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Multi-step outflow experiment: From soil preparation to parameter estimation

by

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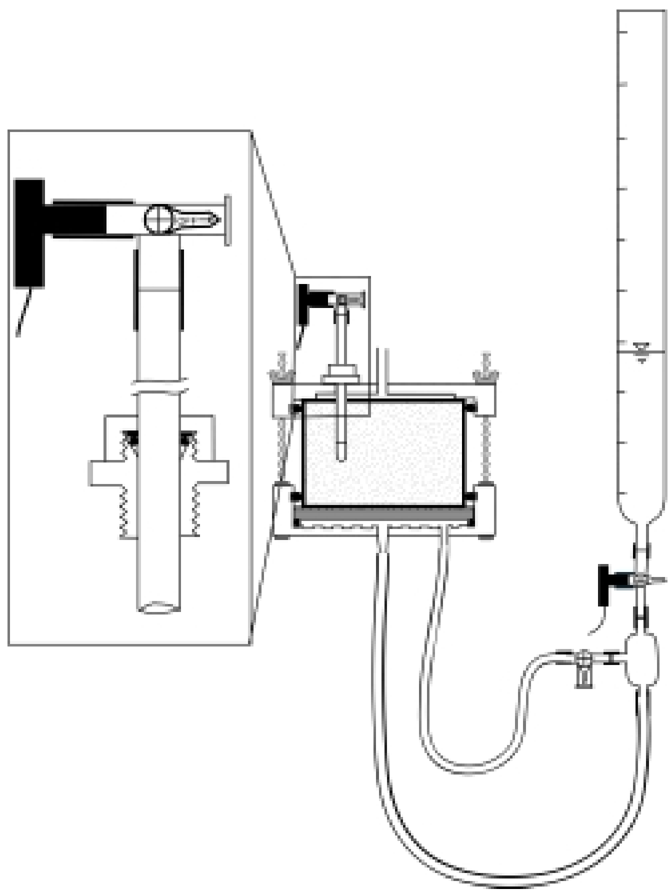

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1. INTRODUCTION

The success of modeling unsaturated soil water transport problems often depends on the availability of soil hydraulic functions, the water retention $\theta(h)$, and the hydraulic conductivity, (K), as a function of soil water matric head, h, or water content, θ. Traditional techniques for determining $\theta(h)$ involve stepwise equilibrium desorption or sorption experiments. $K(\theta)$ is often determined by steady state methods. Unfortunately, it is often tedious and time consuming to determine these functions in a traditional way. Over the last several years, indirect laboratory methods have been developed that are fast, conveniently controlled, and relatively inexpensive. One such technique is the parameter estimation by the inverse modeling from transient outflow measurement.

Kool et al. (1985a) were among the first to apply the inverse technique by numerical solution of the Richards equation for a one-step outflow experiment. Subsequently, Parker et al. (1985) experimentally applied the one-step outflow method to four soils of different texture and showed that soil hydraulic functions ($\theta(h)$ and $K(\theta)$) can be optimized simultaneously by using cumulative outflow as a function of time. Although optimization of the parameters describing the soil hydraulic functions in a transient outflow experiment is a promising method to derive soil hydraulic information, estimates from one-step outflow experiments using only cumulative outflow data in the objective function are often unreliable and non-unique (van Dam et al., 1992). To overcome nonunique estimates of soil hydraulic functions, van Dam et al. (1994) introduced the multi-step outflow method, which uses a sequence of smaller pneumatic pressure increments to induce drainage of the soil core. Their laboratory experiments showed that such outflow data contain sufficient information for unique estimates of the soil hydraulic functions, using initial estimates derived from the outflow experiment itself. The experimental work by Eching and Hopmans (1993a, b) and Eching et al. (1994) showed how the multi-step method in combination with automated soil water matric head measurements during drainage of soil cores improved the estimation of parameter values of soil hydraulic functions for four different textured soils. Chen et al.

(1997) reported an updated model version (SFOPT) of the outflow experiment with data file preparation program (DATAPREP).

1.1. Synopsis

This report documents the components of the multi-step outflow method used for parameter estimation of the soil hydraulic functions by inverse modeling. In addition, it includes the documentation for the experimental data processing and the parameter estimation algorithm. The inverse modeling includes three interrelated functional parts (Figure 1): (1) a controlled transient flow experiment with prescribed initial and boundary conditions, and transient flow variables, such as cumulative outflow and matric pressure are accurately measured by pressure transducers; (2) a numerical flow model simulating the transient water flow regime of this experiment using initial estimates of the parametric soil hydraulic functions (see sections 2.1 and 2.2); and (3) a nonlinear optimization algorithm, which estimates the unknown parameters of the hydraulic functions through minimization of the difference between observed and simulated flow variables (residuals) through iterative solution of the transient flow equation (see section 2.3). The quality of the final solution of the parameter estimation problem depends on each of these three individual components as well as their integration within a computational framework. The three individual components are interfaced through input data files that include the experimental, numerical water flow model, and parameter optimization results. Parameters of the hydraulic functions are updated iteratively in the optimization routine, thereby continuously reducing the residuals until a predetermined convergence criterion has been achieved. However, achieving convergence criterion does not mean that an inverse solution is unique for a set of optimized parameters. It is generally recommended to test non-uniqueness by solving the inverse problem repeatedly using new initial parameter estimates (Figure 1).

The experimental components and procedures of the multi-step outflow method are reported in sections 3, 4, and 5. Section 3 also includes topics such as the recommended steps for soil preparation, the required measurements of the soil physical properties before starting the outflow experiment, and the way of keeping experimental records. The transducer calibration (tensiometer and outflow), a method to multiplex several transducers to one datalogger, datalogger communication software and a sample datalogger program are described in sections 4 and 5. Moreover, the photographs of different components of the outflow experiment are shown in Appendix A. The program DATAPREP, which is used to clean collected experimental data, and to prepare input data file for the SFOPT program is introduced and explained in detail in section 6. Finally, in section 7, the description and input file structure for the SFOPT program, which includes both the numerical simulation and nonlinear optimization algorithms are presented. Initial estimates of parameters used in the hydraulic functions, the example problems, input and output files are also provided. The source codes of DATAPREP and SFOPT programs can be found in Appendixes B and C, respectively. The first 12 references on page 83 provide an excellent review of literature and procedures of this report.

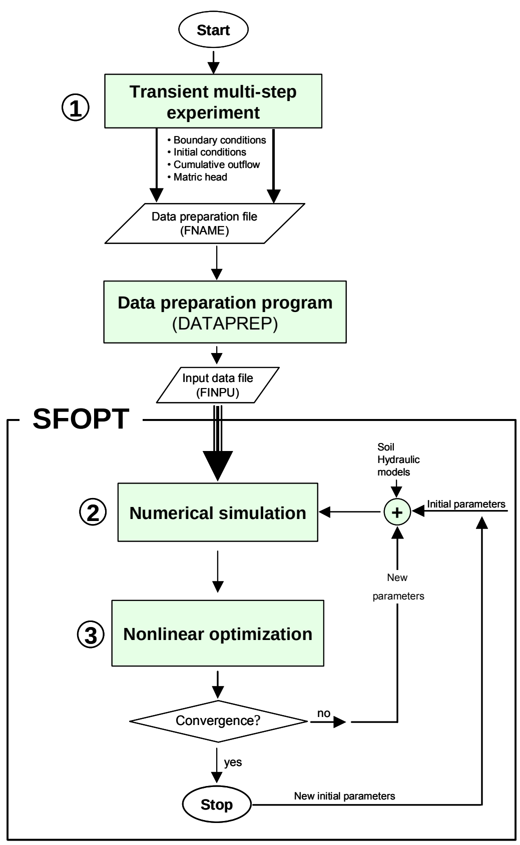

Figure 1. Flow chart of the inverse solution technique for parameter estimation of the soil hydraulic functions.

2. THEORY AND MODELS

2.1. SFOPT development and inverse parameter estimation

The nonlinear parameter optimization program SFOPT (single fluid optimization program) is originally based on the program ONESTEP, which was developed by Kool et al. (1985b) for the estimation of soil hydraulic properties from One-step outflow experiments. Van Dam et al. (1990) adapted the ONESTEP program to conduct multi-step outflow experiments (MULSTP). They made the parametric model more flexible and facilitated testing of uniqueness. Eching and Hopmans (1993a,b) modified the MULSTP code (MLSTPM) to enable the simultaneous use of cumulative outflow volume and soil water matric head data in the inversion process. Finally, Chen et al. (1997) introduced a new version of MLSTPM software (SFOPT), which includes new features and improvements in the optimization algorithm. Here, we will present the features of the SFOPT program, which are used to estimate the parameters of the constitutive functions of a soil sample from a multi-step outflow experiment, neglecting the influence of the non-wetting fluid (air) on the flow regime. Typically, the SFOPT program would be used for an air-water (nonwetting-wetting) soil system, neglecting viscosity in the air phase and its influence on water flow. Application of the inverse solution technique in a two-phase flow experiment is described in Chen et al. (1999) using an optimization code TF-OPT.

Following is a general theoretical description of the inverse parameter estimation procedure for the soil hydraulic functions, specifically for the outflow method used in the SFOPT program. A detailed analysis of inverse methods on flow and optimization can be found in Hopmans et al. (2002). In the outflow method, a soil sample is saturated in a pressure cell with a porous barrier at the bottom. The porous barrier must have an air entry value larger than the maximum applied pressure, so that it remains saturated throughout the outflow experiment. The drainage induced by the soil water potential gradient is assumed to be described by the Richards equation. In its one-dimensional form with the vertical coordinate, $z(L)$, taken positive upward, it is written as

$$C(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} + 1\right)\right] \qquad [1]$$

where $C = d\theta / dh$ is the water capacity (L^{-1}), h is soil matric head (L), K is unsaturated hydraulic conductivity (LT^{-1}) and t denotes time (T). The combined system of soil and porous barrier for the multi-step outflow experiment has the following initial and boundary conditions

$$\begin{aligned} &h(z,t) = h_i(z) && t = 0 \\ &q(z,t) = 0 && t > 0,\ z = L \\ &h = h(0,t) - |h_a| && t > 0,\ z = 0 \end{aligned} \qquad [2]$$

where h_i is the initial matric pressure head (L), q denotes the flux density (LT^{-1}), $z = 0$ is the bottom of the porous plate/membrane, $z = L$ is the top of the soil sample, $h(0,t)$ is the water pressure head at the bottom of the porous plate/membrane, and h_a is either the applied pneumatic gas pressure to the top of the soil core $(z = L)$, or suction applied beneath the porous plate/membrane $(z = 0)$. In SFOPT, a time-dependent lower boundary condition was implemented and automatically measured by the pressure transducer below the burette.

2.2. Soil water retention and hydraulic conductivity models

In order to optimize the soil hydraulic data from the inverse solution of the Richards equation (Eq. [1]), parameterization of the hydraulic functions is necessary. The soil water retention and unsaturated hydraulic conductivity functions can be defined by various expressions. In SFOPT two models are used for the description of soil hydraulic functions. The first model is the soil water retention function proposed by van Genuchten (1980)

$$S_e = \left[1 + |\alpha h|^n\right]^{-m} \qquad [3]$$

with

$$S_e = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} \qquad [4]$$

and $m = 1 - 1/n$, where S_e is called effective water saturation ($0 \le S_e \le 1$), θ_s and θ_r are the saturated and residual water content (L^3L^{-3}), respectively, and α (L^{-1}) and n are empirical parameters. Substituting Eq. [3] in the capillary model of Mualem (1976), van Genuchten (1980) derived the following unsaturated hydraulic conductivity model

$$K(h) = K_s S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \qquad [5]$$

where K_s and l denote saturated hydraulic conductivity (LT^{-1}) and tortuosity/connectivity parameters, respectively. S_e and m are the same parameters as used in Eq. [3]. From the analysis of a variety of soils, Mualem (1976) proposed a value for $l = 0.5$, although l can be considered as another fitting parameter as well (Hopmans et al., 1994; Hopmans et al., 2002).

The second is the lognormal model (Kosugi, 1996) that can be used in addition to the van Genuchten (1980) model. The lognormal model is physically based, and optimization results have been equally successful. The soil water retention curve and the unsaturated hydraulic conductivity functions are expressed by

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = F_n\left[\frac{\ln(h/h_m)}{\sigma}\right] \qquad [6]$$

$$K = K_s S_e^l \left[F_n\left(\frac{\ln(h/h_m)}{\sigma} + \sigma\right)\right]^2 \qquad [7]$$

where F_n is the complementary normal distribution function defined as

$$F_n(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty \exp\left(-\frac{x^2}{2}\right) dx \qquad [8]$$

Alternative expressions for the hydraulic functions of Eqs.[6] and [7] can be written as

$$S_e(\ln h) = \frac{1}{2}\, erfc\left(\frac{\ln h - \ln h_m}{\sigma\sqrt{2}}\right) \qquad [9]$$

$$K(S_e) = K_s S_e^l \left\{\frac{1}{2}\, erfc\left[erfc^{-1}\left(2S_e\right) + \frac{\sigma}{\sqrt{2}}\right]\right\}^2 \qquad [10]$$

where $erfc$ and $erfc^{-1}$ denote the complementary and inverse complementary error functions, respectively. The lognormal model has six parameters h_m, σ, θ_r, θ_s, K_s, and l. The parameter h_m denotes the median matric head at which the effective saturation (S_e) is equal to 0.5 and σ is the standard deviation of the lognormal pore-size distribution. The value of h_m is usually greater than 1 and smaller than 10^6 cm. The value for σ is between 0 and 10. In SFOPT, the value of LOG10(h_m) is used as the fitting parameter, instead of h_m to increase parameter sensitivity.

2.3. Objective function

SFOPT is a one-dimensional finite element flow model combined with a optimization algorithm using the Levenberg-Marquart (LM) maximum neighborhood method (Clausnitzer and Hopmans, 1995). The form of the objective function $O(\mathbf{b})$ to be minimized is

$$O(\mathbf{b}) = \sum_{i=1}^{N}\left[W_i\left(Q_o(t_i) - Q_c(t_i,\mathbf{b})\right)\right]^2 + \sum_{j=1}^{M}\left[W_j\, V_j\left(h_o(t_j) - h_c(t_j,\mathbf{b})\right)\right]^2 + \sum_{k=1}^{L}\left[W_k\, V_k\left(\theta_o(h_k) - \theta_c(h_k,\mathbf{b})\right)\right]^2 \qquad [11]$$

where $\mathbf{b}$ is a vector containing the optimized parameters (θ_s, θ_r, α, n, l, and K_s or $\theta_s, \theta_r, \log h_m, \sigma, l$ and K_s). Vector $\mathbf{b}$ contains only those parameters that need to be optimized. Values of parameters that are known such as θ_s can be fixed. Q and h denote cumulative transient outflow volume (mL) and the soil water matric head (cm), respectively. θ is soil water content, corresponding with a known soil water matric head,

h. Subscripts o and c represent observed and calculated values. N, M, and L denote the number of cumulative outflow, pressure head, and soil moisture content-matric head pairs measured during the multi-step outflow experiment, respectively.

The internal weighting (V_j in the objective function) or normalization method of Kool and Parker (1987) was adapted for weighting of input variables. The program calculates weights for the soil water matric head and soil moisture content data so that the weighting factor is inversely proportional to their mean measured values. Consequently, the measurement type with the lowest mean receives a unit weight, thus preventing one variable from dominating another because of its numerical magnitude. W is a user-supplied weight for differential weighting of each data (default = 1). For example, if a $\theta(h)$ pair is known, a weight (W) of 5 or 10 is assigned to it, thereby forcing the optimized retention curve through this point.

3. MATERIAL AND METHODS

3.1. Sample preparation and bottom plate assembly

The multi-step experiment can be conducted with either a disturbed (laboratory packed) or undisturbed soil sample. The default sample size of the standard Tempe pressure cell accommodates an 8.25-cm (3.5-inch) outside diameter and 6-cm length brass ring (component D of Photo 1 in Appendix A). Before assembling the soil sample in a Tempe pressure cell, various procedures need to be followed to saturate the soil sample. If a disturbed soil sample is used, a wet strength filter paper[1] is glued to one end of the brass ring before the ring is packed with the soil. For undisturbed soils, cheesecloth at the bottom of the soil will be sufficient to prevent soil loss. The samples (disturbed or undisturbed) are soaked in a 0.01 M $CaCl_2$ solution while keeping the chloride solution about 1 cm below the soil's top surface. The samples continue to be soaked until water appears on the surface. The samples are subsequently placed on a screen to measure the saturated hydraulic conductivity using a constant head method (Klute and Dirksen, 1986). After the saturated hydraulic conductivity measurement, the filter paper is removed and

[1]Whatman Inc. 9 Bridewell Place, Clifton, NJ 07014. Phone: 800 631 7290. Cat No 1114125

the saturated soil sample with the ring is assembled in the Tempe pressure cell upside down. Early on, an appropriate air-entry value ceramic plate was placed in the bottom of the Tempe cell to serve as a porous barrier. However, we propose to use a nylon[1] membrane (MAGNA nylon disk filter, supported, plain type with 1.2 micron pore size and 142 mm diameter), instead of a ceramic plate (Photo 2 in Appendix A). A nylon membrane has several advantages:

- Low hydraulic resistance,
- High flow rate with high air entry value (1700 cm), although various pore sizes can be purchased,
- Pressure difference across the membrane is small,
- Do not need to specify conductivity of the membrane in flow code,
- Flow is not controlled by membrane but solely by the soil thereby improving the parameter optimization procedure,
- An estimate of $K(S_e)$, directly from outflow and tensiometer measurements can be obtained (Eching et al., 1994).

The flow properties of the nylon membrane in comparison with other porous materials are listed in Table 1. The saturated hydraulic conductivities of the nylon membrane and ceramic plate are determined from cumulative outflow volume from Tempe cells filled with water when subjected to an arbitrarily chosen pneumatic pressure of 400 mbar. To support the nylon membrane, a perforated 26-gauge stainless steel screen[2] (0.045" round perforations on 0.066" straight center, 225 holes per sq. in. with a 36 % open area) was cemented on a Plexiglas ring with two-ton epoxy (Figure 2a). The hydraulic resistance of the porous material, R_p, is equal to the ratio of plate thickness (l_t) and saturated hydraulic conductivity, K_s, of the porous material (Table 1). To prepare the support assembly, the wet strength Whatman filter paper is cut to a diameter equal to the stainless steel screen support and placed on the smooth side of the steel support (Figure 2b).

[1] Osmonics Inc. 5951 Clearwater Drive, Minnetonka, MN 55343. Phone: 800-848-1750. Catalog No: R12SP14225

[2] Small Parts Inc, 13980 NW South Crt, PO Box 4650, Miami Lakes, FL 33014-0650: 1-800-220-4242. Catalog No: A-PMX-045.

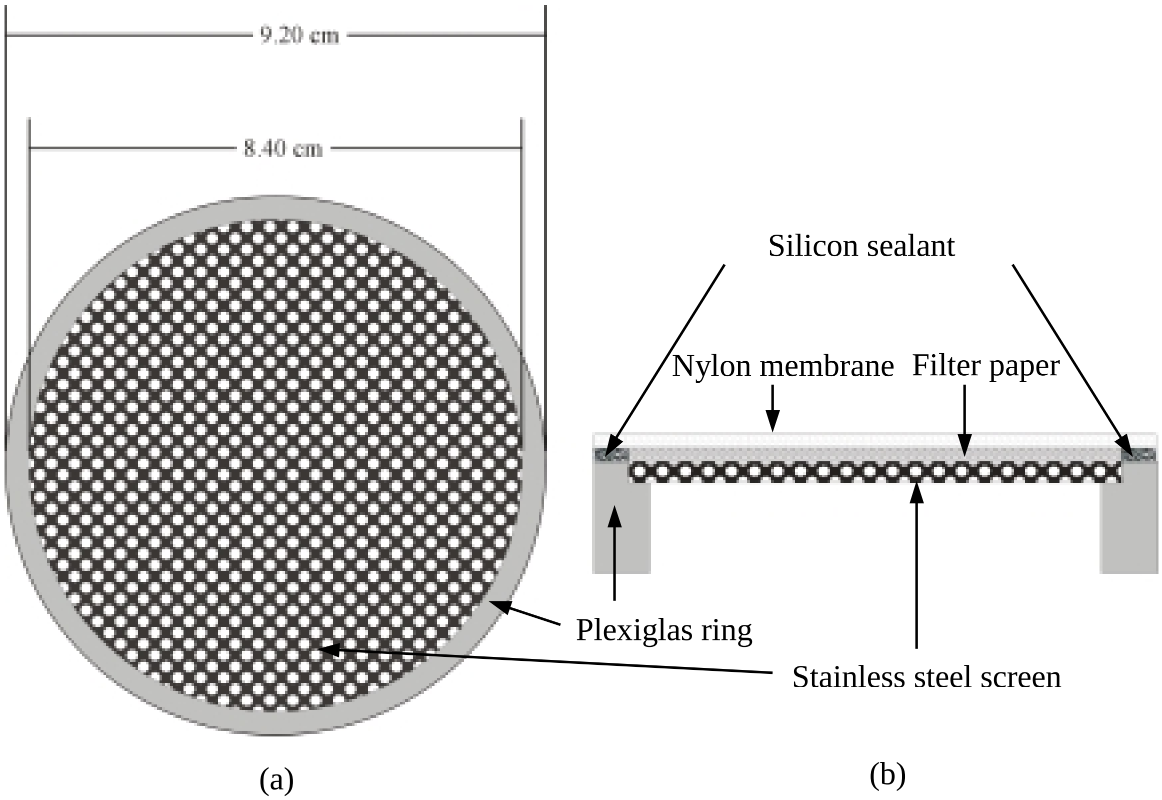

Figure 2. Perforated stainless steel screen support (a), and support assembly (b)

Table 1. Physical properties of different porous materials (l_t = thickness; $R_p = l_t / K_s$)

Porous Material	l_t (cm)	K_s (cm/h)	R_p (h)	Air-entry pressure (cm)
Ceramic	0.58	0.0071	81.48	1000
Plastic	0.05	0.017	3.01	400
Stainless Steel	0.1	0.027	3.77	250
Nylon	0.01	0.014	0.71	1700

The paper filter is used to prevent perforation of the nylon membrane. Then, waterproof silicon sealant[1] is applied to the Plexiglas ring around the filter paper and a pre-cut nylon membrane with a diameter equal to the Plexiglas ring is glued to the plate assembly. Note

[1] Bostik, RTV Silicon Sealant

that silicon sealant must be applied quite thick to give spongy effect for better airtight seal when soil sample is assembled in the Tempe cell.

3.2. Tensiometers and transducers

After laying the support assembly into the Tempe cell, the saturated soil sample is placed on the support (Figure 3). Figure 3 shows the basic arrangement of the pressure cell experiment. The soil water matric head is measured with a mini-tensiometer-transducer arrangement (Photo 3 in Appendix A). A mini-tensiometer is constructed by gluing a 1-cm long 0.635-cm O.D. ceramic cup[1] to a 12 cm long 0.63-cm O.D. acrylic tube with a copper coupler using a clear all-purpose two-ton epoxy. The acrylic tubing is connected to a three-way valve by a piece of tygon or rubber tubing. To ensure a rigid connection, the acrylic tube and three-way valve connection must be fully abutted. Flexibility of the wall of the tensiometer-transducer causes long response times of the tensiometer and fluctuation in the transducer signal. The transducer[2] has a working pressure range of ±15 psi. After filling the tensiometer and three-way valve with 0.01 M $CaCl_2$ solution, the transducer is connected to the valve making sure that it has an open connection with the laboratory at atmospheric pressure. This ensures that the transducer membrane is not damaged during the connection of the transducer with the tensiometer as high pressures may occur. A similar procedure is used to connect the outflow transducer[3] (Photo 1E and G), with an operating pressure range between ±1 psi, to a three-way valve below the burette (Figure 3). Each transducer is checked independently for proper operation. Calibration must be done over the entire operating pressure and outflow ranges before each outflow experiment (section 4).

All transducers are connected to a 21X micrologger[4] (Photo 1B) through an AM416 multiplexer[4] (Photo 1C) with modular-type 4-line telephone cables. Two lines of the transducer are directly connected for excitation through an independent 10 Volts DC source[5] (Photo 1A) while the other two lines are attached to the input (sensor) terminals

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[1] Part #: 0652X03-B01M3. Soil Moisture Equipment Corp. 801 S. Kellogg Ave. Goleta 93117 CA
[2] 136PC15G2. Honeywell Micro switch Sensing and control. 11 West Spring Street Freeport, IL 61032.
[3] 136PC01G2. Honeywell Micro switch Sensing and control. 11 West Spring Street Freeport, IL 61032.
[4] Campbell Scientific, Inc. 815 West 1800 North. Logan, Utah 84321-1784. Phone: 435-753-2342.
[5] Omega Engineering Inc. Stamfort, CT, Power supply. Phone: 203-359-1660.

of the AM416 multiplexer. We use an external excitation source instead of the datalogger, because the AM416 does not have enough channels for both measurement and excitation of 20 transducers (see section 5).

3.3. Top and bottom plates of the Tempe cell

The cover of the Tempe pressure cell is modified to accommodate the vertical-placed tensiometer (Figure 3 and Photo 4). Airtight fitting of the tensiometer in the cover plate is ensured by a compression fitting, with a 1/4" cap and 1/8" NPT pipe thread stem. This type of compression fitting is available in most hardware stores. It needs, however, to be bored out for the tensiometer to fit. The O-ring in the assembly provides a pressure tight seal and yet allows the tensiometer to be adjusted vertically when the cap is not fully tight. Alternatively, we used a Swagelok[1] brand Stainless steel tapered thread male connector (Part#: SS-400-1-2)[1], but it also needs to be bored out for the tensiometer to fit. Instead of an O-ring, nylon front and back ferrules (Part#: NY-403-1 and NY-404-1, respectively)[1] were used to provide a pressure tight seal. The nylon ferrules do not deteriorate like the O-rings, so that they can be used for a longer time. For the top cover of the Tempe cell, a 1/4" Hose I.D. with a 1/8" NPT thread size stem male hose connector (Part#: SS-4-HC-1-2)[1] was used for the pressure inlet port. The bottom cover (Photo 5) of the cell uses a 1/4" Hose I.D. with a 1/8" NPT thread size stem male hose as a drainage port and a 3/16" Hose I.D. with a 1/8" NPT thread size stem male hose connector (Part#: SS-3-HC-1-2)[1] as the air removal port.

After attaching the top cover to the cell using threaded rods, and insertion of the tensiometer, soil samples are re-saturated and flushed by wetting trough the bottom plate. Accurate outflow data requires that the tubing between the Tempe cell and burette is air free. De-aerated 0.01 M $CaCl_2$ solution is used to minimize dispersion of the soil. For undisturbed soil samples, a hole may need to be drilled in the soil sample to allow tensiometer insertion without too much force. However, a tensiometer can usually be easily installed in wet disturbed soils. After saturation, the 3-way valve above the air trap is turned off in the direction of air trap and water in the burette is removed to the 20 ml

[1] Swagelok, Oakland valve and Fitting. 2441 Sprig Court-Unit A, Concord, CA 94520. Phone: 925-676-4100.

level by insertion of a syringe into the burette. After connecting the air pressure hose to the top cover, an initial air pressure is applied. The magnitude depends on the soil's textural characteristics. Pressurized nitrogen gas (N_2) is used instead of air pressure to minimize dissolution of oxygen into the water phase.

3.4. Adaptors for small diameter soil cores in the 2.5-inch Tempe pressure cell

The assembling procedure described in sections 3.1 to 3.3 is exclusively for 3.5-inch O.D. soil cores, that fit the standard 3.5-inch Tempe pressure cell. However, also top and bottom plates for 2.5-inch Tempe pressure cells are available that can accommodate soil cores with outside diameters equal or smaller than 2.5" outside diameter (O.D.). Examples of the soil cores that have been adapted to fit the 2.5" pressure cell are (1) two-inch aluminum rings (0.051 wall thickness), collected with a Giddings hand sampler, (2) two-inch standard well soil cores (preferably larger than 0.064" wall thickness) as extracted by a split spoon core sampler using well drilling equipment, (3) 1.75" O.D. PVC liner of macrocore sampler from a GeoProbe® soil core sampler, and (4) 2" O.D. PVC liner as used in 3.25" Dual Tube (DT) sampler of GeoProbe®. In either case, special adapters and procedures were developed to accommodate the various size core samples. Irrespective of size, 4" tall soil cores are needed, that will be trimmed back to a 3-inch soil core. The following procedure describes the fitting of a 1.75" PVC liner into the 2.5" Tempe pressure cell. Photographs 6 through 11 show the various components described in this procedure.

1. Trim the 4'' PVC liner to a 3.5" length by cutting 0.5" off one end of the soil sample. The abrasive cutoff wheel of the Dremel tool is used to trim through the PVC;
2. Glue wet strength Whatman filter paper at one end of the 2" Aluminum sleeve (Photo 6). This sleeve contains lubricated O-rings at the bottom and top end, and ensures a watertight fit of the soil core in the sleeve. We apply high vacuum grease or white petroleum jelly, for general lubrication purposes;

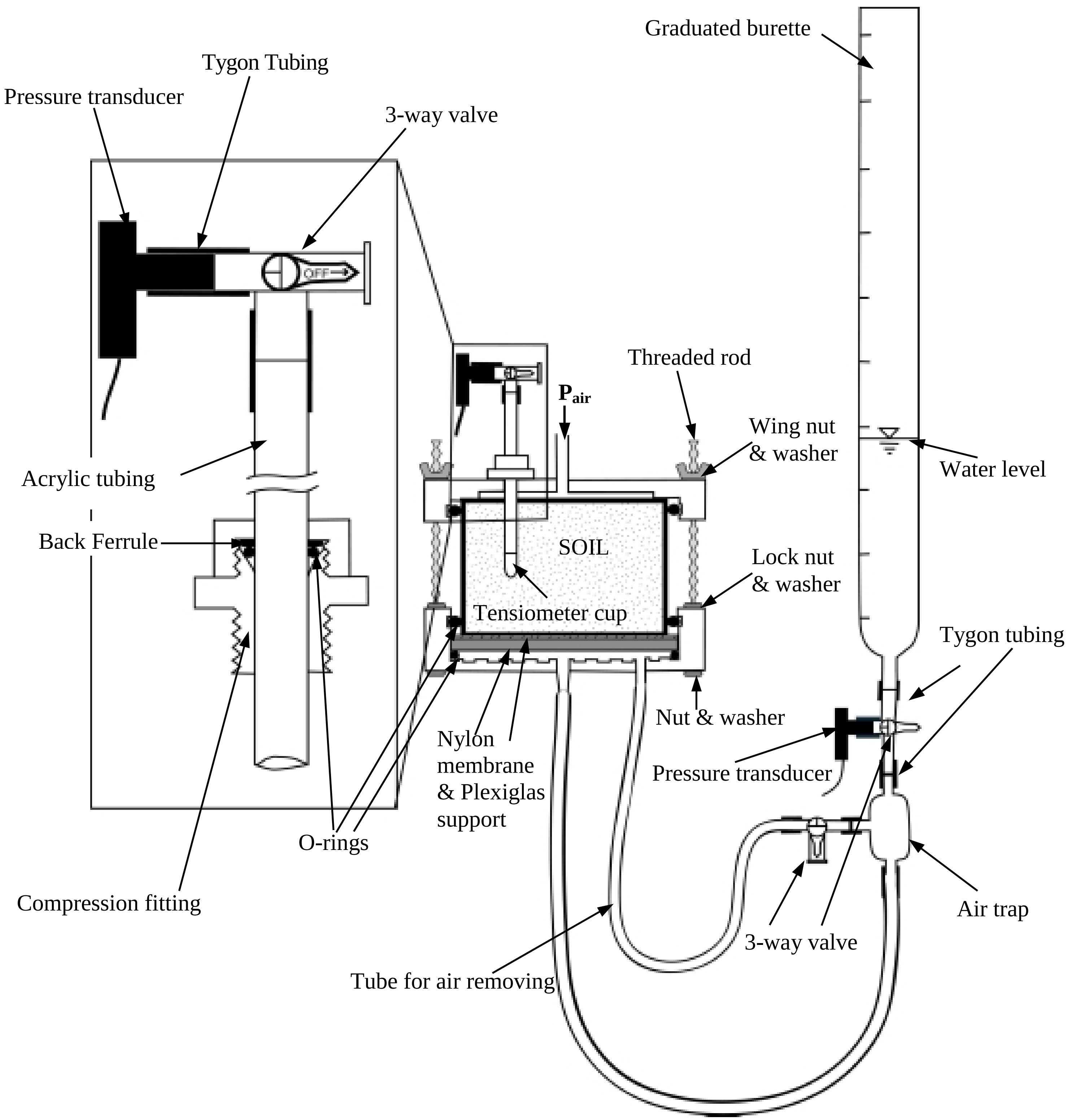


Figure 3. Modified Tempe pressure cell.

3. Push the open end of the sleeve over the trimmed end of the soil sample. To ensure hydraulic contact between the filter paper and the soil, it is recommended to wet the trimmed end of the soil sample first with a water spray. Also, to allow easy assembling, it is suggested to sand the outer edge of the PVC, thereby removing nicks and burrs that may puncture the nylon filter;
4. Turn the PVC-aluminum sleeve assembly around, and trim the other end of the soil sample;
5. Push a 2.5” O.D. Plexiglas (acrylic) (3” long) sleeve (with 2 O-rings) about one inch over the aluminum sleeve, so that the remaining 2.0” of acrylic sleeve can be used as a constant-head device (Photo 7) for the saturated hydraulic conductivity measurement (section 3.1). The soil sample is saturated first (see section 3.1) before the saturated hydraulic conductivity measurement.
6. Immediately transfer the wet soil sample (with the 2 adapters) to the 2.5” Tempe cell. Do this by placing the upright soil sample on a stand, and pushing the prepared bottom plate assembly (see Photo 8, 9, and 10) over the cleaned soil sample. The outside and bottom of the acrylic sleeve must be clean of soil particles, to prevent air leakage and puncturing the nylon membrane during pressurization. Then, turn the whole assembly back to the upright position, so that the wet strength Whatman filter paper is visible on the top of the soil sample;
7. Attach the 2.5” top plate to the pressure cell. Saturate the soil sample making sure that water is flushed out from the top. Then, install the tensiometer, while pushing it through the filter paper (Photo 11). Hereafter, the multi-step outflow procedure is similar as for the 3.5” soil samples (Photo 12).

If instead, the soil samples are 2” in diameter, they can be directly fitted into the 2.5” O.D. acrylic sleeve. For 2.5” O.D. soil cores, it is proposed to use 3.5” O.D. adapter sleeves (0.5” wall thickness) that fit the 3.5” Tempe pressure cell.

3.5. Data collection

The motivation to start the experiment at an initial soil matric potential below saturation was presented by Hopmans et al. (1992), so that the Richards’ equation (Eq.

[1]) assumption of air continuity throughout the sample is valid. They suggested that better results are obtained if the sample is initially unsaturated. Therefore, an initial pneumatic pressure of a range between 20-50 mbar depending on the soil's air entry value, is applied to unsaturate the soil sample.

In this setup, either a one-step or a multi-step experiment can be conducted. Cumulative outflow volume and soil water matric head are measured as a function of time. Water pressure and outflow readings are recorded automatically at desired time intervals. A 5 minutes interval during the experiment is recommended. However, one may choose other pressure steps and time intervals by changing parameters in the datalogger program (See section 5.3).

The soil water matric head in the pressure experiments is computed as the difference between the measured tensiometer pressure and the applied pneumatic pressure (Figure 4b), because tensiometer pressure from the transducers is the sum of pneumatic and matric pressure. A typical tensiometer response during a sequence of the pneumatic pressure steps is depicted in Figure 4a. The numbers near the peaks denote drainage period for this sequence of the applied pressure steps. The water pressure head measured by pressure transducers of the tensiometer is represented by the solid line, which has a range between 0 and the pressure difference between the current and previous increment. The pressure head at the bottom of the porous barrier is plotted by the dashed line and is determined by the water level in the burette (Figure 4a). When a pressure step is applied, the tensiometer responds corresponding with an immediate peak. For the small-applied pressures, the water held in the largest pores drain quickly, which is indicated by the rapid decline of tensiometer response towards hydraulic equilibrium with the water pressure in the burette (Figure 4a). When the response curve reaches a plateau, the water pressure in the tensiometer cup must theoretically be equal to the distance between the water level in the burette and the bottom of the porous barrier. However, for the larger applied pressure increments, tensiometer response is slower and the time required for the hydraulic equilibrium increases due to the decrease in the unsaturated hydraulic conductivity with decreasing water content. Consequently, it takes more time for cumulative outflow and matric pressure curve to approach a plateau value. It is recommended to increase the applied pressure increment if a plateau values has been attained.

In the multi-step experiment, the choice and number of pressure steps will depend on objectives. We have found for many soils, that pressure steps of 60, 80, 120, 200, 300, 400, and 550 cm are adequate. Generally, the pressure can be changed at time intervals of one day. However, in many cases we prefer to wait for near zero drainage rate before increasing the applied pressure, so that soil water retention points can be directly determined from the multi-step outflow data. Since outflow is measured continuously with the transducer of the burette (Figure 3), the cumulative outflow data can be used to determine the timing of a pressure increment (Figure 4c). The water level in the burette does not need to be adjusted to provide a constant pressure below the porous membrane. This is so because the adapted SFOPT program can handle time-dependent lower boundary conditions at the bottom of the membrane.

If the pressures are changed daily, the multi-step outflow experiment generally takes 5-6 days, however, a typical experiment lasts 10-14 days. After the experiment is completed, the soil samples are removed from the pressure cells, weighed, oven dried at 105 ^{o}C for 24 hours, and weighed again to estimate the volumetric water content at the end of the experiment. Sometimes it is preferred to include a retention point at a soil water matric potential, much lower than corresponding with the highest applied pressure. Additional retention points can be collected using the 5-bar pressure plate apparatus (Klute, 1986). The additional value combined with the cumulative outflow volume is subsequently used to calculate saturated and initial soil water content values. In the parameter optimization procedure, the cumulative outflow and corresponding water content values combined are used to compute the temporal changes in soil water content with the corresponding soil water matric head values of the draining soil core.

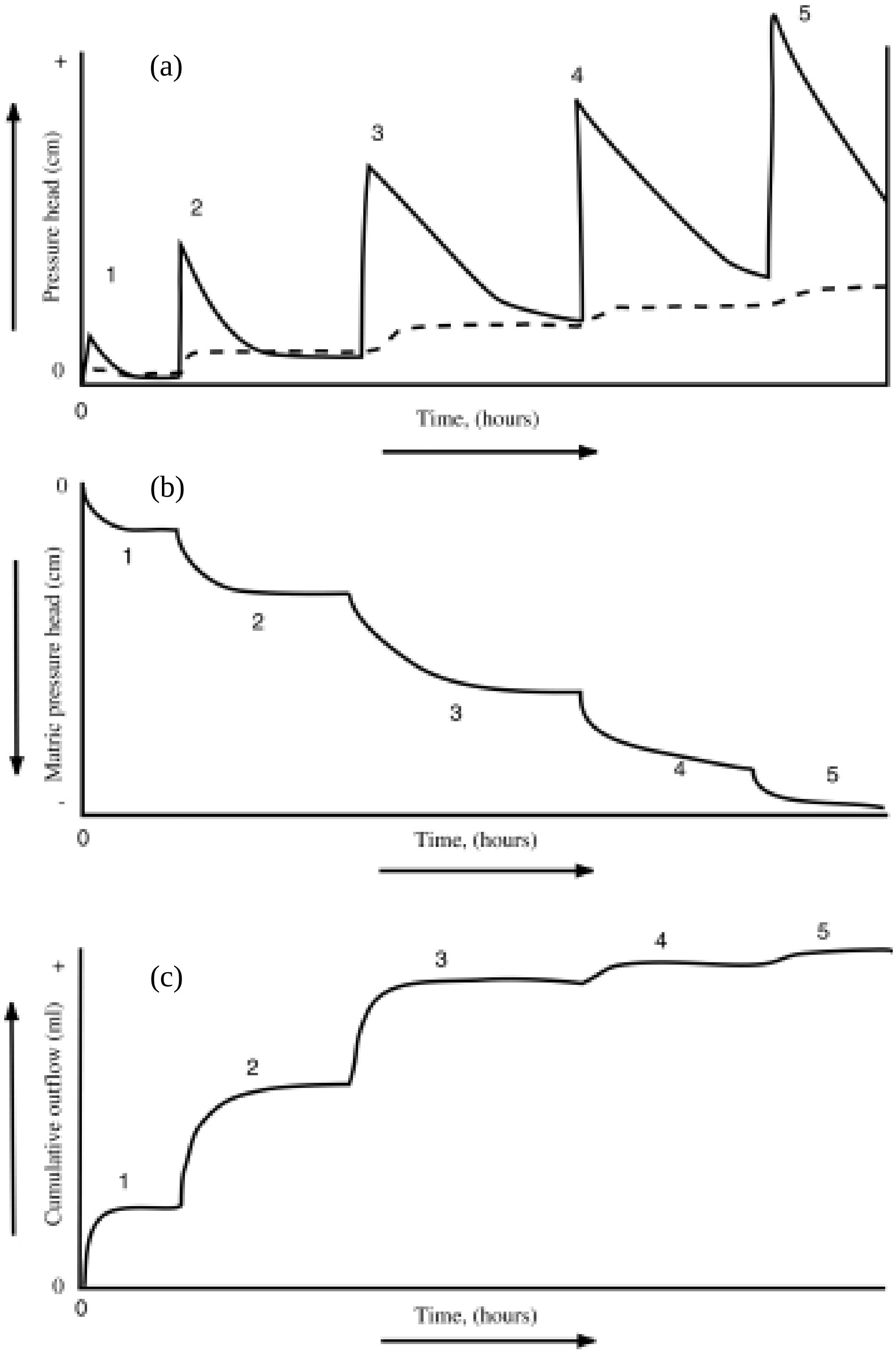


Figure 4. Tensiometer pressure head (solid line) and pressure head at the bottom of the porous barrier (dashed line) (a), matric pressure head (b), and cumulative outflow (c) as a function of time.

3.6. Keeping the experimental records

One must realize that keeping complete experimental records during the different experimental steps (before, during, and after) are vital to the experimental objectives and the later data processing. In this section, some example datasheets are presented to demonstrate the type of records that must be kept throughout the outflow experiments. For the saturated hydraulic conductivity experiment, the datasheet of Figure 5 is suggested. The numbers used in this datasheet is just for illustration purposes only.

Saturated Hydraulic Conductivity of Soils										
Plot	**Depth**	**Sample #**	**Total Time**	**Δt**	**ΔH**	**Q**	**A**	**L**	**K_{sat}**	**K_{sat}**
	cm		HH:MM	min	cm	ml	cm^2	cm	cm / min	cm / h
6-1	25	91	1:27	87.0	8.9	92.0	53.5	6	0.01334	0.800
6-2	50	92	0:55	55.0	9.1	85.5	53.5	6	0.01918	1.151
6-3	25	93	2:04	124.0	9.3	21.0	53.5	6	0.00204	0.123
6-4	50	94	2:03	123.0	9.2	65.0	53.5	6	0.00645	0.387

Figure 5. Datasheet for the saturated hydraulic conductivity experiment.

In Figure 5, ΔH is total hydraulic head difference across the soil sample, *Q* is amount of water collected at the corresponding time interval, Δt, A and L are the cross-sectional area and the length of the soil sample, respectively.

The most involved part of the data recording is the steps of the multi-step outflow experiment. One must record all steps and readings with the date and time during the course of the experiment. Before starting the multi-step outflow experiment, some measurements for the DATAPREP program must be taken from the experimental set up (see section 6.1 and Figure 20) and are recorded, separately. Figure 6 shows a recommended datasheet to use. The numerals with arrows of Figure 6 correspond with the following descriptions:

1. Tempe Cell number of soil sample.

2. Corresponding placed soil sample number.
3. Heading for date & time (military), current applied pressure (mbar), mV (milivolt), and ml (milliliter) readings.
4. Heading for real-time milivolt (mV) readings of tensiometer (T mV) and outflow (*Q* mV) from PC208W[1] program and sight-reading of outflow (*Q* ml) from the burette.

1	Tempe Cell # →		***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***
2	Sample # →		91	92	93	94						
3	Date & Time	mV & ml readings										
	Pressure											
4												
			Initial readings before pressure application									
5	3/11/01	T mV	-0.399	-0.941	-0.381	-0.566						
6	1012 am	Q mV	1.926	1.841	1.793	1.964						
7	0 mbar	Q ml	20	20	20	20						
8			INITIAL AIR PRESSURE 20 mbar on 3/11/01 1020 am									
9	1024 am	T mV	0.078	-0.422	-0.197	-0.081						
10	3/11/01	T mV	-0.569	-1.06	-0.453	-0.818						
	2012 pm	Q mV	2.486	2.431	2.707	2.186						
	20 mbar	Q ml	34	34	38	30						
			NEW AIR PRESSURE 100 mbar on 3/11/01 2025 pm									
	1024 am	T mV	2.380	4.580	4.539	4.290						
10	3/12/01	T mV	-0.102	-0.474	-0.037	-0.187						
	0722 am	Q mV	3.154	3.304	3.854	2.822						
	100 mbar	Q ml	50	55	65.5	47						
			NEW AIR PRESSURE 200 mbar on 3/12/01 0738 am									
	0745 am	T mV	2.380	4.580	4.539	4.290						
	3/13/01	T mV	1.190	-0.130	0.280	2.140						
	2144 pm	Q mV	3.610	3.860	4.460	3.410						
	200 mbar	Q ml	60.5	68.5	80	60.5						
11			***AIR FLUSH*** 200 mbar on 3/13/01 2151 - 2207 pm									
12	2215 pm	Q mV	3.216	3.562	4.320	3.210						
		Q ml	55.5	67.0	77.5	57.5						
	3/14/01	T mV	0.810	-0.280	0.260	1.910						
	0725 am	Q mV	3.510	3.850	4.370	3.360						
	200 mbar	Q ml	58.5	68.0	78.0	59.0						
13			***AIR FLUSH*** 200 mbar on 3/14/01 0731 - 0745 am									
14	0747 am	Q mV	3.230	3.563	4.373	3.285						
		Q ml	56.0	67.0	78.0	58.5						
15			NEW AIR PRESSURE 400 mbar on 3/14/01 0815 am									
	0820 am	T mV	8.56	13.77	14.31	14.99						

Figure 6. Datasheet during the multi-step outflow experiment.

[1] Campbell Scientific, Inc. 815 West 1800 North. Logan, Utah 84321-1784: Phone: 435.753.2342

5. Date of initial readings before the first pressure step is applied.
6. Military time of readings.
7. Current applied pressure.
8. Comment line for information on INITIAL AIR PRESSURE.
9. Time and values of the real-time tensiometer readings after pressure application.
10. Readings and sight-reading of T and *Q* before 100-mbar and 200-mbar NEW AIR PRESSURE applications.
11. Comment line for information on ***AIR FLUSH*** and what pressure is currently being applied.
12. Time of measurements of (*Q* mV) and (*Q* ml) after Air Flushing. It may not necessary to record tensiometer readings since the readings have not changed.
13. Comment line for the second ***AIR FLUSH*** before the 400-mbar NEW AIR PRESSURE increment is applied.
14. Time of measurements of (*Q* mV) and (*Q* ml) after the second Air Flushing and just before the 400-mbar NEW AIR PRESSURE application.
15. Comment line for the information on 400-mbar NEW AIR PRESSURE is applied.

Figure 7 shows an example datasheet that may be used for recording data to calculate the volumetric water content, dry bulk density, and porosity at the end of experiment.

Determination of water content value, dry bulk density, and porosity									
Sample #	Depth	Wet soil + Ring at the last pressure step	Oven Dry Soil + Ring	Ring weight	Ring volume	Water content @ saturation	Water content	Dry bulk density	Porosity
	cm	g	g	g	cm^3	cm^3 / cm^3	cm^3 / cm^3	g / cm^3	cm^3 / cm^3

Figure 7. Datasheet for the parameters obtained at the end of the experiment.

3.7. Air flushing

When a nylon membrane is used as porous barrier, air accumulation may occur during the high pressure steps of the experiment, due to air diffusion through the thin membrane. Two ports at the bottom of the cell and the air trap permit flushing of trapped air under the nylon membrane. For air flushing, the Luerlok type 60 cc Syringe[1] is connected to the 3-way valve closing the connection to the air trap (Component F of Photo 1). The plunger of the syringe is pulled back slowly for extracting accumulated air under the bottom of the membrane. This procedure has to be done slowly to prevent additional suction to the soil sample. By changing the valve opening direction, the extracted air is pushed back slowly into the air trap. Air escapes from the air trap through the burette, lowering the water level in the burette to the level now indicating the true drainage volume. This “Air Flushing” procedure is repeated several times during the experiment, whenever air accumulates. Air flushing times must be recorded since air accumulation gives erroneous outflow readings and must be corrected between air flushings. For that purpose, a software program DATAPREP, written in free format FORTRAN language, is used to correct the outflow data, and to transform the experimental data of tensiometer and outflow transducer readings (mV) to units of pressure (cm water). Since the number of data pairs collected by the datalogger is large, the DATAPREP program also helps to select a user-specified number (approximately between 250-500) of data pairs (tensiometer and outflow readings), and prepares the input data file for the SFOPT optimization program. Details of this program and data processing procedure are given in section 6.

3.8. Some experimental problems and remarks

Major problems that may be encountered during the outflow experiment are:

1. Poor contact between the soil sample and porous plate or nylon membrane. When the contact between the porous material and soil is poor, cumulative volume outflow can be very small. Cumulative volume outflow values for fine textured

[1] Becton Dickinson & Co. Franklin Lakes, NJ 07417-1884

soils are usually small as well. Optimized hydraulic functions are generally questionable in that case.

2. A cracked ceramic plate or perforated nylon membrane. It is possible to crack the ceramic plate if the Tempe cell pressure lid is screwed on too tight. Moreover, the edge of the brass ring touching the nylon membrane must be soil particle free, to prevent perforation of the nylon membrane. Damage of the porous membrane causes the presence of air bubbles in the burette.
3. Soil particles between the sample cylinder and the O-ring of the pressure cell will cause air leakage during the experiment. Applying soapy water on the O-ring after assembling the pressure cell provides a good leakage test. It is recommended that this is done at the beginning of each pressure increment.
4. Do not increase the pressure step immediately after air flushing. It is important to wait at least 30 minutes after air flushing, so that pressure transducers (tensiometer and outflow) can stabilize.

4. PRESSURE TRANSDUCER CALIBRATION

Pressure transducers for the multi-step outflow experiment must have a high output to input voltage ratio, low noise, and a stable calibration. There are several transducers avaliable that fulfill these requirements, though they may not be specifically applied to soil research (Eching and Hopmans, 1993b). Here, we provide an example of how to calibrate differential pressure transducers for the tensiometer and outflow, with one side of the pressure sensitive membrane open to the atmosphere.

An experimental set up for simultaneous checking and calibrating the slope of both tensiometer and outflow transducers are shown in Figure 8a and b, respectively. Each tensiometer is filled with $CaCl_2$ solution, and is submerged in solution to prevent the tensiometer from draining. Initially, the 3-way valve is turned off in the direction of the tensiometer cup so that the transducer is open to the atmosphere (Figure 8a). A piece of tygon tubing connects to the open end of the valve and the pressure source (N_2 gas). The 3-way valve of the transducer below the graduated burette is closed towards the glass air trap (Figure 3 and Figure 8b), while the burette is filled with the same solution to the 100 ml level. All transducers are connected to the datalogger and the external power source[1] of 10 V. Transducers are automatically scanned at 20-seconds intervals and the one-minute average readings with the Julian date and military time is stored. A 10-minute data collection is adequate for each calibration step. Typical applied pressures are 20, 40, 80, 160, 320, and 540 mbar whereas burette levels of 100, 90, 80, 60 40, and 20 ml provide an appropriate range of water pressures. When the new pressure is applied to the tensiometer transducers, the burette levels are lowered to the next level.

Calibration parameters are obtained using linear regression analysis to the transducer's readings (mV) and corresponding applied pressure and outflow values. Results have shown that the slope of the curves is generally stable and do not change much with the time. However the interception may change considerably between experiments (Figure 9). Therefore, only the slope is used as an input parameter for the DATAPREP program. Using this known slope value, DATAPREP finds the intercept

[1] Omega Engineering Inc. Stamfort, CT, Power supply. Phone: 203-359-1660.

from subsequent experimental data measured at the beginning of the multi-step experiment, assuming that hydraulic equilibrium is attained quickly.

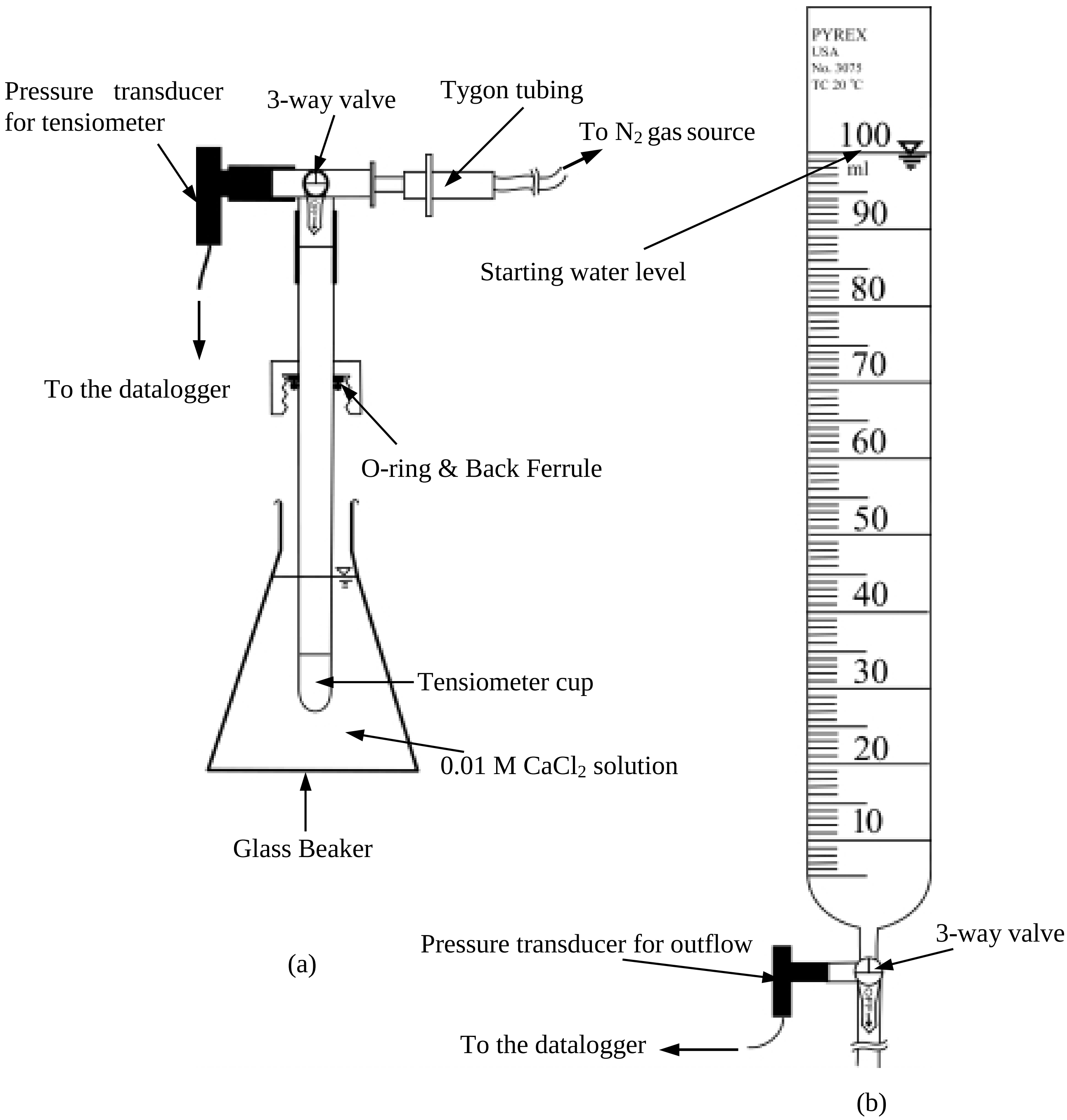


Figure 8. Experimental set up for calibration (slope) of the tensiometer (a) and outflow transducers (b).

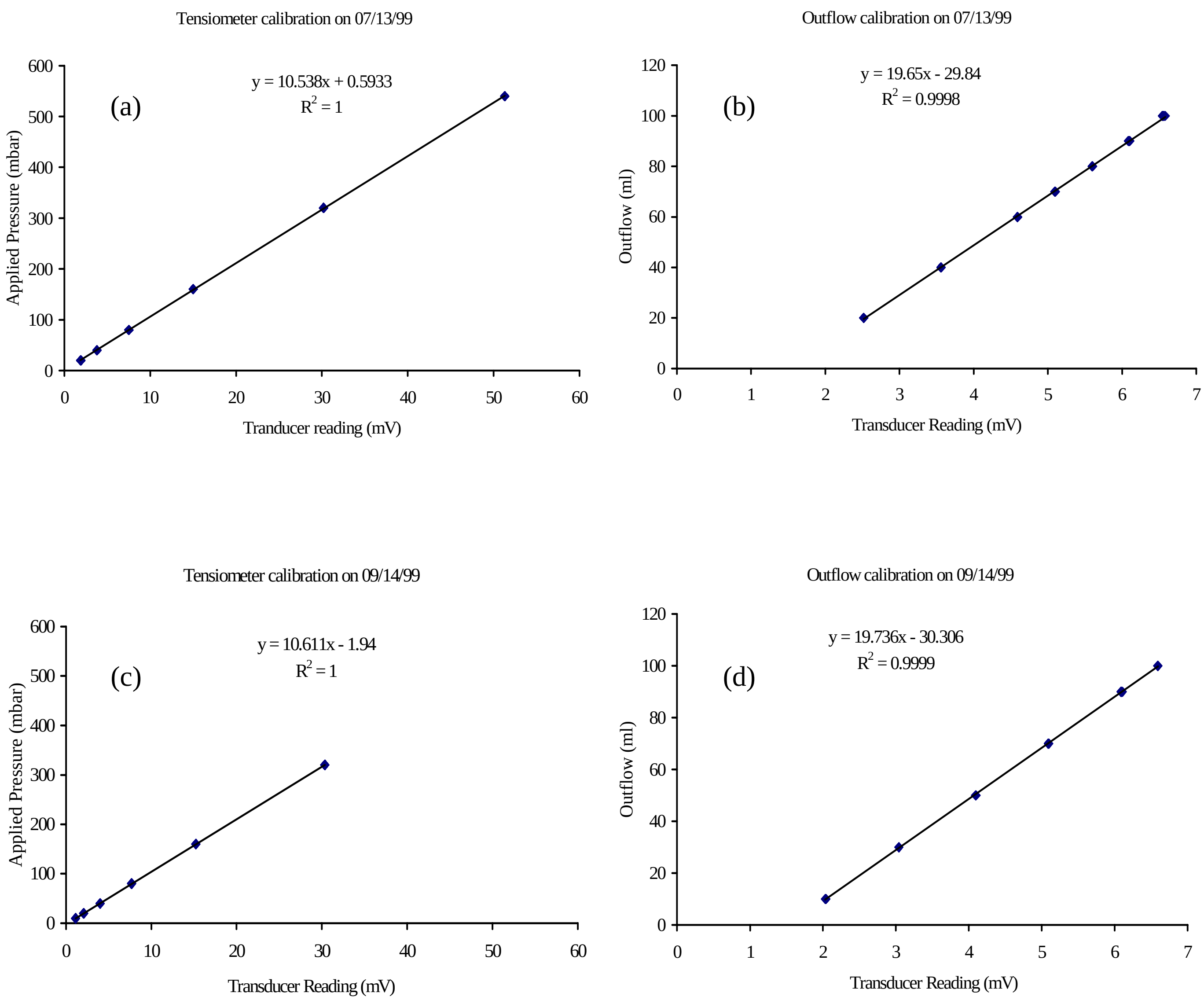


Figure 9. Calibration of the tensiometer (a, c) and outflow (b, d) pressure transducers at two dates

5. MULTIPLEXING

5.1. Multiple sensor set up

Figure 10 shows a schematic of equipment used for matric head and outflow measurements for a set of 10 pressure cells through an AM416 multiplexer (Component C of Photo 1). The AM416 Multiplexer allows connection of a larger number of pressure transducers than there are 21X datalogger input channels. No multiplexer would be needed, if only 8 pressure transducers were used. AM416 is an acronym for **A**(nalog) **M**(ultiplexer) **4**(lines x) **16**(sets) meaning that a maximum of 16 differential full bridge transducers (consist of 4 pins) can be scanned (Campbell Scientific, 1996a). Without using an external power source, each of the common line ports (COM1 and COM2) of the AM416 can serve 8 channels. Each channel consists of 4 terminals (2 for excitation and 2 for data input). Thus, up to 16 transducers can be connected if the multiplexer is connected to and powered by the datalogger (12 VDC). For our experimental set up, however, the multiplexer and external power supply (10 VDC) are needed to connect 20 transducers (Component E of Photo 1) for monitoring 10 Tempe cells (Photo 12). A stable power (voltage) supply, such as a DC converter with voltage stabilizer is essential to reduce the transducer noise. For each pressure transducer, pin #1 and 3 (yellow and red wires) are connected to the external power supply (Component A of Photo 1) using black terminal strips in the multiplexer box (see Photo 1). The other pair (pin #2 and 4; green and black wires) are connected to the measurement (Input) terminal strips (H and L) of the channels of the multiplexer. With this configuration, in principle, up to 32 transducers can be connected and measured simultaneously with excitation voltage supplied by the external power source.

To collect data from the 20 transducers, the multiplexer must be connected to the 21X datalogger. For this purpose, two input channels 1 and 2 (with H and L terminals on the top strips) of the 21X datalogger (Component B of Photo 1) is connected to the common lines COM1 and COM2 of the AM416. Channel #1 (H and L terminals) of the datalogger is connected to the multiplexer's common line 1 (COM H1, COM L1), while channel #2 (H and L terminals) is connected to the common line 2 (COM H2, COM L2).

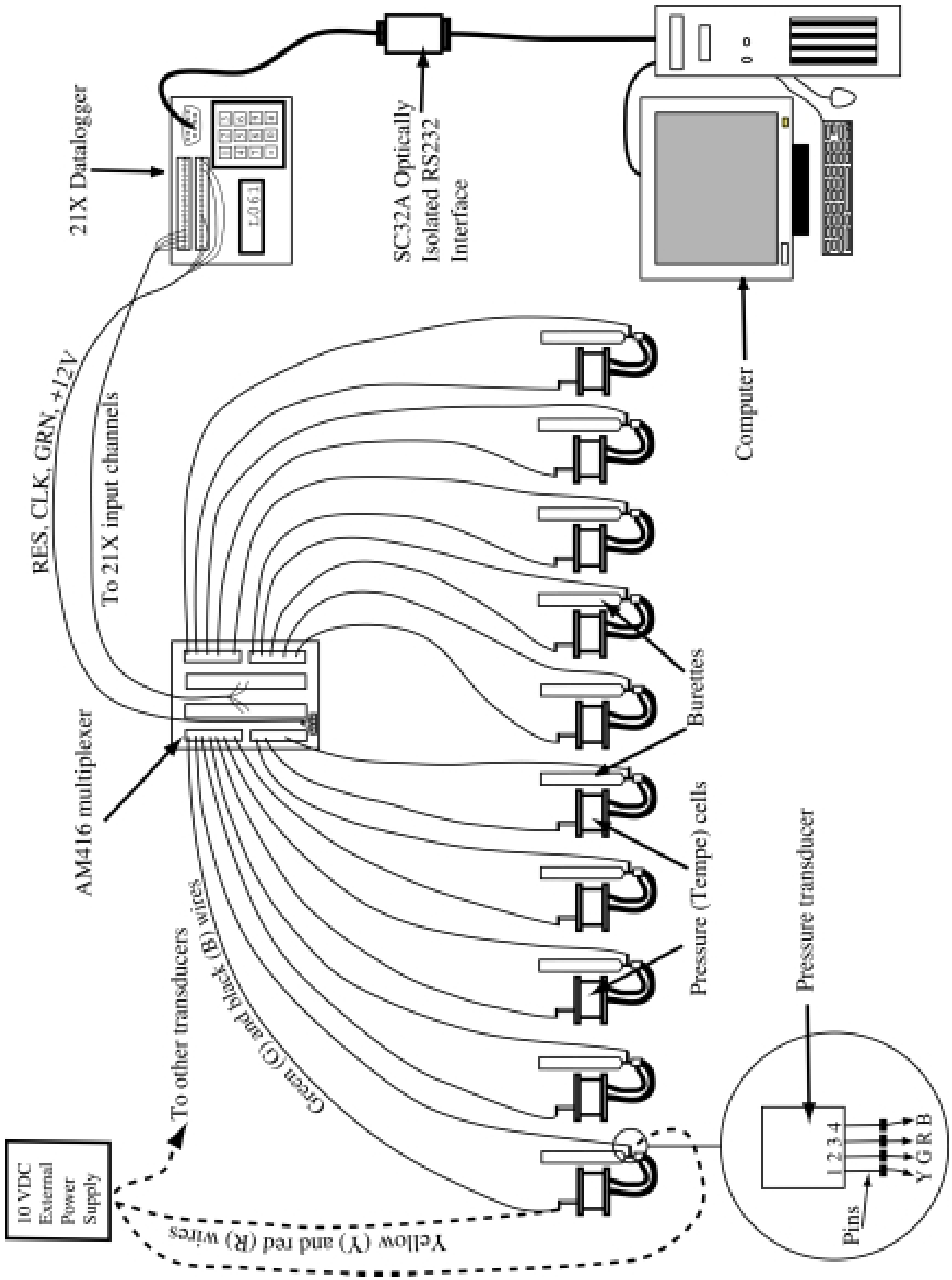


Figure 10. Schematic view of the pressure transducer multiplexing.

The AM416's RESET (RES), CLOCK (CLK), GROUND (GND) and +12V terminals are connected to the 21X's CONTROL1, EXCITATION1, GROUND, and +12V (on the bottom strip of the datalogger), respectively. These terminals are used for control and excitation of the AM416.

5.2. PC208W datalogger support software

The 21X datalogger is, in turn, connected to a computer via the SC32A[1] optically isolated RS232 interface (Figure 10). The PC208W datalogger support software is used to establish a communication link between the datalogger and computer and facilitates programming, communication, and reliable data exchange between computer and 21X[1] (Campbell Scientific, Inc. 1998). The PC208W program can handle more than one datalogger simultaneously, however the number depends on the available serial ports of the computer. The following outlines the steps for establishing communication between datalogger and PC:

1. Start PC208W program on the desktop. A toolbar with eight buttons is opened (Figure 11).

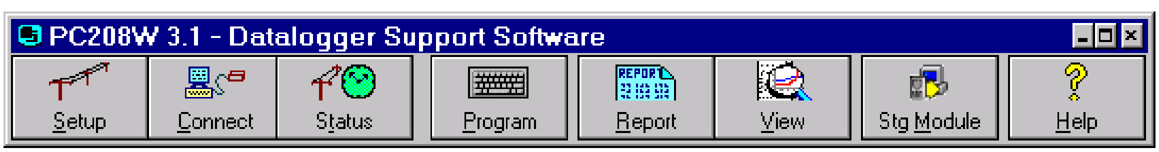


Figure 11. PC208W toolbar.

The buttons on the toolbar are:

Setup: Configure the devices for hardware, data collection, and collection schedules.

Connect: Go on-line with the datalogger to set the clock, send programs, collect data, view and graph measurements

Status: Check the communication and data collection status of all devices you work with, and trigger manual data collection.

Program: Create and edit datalogger programs with EDLOG.

[1] Campbell Scientific, Inc. 815 West 1800 North. Logan, Utah 84321-1784: Phone: 435.753.2342

Report: Process the data files and creates reports using SPLIT.

View: View any file in either ASCII or Hex (useful for checking data files).

Stg Module: Retrieve files from Storage modules.

Help: Enter the PC208W help system.

2. Click on **Setup** button. A setup connections window will be opened with default COM1 port in the **Device Map** column (Figure 12).

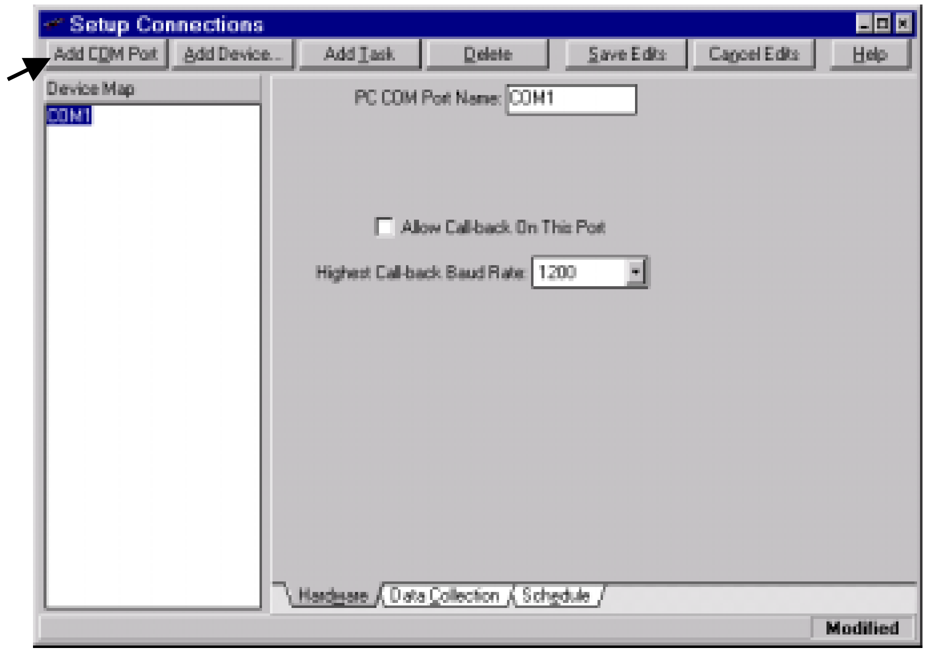
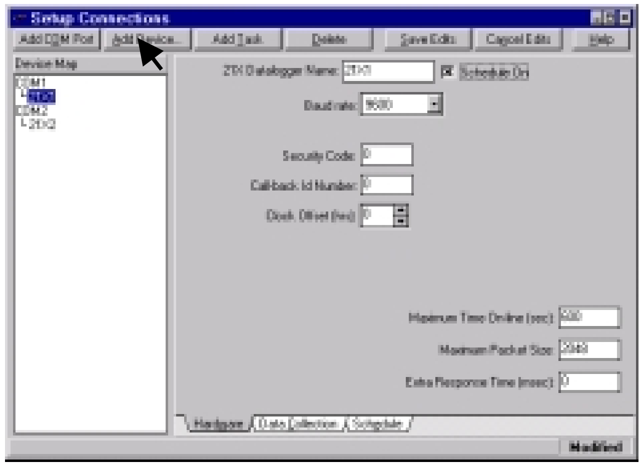


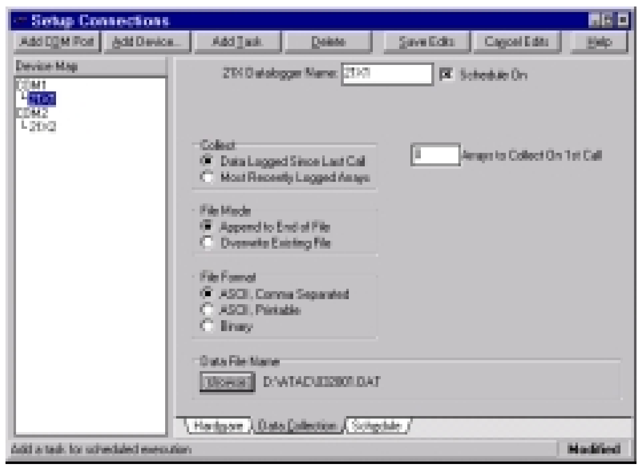
Figure 12. Setup connection window.

Since our computer has 2 serial ports, another COM port can be added by clicking **Add COM Port** button. After adding the second COM port (COM2), click **Add Device** button to connect 21X datalogger with corresponding COM ports (Figure 13a).

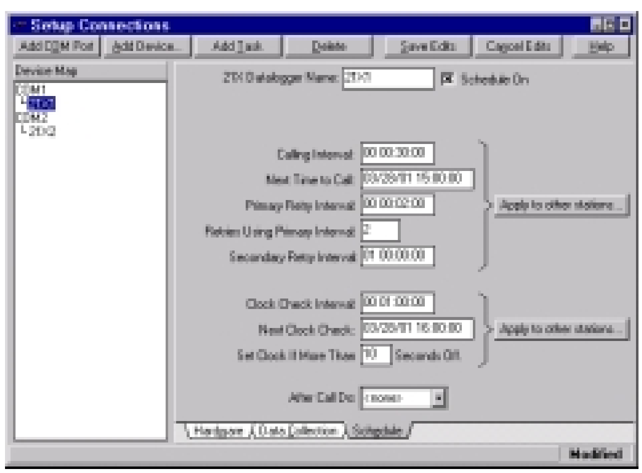
3. Highlight by clicking on device name in the **Device Map** column in Figure 13a and assign required parameters. Each device has its own **Hardware**, **Data Collection**, and **Schedule** tab. Using the **Hardware** tab, The PC208W inserts default values for most



(a)



(b)

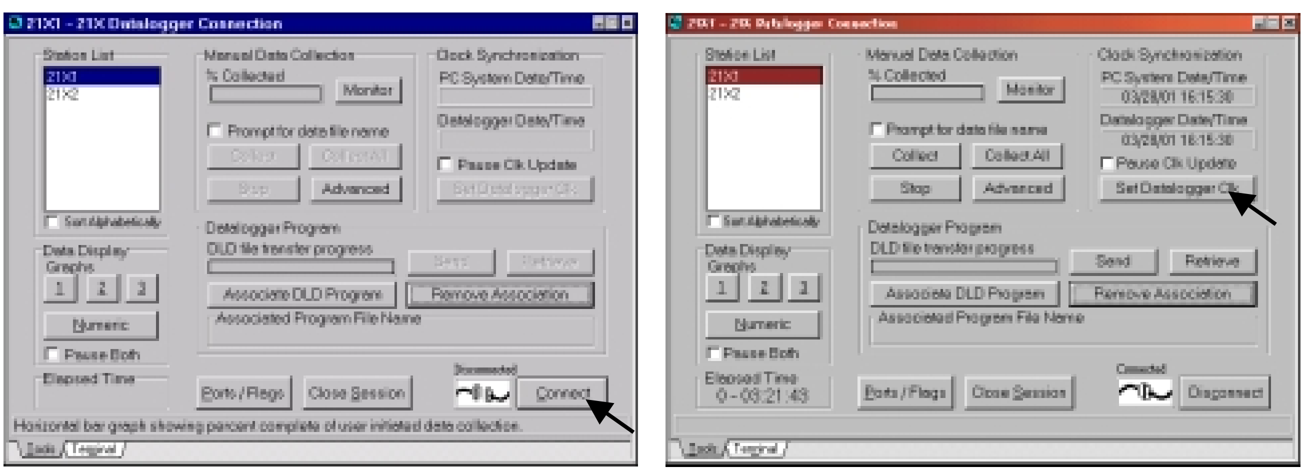


(c)

Figure 13. Setup window with the connected dataloggers: (a) **Hardware** tab, (b) **Data Collection** tab, (c) **Schedule** tab.

parameters of the 21X. Checking the "Schedule On" box enables automatic data collection from the datalogger storage to the computer's specified directory (Figure 13a). Using the **Data Collection** tab, data manipulation is set up. While a filename for the data file is suggested, the user also can specify the data file name and its directory to collect measured data from the datalogger (Figure 13b). If one selects automatic data collection, data collection and retry information must be specified on the **Schedule** tab (Figure 13c). Moreover, the 'Calling interval" for data collection and the datalogger clock synchronization based on PC time must be entered.

4. Click on **Save Edits** button.
5. Turn on the power of the datalogger 21X1 and wait until 11:111111 is displayed on the LCD panel of the datalogger. This indicates that the memory check was passed. When 0's appear instead, the memory check failed and indicates bad memory.
6. Click on **Connect** button of the PC208W toolbar. **Connect** button brings up a window, which gives you real time access to any of the datalogger in your **Device Map**. Here, one can transfer programs to a datalogger, set the datalogger clock, collect data from the datalogger, and display or graph datalogger measurements. Only one datalogger is connected at any given time. If one wants to connect another datalogger in the **Station List** box, the desired datalogger must be highlighted by clicking on it.
7. Click on **Connect** button of the Connection window (Figure 14a). Wait until connection is established and then press **Set Datalogger Clk** button (Figure 14b).



(a) (b)

Figure 14. Connection window: (a) before connection, (b) after connection.

8. Click on the **Program** button on the toolbar (Figure 11). This invokes the program EDLOG, which is a tool for creating, editing, and documenting programs for dataloggers (section 5.3). After creating the program (Figure 15), EDLOG compiles and save the datalogger program in a specified directory. When an EDLOG program is saved, EDLOG automatically adds a .CSI extension to the program name. An existing program with .CSI extension can also be loaded for editing. Moreover, whenever an EDLOG program is compiled a file with .DLD extension is created for sending to the datalogger. Close the EDLOG program.

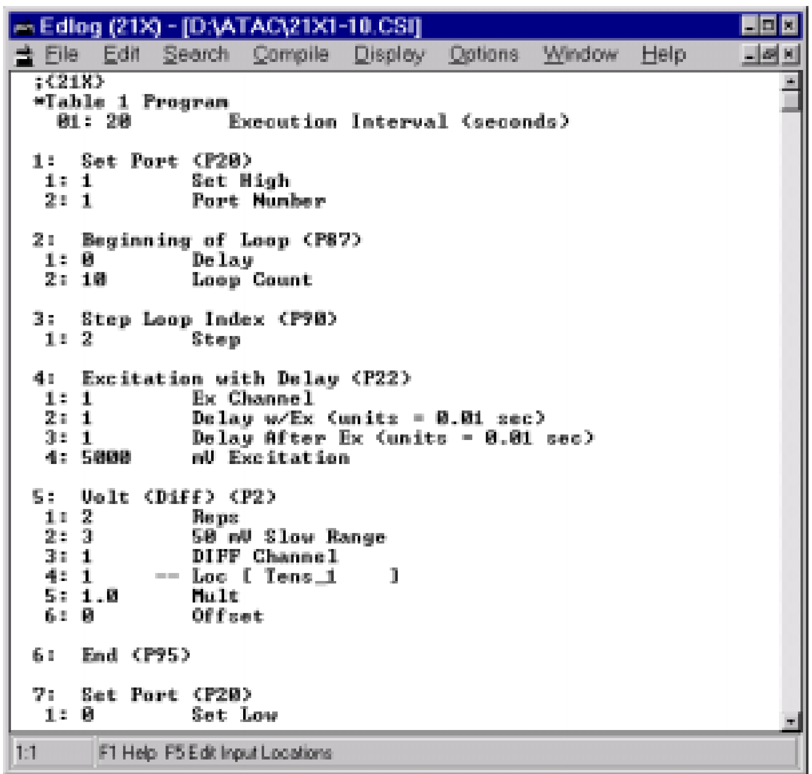
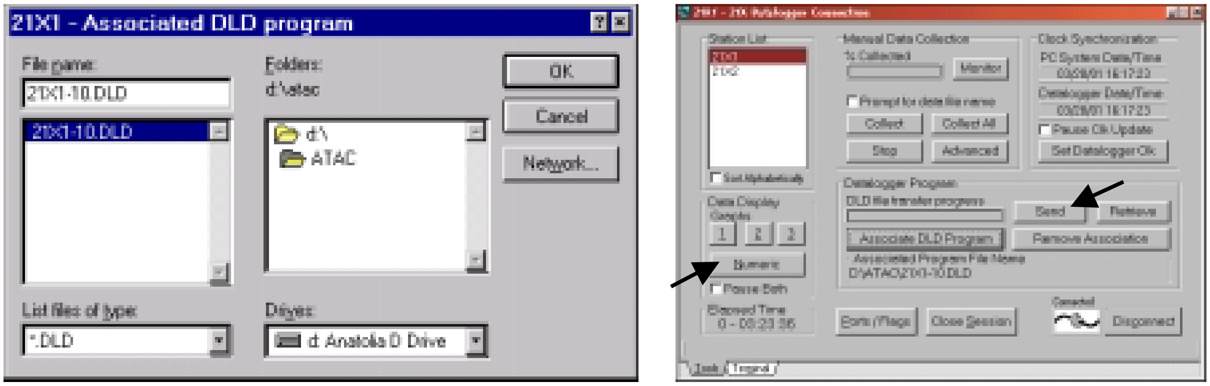


Figure 15. Edlog program window.

9. Go back to the Connection window (Figure 14b) and click on **Associate DLD Program** button. Open the directory, where the datalogger program was saved (Figure 16a). Find the corresponding DLD-file that you wish to send to the datalogger. Click OK, and the Associated Program File Name appears on the connection window (Figure 16b). The program is now ready to send to the datalogger.

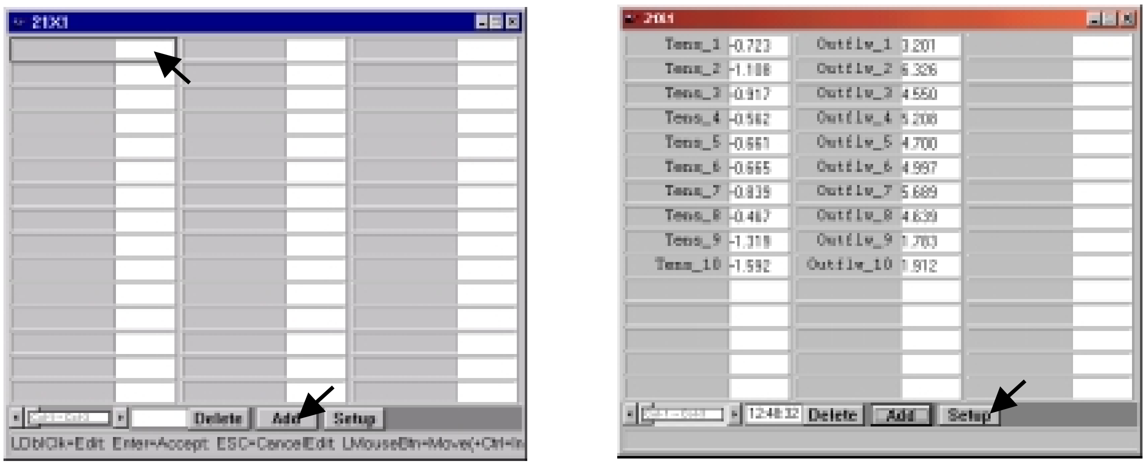


(a) (b)

Figure 16. Association of datalogger program: (a) Program directory, (b) after association of DLD file.

10. Click on **Send** button (Figure 16b) and wait to hear a sequence of sounds from the multiplexer. It is extremely important to remember that, when you send a DLD program to the datalogger, all existing data are deleted from the storage memory of the datalogger.
11. Click on **Numeric** button (Figure 16b) to visualize real-time transducer measurements. First select a cell (Figure 17a) and click on the **Add** button. This will open a window, which shows all transducers. Highlight the tensiometer transducers you wish to be monitored. Click on **Paste** button. Do the same thing for the outflow transducers (Figure 17b). The real-time measurements will appear and refresh when new data are collected (see **Setup** button).
12. Go back to PC208W toolbar and press **Status** button. This button displays information for all the dataloggers on the **Device Map**. One can check the status of data collection, including scheduled calls, errors, retries, and how much new data were collected (Figure 18).

In our laboratory, the outlined procedure has already been conducted. If the user wants to run a new experiment, all steps except #2 and 8 must be followed. Note that if the "Schedule on" option is selected from the Hardware tab, the computer and PC208W program must be run continuously after the proper parameters have been entered. All other program windows can be closed.



(a) (b)

Figure 17. Numeric window for real-time data monitoring: (a) before adding transducers, (b) after adding transducers.

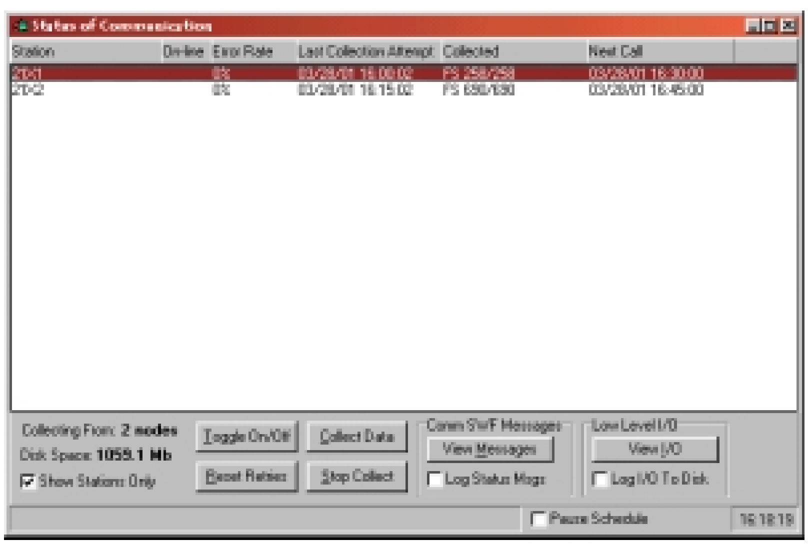


Figure 18. Status window.

5.3. Datalogger program for transducer multiplexing

The example datalogger program, which can be used with a multiplexer and 21X datalogger to measure output voltages from 20 transducers simultaneously, is provided below. Only one program line must be changed, when a different number of transducers are used. The loop count under program command P87 must be equal to half of the number of the transducers. Editing of this program allows changing the sequence and frequency of measurements. For more information, the user is referred to the program language section of the 21X datalogger and the PC208W manuals (Campbell Scientific, Inc., 1996b, 1998). The automatic collection into an indexed array (parameter 4 of the program command P2 and parameter 2 of program command P71) is discussed in the AM416 multiplexer manual (Campbell Scientific, Inc., 1996a).

```
;{21X}
*Table 1 Program
  01: 20   Execution Interval (seconds)

1:  Set Port (P20)
 1: 1        Set High
 2: 1        Port Number

2:  Beginning of Loop (P87)
 1: 0        Delay
 2: 10       Loop Count

3:  Step Loop Index (P90)
 1: 2        Step

4:  Excitation with Delay (P22)
 1: 1        Ex Channel
 2: 1        Delay w/Ex (units = 0.01 sec)
 3: 1        Delay After Ex (units = 0.01 sec)
 4: 5000     mV Excitation

5:  Volt (Diff) (P2)
 1: 2        Reps
 2: 3        50 mV Slow Range
 3: 1        DIFF Channel
 4: 1     -- Loc [ Tens_1    ]
 5: 1.0      Mult
 6: 0        Offset

6:  End (P95)
```

```
7:  Set Port (P20)
 1: 0        Set Low
 2: 1        Port Number

8:  If Flag/Port (P91)
 1: 21       Do if Flag 1 is Low
 2: 30       Then Do

9:  If time is (P92)
 1: 0        Minutes into a
 2: 5        Minute Interval
 3: 10       Set Output Flag High

10:  Resolution (P78)
 1: 1        High Resolution

11:  Real Time (P77)
 1: 110      Day,Hour/Minute (midnight = 0000)

12:  Average (P71)
 1: 20       Reps
 2: 1        Loc [ Tens_1    ]

13:  Else (P94)

14:  If time is (P92)
 1: 0        Minutes into a
 2: 5        Minute Interval
 3: 10       Set Output Flag High

15:  Resolution (P78)
 1: 1        High Resolution

16:  Real Time (P77)
 1: 110      Day,Hour/Minute (midnight = 0000)

17:  Average (P71)
 1: 20       Reps
 2: 1     -- Loc [ Tens_1    ]

18:  End (P95)

*Table 2 Program
  01: 0.0000    Execution Interval (seconds)

*Table 3 Subroutines

End Program
```

6. DATA FILE PREPARATION PROGRAM (DATAPREP)

6.1. Description and requirements of DATAPREP

The program DATAPREP (Appendix B) transforms the multi-step outflow experimental data, which are collected by the datalogger, to a new file (filename is FINPU), which is used as an input file for SFOPT. To create FINPU with DATAPREP, the data preprocessing procedure of Figure 19 must be followed. One must follow the required data cleaning and preparation procedures outlined in sections 6.2 and 6.3 for creating the input data file, FNAME. Note that FNAME and FINPU are the character variables for the experimental and input file names, respectively of the DATAPREP program code (line 37 and 39 in Appendix B)

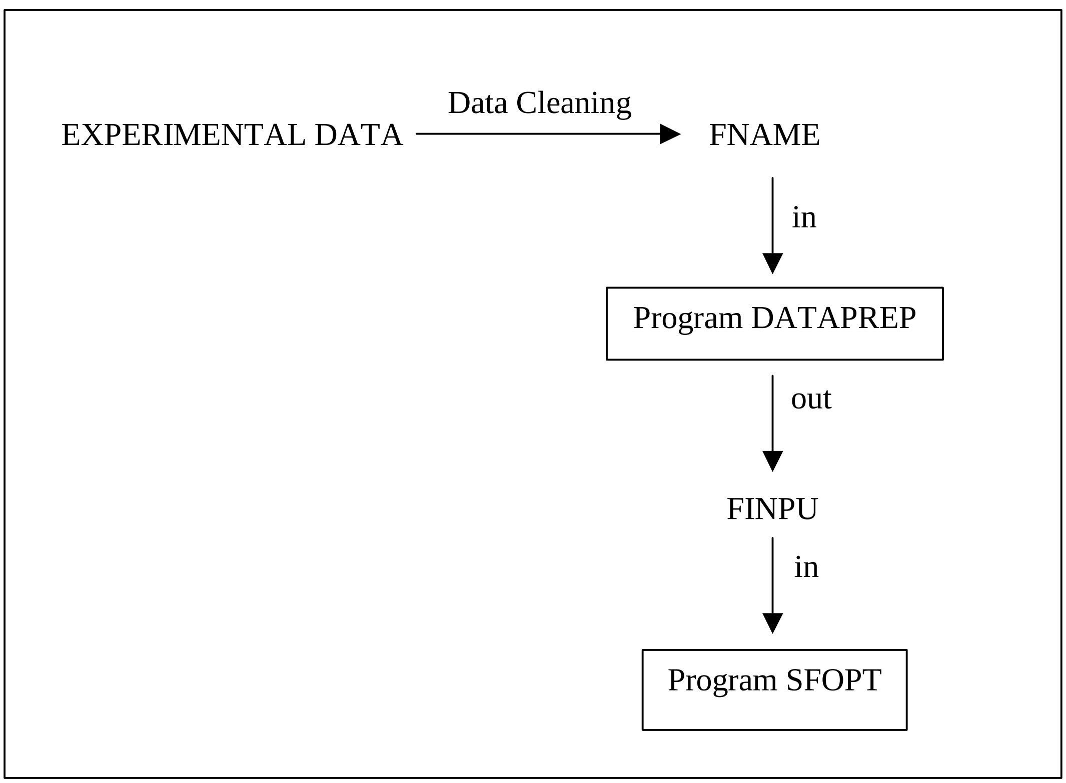


Figure 19. Schematic diagram of data processing procedure.

The program DATAPREP requires measured values for sample height (**samhe**), sample diameter (**samdi**), sample volume (**samvo**), thickness of porous membrane (**porhe**), distance between center of the porous cup and bottom of the porous membrane (**tenhe**), burette reading at the beginning of the experiment after soil sample saturation (**watvo**), water height in burette from bottom of porous membrane at the beginning of the experiment after soil saturation (**wathe**), and change of water height in burette per ml of outflow volume (**whinc** = 0.181 cm/ml) (Figure 20). In addition, although DATAPREP does provide default values, the user must specify the total number of nodes (nnsf), the number of nodes in the soil sample (lnnsf), and the saturated conductivity of the porous membrane (cpltsf) used in SFOPT (see description of input file in 7.4). If the porous membrane has negligible thickness, as is the case for a porous nylon membrane, values for nnsf and lnnsf are identical and cpltsf can be set to a default value of 999. The variable definitions for the required input file for the DATAPREP program are presented in Table 2.

To ensure adequate number of data for the whole experiment, the maximum time interval between data pairs is set to 2 hours. After providing the DATAPREP program with the approximate number of data pairs (ntob) required for FINPU, the allowable change in capillary pressure and outflow volume between data pairs is computed from the difference between the maximum and minimum measured values during the outflow experiment. Unreasonable fluctuations of the measurements are removed using a computational filter, thereby providing a smooth set of data values. Outliers are treated in two ways. First, if the data value is lower than the n subsequent values for h (h denotes matric potential, $h < 0$), or higher than the n subsequent values of Q ($Q > 0$, where Q denotes cumulative drainage volume), the specific data value pair (h and Q) is removed from the data set. The current default value for n is set to 5, but this value may need to be changed depending on the number of erroneous data values. Second, if the particular data value is larger, within a specified tolerance, than the previous value for h (< 0) or smaller than the previous Q-value (> 0), this specific data pair (Q and h) is eliminated as well. Default values for these differences are 1 cm for h and 0.1 ml for Q. Also, these criteria can be changed depending on the magnitude of the measurement error. At the end of each run, DATAPREP automatically displays a graphical representation (Figure 23) on the computer screen, showing a comparison of the original and transformed cumulative

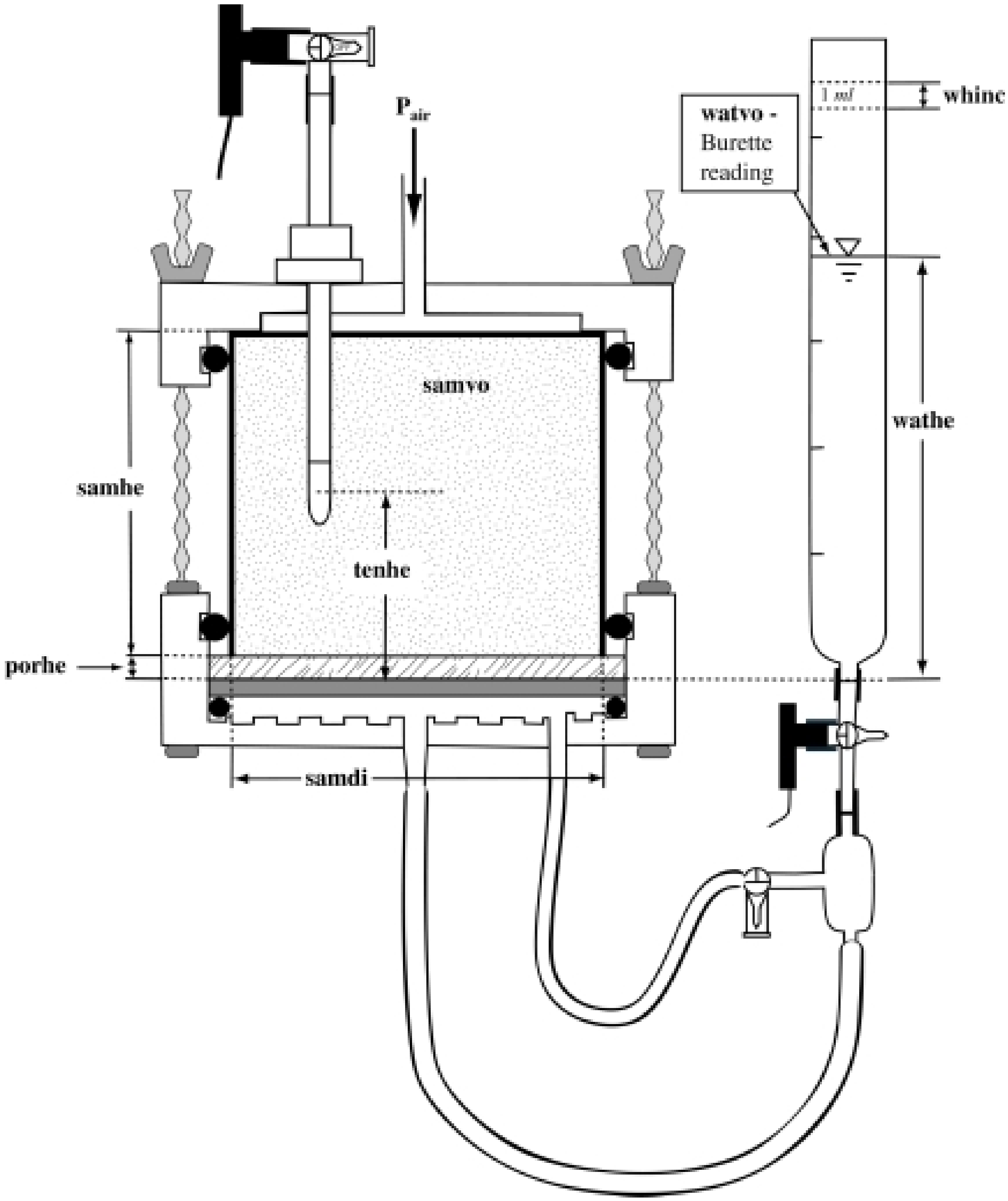


Figure 20. Schematic view of the experimental set up.

Table 2. Description of variables for input file 'FNAME' of the DATAPREP.

Line	Variable	Description
1	XSS	Saturated water content
2	APINI	Initial air pressure at hydraulic equilibrium in mbar (ZX (cm) in SFOPT)
3	QOINI	Burette reading at initial equilibrium (time = 0, ml)
4	QOEND	Burette reading at end of outflow experiment (ml)
5	A(1)	Slope of pressure transducer of tensiometer (mbar/mV)
6	A(2)	Slope of pressure transducer of burette (ml/mV)
7	NCHANGE	Number of air pressure step (AIRP in SFOPT)
8	For I=1,.., AIRP	
	CDATE(I)	Day of change of air pressure (Julian date)
	CTIME(I)	Time of change of air pressure (hhmm)
	P(I)	New air pressure (mbar)
12(if AIRP=4)	NFLUSH	Number of air flushings + 1
13-24(if NFLUSH=12)		For I=1, ….,NFLUSH
	FDATE(I)	Day of air flushing (Julian date, I=1 corresponds with date when air accumulation started)
	FTIME(I)	Time of air flushing (hhmm, I=1 corresponds with time when air accumulation started)
25-END	DATE(I)	Day of measurement (julian date, I=1 corresponds with data at hydraulic equilibrium at t=0, and is used for calibration of pressure transducers)
	TIME(I)	time of measurement (hhmm, I=1 corresponds with data at hydraulic equilibrium at t=0, and is used for calibration of pressure transducers)
	HO(I)	pressure transducer output signal (mV) for tensiometer
	QO(I)	pressure transducer output signal (mV) for burette

outflow and soil water matric head as a function of time. The graphic also lists the difference in observed (water level in burette) and measured (pressure transducer) total outflow volume. At run time the user will be prompted to specify a file name for a file that will contain this data for graphing in a spreadsheet or other graphing program.

The user should review the description of variables in Section 7.4 to assure the correct values of input parameters for SFOPT. Additionally, it may be necessary to change assumed default values in the program DATAPREP and its input file FNAME.

6.2. Cleaning the raw experimental data

In this section the procedure for cleaning the raw experimental data collected by the data logger via the pressure transducers and for the preparation of the input data file for DATAPREP will be explained in detail. The cleanup is required because (1) the collected data is in output signal (mV) format and must be transformed to the desired units of matric head (cm water) and outflow (mL), (2) the outflow data must be corrected due to possible air accumulation, (3) there are occasional anomalous readings due to transducer malfunctions, and (4) some extra data, which do not represent the experiment, may be collected prior to and after the experiment. The DATAPREP program also selects a specified number of data pairs for use in the inverse modeling. It is necessary to reduce the data to a smaller number of pairs because the collected data may be far too exhaustive. Each of these items will be addressed in the example problem presented in Section 6.3.1. Occasionally, data can be lost or can be erroneous due to: 1) transducer malfunction (including membrane perforation), 2) tensiometer failure (including cracks and poor hydraulic contact), 3) data download failure from datalogger to computer, 4) computer hard drive failure, and/or 5) power outage lasting longer than the storage capacity of the datalogger. The procedure for dealing with these problems in presented in Section 6.5.

For any period during which air accumulates, the program assumes that air accumulation occurs uniformly. Therefore, it is necessary to define the air accumulation duration or period (step 10 in the following section) in FNAME. The term "air accumulation period" refers to the period during which air accumulates. The term "flushing event" refers to the actual act of flushing the air from the system. The first flushing day and time corresponds to the beginning of the first pressure period during which air begins to accumulate. To identify the next flushing event time, remove noisy data that was recorded during the flushing event, and report an intermediate time value in FNAME as the endpoint of the first air accumulation period. This also acts as the beginning of the next air accumulation period. This is the basic technique that is used to identify air accumulation periods and to clean the noisy data that occurs during the flushing event. It is helpful to keep in mind that you are specifying the times at which air accumulation begins and ends. The specification of the flushing times is best illustrated in Example 1 in Section 6.3.1.

6.3. Making an input data file for DATAPREP program

The procedure for creating the preparation file is illustrated below with an example. Here we assume that the experimentalist has recorded all the information requested below during the course of the experiment, such as flushing event times and applied pressure times.

6.3.1. Example 1.

An undisturbed sandy loam soil sample was subjected to 6 pressure applications of 10, 40, 80, 150, 300, and 500 mbars. The 10-mbar pressure is applied as an air entry pressure. The recorded application times for the pressures are shown in Table 3 and the recorded times for flushing events are shown in Table 4. Remember, these times are only approximate. The volume in the outflow burette prior to any pressure application is 20 mL. The sample was completely saturated at the onset of the experiment. The sample volume is 111.64 cm^3. The oven dry weight of the sample is 173.5 grams, the wet weight at the end of the experiment was 189.2 grams, and a total of 18 mL of water drained from the sample during the course of the experiment. Air accumulated and was flushed seven

Table 3. Recorded starting times for pressure applications.

Pressure, mbars	Julian date	Military time
10	77	1746
40	78	0840
80	78	1740
150	79	0830
300	80	1540
500	82	1700

Table 4. Recorded times for flushing events.

Flushing Event #	Julian Date	Military Time
1 (air starts to accumulate)	79	0831
2	79	1850
3	80	1527
4	82	1325
5	83	2148
6	84	1217
7	84	2300
8	85	0822

times. Air began to accumulate during the 150-mbar pressure. The calculations are explained below and the resulting input file (FNAME) for DATAPREP is shown in Table 11. Numerals below correspond with the line numbers of FNAME (page 51). The graphs are included to illustrate the technique used for removal of air flushing event data. This data input file was prepared with Microsoft Excel.

1. Calculate the saturated volumetric water content.
   a) Calculate the mass of water in the core as the difference between the oven dry weight and the wet weight at the conclusion of the experiment: 189.2- 173.5g = **15.7g**
   b) Add to this the mass of water that has drained from the core to get the total mass of water, m_w, at saturation (recall that 1mL water weighs 1 gram):

      m_w=15.7g + 18g = 33.7g
   c) Divide by the mass of the oven dry soil to result in the saturated gravimetric water content, θ_g: θ_g = 33.7g / 173.5g = **0.194**
   d) Calculate the bulk density according to: $\rho_b = m_s / V_t$ where ρ_b is the bulk density, m_s is the oven dry soil mass, and V_t is the total volume of the soil:

      ρ_b = 173.5g / 111.64 cm^3 = **1.55 g/cm^3**
   e) Calculate the volumetric water content, θ_v, according to: $\theta_v = \theta_g \rho_b / \rho_w$ where ρ_w is the density of water: θ_v = 0.194 (1.55) / 1.0 = **0.302 cm^{3}cm^{-3}**

      or directly from $\theta_v = m_w / \rho_w V_t$

2. Enter the initial pressure step that is applied (i.e. "air entry" pressure) **(10 mbars)**.
3. Enter the burette reading at the onset of the experiment. That is, the reading prior to any application of pressure. **(20 mL)**.
4. Enter the burette reading at the conclusion of the experiment. **(38 mL)**.
5. Enter the slope of the calibration curve for the tensiometer-transducer. To see an example of a calibration curve, we refer to Figure 9 in Section 4. The slope for this sample was **10.638**.
6. Enter the slope of the calibration curve for the outflow-transducer. To see an example of a calibration curve, we refer to Figure 9 in Section 4. The slope for this sample was **20.647**.
7. Enter the number of pressure applications minus one. That is, the air entry pressure is excluded **(6 - 1 = 5)**.
8. For each pressure increase (except for the air entry value), enter the Julian date, military time, and pressure value (in mbars) The number of lines in this step must agree with the number declared in step 7 **(5)**. The times declared here may not exactly match the times declared in the experimental folder since the datalogger records several times per minute and can be programmed to average these values every minute or every five minutes. Therefore, it is necessary to look through the data to pinpoint when a pressure step began. The following outlines this procedure:

   Table 5 shows an excerpt from the data file for this example problem. It can be seen that the readings for the tensiometer-transducer are fairly uniform until 08:41 at which time there is a marked change. This change can either be a drop in the value or an increase. What is important to note is that the readings are maintained at some relatively uniform level until some marked change occurs that coincides approximately with a recorded pressure application. Recall that the experimentalist recorded the pressure application time for 40 mbars to be 08:40 (Table 3) but we see in Table 5 that it is instead 08:41. Some data excerpts for the remaining pressure applications are shown in Table 6 through Table 9.

Table 5. Data excerpt for 40 mbar pressure step.

Julian Date	Military Time	Tensiometer transducer	Outflow transducer
78	835	-1.1195	2.3118
78	836	-1.1172	2.3106
78	837	-1.1172	2.3141
78	838	-1.116	2.3129
78	839	-1.1138	2.3118
78	840	-1.1172	2.3153
78	841	-0.96706	2.3448
78	842	-0.60072	2.3744
78	843	-0.64734	2.4381
78	844	-0.72014	2.4802
78	845	-0.80321	2.5099

Table 6. Data excerpt for 80 mbar pressure step.

Julian Date	Military Time	Tensiometer transducer	Outflow transducer
78	1734	-1.0408	2.5218
78	1735	-1.0351	2.5207
78	1736	-1.0363	2.5219
78	1737	-1.0386	2.5242
78	1738	-1.0203	2.6015
78	1739	-1.042	2.5741
78	1740	-0.55625	2.5527
78	1741	0.08758	2.5754
78	1742	-0.15242	2.5845
78	1743	-0.51073	2.5856
78	1744	-0.6882	2.5914

Table 7. Data excerpt for 150 mbar pressure step.

Julian Date	Military Time	Tensiometer transducer	Outflow transducer
79	825	-1.0227	2.6243
79	826	-1.0249	2.6255
79	827	-1.0238	2.6243
79	828	-1.0249	2.6230
79	829	-1.0260	2.6219
79	830	-1.0260	2.6241
79	831	1.1443	2.6366
79	832	4.4054	2.6457
79	833	3.4337	2.6582
79	834	2.8742	2.6628
79	835	2.4874	2.6696

Table 8. Data excerpt for 300 mbar pressure step.

Julian Date	Military Time	Tensiometer transducer	Outflow transducer
80	1534	-0.42545	2.8039
80	1535	-0.48571	2.8289
80	1536	-0.53693	2.8414
80	1537	-0.60516	2.8062
80	1538	-0.6518	2.8004
80	1539	-0.68705	2.8016
80	1540	8.3433	2.8073
80	1541	12.416	2.8209
80	1542	12.246	2.8198
80	1543	12.086	2.8266
80	1544	11.932	2.83

Table 9. Data excerpt for 500 mbar pressure step.

Julian Date	Military Time	Tensiometer transducer	Outflow transducer
82	1655	0.4435	3.0933
82	1656	0.44124	3.0945
82	1657	0.43213	3.0922
82	1658	0.42985	3.0945
82	1659	0.42873	3.0922
82	1700	0.42189	3.1035
82	1701	19.589	3.0966
82	1702	19.554	3.0968
82	1703	19.547	3.0945
82	1704	19.546	3.0956

9. Enter the number of air flushings plus one. Remember that this number signifies the endpoints of the air accumulation periods or intervals **(7 + 1 = 8)**.
10. Enter the Julian date and military time corresponding to the beginning of each air accumulation period. For example, the first flushing day and time corresponds to the start time for the first pressure during which air accumulates (150 mbars) because what you are actually specifying is the time at which air accumulation commenced. So, the time reported for the first air accumulation period is the same as the start time for the 150 mbar pressure, or day 79, at time 08:31 (Table 4). For the remaining flushing events it is necessary to graph the outflow data in order to determine the time to report and to determine which data should be deleted from the file. The outflow-

transducer data for the second flushing event prior to any data removal is graphed in Figure 21. Notice in Figure 21 the plot is relatively flat until a peak begins at 18:46 with a second, smaller peak at 18:52. We removed data from 18:45 to 18:54 and reported an air flushing time of 18:50 (refer to line 38 in Table 10). One could have chosen any other time between 18:46 and 18:53. What is important is that some time during the flushing event is reported to delineate between two periods of air accumulation. Figure 22 shows outflow-transducer versus time for first flushing event after data removal.

11. Follow this same procedure for the remaining air accumulation periods.
12. The remainder of the file consists of the recorded data in the following order per line: Julian date, military time, tensiometer-transducer reading, and outflow-transducer reading.
13. Remove all data after the final flushing event except for the endpoint after the last flushing event because otherwise you will incorporate data that includes uncorrected air accumulation.
14. Save the file as a comma delimited file (*.csv).

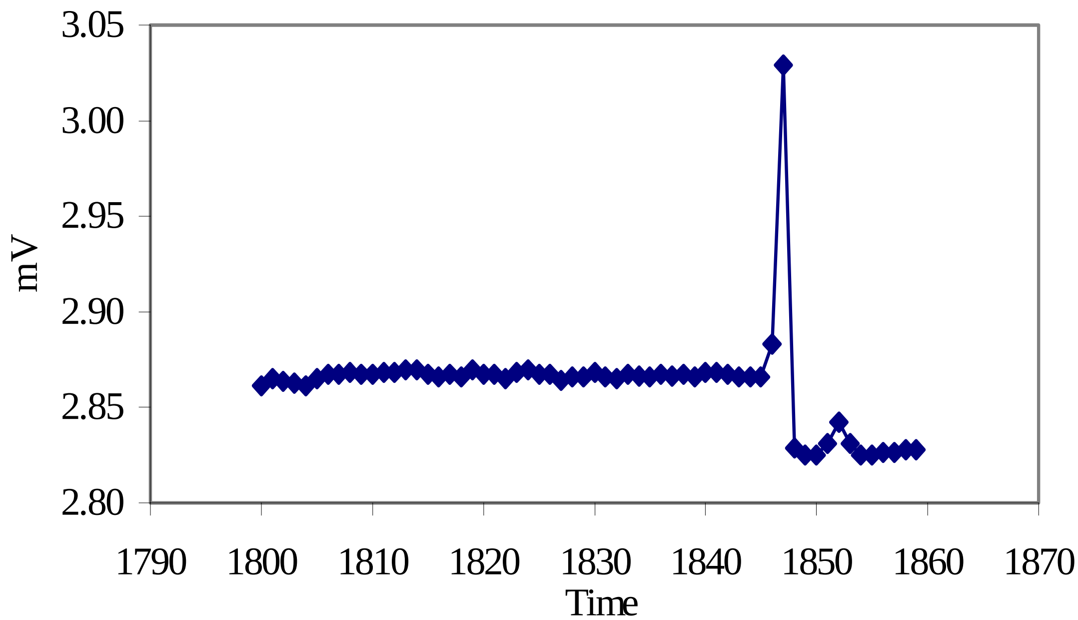


Figure 21. Outflow-transducer voltage versus time for first flushing prior to data removal.

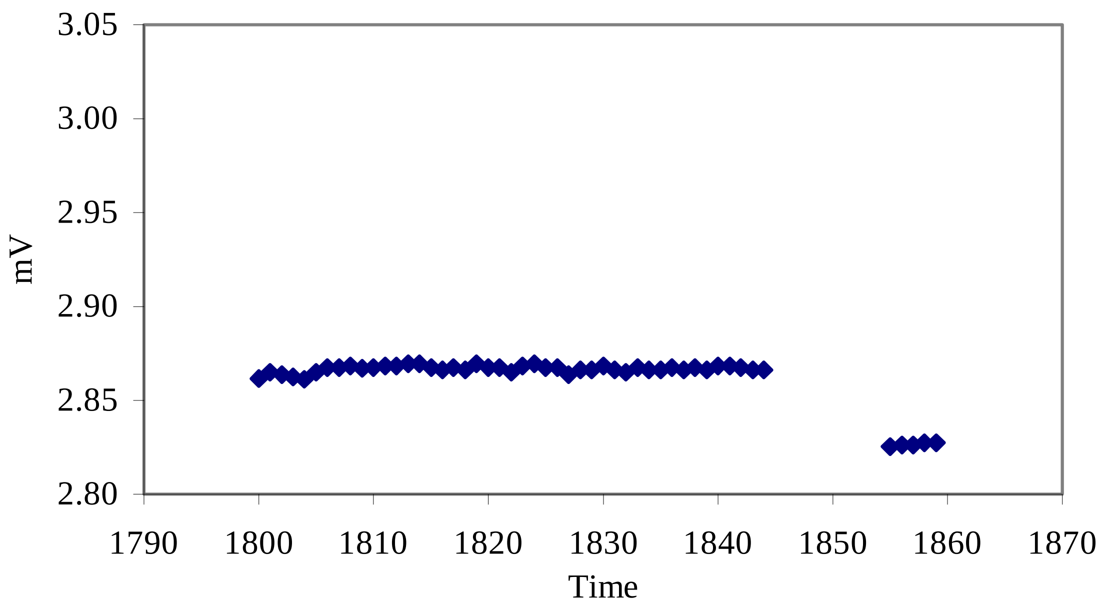


Figure 22. Outflow-transducer voltage versus time for first flushing after data removal.

Table 10. Graphed data after removal.

Line	Military Time	Outflow transducer
1	1808	2.8684
2	1809	2.8672
3	1810	2.8673
4	1811	2.8684
5	1812	2.8684
6	1813	2.8696
7	1814	2.8695
8	1815	2.8673
9	1816	2.8662
10	1817	2.8674
11	1818	2.8662
12	1819	2.8696
13	1820	2.8674
14	1821	2.8674
15	1822	2.8650
16	1823	2.8684
17	1824	2.8696
18	1825	2.8673
19	1826	2.8673
20	1827	2.8639
21	1828	2.8662
22	1829	2.8662
24	1830	2.8684
25	1831	2.8662
26	1832	2.8650
27	1833	2.8674
28	1834	2.8663
29	1835	2.8662
30	1836	2.8673
31	1837	2.8663
32	1838	2.8673
33	1839	2.8662
34	1840	2.8684
35	1841	2.8685
36	1842	2.8674
37	1843	2.8662
38	1844	2.8662
39	1855	2.8253
40	1856	2.8264
41	1857	2.8264
42	1858	2.8277
43	1859	2.8277

Table 11. Example input data file for the DATAPREP (FNAME).

1	0.302			
2	10			
3	20			
4	38			
5	10.63820763			
6	20.64745309			
7	5			
8	78	841	40	
	78	1740	80	
	79	831	150	
	80	1540	300	
	82	1701	500	
9	8			
10	79	831		
11	79	1850		
	80	1527		
	82	1325		
	83	2148		
	84	1217		
	84	2300		
	85	822		
12	78	841	-0.96706	2.3448
	78	842	-0.60072	2.3744
	78	843	-0.64734	2.4381
	78	844	-0.72014	2.4802
	78	845	-0.80321	2.5099

	85	814	10.885	3.4127
	85	815	10.883	3.4115
	85	816	10.88	3.4127
	85	817	10.878	3.4115
	85	818	10.876	3.4138
	85	819	10.874	3.4127
	85	824	10.936	3.2452
	85	832	10.868	3.2591
	85	833	10.866	3.2759
	85	834	10.864	3.2793
	85	835	10.861	3.2805
	85	836	10.861	3.2816

6.4. Running the data preparation program, DATAPREP

Due to its graphics requirement, the DATAPREP program must be run using Digital Visual Fortran 5.0 (Visual Fortran), which uses Microsoft® visual development environment. The visual development environment is also known as Microsoft Developer Studio™. DATAPREP uses run-time library modules (DFLIB) of Visual Fortran for drawing the final output graph to show the end result of the data preparation (cleaning) procedure. Module DFLIB includes run-time functions and subroutines to assist user in special tasks. Thus, DATAPREP has to be opened as a Fortran QuickWin Application project. If a different version of Visual Fortran is used, the run-time library module name (DFLIB) needs to be changed. To run the DATAPREP program, follow the given instructions below

1. From the Windows Start Menu, Select Visual Fortran.
2. Select Developer Studio.
3. To create a new project, choose the File menu and select New. A dialog box opens that has the following tabs:

   - Files
   - Projects
   - Workspaces
   - Other Documents

   The Projects tab displays various project types. Specify the project name and location. Click the QuickWin Application type of Fortran project to be created.

4. Click OK to create the new project.
5. To add Dataprep.f90 file to the project, Select “Add To Project” from the Project menu.
6. Select “Files” from the submenu. The “Insert Files into Project” dialog box appears. Use this dialog box to select the Dataprep.f90 file to be added to the Project.
7. Click OK. The editor appears allowing you to type in source code. The file name appears in the FileView pane.

8. Open prepared folder, double click on Dataprep.f90 file (might have to select View workspace). For new experimental set-up, parameters at the beginning of the program must be changed. If you want to change the weighting it must be done here.
9. After changes made in source code (Dataprep.f90), the program must be re-compiled.
10. Choose the Build Menu and select “compile Dataprep.f90”.
11. Choose the Build Menu and select “Build”.
12. Choose the Build Menu and select “Execute”.
13. Type in file name including .csv extension, give input file name that is wanted for the FINPU file (same name different extension, i.e., *.in), give graph file name (i.e., *.g), give 250 points as the number of desired points. This seems to be ignored, anyway, because it seems that the number of points chosen is never the number you specify.
14. At the end of program run, another window will be opened and shows a final output graph (Figure 23). The gray plot in Figure 23 corresponds to the original outflow data, green is corrected outflow, blue is chosen outflow data points for use in SFOPT, pink is original pressure data, and red are chosen pressure points for SFOPT.
15. Look at the graph to see if there is any additional cleanup to be done. If so go back to the file with the csv extension in MS Excel spreadsheet program and clean up, then re-run DATAPREP.
16. Close workspace.

The user must note that the file with the csv extension has to be in the same project directory created above as the source code (DATAPREP). The output file of the DATAPREP Program is the input file for the SFOPT optimization program. The SFOPT program can be run by a similar procedure as outlined above with the required input file. But this is not a rule of thumb. On the contrary, SFOPT is independent of the program environment. It can be executed with different type of Fortran compilers.

```
Experimental file name :  example1.csv
Input file name :         example1.in
Number of time points :  247     10.638     20.647      8.924    -28.414
Differece between final outflows by burette and transducer :   -1.343 ml
Time : 0 to   167.9 hr    Press. : 0 to -383.2 cm    Outflow : 0 to   19.3 ml
```

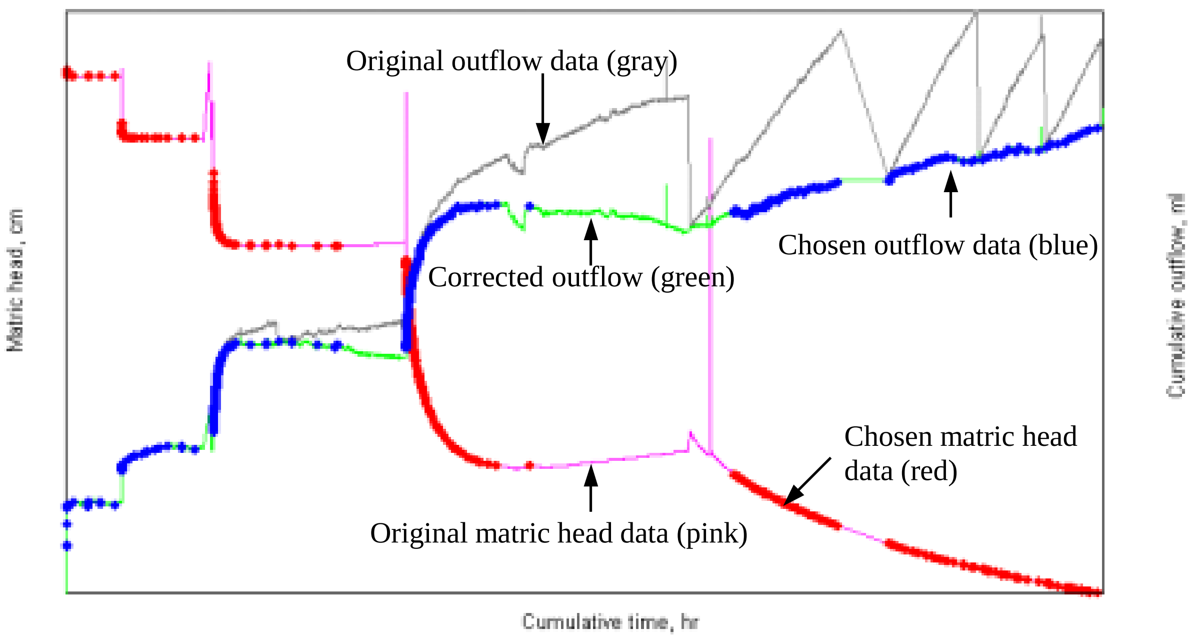


Figure 23. Final output graph of the DATAPREP program.

6.5. Corrections to DATAPREP files in the case of incomplete or erroneous transducer measurements

The DATAPREP program assumes that experimental conditions during the multi-step procedure are according to protocol. It does not account for failure of one or both pressure transducers or for data losses by the data logger. For such conditions it is often possible to adjust for experimental irregularities in the data, prior to inverse modeling. Most times, a repetition of the experiment is not possible, or is too time consuming, and hydraulic properties must be inferred from the available data. The following general types of irregularities may occur:

- Outflow data records from the pressure transducer in the burette are missing, erratic, or erroneous for part or all of the experimental duration; in this case, a shortened record combined with the manually recorded outflow data immediately prior to each pressure step increment must be considered together with a complete matric potential record;
- Matric potential data records from the pressure transducer in the core are missing, erratic, or erroneous for part or all of the experimental duration; in this case, a shortened or interpolated record combined with the manually recorded pressure steps must be considered;
- Automatic data records (from both pressure transducers) are completely lost due to computer failure; in this case only the manually recorded pressure and outflow data at the end of each step are available.

The principle approach in these cases is careful inspection of the available data, of the data selected by DATAPREP, and manipulation of the weights given to matric potential–outflow pairs. Manually recorded data that are deemed reliable are inserted into the records produced by DATAPREP prior to the inverse modeling with SFOPT. Only high-quality data are given a non-zero weight. Weights must be carefully chosen to reflect the imbalance in matric potential and outflow data. The resulting hydraulic data must be clearly identified as being obtained by non-standard procedures and should be documented separately.

In this section, we show two important non-standard procedures, one for an experiment with erratic or irregular outflow data recordings (first category above), and one for the extreme case of a complete loss of the electronic data record (last category above). We show that approximate data pairs may be substituted in the case when a handwritten data log is available. If transient data is lost, equilibrium data pairs can still provide enough information for parameter estimation of the retention curve.

6.5.1. Example 2.

In this example, 10 pressure increments were applied: 10, 60, 80, 90, 100, 125, 150, 200, 250, and 300 mbars. As can be seen in Figure 24, the outflow data are poor for the first eight pressure steps, but the data for the last two steps appear to be of good quality. Notice that the DATAPREP program has not selected any data pairs from pressure steps 2-7 although the pressure data appear to be of good quality. This is because the program selects data according to criteria, specified from lines 162 to line 215 in DATAPREP (See also section 6.1), which eliminate highly fluctuating data. If one type of data (either pressure or outflow) does not satisfy those criteria, the DATAPREP program will not select the data pair in question. However, the proposed modifications make use of the good pressure head data and include the handwritten outflow values from the experimental record. The following steps outline this procedure:

1. Modify the DATAPREP code (Appendix B) by changing the value of the weight parameter “wtq” in line 29 (in the “important parameters” section at the beginning of the code) from a value of 1.0 to a value of 0.0 and by commenting lines 193-197 and line 207. Table 12 reflects these changes (the original format is shown in Appendix B). These changes allow pressure head data to be chosen according to the specified criteria and allow the required outflow pair to be chosen without any restrictions. We do not want to impose any restrictions for choosing outflow since the outflow data are poor. We simply need to obtain the pairs required in SFOPT. Since we do not want erratic outflow data to be used in the parameter estimation, those data are given a weight of 0.0.

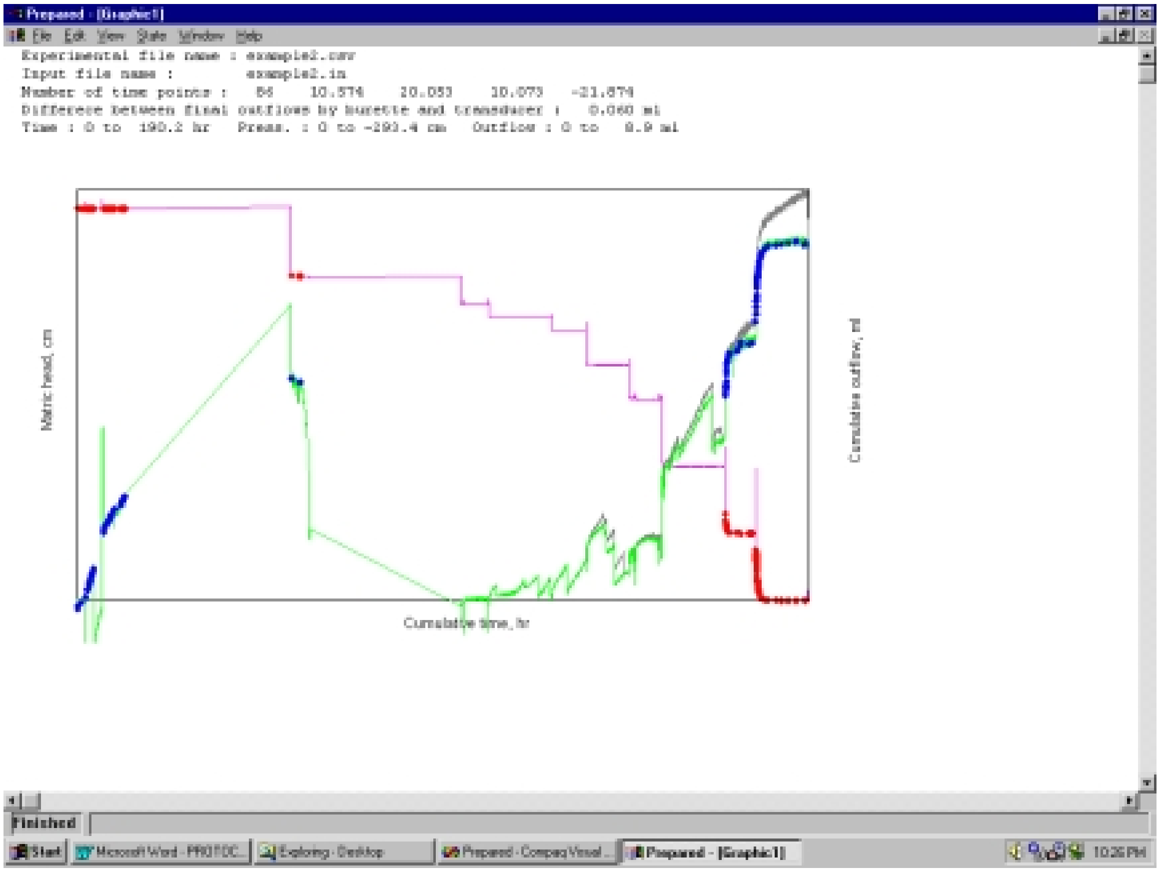


Figure 24. Graphical output window using original DATAPREP program on example2.csv.

Table 12. The lines that must be modified in the DATAPREP code.

```
                         .
                         .
   wtq=0.     !   Weighting factor of cumulative outflow Q-type data     (line 29)
                         .
                         .
!  IF(Q1(N).GT.Q1(N+1)) GOTO 70                                          (line 193)
!   IF(Q1(N).GT.Q1(N+2)) GOTO 70 ! If the current outflow is greater than
!   IF(Q1(N).GT.Q1(N+3)) GOTO 70 ! outflows at the following five time
!   IF(Q1(N).GT.Q1(N+4)) GOTO 70 ! steps, skip the current time step.
!   IF(Q1(N).GT.Q1(N+5)) GOTO 70                                         (line 197)
                         .
                         .
!    IF(Q1(N).LT.Q(M)-.25) GOTO 70                                       (line 207)
```

2. Recompile this version of the code. Be sure to close the graphical output window generated from the first model run or the compilation will result in an error message.
3. Send the data set through the DATAPREP code, but give the resulting optimization input file and graphical output file new names (i.e., “example2a.in” and “example2a.g”) since you will need both files (“example2.in” and “example2a.in”) for step 4. Figure 25 shows the new graphical output. Notice that 264 time points have been selected, whereas previously (Figure 24) only 86 time points were selected.

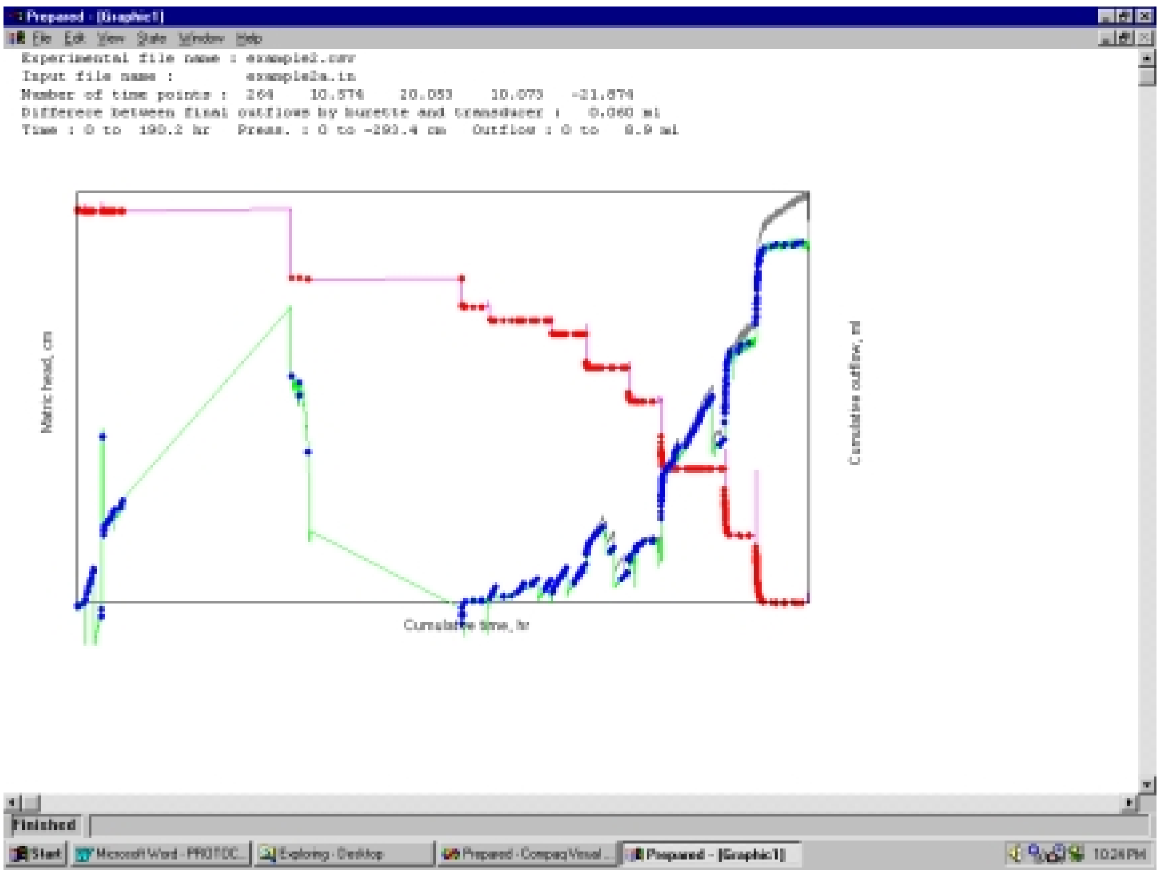


Figure 25. Graphical output windows using modified DATAPREP program on example2.csv.

4. Next, the two input files must be pieced together to provide the appropriately formatted input file for SFOPT. The time at which the two files will be assembled is just prior to the onset of the ninth pressure step of 250 mbars. The starting times for the pressure steps are declared at the end of the optimization input file (see Table 13).

Table 13. Excerpt from SFOPT input file for Example 2 showing the times at which pressure steps begin.

```
--- Pressure steps:
--- Time (hr),   Upper Nonwetting Pressure
    0.00                10.20
    55.60               61.22
    99.88               81.63
    107.13              91.84
    123.45             102.04
    132.23             127.55
    143.32             153.06
    151.78             204.08
    168.18             255.10
    176.35             306.12
```

The 250 mbar (or 255.10 cm) step was applied at 168.18 hours. We want the information for the first 8 steps to come from the "example2a.in" input file, and the information from the last two steps to come from the "example2.in". Thus,

a. Delete the observation data points pertaining to the first 8 steps from the "example2.in" input file (Table 14).
b. Copy the portion of the data listed in "example2a.in" (Table 15) from the beginning of the "observation data points" listing to the time just prior to 168.18 hours (i.e. 167.97).
c. Paste this section into the "example2.in" file in place of the values deleted in step 4a (Table 16).

Now the file contains pairs for the first 8 pressure steps with outflow weighted at zero and the last two pressure steps with both data types weighted at 1.0.

Table 14. “Example2.in” input data file for SFOPT with a weight of 1.0 for outflow.

```
Example2.in
--- NCASES, nprint, nout, khall, nresul
         1          0          0          0          0
 --- TITLE
 Title
 --- SAMPLE
 Sample name
 --- NN(total nodes), LNS(Soil nodes), DNUL, ZD(Z_obs), AIRP(Pres.step No), EPS1, EPS2
  55   55   0.0010   3.7915  -10   1.0000   1.0000
 --- SLL(Soil-L), PLL(Plate-L), IAM(Soil-Diam), CPLT(PlateKs)
   7.583000      0.0000000E+00   4.329500       999.0000
 --- NTOB(Time points),NTOA(Theta points),NTYPE,MDATA,MODE,MIT(Iter.limit)
       172          1          3          1          1         50
 --- IEQ (1-van Genuchten model, 2-Lognormal model)
         1
 --- Initial parameter guesses: alpha, n, thetar, thetas, Ks, l
  0.0400   2.0000   0.1100   0.2370   5.0800   0.5000
 --- Parameter free/fixed index (1-free, 0-fixed)
         1          1          1          0          1          0
 --- Parameter limits:
 --- Minimums:
  0.0010   1.0100   0.0001   0.1000   0.0001 -15.0000
 --- Maximums:
  0.5000  10.0000   0.2070   0.9000  30.0000  15.0000
 --- Ini. air pressure, Ini. outflow height:
   10.20408       2.400000
 --- RhoW, RhoNW (Rho:Fluid density; W:Wetting; NW:NonWetting)
   1.000000      0.0000000E+00
 --- Observation data points
--- Time (hr)  Datatype,  Obs_value,  Obs_height,    WT
      0.15                  1              14.234       3.792      1.000
      0.15                  2              -0.209       2.362      1.000
      0.20                  1              14.504       3.792      1.000
      0.20                  2              -0.118       2.379      1.000
                            .
                            .
                            .
      57.97                 1              65.229       3.792      1.000
      57.97                 2              5.470        3.390      1.000
      168.35                1              244.001      3.792      1.000
      168.35                2              5.242        3.356      1.000
                            .
                            .
                            .
      189.13                1              309.282      3.792      1.000
      189.13                2              8.954        4.238      1.000
       -11.60               3              0.237                   10.000
 --- Pressure steps:
 --- Time (hr),   Upper Nonwetting Pressure
   0.00                   10.20
   .
   .
   176.35                 306.12
```

Delete these data (step 4a) and replace with values copied in step 4b.

Table 15. “Example2a.in” input data file for SFOPT with zero weight for outflow.

```
Example2a.in
--- NCASES, nprint, nout, khall, nresul
        1         0         0         0         0
 --- TITLE
 Title
 --- SAMPLE
 Sample name
 --- NN(total nodes), LNS(Soil nodes), DNUL, ZD(Z_obs), AIRP(Pres.step No), EPS1, EPS2
  55   55   0.0010   3.7915  -10   1.0000   1.0000
 --- SLL(Soil-L), PLL(Plate-L), IAM(Soil-Diam), CPLT(PlateKs)
   7.583000      0.0000000E+00   4.329500       999.0000
 --- NTOB(Time points),NTOA(Theta points),NTYPE,MDATA,MODE,MIT(Iter.limit)
       528          1          3          1          1         50
 --- IEQ (1-van Genuchten model, 2-Lognormal model)
        1
 --- Initial parameter guesses: alpha, n, thetar, thetas, Ks, l
  0.0400   2.0000   0.1100   0.2370   5.0800   0.5000
 --- Parameter free/fixed index (1-free, 0-fixed)
        1         1         1         0         1         0
 --- Parameter limits:
 --- Minimums:
  0.0010   1.0100   0.0001   0.1000   0.0001 -15.0000
 --- Maximums:
  0.5000  10.0000   0.2070   0.9000  30.0000  15.0000
 --- Ini. air pressure, Ini. outflow height:
   10.20408       2.400000
 --- RhoW, RhoNW (Rho:Fluid density; W:Wetting; NW:NonWetting)
   1.000000      0.0000000E+00
 --- Observation data points
--- Time (hr)  Datatype,  Obs_value,  Obs_height,    WT
     0.03         1          12.957                3.792        1.000
     0.03         2          -0.024                2.396        0.000
     0.08         1          14.061                3.792        1.000
     0.08         2          -0.090                2.384        0.000
     0.22         1          14.602                3.792        1.000
     0.22         2          -0.050                2.391        0.000
     1.55         1          14.687                3.792        1.000
     1.55         2          -0.004                2.399        0.000
    .
    .
   167.97         1               208.392          3.792        1.000
   167.97         2               4.104            3.146        0.000
   168.22         1               223.976          3.792        1.000
   168.22         2               4.519            3.224        0.000
    .
    .
   188.42         1               309.368          3.792        1.000
   188.42         2               9.038            4.246        0.000
   -11.60         3               0.237                         10.000
 --- Pressure steps:
 --- Time (hr),   Upper Nonwetting Pressure
     0.00          10.20
     .
     .
   176.35          306.12
```

Copy these data (step 4b) and paste into “example2.in” (step 4c)

Table 16. “Example2.in” input data file after copying and pasting.

```
Example2.in
--- NCASES, nprint, nout, khall, nresul
      1        0        0        0        0
                              .
                              .
   0.03       1       12.957              3.792      1.000
   0.03       2       -0.024              2.396      0.000
   0.08       1       14.061              3.792      1.000
   0.08       2       -0.090              2.384      0.000
   0.22       1       14.602              3.792      1.000
   0.22       2       -0.050              2.391      0.000
   1.55       1       14.687              3.792      1.000
   1.55       2       -0.004              2.399      0.000
                              .
                              .
   167.97     1       208.392             3.792      1.000
   167.97     2       4.104               3.146      0.000
   168.35     1       244.001             3.792      1.000
   168.35     2       5.242               3.356      1.000
                  .
                  .
                  .
   189.13     1       309.282             3.792      1.000
   189.13     2       8.954               4.238      1.000
   -11.60     3       0.237                          10.000
--- Pressure steps:
--- Time (hr),   Upper Nonwetting Pressure
   0.00          10.20
    .
    .
    176.35      306.12
```

From “example2a.in” (rows 0.03 through 167.97)

From “example2.in” (rows 168.35 through the end of the pressure steps)

5. Incorporate the hand written data of Table 17 into the “example2.in” input file by converting the known cumulative outflow and applied pressure in mbars to equivalent hydrostatic pressure and centimeters of pressure, respectively. The added data pairs correspond to the experimental times at which water flow is at hydraulic equilibrium, prior to increasing the applied air pressure.

Table 17. Experimental record for Example 2.

Tempe Cell #		*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Sample #		example 2									
Date & Time	mV & ml readings										
Pressure											
		Initial readings before pressure application									
2/2/99	T mV	-0.863									
0915 am	Q mV	2.075									
0 mbar	Q ml	20.0									
		INITIAL AIR PRESSURE 10 mbar on 2/2/99 0927 am									
0927 am	T mV	-1.086									
2/2/99	T mV	-1.372									
2130 pm	Q mV	2.218									
10 mbar	Q ml	22.0									
		NEW AIR PRESSURE 60 mbar on 2/4/99 1704 pm									
1710 pm	T mV	-1.323									
2/5/99	T mV	-1.426									
0806 am	Q mV	2.071									
60 mbar	Q ml	22.0									
		NEW AIR PRESSURE 80 mbar on 2/6/99 1320 pm									
1325 pm	T mV	-1.402									
2/6/99	T mV	-1.413									
2010pm	Q mV	2.092									
80 mbar	Q ml	21.0									
		NEW AIR PRESSURE 90 mbar on 2/6/99 2035 pm									
2040 pm	T mV	-1.3942									
2/7/99	T mV	-1.490									
1244 pm	Q mV	2.098									
90 mbar	Q ml	21.5									
		NEW AIR PRESSURE 100 mbar on 2/7/99 1255 pm									
0100 pm	T mV	-1.4069									
2/7/99	T mV	-1.413									
2131 pm	Q mV	2.143									
100 mbar	Q ml	21.5									
		NEW AIR PRESSURE 125 mbar on 2/7/99 2142 pm									
2148 pm	T mV	-1.3511									
2/8/99	T mV	-1.406									
0726 am	Q mV	2.146									
125 mbar	Q ml	22.0									
		AIR FLUSH 125 mbar on 2/8/99 0735 - 0743 am									
0750 am	Q mV	2.122									
	Q ml	22.0									
		NEW AIR PRESSURE 150 mbar on 2/8/99 0846 am									
0850 am	T mV	-1.0053									
2/8/99	T mV	-1.157									
1707 pm	Q mV	2.139									
150 mbar	Q ml	23.0									

a. Convert the tensiometer transducer mV readings to pressure head in centimeters, using the slope and intercept of the tensiometer transducer. The slopes of tensiometer and outflow and the intercepts of tensiometer and outflow are listed on the third line in the graphical output window (Figure 24 and Figure 25). Multiply the mV by the slope and add the intercept to convert from mV to mbars, then subtract the applied pressure in mbars. Divide this amount by –0.98 to convert from mbars to cm. For example, the conversion for the 08:06 reading on 2/5/99 during the 60 mbar pressure is:

   (-60mbar + 10.073 + 10.574*-1.426mV)/(-0.98) = **66.33 cm**

b. Convert the outflow to cm of hydrostatic pressure head by multiplying the number of mL's greater than the initial burette volume by 0.181, the number of centimeters per mL in the burette. For example, the 08:06 mL reading on 2/5/99 is 22.0 mL and the initial volume was 20.0 mL. Therefore, this conversion yields (2.0)(0.181) = **0.362 cm** associated with **2mL** cumulative outflow**.**

c. Calculate the cumulative time at which to insert these values. Look at Table 13 and notice that the 60 mbar pressure started at 55.6 hours. In Table 17 notice that this corresponds to 17:04 on 2/4/99. Calculate the number of hours from 17:04 on 2/4/99 to 08:06 on 2/5/99 (15.03 hours) and add to the 55.6 hours to yield **70.63 hours**.

d. Type the above values into "example2.in" and give both data types a weighting value of 1.0. The value from step 5a (**66.33 cm)** is in column 3 on the line corresponding to type 1 (pressure head) data. The values from step 5b are placed in columns 3 (**2.000**) and 4 (**0.362**) and are associated with type 2 (cumulative outflow) data. Table 18 shows the file before and after the inclusion of these values.

Don't worry that the pressure at 70.63 hours is greater than at 99.88 hours. It is normal for some noise to occur in the transducer readings. Also, don't worry that the observed value for outflow is so different from the observed values of the times before and after 70.63 hours. Remember, the reason we are going through these steps is because the outflow data recorded by the datalogger are meaningless. Hence, the outflow values before and after 70.63 hours have a weight of 0.0.

Table 18. Portion of "example2.in" input before and after insertion of the first handwritten value from the experimental record.

BEFORE

--- Observation data points

--- Time (hr) Datatype, Obs_value, Obs_height, WT

•

•

59.97	1	65.439	3.792	1.000	
59.97	2	3.786	3.085	0.000	← Insert values for 70.63 hours here
99.88	1	65.253	3.792	1.000	
99.88	2	-0.120	2.378	0.000	

AFTER

--- Observation data points

--- Time (hr) Datatype, Obs_value, Obs_height, WT

•

•

59.97	1	65.439	3.792	1.000	
59.97	2	3.786	3.085	0.000	
70.63	**1**	**66.330**	**3.792**	**1.000**	} Inserted values
70.63	**2**	**2.000**	**0.362**	**1.000**	
99.88	1	65.253	3.792	1.000	
99.88	2	-0.120	2.378	0.000	

The conversion for the other handwritten values from Table 17 are shown in columns 7, 8 and 9 of Table 19. Follow steps a-d to calculate these values.

6. Count the number of observation data points that are now in the input file. Change the value of NTOB, on line 13 of the input file, to reflect the new number of data pairs. This number does not include the “air entry” value (NTOA), designated by type 3, that appears at the bottom of the observation data points listing.

Table 19. Converted handwritten values from experimental record.

Julian Day	Time	Applied Pressure (mbar)	Tensiometer transducer (mV)	Observed value (cm)	Outflow (mL)	Obs value (mL)	Observed height (cm)	Cumulative time (hours)
36	8:06	60	-1.426	66.332	22.0	2.0	0.362	70.63
37	20:10	80	-1.413	86.600	21.0	1.0	0.181	106.7
38	12:44	90	-1.49	97.635	21.5	1.5	0.272	123.28
38	21:31	100	-1.413	107.008	21.5	1.5	0.272	132.05
39	7:26	125	-1.406	132.443	22.0	2.0	0.362	141.96
39	17:07	150	-1.157	155.266	23.0	3.0	0.543	151.65
40	8:45	200	-1.358	208.456	25.0	5.0	0.905	167.28
40	17:40	250	-1.279	258.624	27.5	7.5	1.358	176.2
41	7:20	300	-1.252	309.353	29.0	9.0	1.629	190.05

6.5.2. Example 3.

In the occasion of a total loss of the electronic data record one must rely on the handwritten experimental record, such as that shown in Table 17. In such a case one must assume that the handwritten values are recorded at equilibrium. Since the transient data are unavailable there is not sufficient data for parameter estimation of the unsaturated hydraulic conductivity function; however, it is possible to obtain the soil water retention function parameters. If the unsaturated hydraulic conductivity prediction is desired, we suggest its estimation from either 1) substitution of retention function parameters into the Mualem (1976) model, or 2) neural networks (Schaap et al., 1998). For the estimation of the soil water retention parameters we suggest the use of the solver tool available in many spreadsheet programs (Wraith, et al., 1998).

7. PARAMETER ESTIMATION PROGRAM (SFOPT)

Several important issues that might be encountered while using SFOPT will be discussed in sections 7.1 and 7.2. Information on the initial estimates of parameters and variables are described in section 7.3. The variable descriptions of the input file will be explained in section 7.4. Following, 3 examples input and output files will be introduced for the user's convenience (section 7.5). One must note that these examples are independent of previous examples given in section 6.3.1. However, the user can refer to these examples to evaluate their own experimental data.

7.1. Description and features of the SFOPT

As mentioned in section 2.1, SFOPT (Chen et al. 1997) is a new version of MLSTPM (Eching and Hopmans, 1993b). In the presented modified version (SFOPT), the basic data and program structure were not changed from the MLSTPM code (Eching and Hopmans, 1993b). However, the described optimization model includes the following new features and modifications:

- A time dependent lower boundary condition was implemented. In MLSTPM, a constant head lower boundary condition was assumed. SFOPT allows a time-dependent head as the lower boundary condition, represented by changes in the burette reading as measured automatically by the pressure transducer.
- The optimization weighting factor calculation allows for the weighting factors to be inversely proportional to the magnitude of the data type.
- Provision of a self-explanatory input file format. The explanation lines have been added in order to increase the readability of the input file. An additional output file has been added to allow simple plotting of cumulative outflow volume and capillary pressure with time.
- Current outflow experiments make use of a thin porous nylon membrane, instead of a ceramic plate. For this new experimental procedure, the user can simply set the plate thickness (PLL) to zero. In that case, CPLT (saturated conductivity of porous membrane) is not used (section 7.4).

- We added the lognormal model to characterize retention and conductivity functions (Kosugi, 1996), in addition to the van Genuchten model as an option. The lognormal model is physically-based, and optimization results have been equally successful.

Although the DATAPREP program prepares an input file for the SFOPT, one must make sure that the input file is correct. Input file includes the capillary pressure (positive) values instead of matric pressure head values (negative). This is just for computational conveniences in the program. Changes in the input file may be needed to obtain acceptable results. You may need to change the parameter-limits, the initial parameter estimates, or adjust the data-type weighting factors. A proper choice of the parametric model for soil water retention and conductivity function may also be needed.

The SFOPT produces two output files. The first file includes all the optimization results and optimized parameters. The second file is for graphing purposes only, e.g. to visualize the agreement between observed and optimized cumulative outflow and matric head values. This file can be transferred to a spreadsheet program to do so. The user is free to give any name to these output files that are asked at the beginning of the SFOPT run. One should notice that matric head values are really capillary pressure, thus they are positive per definition.

7.2. Troubleshooting

The original MLSTPM code (Eching and Hopmans, 1993b) occasionally produced erroneous simulation results with abrupt changes in computed cumulative outflow and matric head values. In most of such cases, the output file warned that "NO. OF STEPS EXCEEDS 1000 AT TIME= ??? DURING ITERATION ???". In SFOPT, NSTEPS was set to 10000 (Line 661 in Appendix C) to fix this problem. The original NSTEPS value was 1000. However, if a similar error occurs despite this change in the code, we propose the following two ad hoc changes to the code:

a) set EPS2 (the iteration weighing coefficient) to 0.0 (the default EPS2 value is 1.0)

b) make line 903 in Appendix C "FC(I)=0.5*(CUMQ1+CUMQ0)" active.

Moreover, we determined that the maximum time step allowed was too large for coarse textured soils. If a large mass balance error is encountered, or large deviation between optimized and measured cumulative outflow or matric pressure occur in the output file, one may reduce the DELMAX variable (line 661 in Appendix C) from 0.5 to 0.05. In some cases, one can also change the DELMIN=0.005*DNUL to smaller values (such as DELMIN=0.001*DNUL), which is in DETERMINE AMOUNT OF WATER IN SAMPLE section of the subroutine FLOW (line 751 in Appendix C).

Since the DATAPREP program prepares the input file for SPOPT, the user is flexible in choosing the number of data pairs. If the number of data pairs is larger than 500, then SPOPT gives an error message and stops running, because the SPOPT processes only 500 data pairs by default. In that case one must change the parameter "NO" accordingly in the SFOPT program (Lines 19, 650, and 1134 in Appendix C). However, one should note that optimization time can become exceedingly high when a large number of data pairs are used. We recommend no more than 200-300 data pairs.

7.3. Initial estimates of parameters

The unknown parameters (elements of vector **b** in the objective function) are optimized by numerical inversion using soil water matric head and cumulative volume outflow as a function of time in the objective function. Although the hydraulic conductivity of the ceramic plate and other known parameters, such as θ_s are fixed to known values, the hydraulic conductivity of the nylon membrane is fixed to 999, indicating that the membrane hydraulic conductivity is much higher than the soil itself. To test uniqueness, each inversion problem is run on the computer three times using different initial estimates of parameters. Initial parameter values are chosen as a combination of low, medium, and high values within their range of possible values. An example of initially chosen parameter values, in our study, for each case, is given in Table 20. These initial estimates were used for both models in the examples of section 6 and 7. One should refer to Hopmans et al. (2002) for more detailed description of the recommended optimization procedures.

Table 20. Initial estimates of parameters used in optimization.

Parameters for Van Genuchten's models						
Case &Range	α	n	θ_r	θ_s	K_s	l
Low	0.004^v	1.01^v	0.055^v	0.414^f	0.07^v	0.5^f
Medium	0.02^v	2.0^v	0.11^v	0.414^f	0.07^v	0.5^f
High	0.04^v	4.0^v	0.22^v	0.414^f	0.07^v	0.5^f
Range	0.001-0.5	1.0-10	0.0-0.3	0.0-0.7	0.0001-1000	-15.0-15.0

Parameters for Lognormal models						
Case &Range	$Logh_m$	σ	θ_r	θ_s	K_s	l
Low	1.6^v	1.0^v	0.015^v	0.414^f	0.07^v	0.5^f
Medium	2.0^v	2.0^v	0.15^v	0.414^f	0.07^v	0.5^f
High	3.0^v	3.0^v	0.30^v	0.414^f	0.07^v	0.5^f
Range	0.0-10.0	0.1-10	0.0-0.44	0.1-0.9	0.0001-1000	-15.0-15.0

f: fixed; v: variable

7.4. Description of variables of input file

The variable descriptions are mostly same as listed by S.O. Eching and J.W. Hopmans (1993b). The newly introduced variables are denoted by the ‘*’ notation.

Line	Variable	Description
1		Comment line
2	NCASES	Number of cases considered
	NPRINT	Number of times h(z) and θ(z) are printed in DISTP.DAT Blank = do not print
	NOUT	Observations: 0 = print in output file 1 = do not print in output file
	KHALL	Option to fix the retention curve and optimize α, n, K_s, and/or l of the conductivity function 0 = simultaneous optimization of θ(h) and K(h)
	NRESUL	1 = Print the simulated data in OBSERV.DAT Blank = do not print
4	TITLE	Title of the problem
6	SAMPLE	Sample number or name
8	NN	Total number of nodes
	LNS	Number of nodes in soil (LNS = NN if PLL ≈0, as for nylon porous membrane instead of ceramic plate
	DNUL	Initial time step (h)
	ZD*	Distance from soil core surface to soil water pressure measurement position (cm, >0)
	AIRP	Positive: One step method → value of pneumatic pressure used (cm of water) Negative: Multi step method → number of pressure steps
	EPS1	Temporal weighting coefficient
	EPS2	Iteration weighting coefficient
10	SLL	Length of soil core (cm, >0)
	PLL	Thickness of porous plate (cm, >0)
	DIAM	Diameter of soil core (cm)
	CPLT	Saturated conductivity of porous plate (cm/h, not used if LNS=NN)
12	NTOB	Number of capillary pressure and/or cumulative outflow observations with time (used in line 30)
	NTOA	Number of soil water retention points in objective function
	NTYPE	Number of data types (1,2 or 3)
	MDATA	Observed data from: 1 = transient flow data only
	MODE	Mode for type of calculation: 0 = flow equation is solved for initial parameter values 1 = optimization is continued until parameter values converge or number of iteration reaches MIT; all intermediate parameter values are printed
	MIT	Maximum number of iteration in optimization routine
14	IEQ*	Index for retention and conductivity model option: 1 = van Genuchten model (VG) 2 = Lognormal model (LN)
16	B(1)	Initial value of parameter α (VG) or $^{10}\log h_m$ (LN)
	B(2)	Initial value of parameter n (VG) or σ (LN)
	B(3)	Initial value of parameter θ_r
	B(4)	Initial value of parameter θ_s
	B(5)	Initial value of parameter K_s (cm/h)
	B(6)	Initial value of parameter l
18	INDEX(I)	Index indicating a parameter is fixed or it is to be optimized: 0 = parameter B(I) is known and is kept constant 1 = parameter B(I) is unknown and will be optimized
21	BMIN(I)	Minimum parameter value for range to be optimized
23	BMAX(I)	Maximum parameter values for range to be optimized
25	ZX*	Initial applied air pressure (cm of water equivalent, >0)
	HO0*	Initial height of water in burette, relative to bottom of porous membrane (cm)
27	RhoW*	Wetting fluid density (1.0 for water)
	RhoNW*	Nonwetting fluid density (0.0 for air)
30 ..	TIME(I)	Observation time (hour)
	Datatype	1 (Capillary pressure), 2 (Cumulative outflow)
	Observation	Capillary pressure head h_c (cm), or cumulative outflow (Q, cm^3 = ml) at time I
	HO(I)*	ZD*(line 8) for datatype 1, or height (cm) of water in burette, relative to bottom of porous membrane at time I (datatype 2)
	WT(I)	Weight factor for observation I
.. I = 1, 2, .., (NTOB) lines		
For each of the following NTOA lines		
	h	Soil water pressure head (<0, cm)
	Datatype	3, and
	θ	Corresponding water content of soil core (each pair corresponds with independently measured soil water retention point)
	WT	Weight factor for each independent soil water retention point
End...	TPRESS(J)	Times at which pressures are changed (h, since start of experiment)
	PRESSU(J	Applied pneumatic pressure (cm of water)
...	J = 1, 2, ..., AIRP lines	

7.5. Example Problems

In this section, we have included 3 examples. Example 1 is identical to the first example in Eching and Hopmans (1993b), which corresponds to data obtained with a ceramic plate and optimized using the van Genuchten model (Eqs [3]-[5]). However, because of changes made in the program the optimized results are slightly different. Furthermore, Examples 2 and 3 correspond to data obtained using a low impedance nylon membrane with an assumed zero thickness, using the lognormal (Eqs. [6]-[10]; example 2) and van Genuchten model (example 3), respectively.

7.5.1. Example 1: Multi-step ouflow, van Genuchten model, ceramic plate

Input File

```
--- NCASES,nprint,nout,khall,nresul
      1      0      0      0      0
--- TITLE
EXAMPLE
--- SAMPLE
YOLO
--- NN(Total nodes),LNS(Soil nodes),DNUL,ZD(Z_obs),AIRP(Pres.step No.),EPS1,EPS2
      48          43        1.00E-03          3.08       -6        1        1
--- SLL(Soil-L), PLL(Plate-L), DIAM(Soil-Diam), CPLT(PlateKs)
          6     0.58         8.25    0.00722
--- NTOB(hc&Q points), NTOA(theta points), NTYPE, MDATA, MODE, MIT(Iter.limit)
         88        1            3     1         1            50
--- IEQ (1-van Genuchten model, 2-Lognormal model)
      1
--- Initial  parameter guesses: alpha, n, thetar, thetas, Ks, l
        0.015     2       0.15      0.558     1.55        0.5
--- Parameter free/fixed index (1-free, 0-fixed)
         1        1         1         0         1           0
--- Parameter limits:
--- Minimums:
      0.001      1.00      0.00001   0.10      0.0001    -15.00
--- Maximums:
      0.5       10.00       0.45     0.90    100.00        15.00
--- Ini. air pressure, Ini.outflow      height:
      31.0      3.58
--- RhoW, RhoNW (Rho:Fluid density;     W:Wetting; NW:Nonwetting)
         1        0
--- Observation     data   points:
--- Time (hr),   Datatype,   Obs_value,   Obs_height,     WT
      0.183         1          35.200       3.080        1.0
      0.183         2           0.500       3.580        1.0
      0.533         1          36.500        3.080       1.0
      0.533          2          1.100       3.580        1.0
      0.933          1         37.000        3.080       1.0
      0.933         2           1.600        3.580       1.0
      1.117          1         37.200        3.080       1.0
      1.117          2          1.800        3.580       1.0
      1.450          1         43.800        3.080       1.0
      1.450          2          5.000       3.580        1.0
      1.783          1         47.000        3.080       1.0
      1.783          2          8.000        3.580       1.0
```

2.433	1	51.100	3.080	1.0
2.433	2	11.800	3.580	1.0
2.983	1	53.500	3.080	1.0
2.983	2	14.000	3.580	1.0
4.267	1	56.600	3.080	1.0
4.267	2	17.000	3.580	1.0
5.733	1	58.000	3.080	1.0
5.733	2	19.000	3.580	1.0
6.267	1	66.500	3.080	1.0
6.267	2	22.000	3.580	1.0
7.033	1	70.500	3.080	1.0
7.033	2	25.000	3.580	1.0
8.600	1	74.700	3.080	1.0
8.600	2	28.000	3.580	1.0
9.767	1	76.200	3.080	1.0
9.767	2	29.400	3.580	1.0
11.350	1	77.300	3.080	1.0
11.350	2	30.400	3.580	1.0
13.150	1	78.000	3.080	1.0
13.150	2	31.000	3.580	1.0
15.000	1	79.300	3.080	1.0
15.000	2	32.800	3.580	1.0
15.217	1	89.800	3.080	1.0
15.217	2	35.000	3.580	1.0
15.550	1	102.600	3.080	1.0
15.550	2	38.000	3.580	1.0
15.917	1	108.900	3.080	1.0
15.917	2	40.000	3.580	1.0
16.633	1	118.800	3.080	1.0
16.633	2	43.000	3.580	1.0
17.383	1	128.000	3.080	1.0
17.383	2	45.000	3.580	1.0
18.300	1	138.600	3.080	1.0
18.300	2	47.000	3.580	1.0
19.867	1	152.700	3.080	1.0
19.867	2	49.000	3.580	1.0
22.083	1	166.500	3.080	1.0
22.083	2	51.000	3.580	1.0
24.050	1	175.000	3.080	1.0
24.050	2	52.000	3.580	1.0
26.550	1	182.500	3.080	1.0
26.550	2	52.800	3.580	1.0
38.750	1	195.400	3.080	1.0
38.750	2	54.300	3.580	1.0
39.200	1	203.700	3.080	1.0
39.200	2	56.000	3.580	1.0
40.000	1	216.800	3.080	1.0
40.000	2	56.800	3.580	1.0
41.750	1	235.000	3.080	1.0
41.750	2	58.200	3.580	1.0
43.850	1	251.600	3.080	1.0
43.850	2	59.300	3.580	1.0
46.350	1	268.200	3.080	1.0
46.350	2	60.200	3.580	1.0
51.117	1	293.300	3.080	1.0
51.117	2	61.700	3.580	1.0
64.533	1	336.700	3.080	1.0
64.533	2	64.000	3.580	1.0
65.700	1	346.000	3.080	1.0
65.700	2	67.000	3.580	1.0
71.417	1	386.400	3.080	1.0
71.417	2	68.000	3.580	1.0
76.250	1	411.500	3.080	1.0
76.250	2	69.000	3.580	1.0
88.317	1	467.300	3.080	1.0

```
    88.317          2         69.800        3.580        1.0
    94.650          1        484.700        3.080        1.0
    94.650          2         70.000        3.580        1.0
   109.733          1        526.000        3.080        1.0
   109.733          2         72.400        3.580        1.0
   119.267          1        549.400        3.080        1.0
   119.267          2         72.900        3.580        1.0
   139.683          1        588.100        3.080        1.0
   139.683          2         73.600       3.580         1.0
   142.417          1        613.300        3.080        1.0
   142.417          2         74.400        3.580        1.0
   -31.000          3          0.458                    10.0
--- Pressure steps:
--- Time(hr), Upper Nonwetting Pressure
      0.000         40.00
      1.150         60.00
      5.767         80.00
     15.133        200.00
     38.833        400.00
     64.583        700.00
```

Output file

```
1          *******************************************************************
           *                                                                 *
           *EXAMPLE                                                         *
           *                       SAMPLE  YOLO                             *
           *                                                                 *
           *******************************************************************


           PROGRAM PARAMETERS
           ==================
           NUMBER OF NODES....................(NN)............... 48
           NODE AT SOIL-PLATE BOUNDARY.........(LNS).............. 43
           INITIAL TIME STEP..................(DNUL)............  .10E-02
           PNEUMATIC PRESSURE.................(AIRP)...........  -6.000
           TEMPORAL WEIGHTING COEFF...........(EPS1)............   1.00
           ITERATION WEIGHTING COEFF..........(EPS2)............   1.00
           MAX. ITERATIONS....................(MIT)............... 50
           DATA MODE..........................(MDATA)............  1
           NO. OF OBSERVATIONS................(NOBB).............. 89


           SOIL AND PLATE PROPERTIES
           =========================
           SOIL COLUMN LENGTH.................(SLL).............   6.000
           COLUMN DIAMETER....................(DIAM)............   8.250
           THICKNESS OF PLATE.................(PLL).............    .580
           PLATE CONDUCTIVITY.................(CONDS(2))......  .7220E-02
           SATURATED MOISTURE CONTENT..........(WCS).............    .558
           RESIDUAL MOISTURE CONTENT...........(WCR).............    .150
           FIRST COEFFICIENT..................(ALPHA)...........    .015
           SECOND COEFFICIENT.................(N)...............   2.000
           SATURATED CONDUCTIVITY SOIL.........(CONDS(1)).....   .1550E+01
           EXPONENT L MUALEM-GENUCHTEN.........(EXPL)............    .500

  OBSERVED   DATA
  ===============
         OBS     HRS     Data        Data-type
          1     .1830    35.2000          1
          2     .1830      .5000          2
          3     .5330    36.5000          1
          4     .5330     1.1000          2
          5     .9330    37.0000          1
          6     .9330     1.6000          2
          7    1.1170    37.2000          1
          8    1.1170     1.8000          2
```

```
  9    1.4500    43.8000          1
 10    1.4500     5.0000          2

      -----------------
      -----------------

 79   94.6500   484.7000          1
 80   94.6500    70.0000          2
 81  109.7330   526.0000          1
 82  109.7330    72.4000          2
 83  119.2670   549.4000          1
 84  119.2670    72.9000          2
 85  139.6830   588.1000          1
 86  139.6830    73.6000          2
 87  142.4170   613.3000          1
 88  142.4170    74.4000          2
 89  -31.0000      .4580          3
```

INITIAL CAPILLARY PRESSURE HEAD AT TOP OF SAMPLE :   34.0

6 STEPS IN PNEUMATIC PRESSURE :

TIME	PRESSURE
.00	40.0
1.15	60.0
5.77	80.0
15.13	200.0
38.83	400.0
64.58	700.0

ITERATION NO	SSQ	ALPHA	N	WCR	CONDS
1	.9223D+01	.0244	1.4130	.1688	1.9289
2	.5185D+01	.0398	1.5697	.1941	4.3536
3	.1231D+01	.0352	1.5864	.1597	4.8155
4	.1199D+01	.0358	1.5888	.1610	4.9946
5	.1199D+01	.0358	1.5888	.1610	4.9946

MASS BALANCE ERROR IN FE SOLUTION DURING FINAL RUN WAS   1.5359 %

RSQUARE FOR REGRESSION OF PREDICTED VS OBSERVED = .99993

CORRELATION MATRIX
==================

	1	2	3	4
1	1.0000			
2	-.4444	1.0000		
3	-.4939	.9340	1.0000	
4	.5125	.4889	.3758	1.0000

NON-LINEAR LEAST-SQUARES ANALYSIS: FINAL RESULTS
==

VARIABLE	VALUE	S.E.COEFF.	95% CONFIDENCE LIMITS LOWER	UPPER
ALPHA	.03578	.0005	.0348	.0367
N	1.58881	.0132	1.5626	1.6151
WCR	.16101	.0044	.1523	.1697
CONDS	4.99463	.2245	4.5483	5.4410

--------   OBSERVED & FITTED   DATA   --------

NO	TIME (HR)	Z	OBS	FITTED	RESI-DUAL
1	.183	3.080	35.200	31.807	3.393
2	.183	3.080	.500	.927	-.427
3	.533	3.080	36.500	33.672	2.828
4	.533	3.080	1.100	2.658	-1.558
5	.933	3.080	37.000	35.027	1.973

```
 6      .933     3.080     1.600    3.845   -2.245
 7     1.117     3.080    37.200   35.553    1.647
 8     1.117     3.080     1.800    4.303   -2.503
 9     1.450     3.080    43.800   39.618    4.182
10     1.450     3.080     5.000    7.985   -2.985

       ---------------------------------
       ---------------------------------

79    94.650     3.080   484.700  488.560   -3.860
80    94.650     3.080    70.000   70.827    -.827
81   109.733     3.080   526.000  533.606   -7.606
82   109.733     3.080    72.400   71.861     .539
83   119.267     3.080   549.400  556.442   -7.042
84   119.267     3.080    72.900   72.335     .565
85   139.683     3.080   588.100  594.571   -6.471
86   139.683     3.080    73.600   73.065     .535
87   142.417     3.080   613.300  598.776   14.524
88   142.417     3.080    74.400   73.141    1.259
89   -31.000     3.080      .458     .458     .000
```

7.5.2. Example 2: Multi-step outflow, lognormal model, nylon membrane

Input file

```
--- NCASES,nprint,nout,khall,nresul
       1      0      0      0      0
--- TITLE
Example 2
--- SAMPLE
Sample
--- NN(Total nodes),LNS(Soil nodes),DNUL,ZD(Z_obs),AIRP(Pres.step No.),EPS1,EPS2
     55      55      0.0010        3.0000      -4         1.000       1.000
--- SLL(Soil-L), PLL(Plate-L), DIAM(Soil-Diam), CPLT(PlateKs)
     6.00      0.00      8.25    999.000
--- NTOB(hc&Q points), NTOA(theta points), NTYPE, MDATA, MODE, MIT(Iter.limit)
          254      1     3     1         1           50
--- IEQ (1-van Genuchten model, 2-Lognormal model)
       2
--- Initial  parameter guesses: LOG10hm, sigma, thetar, thetas, Ks, l
       2.0          2.0       0.15       0.4411     5.0    0.50
--- Parameter free/fixed index (1-free, 0-fixed)
        1            1         1          0         1       0
--- Parameter limits:
--- Minimums:
       0.001      0.10       0.00001      0.10      0.0001     -15.00
--- Maximums:
     10.00      10.00       0.4411      0.90   100.00         15.00
--- Ini. air pressure, Ini.outflow      height:
       20.408    1.40
--- RhoW, RhoNW (Rho:Fluid density;     W:Wetting; NW:Nonwetting)
        1.0       0.0
--- Observation     data   points:
--- Time (hr)  Datatype,  Obs_value,  Obs_height,    WT
      .051       1          32.958      3.000       1.00
      .051       2           9.340      3.090       1.00
      .067       1          35.674      3.000       1.00
      .067       2          11.461      3.474       1.00
      .084       1          39.132      3.000       1.00
      .084       2          12.998      3.753       1.00
      .101       1          42.925      3.000       1.00
      .101       2          14.058      3.945       1.00
```

```
                    ----------------
                    ----------------

   185.634       1          562.355      3.000        1.00
   185.634       2           55.204     11.508        1.00
   187.801       1          565.066      3.000        1.00
   187.801       2           55.300     11.545        1.00
   189.884       1          567.524      3.000        1.00
   189.884       2           55.470     11.595        1.00
   -22.008        3       0.441                     10.00

--- Pressure steps:
--- Time(hr), Upper Nonwetting Pressure
    4.557292E-04      102.040800
       12.417120      204.081600
       48.117120      408.163300
      105.917100      714.285700
```

Output file

```
1          *******************************************************************
           *                                                                 *
           *Example 2                                                        *
           *                       SAMPLE  Sampl                             *
           *                                                                 *
           *******************************************************************


           PROGRAM PARAMETERS
           ==================
           NUMBER OF NODES.....................(NN)................ 55
           NODE AT SOIL-PLATE BOUNDARY.........(LNS)............... 55
           INITIAL TIME STEP...................(DNUL)............  .10E-02
           PNEUMATIC PRESSURE..................(AIRP)............  -4.000
           TEMPORAL WEIGHTING COEFF............(EPS1)............   1.00
           ITERATION WEIGHTING COEFF...........(EPS2)............   1.00
           MAX. ITERATIONS.....................(MIT)............... 50
           DATA MODE...........................(MDATA).............  1
           NO. OF OBSERVATIONS.................(NOBB)..............255


           SOIL AND PLATE PROPERTIES
           =========================
           SOIL COLUMN LENGTH..................(SLL).............   6.000
           COLUMN DIAMETER.....................(DIAM)............   8.250
           THICKNESS OF PLATE..................(PLL).............    .000
           PLATE CONDUCTIVITY..................(CONDS(2))......  .9990E+03
           SATURATED MOISTURE CONTENT..........(WCS).............    .441
           RESIDUAL MOISTURE CONTENT...........(WCR).............    .150
           FIRST COEFFICIENT...................(LOG10hm).......     2.000
           SECOND COEFFICIENT..................(sigma)...........   2.000
           SATURATED CONDUCTIVITY SOIL.........(CONDS(1)).....   .5000E+01
           EXPONENT L MUALEM-GENUCHTEN.........(EXPL)............    .500

  OBSERVED   DATA
  ===============
         OBS     HRS     Data         Data-type
          1     .0510    32.9580          1
          2     .0510     9.3400          2
          3     .0670    35.6740          1
          4     .0670    11.4610          2
          5     .0840    39.1320          1
          6     .0840    12.9980          2
          7     .1010    42.9250          1
          8     .1010    14.0580          2
          9     .1170    46.5850          1
         10     .1170    14.9770          2
```

```
           ----------------
            ----------------

     250  185.6340    55.2040          2
     251  187.8010   565.0660          1
     252  187.8010    55.3000          2
     253  189.8840   567.5240          1
     254  189.8840    55.4700          2
     255  -22.0080      .4410          3
```

INITIAL CAPILLARY PRESSURE HEAD AT TOP OF SAMPLE : 24.2

4 STEPS IN PNEUMATIC PRESSURE :

TIME	PRESSURE
.00	102.0
12.42	204.1
48.12	408.2
105.92	714.3

ITERATION NO	SSQ	LOG10hm	sigma	WCR	CONDS
1	.4303D+01	2.0230	1.8767	.1601	4.6844
2	.3899D+01	2.0180	1.7825	.1698	3.7507
3	.3528D+01	2.0121	1.6922	.1805	3.0183
4	.3167D+01	2.0071	1.6062	.1906	2.5303
5	.2833D+01	2.0038	1.5271	.1999	2.1953
6	.2544D+01	2.0026	1.4569	.2080	1.9588
7	.2311D+01	2.0036	1.3967	.2148	1.7834
8	.2137D+01	2.0062	1.3470	.2203	1.6496
9	.2014D+01	2.0102	1.3066	.2247	1.5392
10	.1952D+01	2.0429	1.1831	.2370	.9445
11	.1797D+01	2.0540	1.1528	.2389	.9696
12	.1793D+01	2.0492	1.1634	.2381	1.0216
13	.1793D+01	2.0493	1.1633	.2381	1.0219

MASS BALANCE ERROR IN FE SOLUTION DURING FINAL RUN WAS .3789 %

RSQUARE FOR REGRESSION OF PREDICTED VS OBSERVED = .99988

CORRELATION MATRIX
==================

	1	2	3	4
1	1.0000			
2	-.5706	1.0000		
3	.2502	-.8657	1.0000	
4	-.9736	.5623	-.2482	1.0000

NON-LINEAR LEAST-SQUARES ANALYSIS: FINAL RESULTS
==

VARIABLE	VALUE	S.E.COEFF.	95% CONFIDENCE LIMITS LOWER	UPPER
LOG10hm	2.04928	.0097	2.0302	2.0683
sigma	1.16332	.0200	1.1240	1.2027
WCR	.23814	.0019	.2343	.2419
CONDS	1.02187	.0940	.8368	1.2070

--------OBSERVED & FITTED DATA --------

NO	TIME (HR)	Z	OBS	FITTED	RESI-DUAL
1	.051	3.000	32.958	38.512	-5.554
2	.051	3.000	9.340	8.218	1.122
3	.067	3.000	35.674	41.986	-6.312
4	.067	3.000	11.461	9.422	2.039
5	.084	3.000	39.132	45.185	-6.053

```
        6      .084     3.000    12.998   10.470    2.528
        7      .101     3.000    42.925   47.999   -5.074
        8      .101     3.000    14.058   11.370    2.688
        9      .117     3.000    46.585   50.420   -3.835
       10      .117     3.000    14.977   12.132    2.845

                    ------------------------------
                    ------------------------------

      250   185.634     3.000    55.204   54.172    1.032
      251   187.801     3.000   565.066  554.332   10.734
      252   187.801     3.000    55.300   54.206    1.094
      253   189.884     3.000   567.524  556.639   10.885
      254   189.884     3.000    55.470   54.238    1.232
      255   -22.008     3.000      .441     .425     .016
```

7.5.3. Example 3: Multi-step outflow, van Genuchten model, nylon membrane

Input file

```
--- NCASES,nprint,nout,khall,nresul
      1      0      0      0      0
--- TITLE
Example 3
--- SAMPLE
Sample
--- NN(Total nodes),LNS(Soil nodes),DNUL,ZD(Z_obs),AIRP(Pres.step No.),EPS1,EPS2
     55     55       0.0010        3.0000      -4         1.000        1.000
--- SLL(Soil-L), PLL(Plate-L), DIAM(Soil-Diam), CPLT(PlateKs)
         6.00     0.00     8.25    999.000
--- NTOB(hc&Q points), NTOA(theta points), NTYPE, MDATA, MODE, MIT(Iter.limit)
        254      1     3     1        1           50
--- IEQ (1-van Genuchten model, 2-Lognormal model)
      1
--- Initial  parameter guesses: alpha, n, thetar, thetas, Ks, l
      0.04        2.0       0.15      0.4411     5.0      0.50
--- Parameter free/fixed index (1-free, 0-fixed)
       1           1          1          0        1         0
--- Parameter limits:
--- Minimums:
      0.001      1.00      0.00001     0.10       0.0001      -15.00
--- Maximums:
      0.5       10.00       0.4411      0.90    100.00         15.00
--- Ini. air pressure, Ini.outflow      height:
      20.408    1.40
--- RhoW, RhoNW (Rho:Fluid density;     W:Wetting; NW:Nonwetting)
       1.0      0.0
--- Observation     data   points:
--- Time (hr)  Datatype,  Obs_value,  Obs_height,    WT
      .051       1           32.958      3.000       1.00
      .051       2            9.340      3.090       1.00
      .067       1           35.674      3.000       1.00
      .067       2           11.461      3.474       1.00
      .084       1           39.132      3.000       1.00
      .084       2           12.998      3.753       1.00
      .101       1           42.925      3.000       1.00
      .101       2           14.058      3.945       1.00

                          ------------------------------
                          ------------------------------

   185.634       1          562.355      3.000       1.00
```

```
   185.634       2           55.204     11.508       1.00
   187.801       1          565.066      3.000       1.00
   187.801       2           55.300     11.545       1.00
   189.884       1          567.524      3.000       1.00
   189.884       2           55.470     11.595       1.00
   -22.008       3            0.441                 10.00
--- Pressure steps:
--- Time(hr), Upper Nonwetting Pressure
    4.557292E-04      102.040800
       12.417120      204.081600
       48.117120      408.163300
      105.917100      714.285700
```

Output file

```
1          ******************************************************************
           *                                                                *
           *Example 3                                                       *
           *                       SAMPLE  Sampl                            *
           *                                                                *
           ******************************************************************


           PROGRAM PARAMETERS
           ==================
           NUMBER OF NODES....................(NN)................ 55
           NODE AT SOIL-PLATE BOUNDARY.........(LNS)............... 55
           INITIAL TIME STEP..................(DNUL)............  .10E-02
           PNEUMATIC PRESSURE.................(AIRP)...........  -4.000
           TEMPORAL WEIGHTING COEFF...........(EPS1)............   1.00
           ITERATION WEIGHTING COEFF..........(EPS2)............   1.00
           MAX. ITERATIONS....................(MIT)............... 50
           DATA MODE..........................(MDATA).............  1
           NO. OF OBSERVATIONS................(NOBB)..............255


           SOIL AND PLATE PROPERTIES
           =========================
           SOIL COLUMN LENGTH.................(SLL).............   6.000
           COLUMN DIAMETER....................(DIAM)............   8.250
           THICKNESS OF PLATE.................(PLL).............    .000
           PLATE CONDUCTIVITY.................(CONDS(2))......  .9990E+03
           SATURATED MOISTURE CONTENT.........(WCS).............    .441
           RESIDUAL MOISTURE CONTENT..........(WCR).............    .150
           FIRST COEFFICIENT..................(ALPHA)...........    .040
           SECOND COEFFICIENT.................(N)...............   2.000
           SATURATED CONDUCTIVITY SOIL.........(CONDS(1)).....   .5000E+01
           EXPONENT L MUALEM-GENUCHTEN.........(EXPL)............    .500

  OBSERVED   DATA
  ===============
         OBS     HRS     Data        Data-type
          1     .0510    32.9580          1
          2     .0510     9.3400          2
          3     .0670    35.6740          1
          4     .0670    11.4610          2
          5     .0840    39.1320          1
          6     .0840    12.9980          2
          7     .1010    42.9250          1
          8     .1010    14.0580          2
          9     .1170    46.5850          1
         10     .1170    14.9770          2

                -----------------
                -----------------

        247  183.4670   559.7910          1
        248  183.4670    55.0950          2
        249  185.6340   562.3550          1
```

250	185.6340	55.2040	2
251	187.8010	565.0660	1
252	187.8010	55.3000	2
253	189.8840	567.5240	1
254	189.8840	55.4700	2
255	-22.0080	.4410	3

INITIAL CAPILLARY PRESSURE HEAD AT TOP OF SAMPLE : 24.2

4 STEPS IN PNEUMATIC PRESSURE :

TIME	PRESSURE
.00	102.0
12.42	204.1
48.12	408.2
105.92	714.3

ITERATION NO	SSQ	ALPHA	N	WCR	CONDS
1	.1125D+02	.0269	1.7137	.2402	.3955
2	.9254D+01	.0092	1.9363	.2466	.3558
3	.2455D+01	.0138	2.1243	.2588	.5637
4	.1457D+01	.0151	2.0785	.2459	.6858
5	.1454D+01	.0150	2.0942	.2463	.6892
6	.1454D+01	.0150	2.0938	.2463	.6913

MASS BALANCE ERROR IN FE SOLUTION DURING FINAL RUN WAS .5674 %

RSQUARE FOR REGRESSION OF PREDICTED VS OBSERVED = .99992

CORRELATION MATRIX
==================

	1	2	3	4
1	1.0000			
2	-.8103	1.0000		
3	-.5364	.8700	1.0000	
4	.7043	-.1886	.1029	1.0000

NON-LINEAR LEAST-SQUARES ANALYSIS: FINAL RESULTS
==

			95% CONFIDENCE LIMITS	
VARIABLE	VALUE	S.E.COEFF.	LOWER	UPPER
ALPHA	.01498	.0004	.0142	.0157
N	2.09380	.0246	2.0454	2.1422
WCR	.24631	.0015	.2434	.2493
CONDS	.69132	.0365	.6194	.7632

--------OBSERVED & FITTED DATA --------

NO	TIME (HR)	Z	OBS	FITTED	RESI-DUAL
1	.051	3.000	32.958	41.678	-8.720
2	.051	3.000	9.340	8.300	1.040
3	.067	3.000	35.674	45.095	-9.421
4	.067	3.000	11.461	9.517	1.944
5	.084	3.000	39.132	48.151	-9.019
6	.084	3.000	12.998	10.573	2.425
7	.101	3.000	42.925	50.779	-7.854
8	.101	3.000	14.058	11.480	2.578
9	.117	3.000	46.585	53.012	-6.427
10	.117	3.000	14.977	12.250	2.727

243	166.884	3.000	538.087	540.150	-2.063
244	166.884	3.000	55.208	52.919	2.289

245	168.967	3.000	541.212	543.458	-2.246
246	168.967	3.000	55.183	52.956	2.227
247	183.467	3.000	559.791	564.424	-4.633
248	183.467	3.000	55.095	53.176	1.919
249	185.634	3.000	562.355	567.278	-4.923
250	185.634	3.000	55.204	53.205	1.999
251	187.801	3.000	565.066	570.065	-4.999
252	187.801	3.000	55.300	53.233	2.067
253	189.884	3.000	567.524	572.685	-5.161
254	189.884	3.000	55.470	53.259	2.211
255	-22.008	3.000	.441	.432	.009

REFERENCES

Campbell Scientific, Inc. 1996a. AM416 relay multiplexer instruction manual. Logan, Utah.

Campbell Scientific, Inc. 1996b. 21X(L) micrologger operator's manual. Logan, Utah.

Campbell Scientific, Inc. 1998. PC208W datalogger support software instruction manual. Logan, Utah.

Chen, J., K. Kosugi, and J.W. Hopmans. 1997. Parameter estimation of multi-step outflow experiments: SFOPT. Land, Air, and Water Resources Paper No. 100036, University of California, Davis, CA.

Chen, J., J.W. Hopmans, and M.E. Grismer. 1999. Parameter estimation of two-fluid capillary pressure-saturation and permeability functions. Advances in Water Resources. 22(5) : 479-493.

Clausnitzer, V. and J.W. Hopmans. 1995. Nonlinear parameter estimation: LM-OPT. General-purpose optimization code based on the Levenberg-Marquardt algorithm. Land, Air, and Water Resources Paper No. 100032, University of California, Davis.

Eching, S.O. and J.W. Hopmans.1993a. Optimization of hydraulic functions from transient outflow and soil water pressure data. Soil Sci. Am. J. 57:1167-1175.

Eching, S.O. and J.W. Hopmans.1993b. Inverse solution of unsaturated soil hydraulic functions from transient outflow and soil water pressure data. Land, Air, and Water Resources Paper No. 100021, University of California, Davis, CA.

Eching, S.O., J.W. Hopmans, and O. Wendroth. 1994. Unsaturated hydraulic conductivity from transient multi-step outflow and soil water pressure data. Soil Sci. Am. J. 58:687-695.

Hopmans, J.W., T. Vogel, and P.D. Koblik. 1992. X-Ray tomography of soil water distribution in one-step outflow experiments. Soil Sci. Soc. Am. J. 56:355-362

Hopmans, J.W., J.C. van Dam, S.O. Eching, and J.N.M. Stricker. 1994. Parameter estimation of soil hydraulic functions using inverse modeling of transient outflow experiments. Trends in Hydrology, 1:217-242.

Hopmans, J.W., J. Simunek, N. Romano and W. Durner. 2002. Simultaneous determination of water transmission and retention properties-inverse methods. In J. Dane, D.E. Elrick, D. Reynolds and B Clothier (eds). Methods of Soil Analysis.

Part I. Third Edition American Society of Agronomy, Monograph No. 9, Madison, WI.

Klute A. 1986. Water retention: Laboratory methods. In A. Klute (ed). Methods of Soil Analysis. Part I. Physical and mineralogical methods. Second edition. American Society of Agronomy, Monograph No. 9, Madison, WI.

Klute A. and C. Dirksen. 1986. Hydraulic conductivity and diffusivity: Laboratory methods. In A. Klute (ed). Methods of Soil Analysis. Part I. Physical and mineralogical methods. Second edition. American Society of Agronomy, Monograph No. 9, Madison, WI.

Kool, J.B., J.C. Parker, and M.Th. van Genuchten. 1985a. Determining soil hydraulic properties from one-step outflow experiments by parameter estimation: Theory and numerical studies. Soil Soc. Am. J. 49:1348-1354.

Kool, J.B., J.C. Parker, and M.Th. van Genuchten. 1985b. One-step: A nonlinear parameter estimation program for evaluating soil hydraulic properties from one-step outflow experiments. Va. Agric. Exp. Stn. Bull. 85-3.

Kool, J.B. and J.C. Parker. 1987. Estimating soil hydraulic properties from transient flow experiment: SFIT User's Guide. VPI and SU Dept. Soils and Environmental Sciences, Blacksburg, VA 24061.

Kosugi K. 1996. Lognormal distribution model for unsaturated soil hydraulic properties. Water Resour. Res. 32:2697-2703.

Mualem, Y. 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resour. Res. 12:513-522.

Parker, J.C., J.B. Kool, and M.Th. van Genuchten. 1985. Determining soil hydraulic properties from one-step outflow experiments by parameter estimation: Experimental studies. Soil Soc. Am. J. 49:1354-1359.

Schaap, M.G. and F.J. Leij. 1998. Using neural networks to predict soil water retention and soil hydraulic conductivity. Soil Till. Res. 47: 37-42.

van Dam, J.C., J.N.M. Stricker, and P. Droogers. 1990. From one-step to multi-step determination of soil hydraulic functions by outflow experiments. Dept. Water Resources Rep. No 7. Wageningen Agricultural Univ., Wageningen, Netherlands.

van Dam, J.C., J.N.M. Stricker, and P. Droogers. 1992. Inverse method for determining soil hydraulic functions from one-step outflow experiments. Soil Sci. Am. J. 56:1042-1050.

van Dam, J.C., J.N.M. Stricker, and P. Droogers. 1994. Inverse method to determine soil hydraulic functions from multi-step outflow experiments. Soil Sci. Am. J. 58:647-652.

van Genuchten, M.Th. 1980. A closed-form equations for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44:892-898.

Wraith, J.M. and D. Or. 1998. Nonlinear parameter estimation using spreadsheet software. J. Nat. Resour. Life Sci. Edu. 27: 13-19.

APPENDIX A. Photographs of the items used in the Multi-step outflow experiment

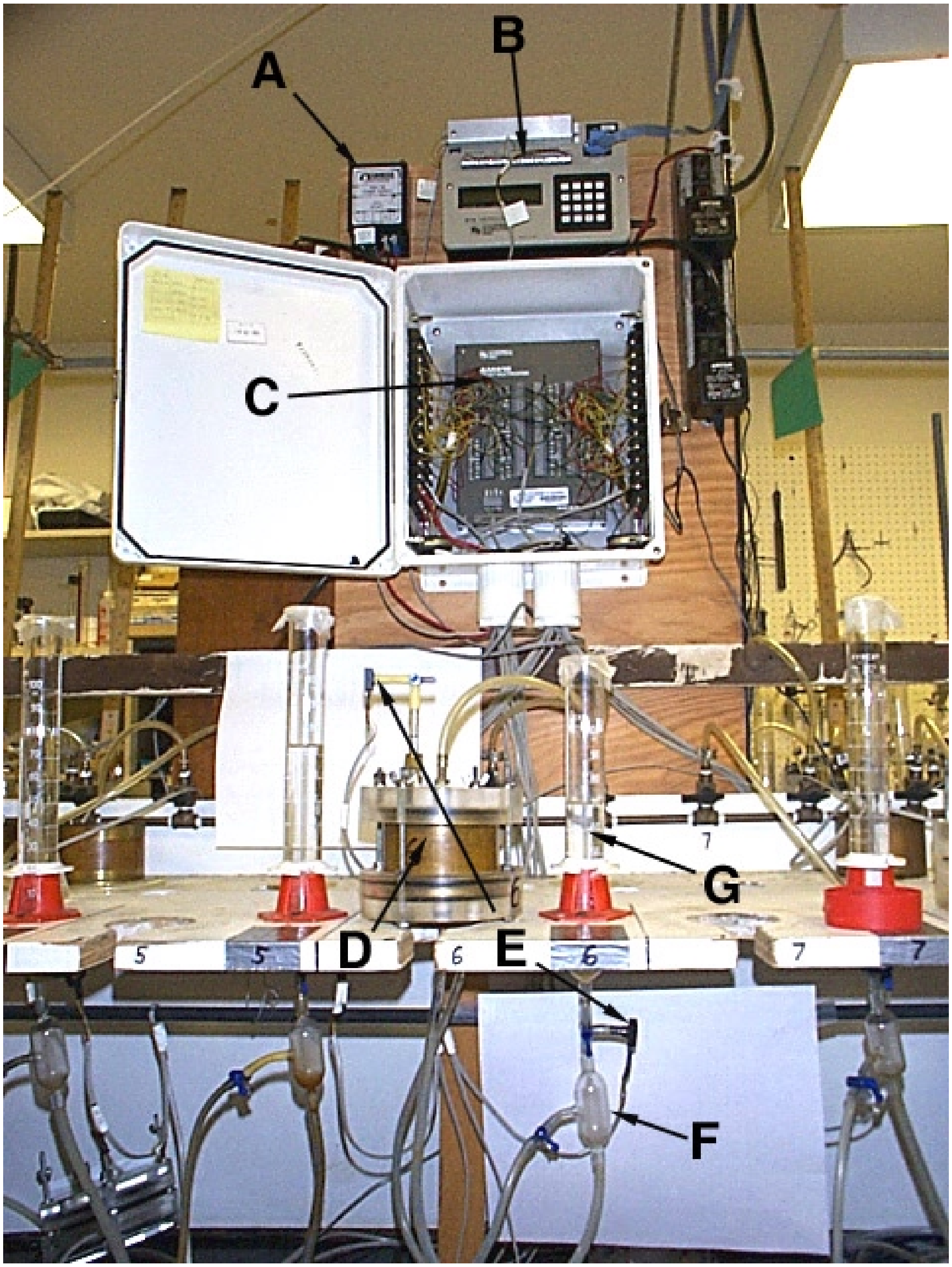


Photo 1. The multi-step outflow experiment set up: (A) External power supply, (B) 21X Datalogger, (C) AM416 Multiplexer, (D) Tempe cell with the ring, (E) Tensiometer and outflow pressure transducers, (F) Air trap, (G) The graduated burette.

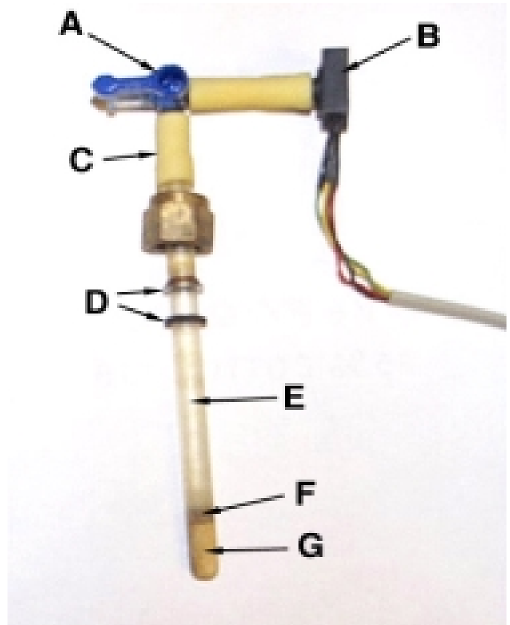


Photo 2. Porous membrane assembly for the 3.5" soil sample.

Photo 3. Mini-tensiometer transducer arrangement: (A) 3-way valve, (B) Pressure transducer, (C) Rubber sleeve, (D) Ferrule & O-ring, (E) Acrylic tube, (F) Copper coupler,(G) Ceramic cup

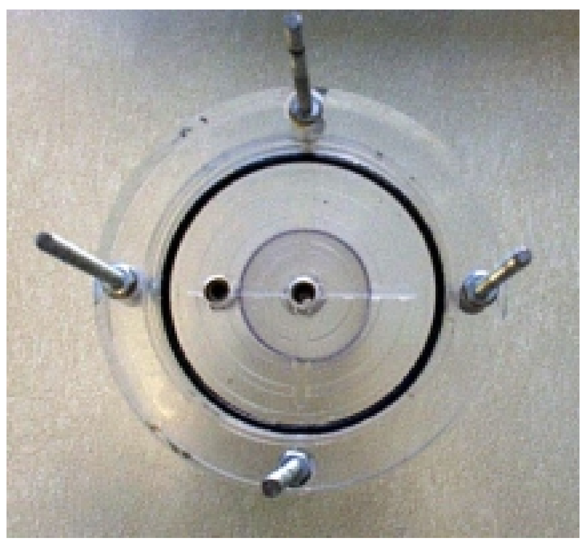


Photo 4. The 3.5" top cover of the Tempe cell.

Photo 5. The 3.5" bottom cover of the Tempe cell.

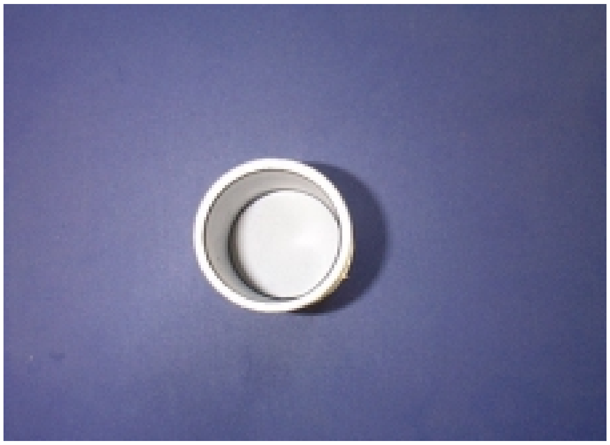


Photo 6. Aluminum sleeve glued with the filter paper (from the top).

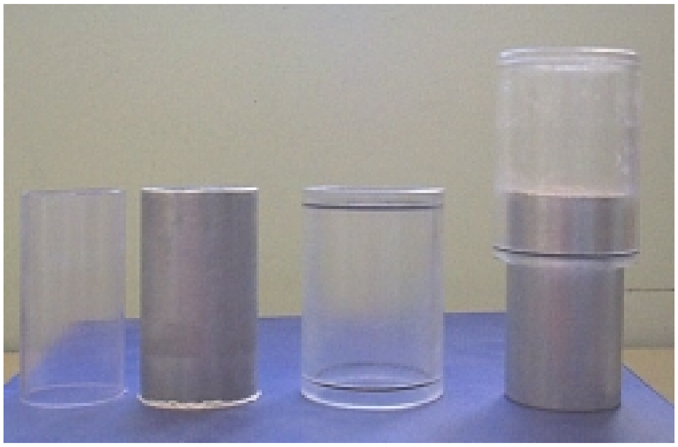


Photo 7. Plastic liner, aluminum sleeve glued with filter paper, Plexiglas sleeve, and saturated hydraulic conductivity set up (from left to right).

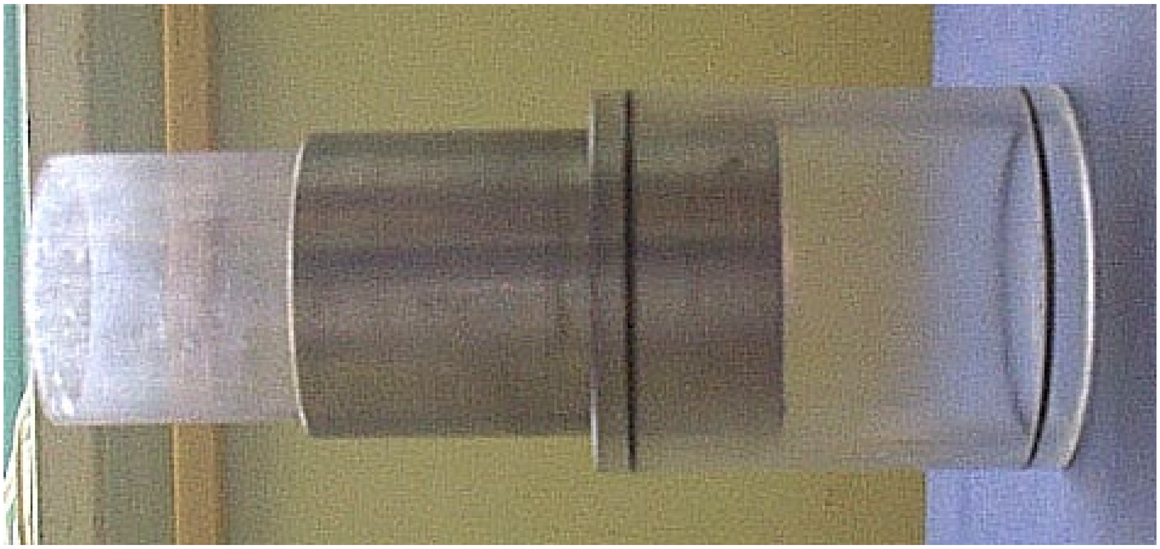


Photo 8. The way of setting up the sample from Geoprobe Macrocore® for the multi-step experiment.

Photo 9. Bottom cover of the 2” Tempe cell.

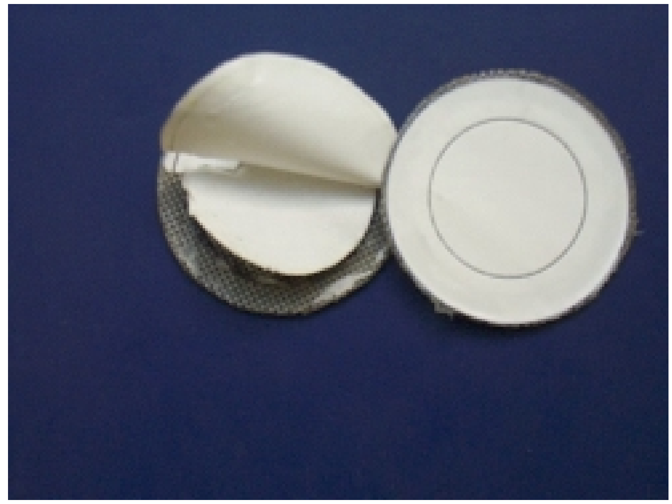


Photo 10. Porous membrane assembly and support.

Photo 11. The 2” Tempe cell set up.

Photo 12. Multi-step experiment set up for the ten 2” Tempe cells.

APPENDIX B. Source file of DATAPREP

```
!+++++   setting for graphics   +++++
USE DFLIB
integer(2) status,index,numfonts
integer(4) deg
type (wxycoord) wxy
real(8) xmin,xmax,ymin,ymax,wxmin,wxmax,wymin,wymax,xval,yval,pymin
!+++++   setting for main program   +++++
PARAMETER (ND=50000)
DIMENSION DATE(ND),TIME(ND),H0(ND),Q0(ND),A(2),B(2),B1(2),B2(2)    &
&        ,P(100),CDATE(100),CTIME(100),FDATE(100),FTIME(100)                     &
&        ,Q1(ND),BC0(ND),H(0:ND),Q(0:ND),T(0:ND),BC(ND)
CHARACTER*20 FNAME,FINPU,GNAME
!+++++
!+++++   IMPORTANT PARAMETER VALUES !!!   +++++
!+++++
!+++++
samhe=6.      ! sample height (cm)
samdi=8.25    ! sample diameter (cm)
samvo=321.       ! sample volume (cm3)
porhe=0.      ! porous membrane height (cm)
tenhe=3.      ! tensiometer height from bottom of porous membrane (cm)
watvo=19.     ! burette reading when soil sample is saturated (ml)
wathe=1.4        ! water height from bottom of porous membrane when soil sample is
saturated (cm)
whinc=0.181   ! increment of water height in burette per 1 ml outflow (cm/ml)
nnsf=55      ! total number of nodes
lnssf=55      ! number of nodes in soil
cpltsf=999.   ! saturated conductivity of porous plate (cm/h)
wthc=1.          ! Weighting factor of capillary pressure hc-type data
wtq=1.           !    Weighting factor of cumulative outflow Q-type data
wtheta=10.       ! Weighting factor for water retention point
!+++++
!+++++
!+++++
!+++++
!+++++   file names & time points   +++++
WRITE(6,*) 'ENTER EXPERIMENTAL FILE NAME'
READ(5,*) FNAME
WRITE(6,*) 'ENTER INPUT FILE NAME'
READ(5,*) FINPU
WRITE(6,*) 'ENTER GRAHING FILE NAME'
READ(5,*) GNAME

!
OPEN(20,FILE=FNAME,STATUS='UNKNOWN')
OPEN(31,FILE=FINPU,STATUS='UNKNOWN')
OPEN(41,FILE=GNAME,STATUS='UNKNOWN')

!
WRITE(6,*) 'HOW MANY TIME POINTS DO YOU NEED?'
READ(5,*) NTOB
!
!+++++   reading parameters   +++++
!
       READ(20,*) XSS
       READ(20,*) APINI
       READ(20,*) Q0INI
       READ(20,*) Q0END
       APINI=APINI/0.98
       DO 10 I=1,2
          READ(20,*) A(I)
  10   CONTINUE
       B2(1)=((Q0INI-watvo)*whinc+wathe-tenhe)*0.98
       B2(2)=Q0INI
       READ(20,*) NCHANGE
       DO 15 I=1,NCHANGE
          READ(20,*) CDATE(I),CTIME(I),P(I)
          P(I)=P(I)/0.98
  15  CONTINUE
       SHOUR=REAL(INT(CTIME(1)/100.))
       SMINU=CTIME(1)-SHOUR*100.
```

```
        STIME=CDATE(1)*24+SHOUR+SMINU/60.
        DO 17 I=1,NCHANGE
           HOUR=REAL(INT(CTIME(I)/100.))
      MINU=CTIME(I)-HOUR*100.
           CTIME(I)=CDATE(I)*24+HOUR+MINU/60.-STIME
  17  CONTINUE
      CTIME(NCHANGE+1)=10000000.
!
        READ(20,*) NFLUSH
        IF(NFLUSH.EQ.0) THEN
           FTIME(1)=10000000.
                GOTO 22
        ENDIF
        DO 20 I=1,NFLUSH
           READ(20,*) FDATE(I),FTIME(I)
           HOUR=REAL(INT(FTIME(I)/100.))
      MINU=FTIME(I)-HOUR*100.
           FTIME(I)=FDATE(I)*24+HOUR+MINU/60.-STIME
  20  CONTINUE
  22  CONTINUE
!
!+++++   reading first line of data   +++++
!
      READ(20,*) DATE(1),TIME(1),H0(1),Q0(1)
                B1(1)=H0(1)
                B1(2)=Q0(1)
        DO 12 I=1,2
           B(I)=B2(I)-A(I)*B1(I)
  12  CONTINUE
      B2(1)=B2(1)/0.98
!
           H0(1)=(H0(1)*A(1)+B(1))/0.98
           Q0(1)=Q0(1)*A(2)+B(2)-Q0INI
           HOUR=REAL(INT(TIME(1)/100.))
      MINU=TIME(1)-HOUR*100.
           TIME(1)=DATE(1)*24+HOUR+MINU/60.-STIME
!
!+++++   reading data   +++++
!
                NMAX=1
      DO 30 N=2,ND
           READ(20,*,END=99) DATE(N),TIME(N),H0(N),Q0(N)
           H0(N)=(H0(N)*A(1)+B(1))/0.98
           Q0(N)=Q0(N)*A(2)+B(2)-Q0INI
           HOUR=REAL(INT(TIME(N)/100.))
      MINU=TIME(N)-HOUR*100.
           TIME(N)=DATE(N)*24+HOUR+MINU/60.-STIME
           NMAX=NMAX+1
  30  CONTINUE
  99  CONTINUE
!+++++   calculation of lower boundary water height values   +++++
      DO 35 N=1,NMAX
           BC0(N)=(Q0(N)+Q0INI-watvo)*whinc+wathe
  35  CONTINUE
!+++++   calculation of pressure head values   +++++
      ISTEP=2
      DO 40 N=2,NMAX
           IF(TIME(N).GT.CTIME(ISTEP)) THEN
              ISTEP=ISTEP+1
           ENDIF
           H0(N)=H0(N)-P(ISTEP-1)
  40  CONTINUE
!+++++   correction of air flushing   +++++
  N0=NMAX+1
      DO 50 N=1,NMAX
           IF(TIME(N).GE.FTIME(1)) THEN
              N0=N
           GOTO 52
           ENDIF
           Q1(N)=Q0(N)
  50  CONTINUE
  52  CONTINUE
        ISTEP=2
```

```
      N0X=N0
      DO 55 N=N0X,NMAX
         IF(TIME(N).GT.FTIME(ISTEP)) THEN
            N1=N-1
            DQ=Q0(N1)-Q0(N)
            DT=TIME(N1)-TIME(N0)
            DO 60 NN=N0,N1
               Q1(NN)=Q0(NN)-DQ*(TIME(NN)-TIME(N0))/(TIME(N1)-TIME(N0))
 60         CONTINUE
            N0=N
            ISTEP=ISTEP+1
            IF(ISTEP.GT.NFLUSH) GOTO 56
         ENDIF
 55   CONTINUE
 56   DO 57 N=N0,NMAX
         Q1(N)=Q0(N)
 57   CONTINUE
!+++++
!+++++   data selection   +++++
!+++++
!+++++
      DT0=2.      !+++   maximum time interval for data selection (hr)
!+++++
!+++++
      DH0=(H0(NMAX)-(B2(1)-APINI))/REAL(NTOB)
      DQ0=Q1(NMAX)/REAL(NTOB)
      M=0
      H(0)=B2(1)-APINI
      Q(0)=0.
      T(0)=0.
      ISTEP=1
      DO 70 N=2,NMAX
         IF(TIME(N).GT.CTIME(ISTEP)) THEN
            ISTEP=ISTEP+1
         GOTO 70
         ENDIF
         HH=H0(N)-H(M)
         QQ=Q1(N)-Q(M)
         TT=TIME(N)-T(M)
         IF((HH.LT.DH0).OR.(QQ.GT.DQ0).OR.(TT.GT.DT0)) THEN
!+++++
!+++++   CONSTRAIN 1 : constrain for data fluctuations   +++++
!+++++
            IF(H0(N).LT.H0(N+1)) GOTO 70
                     IF(H0(N).LT.H0(N+2)) GOTO 70 ! If the current pressure is smaller
than
                     IF(H0(N).LT.H0(N+3)) GOTO 70 ! pressures at the following five time
            IF(H0(N).LT.H0(N+4)) GOTO 70 ! steps, skip the current time step.
            IF(H0(N).LT.H0(N+5)) GOTO 70
!+++++
            IF(Q1(N).GT.Q1(N+1)) GOTO 70
            IF(Q1(N).GT.Q1(N+2)) GOTO 70 ! If the current outflow is greater than
            IF(Q1(N).GT.Q1(N+3)) GOTO 70 ! outflows at the following five time
            IF(Q1(N).GT.Q1(N+4)) GOTO 70 ! steps, skip the current time step.
            IF(Q1(N).GT.Q1(N+5)) GOTO 70
!+++++
!+++++   CONSTRAIN 2 : constrain for unreasonable changes   +++++
!+++++
!+++++  If the current pressure is greater than the previously chosen pressure,
!+++++  skip the current time step. (+1. is to neglect small fluctuations)
                 IF(H0(N).GT.H(M)+1.) GOTO 70
!+++++
!+++++  If the current outflow is smaller than the previously chosen outflow,
!+++++  skip the current time step. (-.1 is to neglect small fluctuations)
                 IF(Q1(N).LT.Q(M)-.1) GOTO 70
!+++++
            M=M+1
                 H(M)=H0(N)
            Q(M)=Q1(N)
            T(M)=TIME(N)
            BC(M)=BC0(N)
         ENDIF
 70   CONTINUE
```

```
!
!+++++   data output   +++++
!
       WRITE(31,*) '--- NCASES, nprint, nout, khall, nresul'
       WRITE(31,*) 1,0,0,0,0
       WRITE(31,*)    '--- TITLE'
       WRITE(31,*) 'Title'
       WRITE(31,*)    '--- SAMPLE'
       WRITE(31,*)    'Sample name'
       WRITE(31,*)    '--- NN(total nodes), LNS(Soil nodes), DNUL, ZD(Z_obs),
AIRP(Pres.step No), EPS1, EPS2'
       WRITE(31,200) nnsf,lnssf,0.001,samhe+porhe-tenhe,-1*NCHANGE,1.,1.
       WRITE(31,*)    '--- SLL(Soil-L), PLL(Plate-L), IAM(Soil-Diam), CPLT(PlateKs)'
       WRITE(31,*)    samhe,porhe,samdi,cpltsf
       WRITE(31,*)    '--- NTOB(Time points),NTOA(Theta
points),NTYPE,MDATA,MODE,MIT(Iter.limit)'
       WRITE(31,*)    M*2,1,3,1,1,50
       WRITE(31,*)    '--- IEQ (1-van Genuchten model, 2-Lognormal model)'
       WRITE(31,*) 1             !+++   (1-van Genuchten model, 2-Lognormal model)
       WRITE(31,*)    '--- Initial parameter guesses: alpha, n, thetar, thetas, Ks, l'
       WRITE(31,210) 0.04,2.,0.11,XSS,5.08,0.5
       WRITE(31,*)    '--- Parameter free/fixed index (1-free, 0-fixed)'
       WRITE(31,*)    1,1,1,0,1,0
       WRITE(31,*)    '--- Parameter limits:'
       WRITE(31,*)    '--- Minimums:'
       WRITE(31,210) 0.001,1.01,0.0001,0.1,0.0001,-15.
       WRITE(31,*)    '--- Maximums:'
       WRITE(31,210) 0.5,10.,XSS-0.03,0.9,30.,15.
       WRITE(31,*)    '--- Ini. air pressure, Ini. outflow height:'
       WRITE(31,*)    APINI,(Q0INI-watvo)*whinc+wathe
       WRITE(31,*)    '--- RhoW, RhoNW (Rho:Fluid density; W:Wetting; NW:NonWetting)'
       WRITE(31,*)    1.,0.
       WRITE(31,*)    '--- Observation data points'
       WRITE(31,890) '--- Time (hr),','Datatype,','Obs_value,','Obs_height,','WT'
       write(41,*) ' Input file name :   ',gname
       write(41,921) m
    write(41,922) Q0END-(Q0INI+Q1(nmax))
    write(41,923) time(nmax),h0(nmax),q0(nmax)
!
       WRITE(41,*)
       WRITE(41,895) '--Time (hr)--','--- H0 ---','--- Q0 ---','--Time (hr)--','--- H ---
','--- Q ---'
       DO 90 N=1, NMAX
          IF (N.LE.M) THEN
            WRITE(41,915) TIME(N),H0(N),Q0(N),T(N),H(N),Q(N)
          ELSE
            WRITE(41,925) TIME(N),H0(N),Q0(N)
          ENDIF
90 CONTINUE
       DO 100 N=1,M
          WRITE(31,910) T(N),1,-1.*H(N),samhe+porhe-tenhe,wthc
          WRITE(31,910) T(N),2,Q(N),BC(N),wtq
  100 CONTINUE
  IF(Q0INI.LE.watvo) THEN
!         WRITE(31,920) B2(1)-APINI,XSS
          WRITE(31,920) B2(1)-APINI+tenhe-(samhe/2.+porhe),3,XSS,wtheta
  ELSE
!         WRITE(31,920) B2(1)-APINI,XSS-(Q0INI-watvo)/samvo
          WRITE(31,920) B2(1)-APINI+tenhe-(samhe/2.+porhe),3,XSS-(Q0INI-
watvo)/samvo,wtheta
  ENDIF
       WRITE(31,*)'--- Pressure steps:'
       WRITE(31,*)'--- Time (hr),   Upper Nonwetting Pressure'
       DO 110 I=1,NCHANGE
          WRITE(31,930) CTIME(I),P(I)
  110 CONTINUE
!
  890 FORMAT(A13,1X,A10,1X,A11,2X,A11,3X,A3)
  895 FORMAT(1(A15,1X),2(A12,1X),1(A15,1X),2(A12,1X))
  900 FORMAT(5(F12.2,1X))
  910 FORMAT(1(F10.2,4X),1(I4,7X),3(F10.3,1X))
  915 FORMAT(6(F10.3,5X))
  920 FORMAT(1(F10.2,4X),1(I4,7X),1(F10.3,1X),1(F21.3,1X))
```

```
  925 FORMAT(3(F10.3,5X))
  930 FORMAT(2(F10.2,7X))
  200 FORMAT(2(I4,1X),2(F8.4,1X),1(I4,1X),2(F8.4,1X))
  210 FORMAT(6(F8.4,1X))
!
!++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
!+++++   drawing graphics   +++++
!
status = setbkcolor(15)
status = settextcolor(int2(0))
status = setcolor(int2(0))
call clearscreen($gclearscreen)
!
write(6,*) ' Experimental file name : ',fname
write(6,*) ' Input file name :        ',finpu
write(6,921) m, A(1), B(1), A(2), B(2)
write(6,922) Q0END-(Q0INI+Q1(nmax))
write(6,923) time(nmax),h0(nmax),q0(nmax)
!
921 format('  Number of time points : ',i4,2X,4(F8.3, 2X))
922 format('  Differece between final outflows by burette and transducer : ',  &
&          f7.3,' ml')
923 format('  Time : 0 to',f7.1,' hr   Press. : 0 to',f7.1,                    &
&          ' cm   Outflow : 0 to',f6.1,' ml')
!
!++++
pixx=780.
pixy=530.-90.
call setviewport(int2(0),int2(90),int2(780),int2(530))
!
!+++++   capillary pressure vs. time   +++++
xmin=0.
xmax=time(nmax)
ymin=0.
ymax=h0(nmax)
DO n=2, nmax
       IF (h0(n).LE.ymax) THEN
           ymax = h0(n)
       END IF
END DO
!
wxmin=xmin-(xmax-xmin)/10.
wxmax=xmax+(xmax-xmin)/10.
wymin=ymin-(ymax-ymin)/10.
wymax=ymax+(ymax-ymin)/10.
!
status=setwindow(.true.,wxmin,wymin,wxmax,wymax)
status=rectangle_w($gborder,xmin,ymax,xmax,ymin)
!
numfonts = INITIALIZEFONTS ()
index = SETFONT('t''Arial''h16')
call moveto_w(((xmax-20)/2),(ymax-2),wxy)
call outgtext('Cumulative time, hr')
!
numfonts = INITIALIZEFONTS ()
index = SETFONT('t''Arial''h14')
call moveto_w((xmin-10),(ymax/1.7),wxy)
deg = 900
call setgtextrotation(deg)
call outgtext('Matrichead, cm')
!
status = setcolor(int2(13))
xval=time(1)
yval=h0(1)
call moveto_w(xval,yval,wxy)
do 310 n=2,nmax
   xval=time(n)
   yval=h0(n)
   status=lineto_w(xval,yval)
310 continue
!
status = setcolor(int2(12))
do 320 n=1,m
```

```
   xval=t(n)
        yval=h(n)
        eval=0.004*xmax
        evaly=eval*(ymax-ymin)/(xmax-xmin)*pixx/pixy
   status=ellipse_w($gfillinterior,xval-eval,yval+evaly,xval+eval,yval-evaly)
320 continue
!
!+++++   cumulative outflow vs. time   +++++
status = setcolor(int2(0))
xmin=0.
xmax=time(nmax)
ymin=0.
ymax=q0(nmax)
DO n=2, nmax
        IF (q0(n).GE.ymax) THEN
            ymax = q0(n)
        END IF
END DO

!
wxmin=xmin-(xmax-xmin)/10.
wxmax=xmax+(xmax-xmin)/10.
wymin=ymin-(ymax-ymin)/10.
wymax=ymax+(ymax-ymin)/10.
!
status=setwindow(.true.,wxmin,wymin,wxmax,wymax)
status=rectangle_w($gborder,xmin,ymax,xmax,pymin)
numfonts = INITIALIZEFONTS ()
index = SETFONT('t''Arial''h14')
call moveto_w((xmax+10),(ymax/3),wxy)
deg = 900
call setgtextrotation(deg)
call outgtext('Cumulative outflow, ml')
!
status = setcolor(int2(8))
xval=time(1)
yval=q0(1)
call moveto_w(xval,yval,wxy)
do 330 n=2,nmax
   xval=time(n)
   yval=q0(n)
   status=lineto_w(xval,yval)
330 continue
!
status = setcolor(int2(10))
xval=time(1)
yval=q1(1)
call moveto_w(xval,yval,wxy)
do 340 n=2,nmax
   xval=time(n)
   yval=q1(n)
   status=lineto_w(xval,yval)
340 continue
status = setcolor(int2(9))
do 350 n=1,m
    xval=t(n)
        yval=q(n)
        eval=0.004*xmax
        evaly=eval*(ymax-ymin)/(xmax-xmin)*pixx/pixy
   status=ellipse_w($gfillinterior,xval-eval,yval+evaly,xval+eval,yval-evaly)
350 continue
call setviewport(0,0,799,610)
!+++
end
```

APPENDIX C. Source file of SFOPT

```
C     *****************************************************************
C     *                                                               *
C     *  EVALUATION OF SOIL HYDRAULIC PROPERTIES FROM                 *
C     *  OUTFLOW DATA  BY PARAMETER ESTIMATION                        *
C     *                                                               *
C     *  version 1.2, mass-lumped FE                                  *
C     *                                 J.B. Kool, 1984,1985,1986,1987 *
C     *                                 J.C. v Dam, 1988,1989         *
C     * Modified by S.O Eching to include H(z,t) data, 1991           *
C     * Modified by Jiayu Chen (1996) to include :                    *
C     *    - Time dependent lower boundary condition                  *
C     *    - Improved weighting factor calculation                    *
C     *    - New input file format                                    *
C     *    - Correction of outflow calculation                        *
C     * Modified by Ken'ichirou Kosugi (1997) to include Lognormal    *
C     *      model of retention and conducitvity functions.           *
C     *****************************************************************
C
      PARAMETER (NO=500,NZ=100)
      CHARACTER*65 TITLE
      CHARACTER*20 TTYPE,FIN,FOUT1,FOUT2
      CHARACTER*7 BI(12)
      CHARACTER*15 SAMPLE
      DOUBLE PRECISION DELZ(NO,6),FC(NO),FO(NO),R(NO),OBS_HEIGHT(NO),
     +WT(NO),A(6,6),D(6,6),E(6),Q(6),C(6),CHI(6)
      DOUBLE PRECISION ANGLE,ARG,GA,SCAL,SSQ,SUM,SUMB,SUM1,SUM2,SUM3,
     +STEP,STOPCR,ZERO,HO(NO),HO0,HOO
      DOUBLE PRECISION SUMFO(10),NOBS(10),SETWT(10),AVFO(10)
      DIMENSION TB(12),AS(6,6),TH(12),BMIN(6),BMAX(6),Z1(NZ),B(6)
      REAL THETA(30),KUNS(30),SSQ01,SSQ02
      COMMON/AAA/delx,P(NZ),NN,AREA,LNS,PLL,SLL,PN1,TO(NO),DNUL,
     *NOB,NOB2,TMINIT,EPS1,EPS2,IINDEX(6),NVAR,CPLT,ITYPE(NO),NOB1,NOBB,
     *PIN(NZ),IRUN,ZD,BC_P,ZX
      COMMON/HYPR/BIN(6),RHOW,RHONW,IEQ
      common/theta/at,rt,wcrt,wcst,khall
      common/press/airp,pressu(10),tpress(10),npress,tprint(NZ),nprint
      DATA STOPCR/.01D0/,TTYPE/'    DATA'/,QRTPI/0.78539816/
      DATA BI(7)/'ALPHA '/,BI(8)/'N     '/,BI(9)/'WCR   '/
      DATA BI(10)/'WCS   '/,BI(11)/'CONDS '/,BI(12)/'EXPL  '/
      DATA MAXTRY/20/,ZERO/0D0/
      NVAR=6
      NU1=NVAR+1
      NU2=2*NVAR
C
C     ----- OPEN INPUT & OUTPUT FILES -----
c
c
      WRITE(*,'(A)')' ENTER INPUTFILE NAME'
      READ(*,'(A)') FIN
      WRITE(*,'(A)')' ENTER OUTPUTFILE NAME1'
      READ(*,'(A)') FOUT1
      WRITE(*,'(A)')' ENTER OUTPUTFILE NAME2'
      READ(*,'(A)') FOUT2
      OPEN(20,FILE=FIN,STATUS='OLD')
      OPEN(21,FILE=FOUT1,STATUS='UNKNOWN')
      OPEN(23,FILE=FOUT2,STATUS='UNKNOWN')
      open(22,file='extract.dat',status='UNKNOWN')
C
C     ----- READ & WRITE TITLE AND PARAMETERS -----------
      READ(20,*)
      READ(20,*) NCASES,nprint,nout,khall,nresul
      if (nresul.eq.1) open(25,file='observ.dat',status='UNKNOWN')
      DO 144 ICASE=1,NCASES
      WRITE(21,1002)
      READ (20,*)
      READ(20,'(A65)') TITLE
      WRITE(21,1006) TITLE
      READ(20,*)
      READ(20,'(A15)') SAMPLE
      WRITE(21,1007) SAMPLE
      WRITE(21,1008)
```

```
      READ(20,*)
      READ(20,*) NN,LNS,DNUL,ZD,AIRP,EPS1,EPS2
      READ(20,*)
      READ(20,*) SLL,PLL,DIAM,CPLT
      READ(20,*)
      READ(20,*) NTOB,NTOA,NTYPE,MDATA,MODE,MIT
       NOBB=NTOB+NTOA
      MODEX=MODE
c     DELX1=SLL/FLOAT(LNS-1)
c     IF (NN .NE. LNS) DELX2=PLL/FLOAT(NN-LNS)
       delx=(sll+pll)/float(nn-1)
      WRITE(21,1018) NN,LNS,DNUL,AIRP,EPS1,EPS2,MIT,MDATA,NOBB
       READ(20,*)
       READ(20,*) IEQ
       if(ieq.eq.2) then
          BI(7)='LOG10hm'
          BI(8)='sigma'
       endif
C
C     ---- READ INITIAL VALUE OF COEFFICIENTS -----
      READ(20,*)
      READ(20,*) (B(I),I=1,NVAR)
      READ(20,*)
      READ(20,*) (IINDEX(I),I=1,NVAR)
      READ(20,*)
      READ(20,*)
      READ(20,*) (BMIN(I),I=1,NVAR)
      READ(20,*)
      READ(20,*) (BMAX(I),I=1,NVAR)
       if(ieq.eq.1) then
      WRITE(21,1026)SLL,DIAM,PLL,CPLT,B(4),B(3),B(1),B(2),B(5),B(6)
       endif
       if(ieq.eq.2) then
      WRITE(21,10268)SLL,DIAM,PLL,CPLT,B(4),B(3),B(1),B(2),B(5),B(6)
       endif
c
C     -----
      npress=0
      IRUN=0
      NITT=0
C
C     ------ REARRANGE PARAMETER ARRAY ------
    4 NP=0
      DO 5 I=NU1,NU2
      I1=I-NVAR
      BIN(I1)=B(I1)
      TB(I)=B(I1)
      IF(IINDEX(I1).EQ.0) GO TO 5
      NP=NP+1
      BI(NP)=BI(I)
      TB(NP)=B(I1)
      TH(NP)=B(I1)
      IF(IRUN.LT.2) THEN
      BMIN(NP)=BMIN(I1)
      BMAX(NP)=BMAX(I1)
      ENDIF
    5 TH(I)=B(I1)
C
C     ---- READ INITIAL CONDITONS -----
      READ(20,*)
      READ(20,*) ZX,HO0
      READ(20,*)
      READ(20,*) RHOW,RHONW
C
C     ----- READ & WRITE INPUT DATA -----
C     ITYPE = 1: HC(X,T) MEASUREMENT
C           = 2: CUMULATIVE OUTFLOW MEASUREMENT
C           = 3: THETA(h) MEASUREMENT
      if(nout.eq.0) then
        write(21,*)
        write(21,*) '                    OBSERVED   DATA'
        write(21,*) '                    ==============='
        WRITE(21,*) '        OBS     HRS       Data        Data-type'
```

```
        endif
      N1=0
      NOBW=0
        KK=0
      READ(20,*)
      READ(20,*)
      DO 6 N=1,NTOB
         READ(20,*) TO(N),ITYPE(N),FO(N),OBS_HEIGHT(N),WT(N)
         IF (ITYPE(N).EQ.2) THEN
                KK=KK+1
                HO(KK)=OBS_HEIGHT(N)
         ENDIF
   11    IF (NOUT.EQ.0) WRITE(21,13) N,TO(N),FO(N),ITYPE(N)
         N1=N1+1
    6 CONTINUE
      DO 7 II=1,NTOA
         N=NTOB+II
       READ(20,*) TO(N),ITYPE(N),FO(N),WT(N)
         TO(N)=-1.*abs(TO(N))
         NOBW=NOBW+1
         IF (NOUT .EQ. 0) WRITE(21,13) N,TO(N),FO(N),ITYPE(N)
    7   CONTINUE
      IF (MODE .EQ. 9) GO TO 144
      NOB=N1
      NOB2=NOBB-NOB
13    FORMAT(1X,I10,2(F10.4,1X),I10)
        HOO=0.5*(HO0+HO(1))
      HT_BC=-ZX+HOO-(SLL+PLL)*RHOW
        WRITE(21,1023) -1.*HT_BC
      DO 10 L=1,NN
         IF (L .LE. LNS) THEN
c           X=(L-1)*DELX1
            x=(l-1)*delx
            P(L)=HT_BC+X*RHOW
            Z1(L)=SPR(1,P(L),X)
         ELSE
c           X=SLL+(L-LNS)*DELX2
            x=(l-1)*delx
            P(L)=HT_BC+X*RHOW
         ENDIF
   10 CONTINUE
      AREA=QRTPI*DIAM**2
C
C...  wls : adjust weights according to ITYPE -----
      DO 51 I = 1,NTYPE
         SUMFO(I) = 0.
         NOBS(I) = 0
51    CONTINUE
      DO 61 I = 1,NOBB
         SUMFO(ITYPE(I)) = SUMFO(ITYPE(I))+FO(I)
         NOBS(ITYPE(I)) = NOBS(ITYPE(I))+1
61    CONTINUE
      DO 70 I = 1,NTYPE
         IF (NOBS(I) .GT. 0)  AVFO(I) = SUMFO(I)/(NOBS(I))
70    CONTINUE
      DO 73 I = 1,NTYPE
         SETWT(I) =  DABS( DBLE(AVFO(2) / AVFO(I)) )
73    CONTINUE
      DO 81 I = 1,NOBB
         WT(I) = WT(I) * DABS(DBLE(AVFO(2) /AVFO(ITYPE(I))))
81    CONTINUE
C
c     ----- read applied pressure steps ---------
      if (airp .lt. 0) then
          npress=-int(airp-0.5)
          write(21,1088) npress
          read(20,*)
          read(20,*)
          do 19 i=1,npress
             read(20,*) tpress(i),pressu(i)
             write(21,1090) tpress(i),pressu(i)
   19       continue
          pn1=HOO-pressu(1)
```

```
          bc_p=pressu(1)
       else
          pn1=HOO-airp
       endif
       pn10=pn1
c
c      ----- read times on which pressure distribution is printed ------
       if (nprint.gt.0) read(20,*) (tprint(i),i=1,nprint)
C
C      ----- COMPUTE OUTFLOW FOR INITIAL PARAMETER VALUES ------
   20 GA=1.0D-02
       NOCON=0
       NITT=0
       CALL FLOW(TH,FC,NITT,NOCON,MDATA,MODE,ERRMB,HO,HO0)
       IF (MODE .EQ. 9) GO TO 144
       SSQ=ZERO
       DO 32 I=1,NOBB
         R(I)=WT(I)*(FO(I)-FC(I))
   32 SSQ=SSQ+R(I)*R(I)
       rmsd=sqrt(ssq/nobb)
       IF (NP.EQ.0. OR. MODE.EQ.0) THEN
         WRITE(21,1040)
         WRITE(21,1042)NITT,rmsd
         WRITE(21,1044)ERRMB
         GO TO 110
       ELSE
         WRITE(21,1040) (BI(I),I=1,NP)
       ENDIF
       if (mode.ne.0.and.icase.eq.1.and.(irun.eq.1.or.irun.eq.0))
      1write(22,1047)
       do 33 i=1,np
         e(i)=zero
   33 continue
C
C      ----- BEGIN OF ITERATION -----
   34 NITT=NITT+1
       WRITE(6,1045) sample,irun,nitt
       NET=0
       GA=0.1D0*GA
       DO 38 J=1,NP
       TEMP=TH(J)
       TH(J)=1.01*TH(J)
       Q(J)=ZERO

       CALL FLOW(TH,DELZ(1,J),NITT,NOCON,MDATA,MODE,ERRMB,HO,HO0)
       IF (MODE .EQ. 9) GO TO 144
       DO 36 I=1,NOBB
          DELZ(I,J)=WT(I)*(DELZ(I,J)-FC(I))
   36 Q(J)=Q(J)+DELZ(I,J)*R(I)
       Q(J)=100.D0*Q(J)/DBLE(TEMP)
C
C      ----- STEEPEST DESCENT -----
   38 TH(J)=TEMP
       DO 44 I=1,NP
       DO 42 J=1,I
       SUM=ZERO
       DO 40 K=1,NOBB
   40 SUM=SUM+DELZ(K,I)*DELZ(K,J)
       D(I,J)=1.0D04*SUM/(TH(I)*TH(J))
   42 D(J,I)=D(I,J)
C
C      ----- D = MOMENT MATRIX -----
       SCAL=DSQRT(DMAX1(D(I,I),1.0D-30))
   44 E(I)=DMAX1(E(I),SCAL)
   50 DO 52 I=1,NP
       DO 52 J=1,NP
   52 A(I,J)=D(I,J)/(E(I)*E(J))
C
C      ----- A IS THE SCALED MOMENT MATRIX -----
       DO 54 I=1,NP
          C(I)=Q(I)/E(I)
          CHI(I)=C(I)
   54 A(I,I)=A(I,I)+GA
```

```
      CALL QRSOLV(A,NP,C)
C
C     ----- C/E IS THE CORRECTION VECTOR -----
      STEP=1.0D0
   56 NET=NET+1
      DO 58 I=1,NP
         TB(I)=SNGL(C(I)*STEP/E(I))+TH(I)
         IF(TB(I).LT.BMIN(I)) TB(I)=BMIN(I)
         IF(TB(I).GT.BMAX(I)) TB(I)=BMAX(I)
         C(I)=DBLE(TB(I)-TH(I))*E(I)/STEP
   58 CONTINUE
   60 DO 62 I=1,NP
         IF(TH(I)*TB(I))66,66,62
   62 CONTINUE
      SUMB=ZERO
      CALL FLOW(TB,FC,NITT,NOCON,MDATA,MODE,ERRMB,HO,HO0)
      IF (MODE .EQ. 9) GO TO 144
      DO 64 I=1,NOBB
         R(I)=WT(I)*(FO(I)-FC(I))
   64 SUMB=SUMB+R(I)*R(I)
   66 SUM1=ZERO
      SUM2=ZERO
      SUM3=ZERO
      DO 68 I=1,NP
         SUM1=SUM1+C(I)*CHI(I)
         SUM2=SUM2+C(I)*C(I)
   68 SUM3=SUM3+CHI(I)*CHI(I)
      ARG=SUM1/DSQRT(SUM2*SUM3)
      ANGLE=57.29578*DATAN2(DSQRT(1.-ARG*ARG),ARG)
C
C     ----------
      DO 72 I=1,NP
      IF(TH(I)*TB(I))74,74,72
   72 CONTINUE
      IF(NET.GE.MAXTRY) GO TO 79
      IF(SUMB/SSQ-1.0D0)80,80,74
   74 IF(ANGLE-30.0D0)76,76,78
   76 STEP=0.5D0*STEP
      GO TO 56
   78 GA=DMIN1(100.D0,10.D0*GA)
      GO TO 50
   79 WRITE(21,1086)
      GO TO 96
C
C     ----- PRINT COEFFICIENTS AFTER EACH ITERATION -----
   80 CONTINUE
      DO 82 I=1,NP
   82 TH(I)=TB(I)
      rmsd=sqrt(sumb/nobb)
      WRITE(21,1042)NITT,rmsd,(TB(I),I=1,NP)
   90 DO 92 I=1,NP
      IF(ABS(C(I)*STEP/E(I))/(1.0E-20+ABS(TH(I)))-STOPCR) 92,92,94
   92 CONTINUE
      GO TO 96
   94 SSQ=SUMB
      IF(NITT.LT.MIT) GO TO 34
C
C     ----- END OF ITERATION LOOP -----
   96 CONTINUE
C     IF(SUMB.GT.10.0D0) GO TO 143
C     IF(SUMB.LT.1.0D0) IRUN=IRUN+1
      WRITE(21,1044) ERRMB
      CALL MATINV(D,NP)
C
C     ----- WRITE RSQUARE, CORRELATION MATRIX -----
      SUMS=SNGL(SUMB)
      SUMS1=0.0
      SUMS2=0.0
      DO 98 I=1,NOBB
      FOS=SNGL(FO(I))
      SUMS1=SUMS1+FOS
   98 SUMS2=SUMS2+FOS*FOS
      RSQ= 1.-SUMS/(SUMS2-SUMS1*SUMS1/NOBB)
```

```
      WRITE(21,1050) RSQ
      IF (NP. EQ. 1) GO TO 106
      DO 100 I=1,NP
  100 E(I)=DSQRT(DMAX1(D(I,I),1.0D-30))
      WRITE(21,1046) (I,I=1,NP)
      DO 104 I=1,NP
      DO 102 J=1,I
  102 AS(J,I)=SNGL(D(J,I)/(E(I)*E(J)))
  104 WRITE(21,1048) I,(AS(J,I),J=1,I)
C
C     ----- CALCULATE 95% CONFIDENCE INTERVAL -----
  106 Z=1./FLOAT(NOBB-NP)
      SDEV=SQRT(Z*SUMS)
      WRITE(21,1052)
      TVAR=1.96+Z*(2.3779+Z*(2.7135+Z*(3.187936+2.466666*Z**2)))
      DO 108 I=1,NP
         SECOEF=SNGL(E(I))*SDEV
         TSEC=TVAR*SECOEF
         TMCOE=TH(I)-TSEC
         TPCOE=TH(I)+TSEC
  108 WRITE(21,1058) BI(I),TH(I),SECOEF,TMCOE,TPCOE
C
C     ----- PREPARE FINAL OUTPUT -----
  110 WRITE(21,1066) TTYPE
      DO 118 I=1, NOBB
         FOS=SNGL(FO(I))
         FCS=SNGL(FC(I))
         RS=FOS-FCS
         if (nresul .eq. 1) write(25,'(2f10.3)') TO(i),fcs
           IF (I.LE.NOBB-1) THEN
            WRITE(21,1068) I,TO(I),OBS_HEIGHT(I),FOS,FCS,RS
           ELSE
             WRITE(21,1068) I,TO(I),ZD,FOS,FCS,RS
           ENDIF
  118 CONTINUE
      WRITE(23,119)'#','TIME(hr)','HC_OBS(cm)','HC_OPT(cm)','DFHC',
     +'Q_OBS(ml)','Q_OPT(ml)','DFQ'
  119 FORMAT(1X,A6,2X,A9,2X,A7,4X,A7,5X,A5,6X,A6,5X,A6,7X,A4)
      DO 120 I=1,NOBB,2
         DHC=ABS(FO(I)-FC(I))
        DQ=ABS(FO(I+1)-FC(I+1))
        WRITE(23,122) I,TO(I),FO(I),FC(I),DHC,FO(I+1),FC(I+1),DQ
  120 CONTINUE
  122 FORMAT(1X,I6,7(F10.4,1X))
C
C     ----- WRITE SOIL HYDRAULIC PROPERTIES -----
      press=-1.412532
      ssq01=0
      ssq02=0
       x=0.
      do 140 i=1,30
         press=1.412532*press
           wc=spr(1,press,x)
           akln=spr(2,press,x)
         if (irun .eq. 1) then
              theta(i)=100*wc
              kuns(i)=akln
         endif
  140 continue
  144 CONTINUE
C
C     ----- END OF PROBLEM -----
 1002 FORMAT(1H1,10X,67(1H*),65X,1h*/11X,1H*,65X,1H*)
 1006 FORMAT(11X,1H*,A65,1H*)
 1007 FORMAT(11X,1H*,23X,'SAMPLE  ',A15,19X,1H*)
 1008 FORMAT(11X,1H*,65X,1H*/11X,67(1H*))
 1014 FORMAT(/2I5,E10.1,10X,3F10.0)
 1016 FORMAT(4F10.0,4I5/)
 1018 FORMAT(//11X,'PROGRAM PARAMETERS'/11X,18(1H=)/11X,
     +'NUMBER OF NODES.....................(NN)................',I3/11X,
     +'NODE AT SOIL-PLATE BOUNDARY.........(LNS)...............',I3/11X,
     +'INITIAL TIME STEP...................(DNUL)............',E9.2/11X,
     +'PNEUMATIC PRESSURE..................(AIRP)...........',F8.3/11X,
```

```
     +'TEMPORAL WEIGHTING COEFF............(EPS1)............',F7.2/11X,
     +'ITERATION WEIGHTING COEFF...........(EPS2)............',F7.2/11X,
     +'MAX. ITERATIONS.....................(MIT)...............',I3/11X,
     +'DATA MODE...........................(MDATA).............',I3/11X,
     +'NO. OF OBSERVATIONS.................(NOBB)..............',I3)
 1020 FORMAT(6F10.0)
 1021 FORMAT(3F10.0,I5,F10.0)
 1022 FORMAT(6I10)
 1023 FORMAT(/11X,'INITIAL CAPILLARY PRESSURE HEAD AT TOP OF SAMPLE :'
     +,F8.1)
 1024 FORMAT(//11X,'PARAMETERS OF THE FIXED RETENTION CURVE :'/11X,
     +'FIRST COEFFICIENT...................(ALPHA)...........',F8.3/11X,
     +'SECOND COEFFICIENT..................(N)...............',F8.3/11X,
     +'RESIDUAL MOISTURE CONTENT...........(WCR).............',F8.3/11X,
     +'SATURATED MOISTURE CONTENT..........(WCS).............',F8.3)
10248 FORMAT(//11X,'PARAMETERS OF THE FIXED RETENTION CURVE :'/11X,
     +'FIRST COEFFICIENT...................(LOG10hm).......',F8.3/11X,
     +'SECOND COEFFICIENT..................(sigma)...........',F8.3/11X,
     +'RESIDUAL MOISTURE CONTENT...........(WCR).............',F8.3/11X,
     +'SATURATED MOISTURE CONTENT..........(WCS).............',F8.3)
 1026 FORMAT(//11X,'SOIL AND PLATE PROPERTIES'/11X,25(1H=)/11X,
     +'SOIL COLUMN LENGTH..................(SLL).............',F8.3/11X,
     +'COLUMN DIAMETER.....................(DIAM)............',F8.3/11X,
     +'THICKNESS OF PLATE..................(PLL).............',F8.3/11X,
     +'PLATE CONDUCTIVITY..................(CONDS(2))......  ',E9.4/11X,
     +'SATURATED MOISTURE CONTENT..........(WCS).............',F8.3/11X,
     +'RESIDUAL MOISTURE CONTENT...........(WCR).............',F8.3/11X,
     +'FIRST COEFFICIENT...................(ALPHA)...........',F8.3/11X,
     +'SECOND COEFFICIENT..................(N)...............',F8.3/11X,
     +'SATURATED CONDUCTIVITY SOIL.........(CONDS(1)).....   ',E9.4/11X,
     +'EXPONENT L MUALEM-GENUCHTEN.........(EXPL)............',F8.3)
10268 FORMAT(//11X,'SOIL AND PLATE PROPERTIES'/11X,25(1H=)/11X,
     +'SOIL COLUMN LENGTH..................(SLL).............',F8.3/11X,
     +'COLUMN DIAMETER.....................(DIAM)............',F8.3/11X,
     +'THICKNESS OF PLATE..................(PLL).............',F8.3/11X,
     +'PLATE CONDUCTIVITY..................(CONDS(2))......  ',E9.4/11X,
     +'SATURATED MOISTURE CONTENT..........(WCS).............',F8.3/11X,
     +'RESIDUAL MOISTURE CONTENT...........(WCR).............',F8.3/11X,
     +'FIRST COEFFICIENT...................(LOG10hm).......',F8.3/11X,
     +'SECOND COEFFICIENT..................(sigma)...........',F8.3/11X,
     +'SATURATED CONDUCTIVITY SOIL.........(CONDS(1)).....   ',E9.4/11X,
     +'EXPONENT L MUALEM-GENUCHTEN.........(EXPL)............',F8.3)
 1027 FORMAT(//11X,'INITIAL CONDITIONS'/11X,18(1H=)/11X,'NODE',2X,'DEPTH
     1',2X,'PRESSURE HEAD',5X,'MOISTURE CONTENT')
 1028 FORMAT(2I5,2F10.0)
 1030 FORMAT(//5X,8(1H*),'ERROR ENCOUNTERED WHILE READING INITIAL CONDIT
     1IONS, CHECK NODE',I4,1X,'EXECUTION TERMINATED',9(1H*))
 1032 FORMAT(//11X,'OBSERVED ',A/11X,16(1H=)/14X,'OBS',5X,'HRS',5X,A,4X,
     1'TYPE',4X,'WEIGHT')
 1038 FORMAT(42X,6(F8.4,3X))
 1040 FORMAT(///2X,'ITERATION NO',6X,'SSQ',5X,6(5X,A))
 1041 FORMAT(T2,A5,I3,F8.3,F8.2,F8.4,5F8.3,2F8.1)
 1042 FORMAT(6X,I2,5X,D12.4,8X,6(F8.4,3X))
 1044 FORMAT(//11X,'MASS BALANCE ERROR IN FE SOLUTION DURING FINAL RUN W
     1AS ',F12.4,' %')
 1045 FORMAT('+',T4,'SAMPLE: ',A15,'  PAR. SET: ',I8,'  ITERATION: ',I2)
 1046 FORMAT(//11X,'CORRELATION MATRIX'/11X,18(1H=)/14X,10(4X,I2,5X))
 1047 FORMAT(T2,'   NR IT     SSQ    MBAL    ALFA       N    ORES',
     1       '    OSAT    KSAT       L')
 1048 FORMAT(11X,I3,10(2X,F7.4,2X))
 1050 FORMAT(//11X,'RSQUARE FOR REGRESSION OF PREDICTED VS OBSERVED =',
     1F7.5)
 1052 FORMAT(//11X,'NON-LINEAR LEAST-SQUARES ANALYSIS: FINAL RESULTS'/
     111X,48(1H=)/53X,'95% CONFIDENCE LIMITS'/11X,'VARIABLE',8X,'VALUE',
     27X,'S.E.COEFF.',4X,'LOWER',8X,'UPPER')
 1058 FORMAT(13X,A,4X,F10.5,5X,F9.4,3X,F9.4,3X,F9.4)
 1062 FORMAT(10X,I4,1X,F7.2,F11.3,8X,F9.4)
 1066 FORMAT(//10X,8(1H-),'OBSERVED & FITTED ',A,8(1H-)/54X,'RESI-'/1
     10X,'NO',3X,'TIME (HR)',6X,'Z',6X,'OBS',4X,'FITTED',4X,'DUAL')
 1068 FORMAT(7X,I5,2F10.3,1X,3F9.3)
 1069 FORMAT(1H1,10X,'PRESSURE',4X,'LOG P',6X,'WC',7X,'REL K',5X,'LOG RK
     1',6X,'ABS K',4X,'LOG KA',5X,'DIFFUS',5X,'LOG D')
 1070 FORMAT(10X,E10.3,F8.3,F10.4,3(E13.3,F8.3))
```

```
 1072 FORMAT(10X,E10.3,8X,F10.4,E13.3,8X,E13.3)
 1074 FORMAT(//3X,'SSQ OF RETENTION CURVE : ',F8.3,/3X,'SSQ OF
     1CONDUCTIVITY CURVE : ',F8.3)
 1080 FORMAT(//11X,'FINAL CONDITIONS'/11X,16(1H=)/25X,'PRESSURE HEAD',1
     1X,'MOISTURE CONTENT'/11X,'NODE',2X,'DEPTH',3X,'FUNCTION',3X,'GRADI
     2ENT',6X,'FUNCTION',3X,'GRADIENT')
 1082 FORMAT(//11X,'INITIAL AMOUNT OF MOISTURE IN SAMPLE     =',F8.3,' C
     1M3'/11X,'FINAL     ,,         ,,                  =',F8.3,'  ,, ')
 1086 FORMAT(//11X,'NO FURTHER REDUCTION IN SSQ OBTAINED, OPTIMIZATION S
     1TOPPED')
 1088 FORMAT(//11X,I5,' STEPS IN PNEUMATIC PRESSURE  :',/11X,'    TIME',
     1'  PRESSURE'/)
 1090 FORMAT(11X,F8.2,F10.1)

      STOP
      END
      SUBROUTINE QRSOLV(A,NP,B)
C
C     PURPOSE: TO SOLVE LINEAR SYSTEM A*X=B BY QR-DECOMPOSITION
C              WHERE A IS J'*J , B IS J'*R, AND ' DENOTES TRANSPOSE.
C              THE SOLUTION X IS THE PARAMETER CORRECTION
C
      DOUBLE PRECISION A(6,6),B(6),A1(6),A2(6),SS,SIGM,TERM
C
C     REDUCE A TO UPPER TRIANGULAR FORM BY HOUSEHOLDER TRANSFORMATIONS
C     ----------
      IF(NP.EQ.1) THEN
        B(NP)=B(NP)/A(NP,NP)
        GO TO 300
      ENDIF
      NR=NP-1
      DO 200 K=1,NR
        IF(A(K,K).EQ.0.0D0) THEN
          A1(K)=0.0D0
          GO TO 200
        ENDIF
        SS=0.0D0
        DO 20 I=K,NP
          A(I,K)=A(I,K)
          SS=SS+A(I,K)*A(I,K)
   20   CONTINUE
        SIGM=DSQRT(SS)
        IF(A(K,K).LT.0.0) SIGM= -SIGM
        A(K,K)=A(K,K)+SIGM
        TERM=SIGM*A(K,K)
        A1(K)=TERM
        A2(K)=-SIGM
        DO 100 J=K+1,NP
          SS=0.0
          DO 80 I=K,NP
            SS=SS+A(I,K)*A(I,J)
   80     CONTINUE
          SS=SS/TERM
          DO 90 I=K,NP
            A(I,J)=A(I,J)-SS*A(I,K)
   90     CONTINUE
  100   CONTINUE
  200 CONTINUE
      A2(NP)=A(NP,NP)
C
C     ------ APPLY TRANSFORMATIONS TO B ------
      DO 230 J=1,NR
        SS=0.0D0
        DO 210 I=J,NP
          SS=SS+A(I,J)*B(I)
  210     CONTINUE
        SS=SS/A1(J)
        DO 220 I=J,NP
          B(I)=B(I)-SS*A(I,J)
  220     CONTINUE
  230 CONTINUE
C
C     ------ SOLVE TRIANGULAR SYSTEM -----
```

```
      B(NP)=B(NP)/A2(NP)
      DO 260 I=NR,1,-1
        SS=0.0D0
        DO 250 J=I+1,NP
          SS=SS+A(I,J)*B(J)
  250     CONTINUE
        B(I)=(B(I)-SS)/A2(I)
  260 CONTINUE
C
C     ----- DONE, SOLUTION IS RETURNED IN B -----
  300 RETURN
      END
C     -------
      SUBROUTINE MATINV(A,NP)
C
C     PURPOSE : TO INVERT J'*J
C     ----------
      DOUBLE PRECISION A(6,6),INDX(6,2),P,AMAX
      DO 2 J=1,6
    2 INDX(J,1)=0
      I=0
    4 AMAX=-1.0D0
      DO 12 J=1,NP
      IF(INDX(J,1).NE.0.0) GO TO 12
    6 DO 10 K=1,NP
      IF(INDX(K,1).NE.0.0) GO TO 10
    8 P=DABS(A(J,K))
      IF(P.LE.AMAX) GO TO 10
      IR=J
      IC=K
      AMAX=P
   10 CONTINUE
   12 CONTINUE
      IF(AMAX) 30,30,14
   14 INDX(IC,1)=IR
      IF(IR.EQ.IC) GO TO 18
      DO 16 L=1,NP
      P=A(IR,L)
      A(IR,L)=A(IC,L)
   16 A(IC,L)=P
      I=I+1
      INDX(I,2)=IC
   18 P=1./A(IC,IC)
      A(IC,IC)=1.0D0
      DO 20 L=1,NP
   20 A(IC,L)=A(IC,L)*P
      DO 24 K=1,NP
      IF(K.EQ.IC) GO TO 24
      P=A(K,IC)
      A(K,IC)=0.0
      DO 22 L=1,NP
   22 A(K,L)=A(K,L)-A(IC,L)*P
   24 CONTINUE
      GO TO 4
   26 IC=INDX(I,2)
      IR=INDX(IC,1)
      DO 28 K=1,NP
      P=A(K,IR)
      A(K,IR)=A(K,IC)
   28 A(K,IC)=P
      I=I-1
   30 IF(I) 26,32,26
   32 RETURN
      END
C
C
      SUBROUTINE FLOW(BN,FC,NITT,NOCON,MDATA,MODE,ERRMB,HO,HO0)
      PARAMETER (NO=500,NZ=100)
      DOUBLE PRECISION FC(NO),HO(NO),HO0,HOO
      DIMENSION T(NZ),PE(NZ),TE(NZ),BN(12),D(NZ),COND(NZ)
      DIMENSION CAP(NZ),A(NZ),F(NZ),DEPTH(NZ)
      COMMON/ST1/IOBS,SMT1,ISTP1,IFLAG,OLDT
      COMMON/HYPR/PARM(6),RHOW,RHONW,IEQ
```

```
      common/theta/at,rt,wcrt,wcst,khall
      common/press/airp, pressu(10),tpress(10),npress,tprint(NZ),nprint
      COMMON /AAA/delx,P(NZ),NN,AREA,LNS,PLL,SLL,PN1,TO(NO),
     + DNUL, NOB,NOB2,TMINIT,EPS1,EPS2,IINDEX(6),NVAR,CPLT,ITYPE(NO),
     + NOB1,NOBB,PIN(NZ),IRUN,ZD,BC_P,ZX
      DATA NITMAX/10/,TOL1/0.50/,TOL2/0.0025/,NSTEPS/10000/,DELMAX/0.05/
      DATA NOMAX/45/
C
C     ----- DEPTH FOR DISTRIBUTION ----
      DO 3 I=1,NN
c          IF (I .LE. LNS) DEPTH(I)=(I-1)*DELX1
c          IF (I .GT. LNS) DEPTH(I)=SLL+(I-LNS)*DELX2
                         depth(i)=(i-1)*delx
   3  CONTINUE
      TREFF=0.123

        HOO=0.5*(HO0+HO(1))
      DO 35 L=1,NN
c         IF (L .LE. LNS) THEN
c           P(L)=(-ZX+HOO-(SLL+PLL)*RHOW)+(L-1)*DELX1*RHOW
c         ELSE
c           P(L)=(-ZX+HOO-(SLL+PLL)*RHOW)+(SLL+(L-LNS)*DELX2)*RHOW
c         ENDIF
            P(L)=(-ZX+HOO-(SLL+PLL)*RHOW)+(L-1)*DELX*RHOW
  35  CONTINUE

      if (airp .lt. 0) then
         pn1=HOO-pressu(1)
         bc_p=pressu(1)
      else
         pn1=HOO-airp
         bc_p=airp
      endif

C     ----- UPDATE PARAMETER ARRAY ----
      K=0
      NU1=NVAR+1
      NU2=NVAR*2
      DO 2 I=NU1,NU2
      IF(IINDEX(I-NVAR).EQ.0) GO TO 2
      K=K+1
      BN(I)=BN(K)
    2 CONTINUE
      PARM(1)=BN(7)
      PARM(2)=BN(8)
      PARM(3)=BN(9)
      PARM(4)=BN(10)
      PARM(5)=BN(11)
      PARM(6)=BN(12)
C     ----- DEFINE INITIAL CONDITIONS & CALCULATE OUTFLOW
C                                   DURING SATURATED STAGE--------
      NE=NN-1
      iprint=1
      ipress=2
      PNB=PN1
      DRAIN=0.0
      NMB=0
      ERRMB=0.0
      EPSM=1.-EPS2
      ISTP1=1
      IOBS=1
      QOUT=0.
      IFLAG=0
      SMT1=0
      IF((NITT.GT.0).OR.(IRUN.GT.1)) GO TO 5
      DO 4 I=1,NN
      PIN(I)=P(I)
    4 CONTINUE
      NOB1=NOB-1
      IF(MDATA.LE.1) NOB1=NOB
    5 DO 6 I=1,NN
      P(I)=PIN(I)
    6 CONTINUE
```

```
      P(NN-1)=PNB
C
C     ----- SOLVE FOR FIRST STAGE OF OUTFLOW -----
      CUMDR=QOUT
      DO 8 I=1,NN
         PE(I)=P(I)
         IF (I .LE. LNS) THEN
c           X=(I-1)*DELX1
            X=(I-1)*DELX
            IF (KHALL .EQ. 0) T(I)=SPR(1,P(I),X)
            IF (KHALL .NE. 0) T(I)=SPRT(1,P(I))
         ENDIF
    8 CONTINUE
C
C     ------ DETERMINE AMOUNT OF WATER IN SAMPLE -----
      TMIN=AREA*TOTALM(T,DELX,LNS)
      TMINIT=TMIN+QOUT
      TMW0=TMINIT
      CUMQ0=0.
      CUMQ1=0.
      CUMQ2=0.
      DELT=DNUL
      DELMIN=0.00005*DNUL
      SUMT=SMT1+DELT
      ISTEP=ISTP1
C
C     ----- DYNAMIC PART OF PROGRAM -----
   10 NIT=0
   12 NIT=NIT+1
      DO 14 I=1,NN
         T(I)=PE(I)
C     ---- NODAL CONDUCTIVITY & CAPACITY -----
          IF (I .LE. LNS) THEN
c            X=(I-1)*DELX1
             X=(I-1)*DELX
             PR=0.5*(P(I)+PE(I))
c            COND(I)=SPR(2,PR,X)/DELX1
             COND(I)=SPR(2,PR,X)/DELX
c            CAP(I)=SPR(3,PR,X)*DELX1/DELT
             CAP(I)=SPR(3,PR,X)*DELX/DELT
          ELSE
c            COND(I)=CPLT/DELX2
             COND(I)=CPLT/DELX
             CAP(I)=0.0
          ENDIF
   14 CONTINUE
C
C     ----- CONSTRUCT GENERAL MATRIX EQUATION -----
      F(1)=(2.*CAP(1)+CAP(2))/6.
      A(1)=-0.5*(COND(1)+COND(2))
      D(1)=-A(1)+F(1)
      DO 16 I=2,NE
      F(I)=(CAP(I-1)+4.*CAP(I)+CAP(I+1))/6.
      A(I)=-0.5*(COND(I)+COND(I+1))
      D(I)=0.5*(COND(I-1)+2.*COND(I)+COND(I+1))+F(I)
   16 CONTINUE
      F(NN)=(CAP(NE)+2.*CAP(NN))/6.
      D(NN)=-A(NE)+F(NN)
      FNN=F(NN)
      F(1)=F(1)*P(1)-0.5*DELX*(COND(1)+COND(2))*RHOW
      DO 18 I=2,ne
      F(I)=F(I)*P(I)+0.5*DELX*(COND(I-1)-COND(I+1))*RHOW
   18 CONTINUE
c     IF (NN .NE. LNS) THEN
c     F(LNS)=F(LNS)*P(LNS)+(DELX1*COND(LNS-1)-DELX1*COND(LNS+1))*RHOW/2.
c     DO 19 I=LNS+1,NE
c     F(I)=F(I)*P(I)+0.5*DELX1*(COND(I-1)-COND(I+1))*RHOW
c  19 CONTINUE
c     ENDIF
      F(NN)=F(NN)*P(NN)+0.5*DELX*(COND(NE)+COND(NN))*RHOW
C
C     ----- LOWER BOUNDARY CONDITION -----
   20 PE(NN)=PNB
```

```
      DRAIN=F(NN)-D(NN)*PE(NN)
      F(NN)=PE(NN)
      D(NN)=1.
      ANE=A(NE)
      F(NE)=F(NE)-ANE*PE(NN)
      A(NE)=0.
C
C     ----- SOLVE FOR NEW PRESSURE HEAD VALUES -----
   22 DO 24 I=2,NN
      R=A(I-1)/D(I-1)
      D(I)=D(I)-R*A(I-1)
      F(I)=F(I)-R*F(I-1)
   24 CONTINUE
      PE(NN)=F(NN)/D(NN)
      DO 26 I=2,NN
      J=NN-I+1
      PE(J)=(F(J)-A(J)*PE(J+1))/D(J)
   26 CONTINUE
      DRAIN=DRAIN-ANE*PE(NE)
C
C
C     ----- CHECK ITERATIVE PROCESS -----
   28 DO 30 I=1,NN
      TOL=TOL1+TOL2*ABS(T(I))
      IF (ABS(PE(I)-T(I)) .GT. TOL) GO TO 32
   30 CONTINUE
C     WRITE(21,1002) NIT,DELT,ISTEP,SUMT,(PE(I),I=1,NN)
      IF (DELT .LT. DELMIN) GO TO 38
      GO TO 46
   32 IF (NIT .GE. NITMAX) GO TO 36
      DO 34 I=1,NN
         TEMP=EPS2*PE(I)+EPSM*TE(I)
         TE(I)=PE(I)
         PE(I)=TEMP
   34 CONTINUE
      GO TO 12
   36 NOCON=NOCON+1
      DELT=0.5*DELT
      IF (DELT.GE.DELMIN .AND. NOCON.LE.NOMAX) GO TO 42
      IF (NOCON .GT. NOMAX) WRITE(21,1007)
   38 IF (DELT .LT. DELMIN) WRITE(21,1008) DELT,DELMIN,SUMT,NITT
      WRITE(21,1009)
      DO 40 I=1,NN
c        IF (I .LE. LNS) X=(I-1)*DELX1
c        IF (I .GT. LNS) X=SLL+(I-LNS)*DELX2
                        x=(i-1)*delx
      WRITE(21,1010)I,X,P(I),PE(I)
   40 CONTINUE
      MODE=9
      RETURN
   42 SUMT=SUMT-DELT
      DO 44 I=1,NN
   44 PE(I)=0.5*(P(I)+PE(I))
      GO TO 10
C
C     -----
   46 DRINC=AREA*DELT*DRAIN
      CUMDR=CUMDR+DRINC
C
c     ------ calculate distribution of p and theta ----------
      if ((sumt.ge.tprint(iprint)) .and. (iprint.le.nprint) .and.
     *(nprint.gt.0)) then
            write(24,1020) tprint(iprint)
            write(24,1022)
            do 31 i=1,lns
c                 x=(i-1)*delx1
                  x=(i-1)*delx
                  delf=(sumt-tprint(iprint))/delt
                  prt=pe(i)-delf*(pe(i)-p(i))
                  theta=spr(1,prt,x)
                  write(24,1021) depth(i),prt,theta
31          continue
            do 33 i=lns+1,nn
```

```
                   write(24,1021) depth(i),pe(i)
33          continue
             iprint=iprint+1
      endif
c
C     ---- CALCULATE CUM. OUTFLOW IF IFLAG=1 ------
      IF (IFLAG .EQ. 0) GO TO 50
      DO 47 I=IOBS,NOB
         IF (TO(I). GT. TO(IOBS)) GO TO 49
c        TERM=ZD/DELX1
         TERM=ZD/DELX
         NMIN=INT(TERM)+1
         NPLUS=MIN0(NMIN+1,NN)
         XINT=NMIN-TERM
         DELF=(SUMT-TO(I))/DELT
         TDRAIN=CUMDR-DELF*DRINC
         DO 48 J=1,LNS
c               X=(J-1)*DELX1
                X=(J-1)*DELX
            PRT=PE(J)-DELF*(PE(J)-P(J))
                T(J)=SPR(1,PRT,X)
   48   CONTINUE
        IF (ITYPE(I) .EQ. 2) THEN
C    ----------CUMULATIVE DRAINAGE--------
            TMIN=AREA*TOTALM(T,DELX,LNS)
            FC(I)=DBLE(TMINIT-TMIN)
C          IF (ITYPE(I) .EQ. 2) THEN
C    ----------CUMULATIVE DRAINAGE--------
C              FC(I)=0.5*(CUMQ1+CUMQ0)
            HOO=0.5*(HO(I/2-1)+HO(I/2))
            PNB=HOO-BC_P
        ELSEIF (ITYPE(I) .EQ. 1) THEN

C     --------H(X,T)---------------------

            TPLUS=DELF*P(NPLUS)+(1.-DELF)*PE(NPLUS)
            TMIN=DELF*P(NMIN)+(1.-DELF)*PE(NMIN)
            FC(I)=0.5*SLL*RHONW-DBLE(XINT*TMIN+(1.-XINT)*TPLUS)
        ENDIF
   47 CONTINUE
   49 ERRMB=ERRMB+100.*((DBLE(TMINIT-TMIN)-TDRAIN)/DBLE(TMINIT
     * -TMIN))
      IOBS=I
      NMB=NMB+1
      IFLAG=0
C
C     ----- PREPARE FOR NEXT TIME STEP -----
   50 IF (IOBS.GT.NOB1 .OR. ISTEP.GE.NSTEPS) GO TO 54
      DELCH=1.0
      IF (NIT .LE. 2) DELCH=1.25
      IF (NIT .GE. 6) DELCH=0.80
      DELCH=AMIN1(DELCH,DELMAX/DELT)
      DELT=DELT*DELCH
      DO 52 J=1,NN
        PE1=PE(J)-P(J)
        P(J)=PE(J)
c       PE(J)=P(J)+DELCH*PE1
   52 CONTINUE
      DO 53 J=1,LNS
c              X=(J-1)*DELX1
               X=(J-1)*DELX
               PRT=PE(J)
            T(J)=SPR(1,PRT,X)
   53 CONTINUE
      TMW1=AREA*TOTALM(T,DELX,LNS)
      CUMQ2=CUMQ1+(TMW0-TMW1)
      CUMQ0=CUMQ1
      CUMQ1=CUMQ2
      TMW0=TMW1
      sumt1=sumt
      sumt=sumt+delt
      if ((sumt.ge.tpress(ipress)).and.(ipress.le.npress)) then
        if (sumt1.eq.tpress(ipress)) then
```

```
c             pnb=pnb+pressu(ipress-1)-pressu(ipress)
              if (airp .lt. 0) then
                     PNB=HOO-PRESSU(IPRESS)
                     bc_p=pressu(IPRESS)
              else
                     PNB=HOO-airp
                     bc_p=airp
              endif
              ipress=ipress+1
              delt=dnul
              sumt=sumt1+delt
        else
            delt=tpress(ipress)-sumt1
            sumt=tpress(ipress)
        endif
      endif
      IF (SUMT .GE. TO(IOBS)) IFLAG=1
      ISTEP=ISTEP+1
      GO TO 10
C
C     --------------------
   54 IF(ISTEP.GE.NSTEPS) WRITE(21,1014)NSTEPS,SUMT,NITT
   58 DO 60 I=1,NN
         P(I)=PE(I)
   60 CONTINUE
C
C     ------ CALCULATE THETA(h) AND/OR K(h) IF NOB2 > 0 -----
      IF(NOB2.EQ.0) GO TO 64
      N1=NOB+1
      N2=NOB+NOB2
      X=0.5*SLL
      DO 62 I=N1,N2
            IF (ITYPE(I) .EQ. 3) FC(I)=SPR(1,TO(I),X)
            IF (ITYPE(I) .EQ. 4) FC(I)=SPR(2,TO(I),X)
   62 CONTINUE
   64 IF (NMB .NE. 0) ERRMB=ABS(ERRMB/FLOAT(NMB))
      RETURN
C
C     ----------
 1001 FORMAT(11X,4E10.3)
 1002 FORMAT(/11X,'PE(I) DURING ITERATION (NIT=',I3,' DELT=',E10.2,' IST
     1EP=',I4,' SUMT=',E10.3,')'/(10X,10F11.3))
 1003 FORMAT(11X,2F10.5)
 1007 FORMAT(//11X,'TROUBLE CONVERGING, START AGAIN WITH DIFFERENT INITI
     1AL VALUES ')
 1008 FORMAT(//11X,8(1H*),'DELT =',E11.4,', IS LESS THAN DELMIN (=',E11.
     14,'), EXECUTION TERMINATED AT TIME =',E11.4,' (NIT=)',I5)
 1009 FORMAT(//1X,' LAST CALCULATED VALUES'/11X,22(1H*)/11X,'NODE',5X,'D
     1EPTH',9X,'P(I)',9X,'PE(I)')
 1010 FORMAT(11X,I4,F10.2,2(3X,F12.4))
 1014 FORMAT(/11X,'NO. OF STEPS EXCEEDS',I4,' AT TIME=',F10.3,' DURING
     1ITERATION',I4)
 1016 FORMAT(11X,I5,F10.3,2(2X,F10.3))
 1020 FORMAT(//,' DISTRIBUTION OF PRESSURE AND WATER AFTER T = ',F8.4,
     1' HOUR'/)
 1021 FORMAT(T2,F8.2,F8.1,F8.3)
 1022 FORMAT(T2,'   DEPTH       P   THETA')
      END

C
C     -------------------
C
      FUNCTION SPR(N,PR,X)
C
C
C     PURPOSE: TO CALCULATE THE SOIL-HYDRAULIC PROPERTIES
C
      COMMON/HYPR/A,R,WCR,WCS,CONDS,EXPL,RHOW,RHONW,IEQ
      DATA SS/0.0/
C..
C...  VAN GENUCHTEN MODEL
        IF (IEQ .EQ. 1) THEN
        S=1.-1./R
```

```
        P=-(X*RHONW-PR)
      IF(P)1,10,10
    1 P=-P
      THETA=(1.+(A*P)**R)**(-S)
      IF(N-2) 2,4,6
    2 SPR=WCR+(WCS-WCR)*THETA
      RETURN
    4 T=1.-THETA*(A*P)**(R-1.)
C     IF (THETA .LT. WCR) T=S*THETA**(1./S)
      cond=conds*theta**expl*t*t
      SPR=cond
C     SPR=AMAX1(COND,1.E-08)
      RETURN
    6 T=1.+(A*P)**R
      WC=WCR+(WCS-WCR)*THETA
      SPR=(WC-WCR)*(R-1.)*A*(A*P)**(R-1.)/T + WC*SS/WCS
      RETURN
   10 GO TO (12,14,16,18),N
   12 SPR=WCS
      RETURN
   14 SPR=CONDS
      RETURN
   16 SPR=SS
      RETURN
   18 THETA=(P-WCR)/(WCS-WCR)
      S=R/(1.-R)
      IF(THETA.GT.0.999999) GO TO 20
      SPR=-(THETA**S-1.)**(1./R)/A
      RETURN
   20 SPR=0.
        RETURN
      ENDIF
C..
C...  LOGNORMAL MODEL
        IF (IEQ .EQ. 2) THEN
        P=-(X*RHONW-PR)
      IF(P)188,1088,1088
  188 P=-P
      psim=10.**a
        theta=qnorm((log(p/psim))/r)
      IF(N-2) 288,488,688
  288 SPR=WCR+(WCS-WCR)*THETA
      RETURN
  488 t=qnorm((log(p/psim))/r+r)
      cond=conds*theta**expl*t*t
      SPR=cond
c     SPR=AMAX1(COND,1.E-08)
      RETURN
  688 t=exp(-1.*(log(p/psim))**2./(2.*r**2.))
      spr=(wcs-wcr)/(2.*3.141592654)**0.5/r/p*t
      RETURN
 1088 GO TO (1288,1488,1688,1888),N
 1288 SPR=WCS
      RETURN
 1488 SPR=CONDS
      RETURN
 1688 SPR=SS
      RETURN
 1888 THETA=(P-WCR)/(WCS-WCR)
      S=R/(1.-R)
      IF(THETA.GT.0.999999) GO TO 2088
      SPR=-(THETA**S-1.)**(1./R)/A
      RETURN
 2088 SPR=0.
        RETURN
      ENDIF
C
      END
C
c     -------------------
c
      function sprt(n,pr)
c
```

```
c
c     purpose: to calculate the fixed retention curve and the capacity
c
      common/theta/at,rt,wcrt,wcst,khall
      COMMON/HYPR/A,R,WCR,WCS,CONDS,EXPL,RHOW,RHONW,IEQ
      data ss/1.e-07/
       write(6,*) 'The lognormal model does NOT support this option !!!'
      s=1.-1./rt
      if(pr)1,10,10
    1 p=abs(pr)
      theta=(1.+(at*p)**rt)**(-s)
      if(n-2) 2,2,6
    2 sprt=wcrt+(wcst-wcrt)*theta
      return
    6 t=1.+(at*p)**rt
      wc=wcrt+(wcst-wcrt)*theta
      sprt=(wc-wcrt)*(rt-1.)*at*(at*p)**(rt-1.)/t + wc*ss/wcst
      return
   10 go to (12,14,16,18),n
   12 sprt=wcst
      return
   14 sprt=conds
      return
   16 sprt=ss
      return
   18 theta=(pr-wcrt)/(wcst-wcrt)
      s=rt/(1.-rt)
      if(theta.gt.0.999999) go to 20
      sprt=-(theta**s-1.)**(1./rt)/at
      return
   20 sprt=0.
      return
      end
C
C     -------------------
C
      FUNCTION TOTALM(WC,DELX,LNS)
C
C     PURPOSE: TO EVALUATE TOTAL MOISTURE IN PROFILE
C     -----
         PARAMETER (NO=500,NZ=100)
      DIMENSION WC(NZ)
      TOTALM=0.0
      N=1
      NS=LNS-2
      IF(MOD(LNS,2).NE.0.0) GO TO 4
c     TOTALM=3.*DELX1*(WC(1)+3.*WC(2)+3.*WC(3)+WC(4))/8.
      TOTALM=3.*DELX*(WC(1)+3.*WC(2)+3.*WC(3)+WC(4))/8.
      N=4
    4 DO 10 I=N,NS,2
c         TOTALM=TOTALM+DELX1*(WC(I)+4*WC(I+1)+WC(I+2))/3.
          TOTALM=TOTALM+DELX*(WC(I)+4*WC(I+1)+WC(I+2))/3.
   10 CONTINUE
      RETURN
      END
c
        function qnorm(x)
c        implicit real*8 (a-h,o-z)
        z=abs(x/2.**(.5))
        t=1./(1.+0.5*z)
        erfc=t*exp(-z*z-1.26551223+t*(1.00002368+t*(0.37409196+
     *    t*(.09678418+t*(-.18628806+t*(.27886807+t*(-1.13520398+
     *    t*(1.48851587+t*(-.82215223+t*.17087277)))))))))
        if(x.lt.0.) erfc=2.-erfc
        qnorm=erfc/2.
        return
        end
```