the starting times of the different samples by 10 seconds for ease of data collection.

6. Record outflow at one minute intervals for the first 5 minutes, then use gradually increasing measurement time intervals. Lower the burette to keep the suction at the base of the core close to zero. The frequency at which readings are made will depend on the rate of outflow, it is important for the quality of the analysis that the readings are widely enough spaced to ensure that the quantity of outflow being measured is large in relation to the measurement precision. Sufficient measurement points are required throughout stage II and stage III outflow to allow clear determination of the time at which the outflow stage changes.

7. When the burette fills, remove excess water with a syringe. Weigh the syringe before and after to record water removed. This is more accurate than reading the burette directly. This will not be necessary if using a large enough flask on a weighing platform.

8. After 4 hours check for air under the plate prior to each reading. Disconnect the air line so the cell can be turned on its side and any air removed through the two-way tap using the syringe. Return any water removed to the burette or weigh the water. Reconnect the air line with as little delay as possible.

9. When outflow ceases (for loamy soils assume equilibrium when outflow is less than 0.1 ml h^{-1} but heavy clays will continue to drain for several days at rates less than 0.05 ml h^{-1}) disconnect the cell and weigh it. With very slow draining cores it may be desirable to continue measuring outflow for another day to ensure the core is at equilibrium with the 100 kPa pressure applied.

10. Weigh the core after removal from the cell to obtain a final weight. Then record core length, core diameter, and ring weight. The observed weight change measured should closely approximate the measured outflow. Check this on a routine basis. The initial sample weight used for the calculation is back calculated as the final weight of the core plus the difference in initial and final apparatus weights (i.e. Tempe cell + ring + core).

11. The data is recorded on a template as shown in Appendix 1.

Calculation steps

A spreadsheet template was compiled for the routine calculations of the one-step outflow data following Passioura (1976). The following steps are required to complete the calculation:

1. Copy the values of θ_i , θ_f (initial and final water contents), length of the core (L) and core volume (V) from the first part of the template files (ONESTEP; appendix 1) to a new worksheet (WORKING).

2. Copy the outflow data (cumulative outflow Q (cm^3)) from the second page of the template files (called OUTFLOW) to the WORKING sheet.

3. Calculate the square root of time and add as a new column.
4. Plot Q vs $t^{0.5}$ and find the time when stage III starts i.e. the time when the linear relation between Q and $t^{0.5}$ ceases.
5. Discard any measurement points where outflow change is zero.
6. Calculate the volume of water remaining in the soil (W) at each time step from:
   $\theta * V$
   Calculations start at the equilibrium (last) entry; $W = \theta_f * V$
   At each time step (i) then working backwards, $W_i = W_{i+1} + \Delta Q_i$
   ΔQ is found by differencing the Q entries (e.g. $\Delta Q_2 = Q_3 - Q_2$).

7. Calculate the rate of outflow F (cm^3 h^{-1}) by dividing the differences in Q by the differences in time (t) (e.g. $F_2 = (Q_1 - Q_3)/(t_1 - t_3)$).

8. Using data from stage III only (from now on), try fitting different functions (polynomials, power law, or exponential) to F-W data. Graph the results and choose the function which gives a better fit. Note that the curve must be monotonic.

9. Using the function from step 8 (above), calculate the fitted F values for each value of W.

10. Calculate dF/dW from fitted F values using central differencing
    (e.g. $dF/dW_2 = (F_1 - F_3)/(W_1 - W_3)$).

11. Calculate D from $D = dF/dW * (L^2/2)$.

12. Add a column for $\ln D$.

13. Calculate $\overline{\theta} = W / V$ for each entry.

14. Plot $\ln D$ vs $\overline{\theta}$. Find the slope of this curve at the point $\overline{\theta} = (\theta_i + \theta_f)/2$. Call the slope B. Then calculate $\delta = 0.61/B$.

15. Calculate θ_j values as $\theta_j = \overline{\theta} + \delta$.

16. Calculate $\theta_k = \theta_f + \pi/2 * (\bar{\theta} - \theta_f)$.

17. Plot θ_j and θ_k vs $\bar{\theta}$ on the same graph.

18. From this graph we derive θ_L vs $\bar{\theta}$. Smoothing in the region where the two lines meet can be done by drawing a third line between midpoints of them. Find the intersection point of the two lines (θ_j and θ_k vs $\bar{\theta}$). Then find the mid points of lines past the intersection point($\bar{\theta}_{m1}$, and $\bar{\theta}_{m2}$). A line is drawn between those two points (Figure 4).

19. For each $\bar{\theta}$ enter θ_L from 18 following the rules:

$$\text{If } \bar{\theta} > \bar{\theta}_{m1} \quad \Rightarrow \quad \theta_L = \theta + \delta \qquad \text{read off the } \theta_j \text{ line}$$

$$\text{If } \bar{\theta} < \bar{\theta}_{m1} \quad \Rightarrow \quad \theta_L = \theta_f + \frac{\pi}{2}\left(\bar{\theta} - \theta_f\right) \qquad \text{read off the } \theta_k \text{ line}$$

$$\text{If } \bar{\theta}_{m2} < \bar{\theta} < \bar{\theta}_{m1} \quad \Rightarrow \quad \theta_L = a\bar{\theta} + b \qquad \text{calculated in step 17.}$$

Where *a* and *b* are the slope and intercept of the line calculated in step 18.

20. This completes the $D(\theta_L)$ vs θ_L calculation.

21. To determine $K(\theta)$ vs θ, first copy the soil water characteristic data to the working sheet.

22. Taking natural log of suction (*h*) and water content (θ), find the slope ($d\ln h/d\ln\theta$) of the soil water characteristic curve at each entry using forward differencing (consecutive entries) (refer to example calculation in appendix 1).

23. For each θ_L value, find the corresponding (*h*) value by linear interpolation on the natural log scale, using values in step 22. The slope of the soil water characteristic curve is determined using forward differencing (consecutive entries) (refer to example calculation in appendix 1).

24. Calculate *K* values as products of $D * (dh/d\theta)$.

25. Summarise the results in the summary sheet of the spreadsheet template.

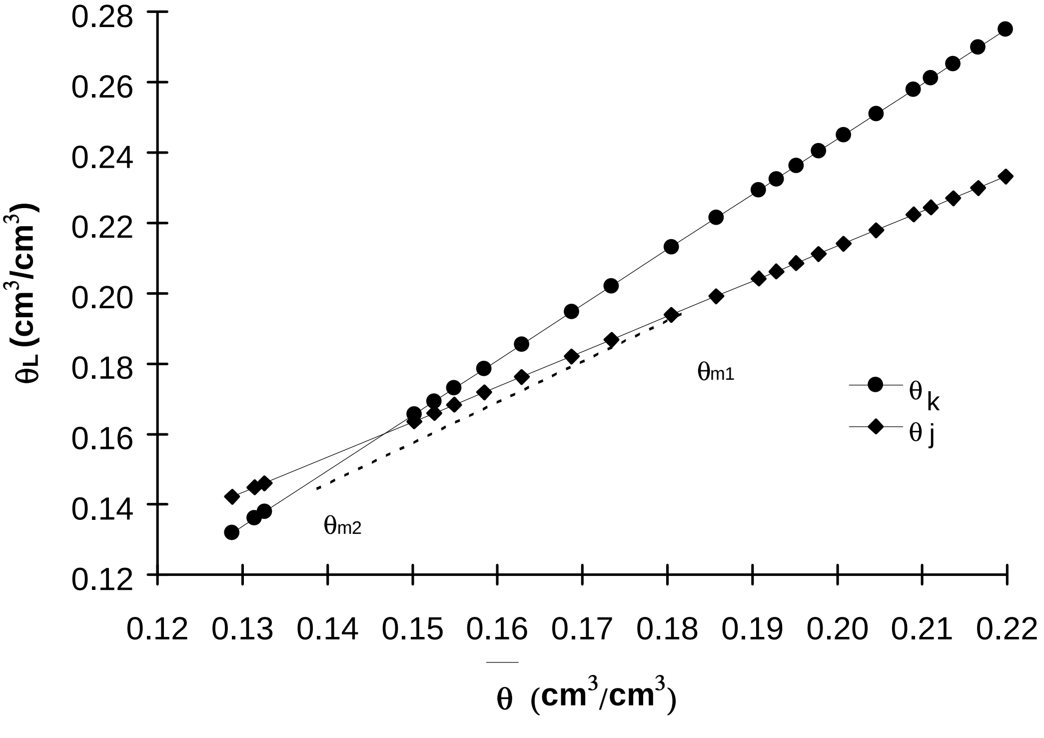
Note that the determination of $D(\theta)$ is dependent on the first and second derivatives of the measured outflow ($Q(t)$) data. These derivatives can be estimated using alternative methods to those described above. For example, Jaynes and Tyler (1980) used the first and second derivatives of a quadratic equation fitted to the $Q(t)$ data to determine $D(\theta_L)$. They used a piece-wise least squares fitting and smoothing procedure with quadratic equations which were used to estimate derivatives at each $Q(t)$ point. Borcher *et al.* (1987) followed Jaynes and Tyler (1980) but used a power function for piece-wise fitting and smoothing of the *Q* versus *t* data. Here simple forward differencing has been used to calculate the *F*-*W* data. Then the form of function that best describes the *F*-*W* data is established and the fitted *F* values for each value of *W* are used with central differencing to determine d*F*/d*W*. We have applied the smoothing procedures of Jaynes and Tyler (1980), and Borcher *et al.* (1987) on several samples and found no improvement over the method of calculation described here.

The routine plotting of the data as used here (refer to Appendix 1) ensures that existence or absence of monotonic behaviour is readily apparent.

Extra steps have been considered to avoid error in determining *B* which is slope of ln*D* versus $\bar{\theta}$. Determination of *B* through using the slope of a straight line (best line fit through all of the data) has been compared with simply determining *B* at the midpoint ln*D* versus $\bar{\theta}$ plot as was done by Passioura (1976). Differences did occur between these two approaches but analysis showed that the sensitivity of the *D* calculations to the values of *B* was small. The approach that we take is to plot and view the ln*D* versus $\bar{\theta}$ relationship and estimate the slope at the midpoint ($\bar{\theta} = (\theta_i + \theta_f)/2$). For some samples that the midpoint represented a non-representative section of the curve, the slope is taken from a section of the curve which appears representative.

An example calculation spreadsheet has been included to show the steps involved in the procedure (appendix 1). Digital copies of the Microsoft Excel™ spreadsheet program used by the authors are available on request. The *D*(θ) and *K*(θ) results from the sample calculation are shown in Figure A6.

Figure 4. Plot of θ_L vs $\bar{\theta}$ and smoothing line (dashed line).



Sources of error

Measurement error

There are some measurement errors which are difficult to eliminate completely even with very careful laboratory procedure. These errors ranked in the order of importance are:

1. Incomplete contact of the soil sample with the ceramic plate potentially causes error, the size of which is difficult to establish. Sample to plate contact is maximised by wetting the soil samples in the Tempe cell and by carefully maintaining a flat surface at the ends of the core samples during sampling and preparation. “Conditioning” the core by wetting and draining it in place prior to the run may help. Visual inspection of the degree of contact can be made when the core is removed and cores with poor contact noted.

2. In some clay soils the 100 kPa pressure step might not drain a sufficiently large proportion of the total pore space to give reliable diffusivity measurement from outflow experiments. The pressure increment used must be large enough to yield a small final water content. Eching and Hopmans (1993) found their 100 kPa pressure step to be insufficient to induce enough drainage from samples > 22.5 % clay content.

3. There is a small but unavoidable amount of soil loss from the core during the measurement process. This occurs as the sample is removed from ceramic plates after the outflow experiment and during soil water characteristic determination. This leads to error in soil water content determination plus error in final bulk density determination. Due to the differences in density between water and soil, losses of a small volume of soil translate into considerably larger errors in water volume. Extreme care should be taken to minimise these losses which occur particularly where the soil is dispersive.

4. Gradual build-up of air beneath the ceramic plate in the Tempe cell will result in displaced water and error in the outflow versus time relationship. This is best minimised through attention to thoroughly wetting the ceramic plate before commencement of the experiment. Air should be removed from beneath the ceramic plate periodically as has been described.

5. Layering of soil within a sample such that the portion of the sample near the ceramic plate is not representative of the complete core will induce error. With the one-step method the part of the core near the ceramic plate appears to have greater influence on the results than the remainder of the sample (van Dam *et al*., 1992). Care needs to be taken that core samples are not taken across horizon boundaries. As we use the top of the core against the ceramic plate care should be taken with near surface samples to avoid organic or crusted surface features.

6. The use of a single 100 kPa pressure step induces large gradients and large initial water flow rates. This might induce flow processes not completely representative of what occurs in the field (van Dam *et al.*, 1992). The method described relies on stage III outflow data which should minimise this non-representative flow problem.

7. Core distortion can occur with gas pressure application (Hopmans *et al.*, 1992), this is unavoidable but some control might be attained through careful selection of the initial core water content. If repacked cores are to be used (not recommended), and they have significant air-filled porosity, then they may collapse when suddenly pressurised.

8. The determination of the amount of outflow is subject to weighing and/or volume determination (burette reading) errors. Due to the need to remove air from beneath the Tempe cell ceramic plate and to empty burettes periodically, the number of weighings gives opportunities for small errors. Burette reading errors are removed by the use of the weighing system for recording outflow. However, extra weighings associated with removal of air from beneath the ceramic plate are still required.

Error from assumptions implicit in the calculation method or in the calculation process

There are sources of error in the calculations, some of which come from the assumptions inherent in Passioura's method. The first example is the uncertainty of calculating $D(\theta_L)$ vs θ_L when θ_L approaches θ_f. That is at the dry end of the curve, where the assumption of $\theta_L >> \theta_f$ does not hold, and thus where equation (3) may not be an accurate description of the flow.

The estimation of K from D represents opportunity for error to be introduced. Interpolation between two points in the soil water characteristic curve is required and derivatives must be estimated.

The $D(\theta)$ calculation is sensitive to the method used to obtain the second derivative of the outflow data. Any smoothing of the data by fitting functions through the outflow data (F vs W) may add to the measurement error. Jaynes and Tyler (1980) and Borcher *et al.* (1987) employed different methods for estimating derivatives than those used by Passioura (1976) but they do not always give good fits at later stages of outflow and still have problems with non-monotonic $D(\theta)$ behaviour.

Non-monotonic $D(\theta)$ relationships can be a problem with the Passioura method. Valiantzas *et al.* (1988) introduced an improved method of one-step outflow calculations which they said could deal with non-monotonic conditions. The improvement is at a cost of having an iterative procedure. We have applied the Valiantzas *et al.* (1988) method but have found it to suffer from instability problems. We have chosen not to adopt their method because of this instability problem and because we do not commonly find problems with non-monotonic diffusivity. Occasionally we have observed aberrant behaviour at the dry end of the measured $D(\theta)$ curves for some samples. Such errors are however, readily apparent when the data is plotted and suspect points can be deleted.

Summary and conclusions

The advantages, for our purposes, of the one-step outflow method using the Passioura (1976) analysis are that it is laboratory based, simple, practical for small cores thus enabling sampling of shallow soil horizons, most of the required equipment is available commercially at reasonable cost, and large numbers of samples can be processed in relatively short time in controlled conditions. Disadvantages of the method include that it might be less reliable in clay soils where the 100 kPa pressure step is not sufficient to drain a large enough proportion of the pore space, that applicability might be limited by the prerequisite that D should be monotonicaly increasing with θ (this is rarely a limitation in our experience but can be overcome following the procedures of Valiantzas *et al.*, 1988), that the procedure cannot be used to determine values of hydraulic conductivity very close to saturation due to the difficulty in determining the derivative of the soil water characteristic at small suctions and because only stage III outflow data is used. Also, as with any small core method, disturbance during sampling can affect the integrity of the results attained .However this is usually more of a problem with hydraulic property values at large water contents. That the procedure measures diffusivity can be a disadvantage where unsaturated hydraulic conductivity is of primary interest because of the need for reliance on soil water characteristic interpolation to calculate hydraulic conductivity from diffusivity. Other disadvantages of the method are those sources of measurement and calculation error discussed in the previous section.

The one-step outflow method can be used successfully as a routine method for determination of diffusivity and unsaturated hydraulic conductivity. The description of the method given here should assist anyone who is assessing the method as to its suitability for their purposes, or is wishing to implement the method in their laboratory and is seeking to minimise the time investment required before the method is able to be applied routinely.

Acknowledgments

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Appendix 1. Example calculation with a sample from a red kandosol A-horizon from the CSIRO 'Flushing Meadows' research site at Wagga Wagga, NSW.

ONE STEP OUTFLOW (tempe cell) DATA SHEET

Site :	**FIRST WAGGA PIT**	**Core No:**	**30 E3**		
Sampling date:	**18/10/93**	**Data file name:**	**1W30E3**	**Bulk density (g/cm^3):**	**1.59**
Sleeve length(cm):	**6.1**	**Sleeve volume (cm^3):**	**346.14**	**Sleeve wt. (g) :**	**182.8**
Core volume (cm^3):	**346.14**	**Core length (cm):**	**6.1**	**Oven dry wt. of soil (g):**	**549.9**
Pneumatic pressure (cm) :	**1000**	**Bottom press. head (cm):**	**0**	**Equilibrium cum. outflow (cm^3):**	**75.6**
Initial weight of soil sample with sleeve (g):	**844.4**	**Final weight of soil sample with sleeve (g) :**	**768.8**		
Initial water content: θ_i (cm^3/cm^3):	**0.323**	**Final water content θ_f (cm^3/cm^3):**	**0.104**		

Outflow data:

Time (min)	Reading	Time (hr)	Outflow (cm^3)
0	98.2	0.000	0.000
0.5	93.8	0.008	4.400
1	91.2	0.017	7.000
1.5	88.4	0.025	9.800
2	85.6	0.033	12.600
3	80.8	0.050	17.400
4	77	0.067	21.200
5	73.8	0.083	24.400
6	72.3	0.100	25.900
8	69	0.133	29.200
10	66.8	0.167	31.400
12	64.7	0.200	33.500
15	62.4	0.250	35.800
20	59.4	0.333	38.800
25	57	0.417	41.200
32	54.4	0.533	43.800
40	52.2	0.667	46.000
45	51	0.750	47.200
60	48.3	1.000	49.900
90	44.2	1.500	54.000
120	41.8	2.000	56.400
140	40.4	2.333	57.800
180	38.3	3.000	59.900
215	36.6	3.583	61.600
275	34.4	4.583	63.800
335	32.8	5.583	65.400
390	31.6	6.500	66.600
465	30.2	7.750	68.000
1440	23.3	24.000	74.900
2880	22.6	48.000	75.600

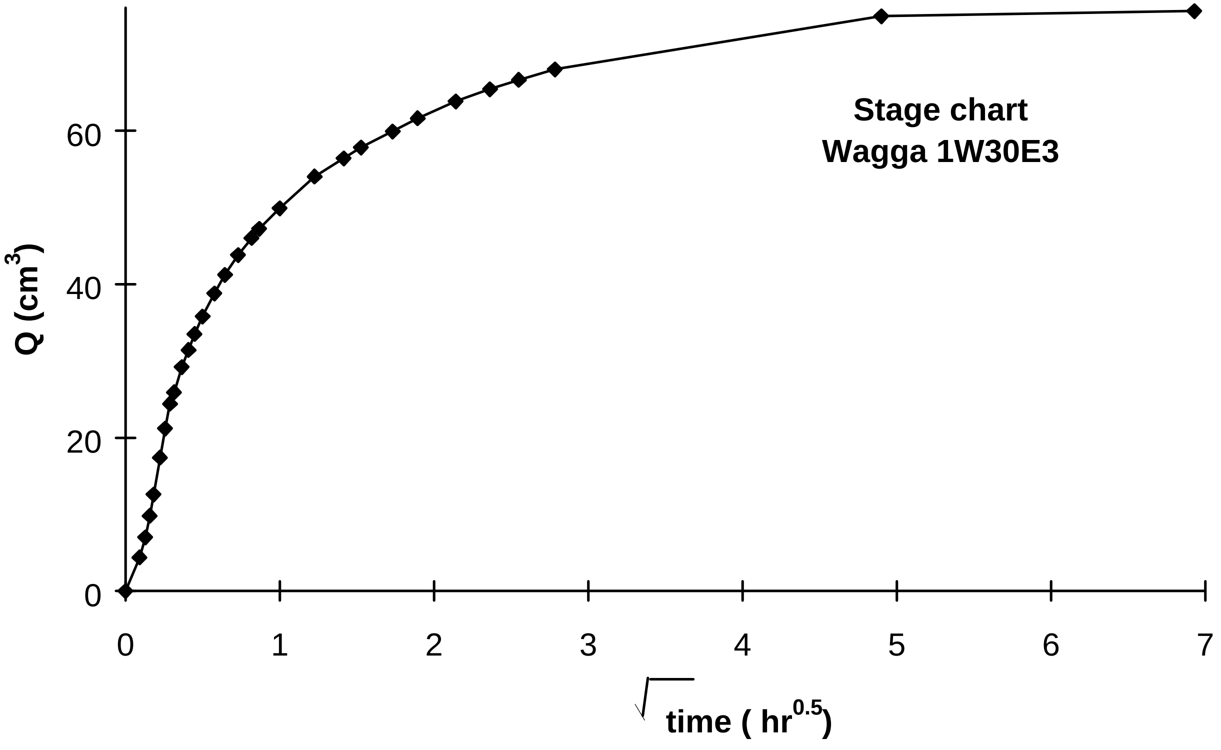
Soil water Characteristic data

suction (cm)	water content (cm^3/cm^3)
0	0.343
10	0.342
30	0.279
50	0.231
100	0.193
330	0.130
660	0.093
1000	0.090
5000	0.059
15000	0.040

WORKING SHEET

Initial water content:	**θ_i (cm^3/cm^3):**		**0.323**
Final water content	**θ_f (cm^3/cm^3):**		**0.104**
		average	**0.214**
Core length (cm):			**6.1**
Core volume(cm^3):		**(Vol.)**	**346.14**

Figure A1. Cumulative outflow volume.



Time(hr)	**Q**	**$t^{0.5}$**	**W**	**F**	**F (fitted)**	**dF/dW**	**D**	**θ**	**ln D**	**θj**	**θk**	**θL**
0.000	0.000	0										
0.008	4.400	0.091287										
0.017	7.000	0.129099			polynomial							
0.025	9.800	0.158114			see the chart below							
0.033	12.600	0.182574							**Interpolation between**			
0.050	17.400	0.223607							**the two lines (steps 15-20)**			
0.067	21.200	0.258199							θι=0.13856 **θm1**=0.18228 **θm2**=0.13245			
0.083	24.400	0.288675							**a=1.0700 b=0.0067**			
0.100	25.900	0.316228		**Stage III**								
0.133	29.200	0.365148	82.531									
0.167	31.400	0.408248	80.331	64.5	64.227628							
0.200	33.500	0.447214	78.231	52.8	52.405527	5.085695	94.61935	0.226006	4.549862	0.245516	0.29543	0.245516
0.250	35.800	0.5	75.931	39.75	41.850572	4.018397	74.76228	0.219362	4.314313	0.238871	0.284992	0.238871
0.333	38.800	0.57735	72.931	32.4	31.108022	3.220444	59.91637	0.210695	4.09295	0.230205	0.271378	0.230205
0.417	41.200	0.645497	70.531	25	24.460173	2.467275	45.90365	0.203761	3.826545	0.223271	0.260487	0.223271
0.533	43.800	0.730297	67.931	19.2	18.771647	1.985	36.93092	0.19625	3.609049	0.21576	0.248688	0.21576
0.667	46.000	0.816497	65.731	15.69231	14.932175	1.654233	30.777	0.189894	3.426768	0.209404	0.238705	0.209404
0.750	47.200	0.866025	64.531	11.7	13.147256	1.318516	24.531	0.186427	3.199938	0.205937	0.233259	0.205937
1.000	49.900	1	61.831	9.066667	9.7899604	1.040438	19.35735	0.178627	2.963072	0.198137	0.221007	0.197881
1.500	54.000	1.224745	57.731	6.5	6.072278	0.814287	15.14982	0.166782	2.717989	0.186292	0.202401	0.185207
2.000	56.400	1.414214	55.331	4.56	4.4970917	0.611899	11.38439	0.159849	2.432243	0.179359	0.19151	0.177788
2.333	57.800	1.527525	53.931	3.5	3.7470608	0.477232	8.878893	0.155804	2.183677	0.175314	0.185157	0.173461
3.000	59.900	1.732051	51.831	3.04	2.8267813	0.396006	7.36769	0.149738	1.997104	0.169247	0.175627	0.166969
3.583	61.600	1.892969	50.131	2.463158	2.2422383	0.296759	5.521198	0.144826	1.708595	0.164336	0.167912	0.161714
4.583	63.800	2.140872	47.931	1.9	1.6694219	0.231607	4.309049	0.138471	1.460717	0.15798	0.157929	0.154913
5.583	65.400	2.362908	46.331	1.46087	1.3621316	0.174805	3.252255	0.133848	1.179349	0.153358	0.150668	0.149967
6.500	66.600	2.54951	45.131	1.2	1.1799667	0.13673	2.543859	0.130381	0.933682	0.149891	0.145223	0.145223
7.750	68.000	2.783882	43.731	0.474286	1.0066341	0.130186	2.422119	0.126337	0.884643	0.145847	0.138869	0.138869
24.000	74.900	4.898979	36.831	0.18882	0.0994191							
48.000	75.600	6.928203	36.13085									

Figure A2. Assessment of fitting alternative functions to outflow rate (F) as a function of volume of water remaining in the soil (W) (using stage III outflow data only).

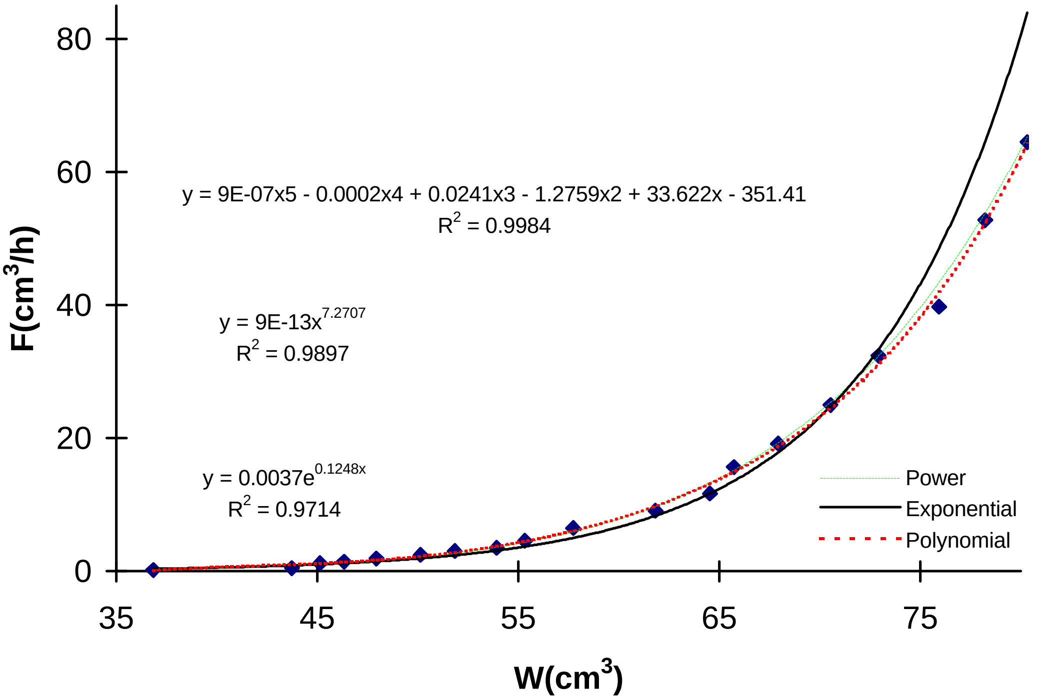


Figure A3. Plot of ln D vs $\overline{\theta}$ for determination of slope of the curve (B).

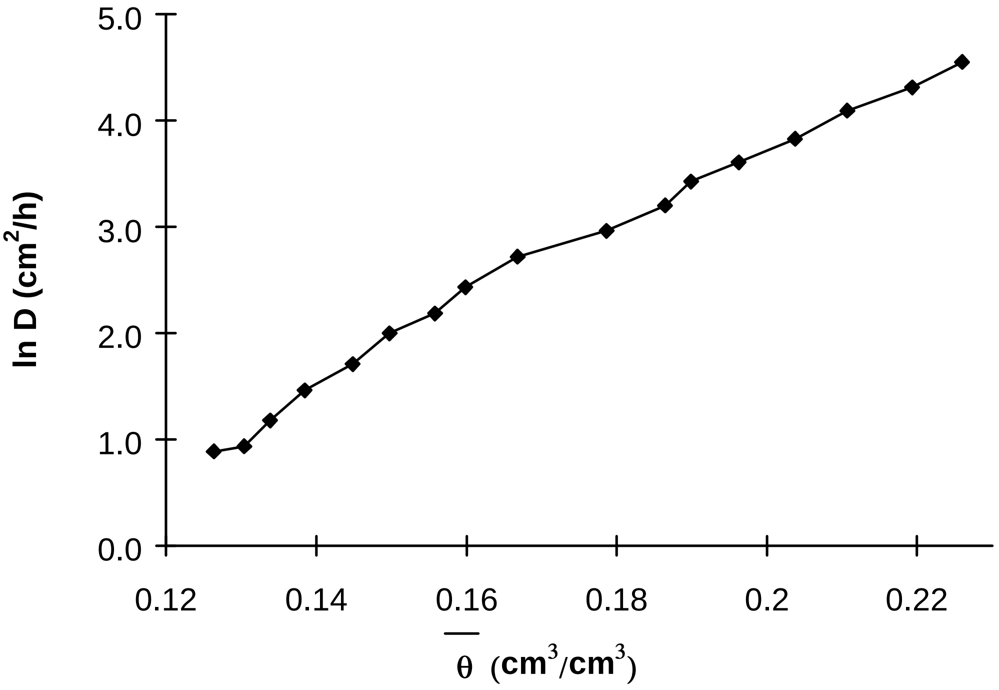


Figure A4. **Plot of θ_j and θ_k vs $\overline{\theta}$ for determination of θ_L vs $\overline{\theta}$ by smoothing at the intersection of the two lines.**

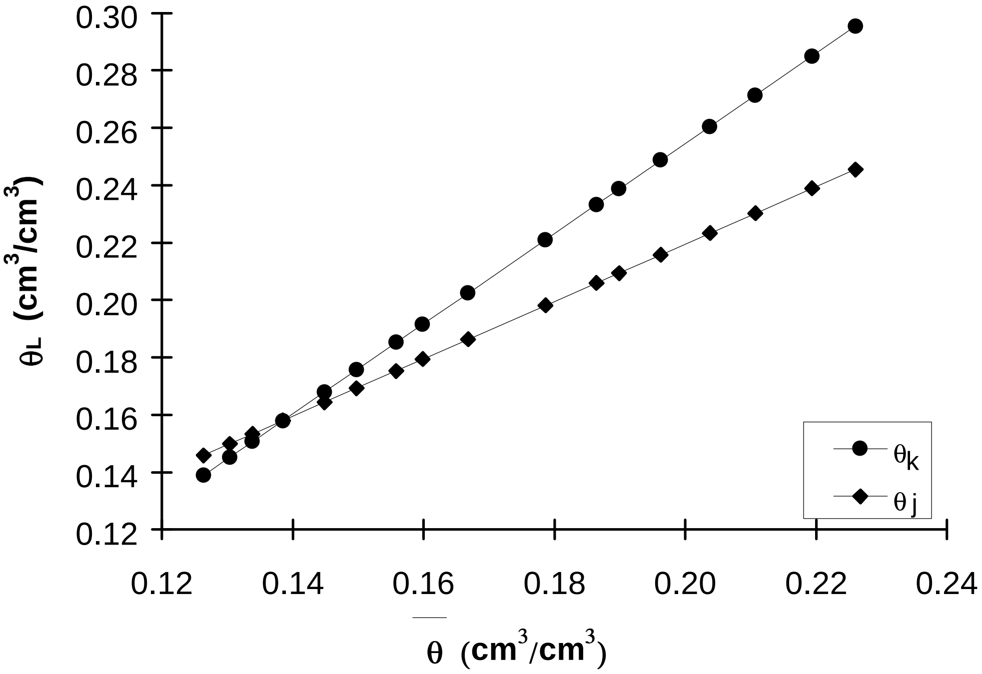
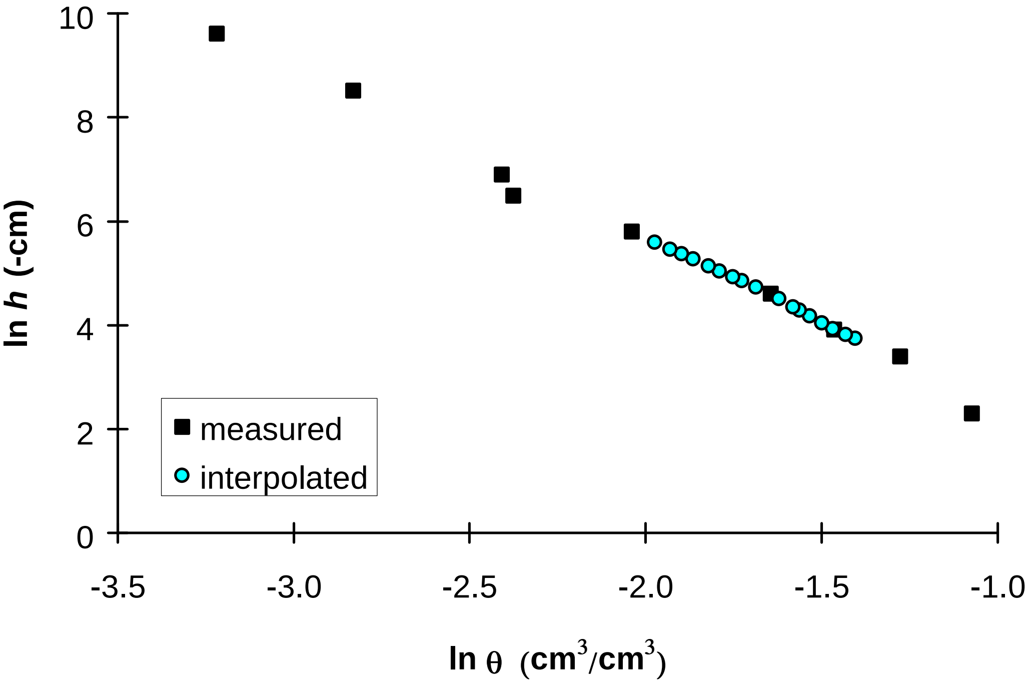


Figure A5. **Measured soil water characteristic as used for deriving unsaturated hydraulic conductivity from diffusivity.**



CALCULATIONS OF THE SLOPE OF SOIL WATER CHARACTERISTIC CURVE (steps 21-25)

SWC curve

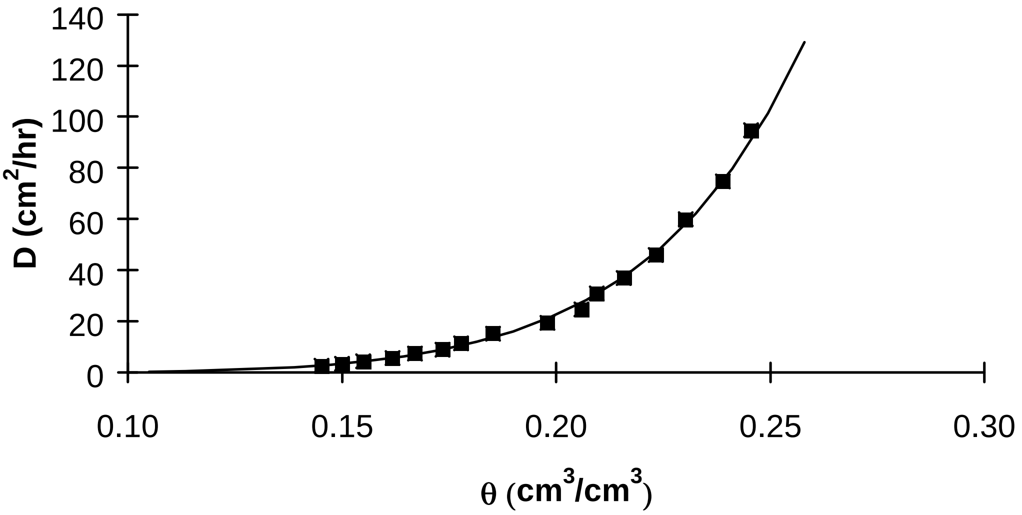
h (cm)	θ (cm^3/cm^3)	ln h	ln θ	slope
10	0.342	2.302585	-1.07294	-0.18532
30	0.279	3.401197	-1.27654	-0.36959
50	0.231	3.912023	-1.46534	-0.25929
100	0.193	4.60517	-1.64507	-0.33097
330	0.13	5.799093	-2.04022	-0.48321
660	0.093	6.49224	-2.37516	-0.07891
1000	0.09	6.907755	-2.40795	-0.26237
5000	0.059	8.517193	-2.83022	-0.35377
15000	0.04	9.615805	-3.21888	

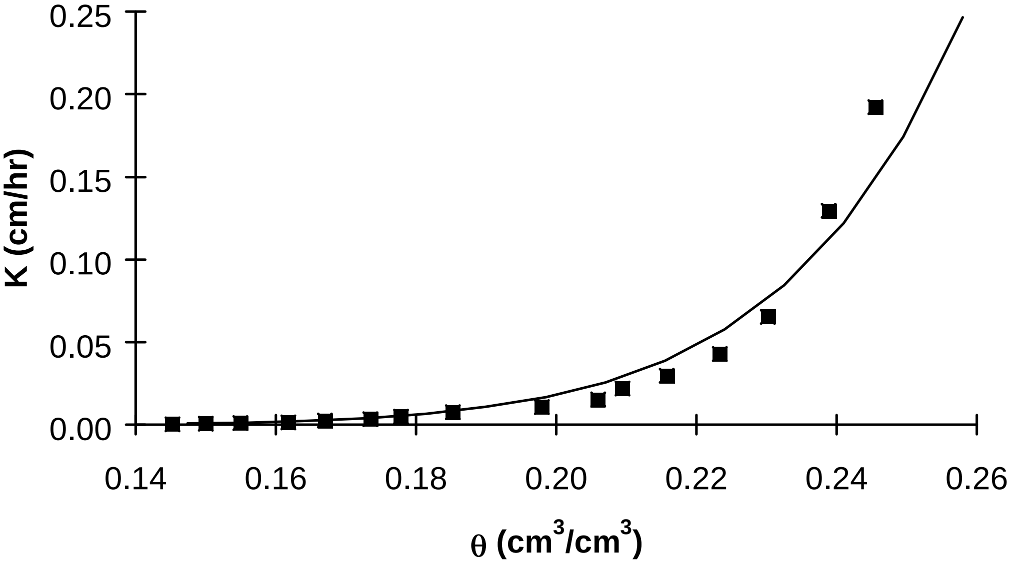
ln θ_L	ln h	h (cm)	slope	K(cm/hr)	θ (cm^3/cm^3)
-1.40439	3.747124	42.39895	-0.00203	0.192423	0.245516
-1.43183	3.82136	45.66629	-0.00173	0.129504	0.238871
-1.46879	3.925327	50.66965	-0.00109	0.065496	0.230205
-1.49937	4.043271	57.01251	-0.00093	0.042866	0.223271
-1.53359	4.175249	65.05607	-0.0008	0.029519	0.21576
-1.56349	4.290564	73.0076	-0.00071	0.021976	0.209404
-1.58018	4.354946	77.86264	-0.00062	0.015255	0.205937
-1.62009	4.508847	90.81705	-0.00056	0.010931	0.197881
-1.68628	4.729699	113.2614	-0.0005	0.007548	0.185207
-1.72716	4.853219	128.1522	-0.00044	0.004974	0.177788
-1.75181	4.927675	138.0581	-0.00038	0.003418	0.173461
-1.78995	5.042917	154.9212	-0.00033	0.002464	0.166969
-1.82193	5.139538	170.637	-0.00029	0.001587	0.161714
-1.86489	5.269348	194.2893	-0.00025	0.001065	0.154913
-1.89734	5.367386	214.302	-0.00022	0.000706	0.149967
-1.92949	5.464524	236.1633	-0.00019	0.000473	0.145223

SUMMARY

K (cm/hr)	θ (cm^3/cm^3)	D (cm^2/hr)
0.1924	0.246	94.6193
0.1295	0.239	74.7623
0.0655	0.230	59.9164
0.0429	0.223	45.9037
0.0295	0.216	36.9309
0.0220	0.209	30.7770
0.0153	0.206	24.5310
0.0109	0.198	19.3573
0.0075	0.185	15.1498
0.0050	0.178	11.3844
0.0034	0.173	8.8789
0.0025	0.167	7.3677
0.0016	0.162	5.5212
0.0011	0.155	4.3090
0.0007	0.150	3.2523
0.0005	0.145	2.5439

Figure A6. Measured diffusivity (a) and unsaturated hydraulic conductivity (b) for the A-horizon of a red kandosol soil from Wagga, NSW (sample 1W30E3, see Appendix 1). The symbols represent the measured points, the curve is a van Genuchten/Mualem hydraulic model fitted simultaneously through the measured diffusivity and soil water characteristic data using the RETC program (van Genuchten et al., 1991).





Appendix 2. Local equipment suppliers

Soil moisture equipment products made by:

Soil Moisture Equipment Corporation
PO Box 30025
Santa Barbara
California 93105
USA

and supplied locally by :

Irricrop Technologies Pty. Ltd.
PO Box 487
Narrabri, NSW, 2390.

Swagelok fittings and teflon tubing supplied by :

Sydney Swagelok Service Pty. Ltd.
Unit 2, 10 Hearne Street (PO Box 126)
Mortdale, NSW, 2223.

“Software Wedge for Windows™” supplied by:

Hearn Scientific Software
level 6, 552 Lonsdale Street
Melbourne , Vic, 3000