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ENVIRONMENTAL SCIENCES DIVISION

MACROPORE-MESOPORE MODEL OF WATER FLOW THROUGH AGGREGATED POROUS MEDIA

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ABSTRACT

A combined, one-dimensional, macropore-mesopore, hydrologic model was developed for simulating water flow through soils for analysis of data related to water and chemical flow in soils. Flows within the macroporous system as well as interactive flows between macroporous and mesoporous systems were modeled. Computer subroutines were written and incorporated into the existing one-dimensional Terrestrial Ecosystem Hydrologic Model (TEHM) developed at ORNL. Simulation showed that macropore flow effects are important during heavy precipitation and are more significant in soils of comparatively low hydraulic conductivity (5 - 10 cm/d). Increased drainage and decreased lateral flow result from the addition of the macropore model. The effect was more pronounced in soils of large macroporosity. Preliminary results indicate that the model is insensitive to geometrical properties of macropores.

Contents

1. SUMMARY

Flow of water through macropores in soil, for which capillary effects are negligible, has important implications toward water-pollution control, waste treatment, and irrigation. Existing models, simulating only mesoporous flow, show significant discrepancies between calculated results and field data. A model was developed to account for macroporous flow within the framework of the existing one-dimensional Terrestrial Ecosystem Hydrologic Model (TEHM) (3).

The expanded model is employed for hydrologic scenarios involving ponding, saturated mesopores, or existing water in macropores. Water infiltrates through the top two layers of macropores, with excess water considered as surface runoff. Flow from mesopores to macropores is simulated when mesopores are saturated. When mesopores are unsaturated, water flows to them from macropores. Flow is assumed to be controlled by mesopores and governed by Darcy's Law. Any excess flow from macropores is considered to be lateral flow. Additional inputs to the model are volumes of macroporosity, pore dimensions, and volumes of dead-end macropores.

Simulation has focused on sensitivity of flow to hydraulic conductivity and macroporosity. For soils of high hydraulic conductivity (120 - 240 cm/d), the macropore effect is not significant, even for a macroporosity of 0.08. Infiltrated water occurs mostly as drainage from mesopores, while both lateral flow and surface runoff are negligible. On the other hand, macropores play a significant role in soils of low hydraulic conductivity (5 - 10 cm/d). An increase in macroporosity results in an increase in drainage and a decrease in lateral flow. Macropore flow effects are readily observed in the daily flow patterns within and between the mesoporous and macroporous systems. A comparison of infiltration and water-content curves for soil under heavy and light precipitation also confirmed the importance of macropores during heavy rainfall.

2. INTRODUCTION

2.1 Background

The phenomena associated with fluid flow through aggregated porous media must be considered to properly understand soil hydrology, enhanced petroleum recovery, and management of waste-disposal sites. Of special interest to this project is the bulk flow of water through soil. There is evidence that classical models based on Darcy's Law are inadequate to simulate the flow, since in many cases they produce unacceptably low infiltration rates, depths of chemical penetration, and rapid drop of water potential gradients. Clearly, a more realistic hydrodynamic model is desirable.

Several investigators (2, 5, 6, 9) concluded that a significant amount of water flows through large channels, or macropores, for which capillary effects are negligible. This channeling diverts water from the more extensive network of mesopores and becomes particularly important when surface ponding arises, during heavy rainfall, or when subsurface ponding (perched water table) occurs in winter. Macropores are defined as being water-filled at water potentials greater than -10 mbar, and mesopores are defined as being water-filled in the water potential range from -100 to -10 mbar. Beven and Germann (1) present a one-dimensional model of bulk flow in a combined mesopore/macropore system. The flow in mesoporous and macroporous systems was considered along with the interaction flow between them. Distributions of cylindrical pores and rectangular slits were adapted for the geometry of the macropores. Equations of laminar flow, based on Poiseuille's Law, were used to model the macroporous system. The presence of macropores increased overall losses to infiltration, with the effect being greatest for soils of intermediate hydraulic conductivities. However, this model was too complicated for direct application to our project.

2.2 Objective and Approach

The Environmental Sciences Division at Oak Ridge National Laboratory has developed a one-dimensional, Terrestrial Ecosystem Hydrologic Model (TEHM) (3) for simulating mesoporous flow of water in soils. The model was tested and illustrated by field data from the Walker Branch Watershed. The goal of this project was to develop a model to account for the macroporous flow and then to incorporate it into the TEHM computer model. First, a conceptual model of the combined macropore/mesopore system was developed. Then subroutines that were compatible with TEHM were written to simulate the flow in the macropores and the interactive flow between macropores and mesopores. Finally, the combined model was tested with field data and a sensitivity analysis was conducted.

3. CONCEPTUAL MODEL

A conceptual model of the macroporous system was developed, based on suggestions by R.J. Luxmoore (4), observation of the field samples, and the literature review. Geometry of pores, pore-size distribution and definition, porosity, and flow equations were considered.

3.1 Geometry of Pores

A theoretical soil profile has three main horizons, identified in order of depth as A, B, and C. The A-horizon, which extends about 30 cm into the soil, contains more sand and silt than the subsequent layers. Its macropores arise largely from biological forces such as roots and worm-holes. The B-horizon contains more clay than the A-horizon and can

extend from 30 to 180 cm into the soil. The macropores are caused mainly by physical forces, such as the expansion and shrinkage of aggregated soil particles.

The A- and B-horizons were of primary concern in our model. The shape of the macropores in those two layers was determined according to the nature of the pores. Cylindrical pores were assumed to be predominant in the A-horizon, as opposed to rectangular cracks in the B-horizon. The pore-size distribution was also analyzed but was not directly applied to the model. Results of that work are described in Appendix 10.5.

3.2 Porosity

An average value for mesoporosity was estimated to be 0.5 ml/ml for soils in both A- and B-horizons, based on findings in the literature (10). As noted above, mesoporosity can be obtained from the change in water content at soil water potentials less than -10 mbar (Fig. 14 in Appendix 10.5). Macroporosity may vary considerably, even for the same soil, due to its random nature. Its value was estimated to be 0.01 to 0.05 ml/ml in the literature (1). An appropriate value was obtained from the field data by assuming that macroporous flow was dominant whenever soil water potential was greater than -10 mbar (see Fig. 14). The change in water content for this range gave macroporosities of 0.05 to 0.15 ml/ml for different depths in the soil block study on the Walker Branch Watershed.

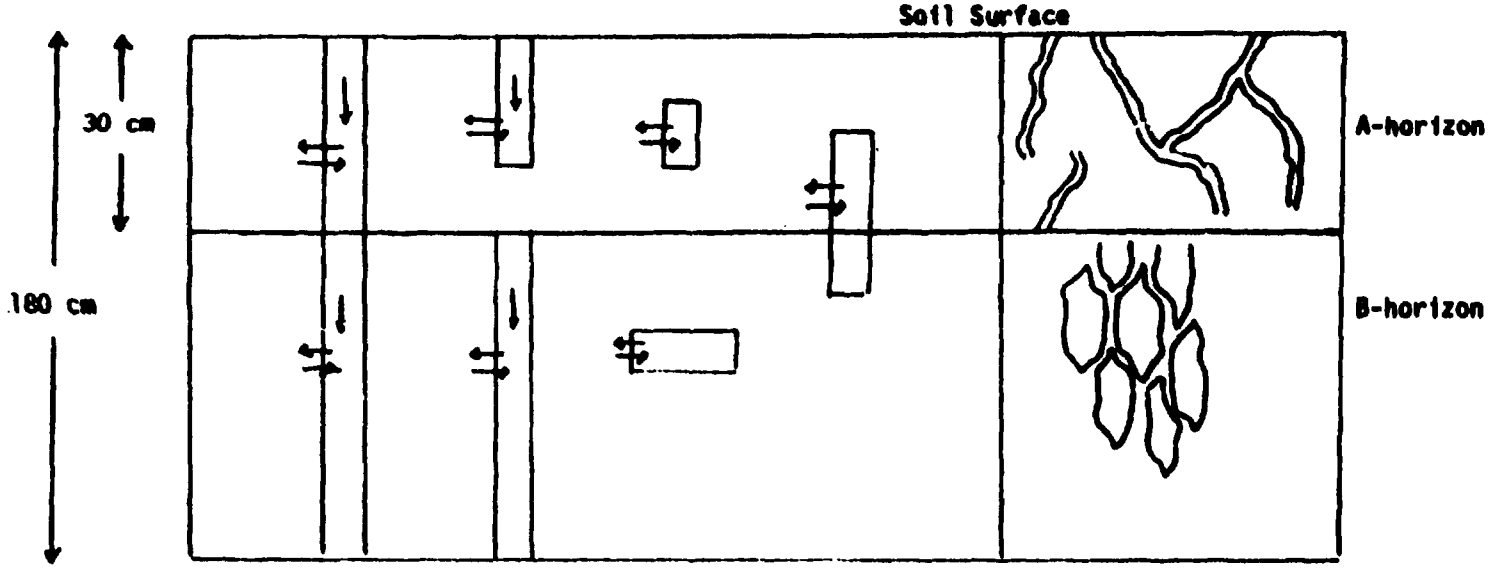
3.3 Flow Equations

Flow equations in an annulus and in a slit were adapted for cylindrical pores and rectangular cracks, respectively. The maximum flow rate allowed in both configurations was calculated for a range of sizes, as shown in Appendix 10.4. An average precipitation rate was at least three orders of magnitude smaller than the maximum flow rate through the macropores, which justified the assumption that flow in the pores was not constrained by pore configuration but rather by pore capacity.

3.4 Configurations of Pores and Flow Interactions

Both continuous and dead-end macropores were considered in the model. The different configurations are shown in Fig. 1.

During surface ponding, infiltration entered the macropores until the macropore capacity of the top two layers was exceeded; the excess was considered as surface runoff. Within each layer, flow from mesopores to macropores was simulated when the mesopores were saturated; flow from macropores to unsaturated mesopores was modeled when the macropores contained water. Only amounts above mesopore saturation were allowed to flow into the



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MACROPORES IN SOIL
WITH MESOPORE INTERACTION

DATE	DRAWN BY	FILE NO.	FIG.
5-5-80	LF	CEPS-X-312	1

macropores. The macropore-to-mesopore flow was modeled as Darcy flow, which was mesopore-controlled:

$$Q = KA \frac{d\psi}{dx} \quad (1)$$

where

Q = flux of water, cm^3/cm^2-d

K = hydraulic conductivity of soil, cm/d

ψ = hydraulic potential between macropores and mesopores, cm water

x = average distance between macropores and mesopores, cm

A = area of interaction, cm^2

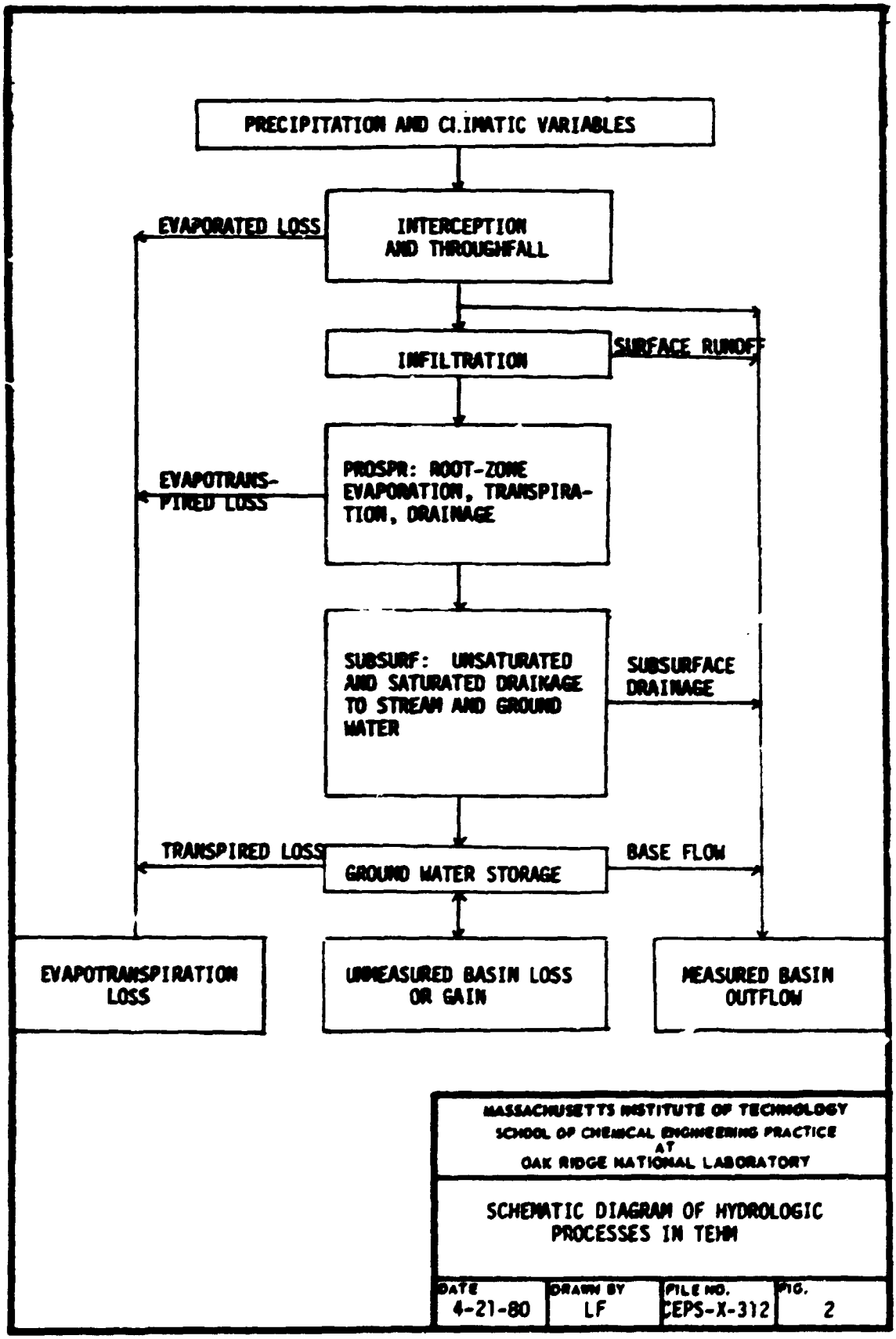
The hydraulic gradient was taken as the water potential difference from macropores to mesopores divided by half the distance between centers of two neighboring macropores.

Flow between layers into macropores was accounted for whenever the mesopores of the upper layer were saturated or if water was present in the macropores of the upper layer. Flow between layers was limited by the capacity of the macropores in the lower layer. Excess from macropores was transferred to the subsequent layer, with the excess from the last layer treated as lateral flow. Therefore, excess from macropores, instead of mesopores (as in TEHM), was considered as subsurface runoff or lateral flow. In hydrologic terms this is called interflow.

4. EXISTING MODEL

The existing Terrestrial Ecosystem Hydrologic Model (TEHM) contains the subroutine for Soil-Plant Water Flow (PROSPR). TEHM is a mechanistic model of hydrologic processes in vegetated land for simulation of interception and throughfall, infiltration, evapotranspiration and drainage, and surface and subsurface flow (3). A schematic diagram of the hydrologic processes involved is shown in Fig. 2. Precipitation data, climatic variables, vegetation characteristics, and soil properties are the major inputs to the model.

PROSPR, a subroutine in TEHM, simulates soil-layer drainage and root-zone soil-plant interactions, as shown in Fig. 3. The subroutines for macropore flow effects were incorporated into the part of PROSPR for modeling water flow through soil layers. In PROSPR, precipitation infiltrates through the surface into the mesopores of the first layer. Any excess out


PRECIPITATION AND CLIMATIC VARIABLES
EVAPORATED LOSS
INTERCEPTION AND THROUGHFALL
INFILTRATION
SURFACE RUNOFF
EVAPOTRANS-PIRED LOSS
PROSPR: ROOT-ZONE EVAPORATION, TRANSPIRATION, DRAINAGE
SUBSURF: UNSATURATED AND SATURATED DRAINAGE TO STREAM AND GROUND WATER
SUBSURFACE DRAINAGE
TRANSPIRED LOSS
GROUND WATER STORAGE
BASE FLOW
EVAPOTRANSPIRATION LOSS
UNMEASURED BASIN LOSS OR GAIN
MEASURED BASIN OUTFLOW
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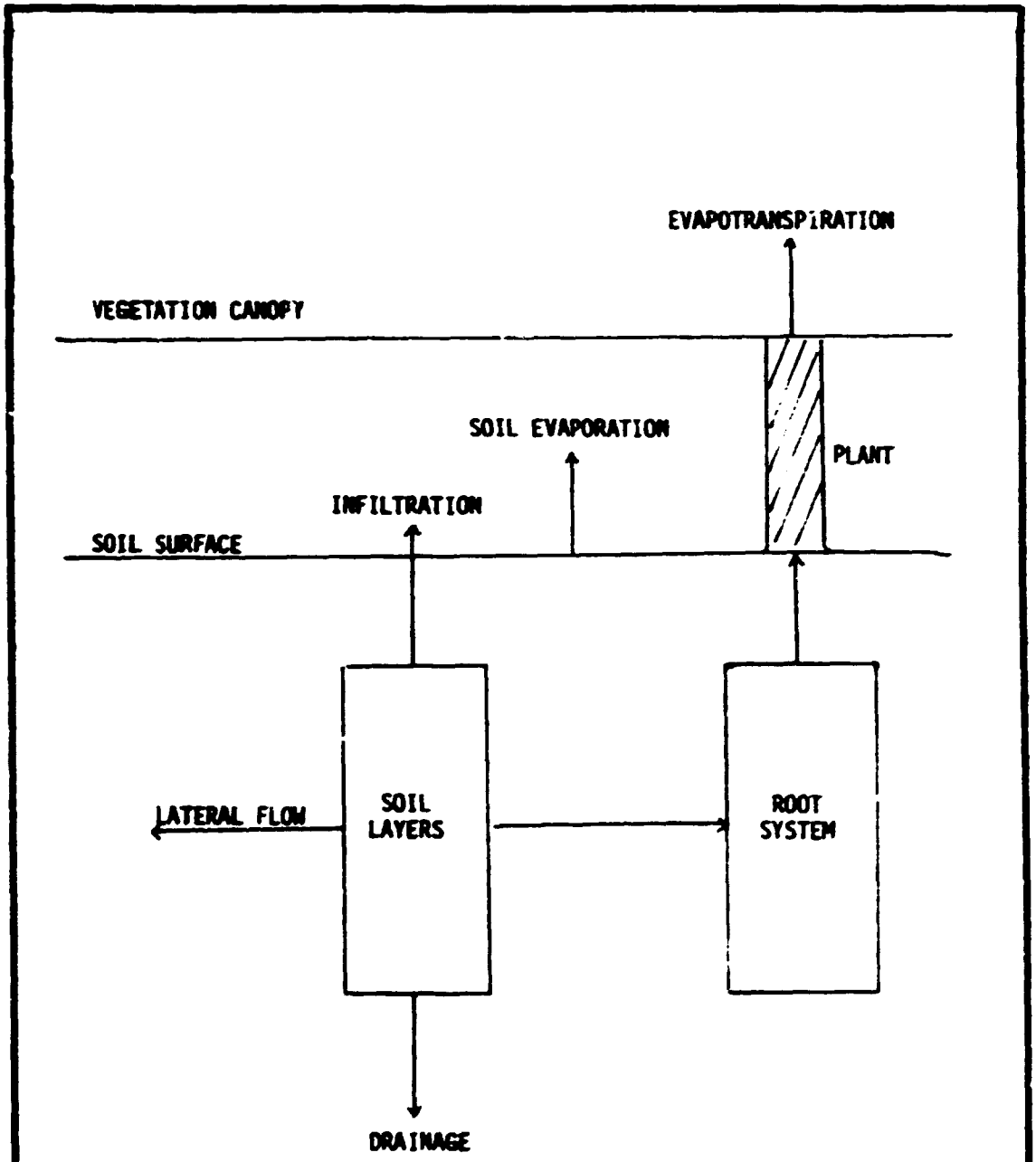
SCHEMATIC DIAGRAM OF HYDROLOGIC PROCESSES IN TEHM
DATE 4-21-80
DRAWN BY LF
FILE NO. CEPS-X-312
FIG. 2



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SCHEMATIC DIAGRAM OF PROSPR - MODEL OF ATMOSPHERE-SOIL-PLANT WATER FLOW

DATE	DRAWN BY	FILE NO.	FIG.
4-21-80	LF	CEPS-X-312	3

of the saturated mesopores is considered surface runoff in addition to that calculated by the infiltration algorithm. The remaining water drains through the layers; any excess at each layer is considered to be lateral flow, or interflow in hydrological terms. The drainage is the flow of mesopore water through the bottom layer of soil.

The interfacing of our model with PROSPR at different points in the program is shown in Fig. 4. Surface ponding was required for water to enter the macropores of the first soil layer. When water was already in the macropores or when the mesopores were saturated in any soil layers, macroporous flow was calculated for the particular layer.

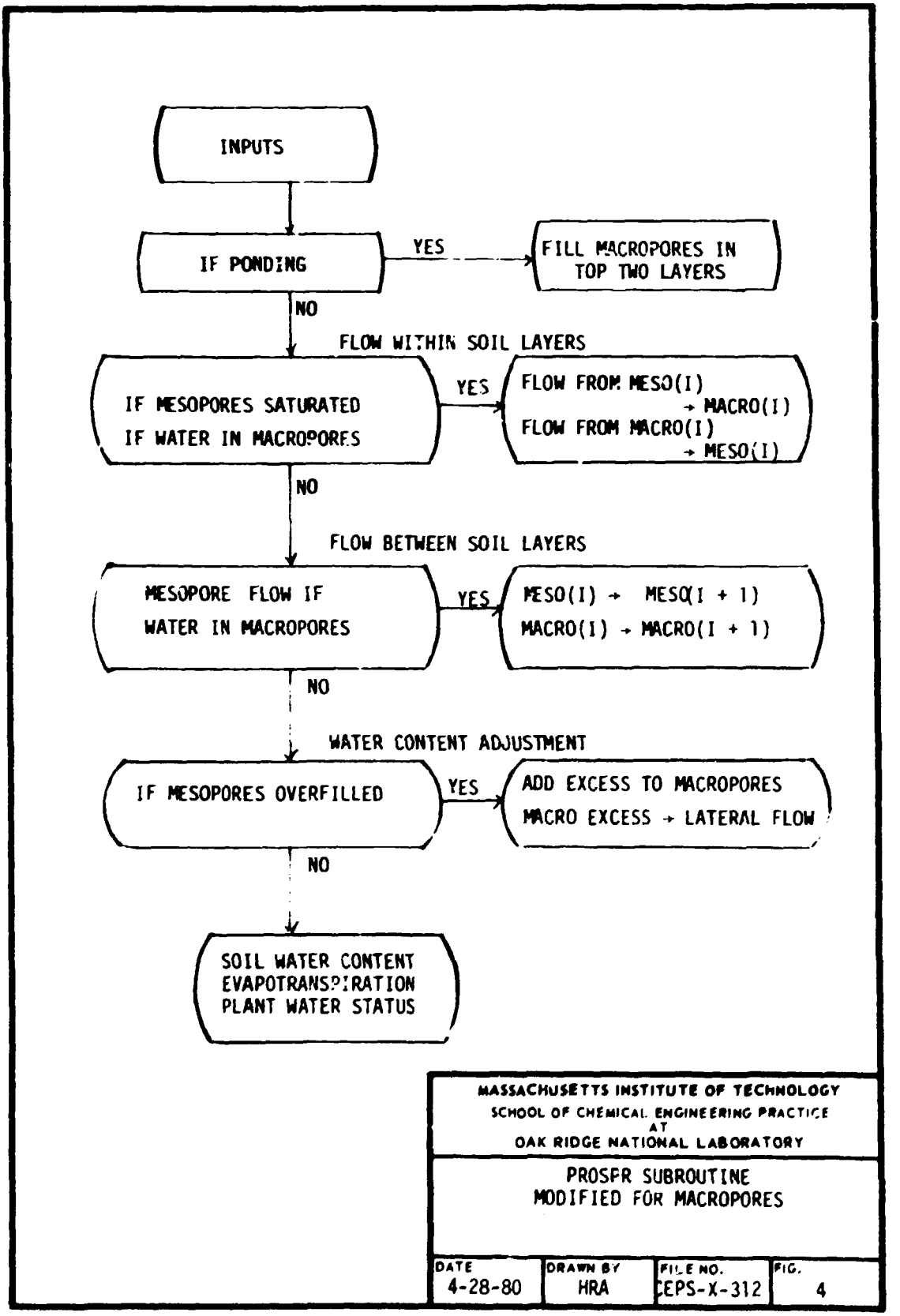
5. COMPUTER PROGRAMS

Macropore flow phenomena were simulated using inputs in the existing TEHM model and additional inputs for macroporosity, macropore geometry, and fraction of dead-end macropores. These inputs and initialization were accomplished in subroutine RSWIFT as outlined in Fig. 5. Interactive flow phenomena were developed as described in Sect. 3.4. In particular, dead-end macropores were considered as a separate but parallel case to continuous macropores, the distinction being that macropore-to-macropore flow was not allowed for dead-end macropores. When ponding existed, water was allowed to enter both continuous and dead-end macropores in the top layer. It was assumed that dead-end macropores in the top layers were open to the surface.

Top-layer flow effects are shown in Figs. 6a and 6b. Infiltration or macropore flow between layers was considered prior to flow between macropores and mesopores. A flow diagram of the general cases is presented in Figs. 7a and 7b. A complete daily and monthly flow history with water content data was obtained from the new model, printed from the WSWIFT subroutine. Programming details are presented in the Appendices.

6. EVALUATION AND SENSITIVITY ANALYSIS

The TEHM model, with the subroutines for macropore flow effects, was analyzed parametrically with data from the Walker Branch Watershed. Meteorological data for April 1953 (close to average conditions) were used and precipitation data were adapted to test the model. Infiltration was increased tenfold for the sensitivity tests of the new subroutines. The additional inputs required in subroutine RSWIFT are described in Appendix 10.6. Sets of input data are also shown in Appendix 10.3. The program was executed for a soil profile with two layers in the A-horizon and three layers in the B-horizon. One size of pores and one configuration of pores were considered in each layer. Within each layer the macropores were assumed to have uniform geometry, porosity, and percentage of dead-end pores. Values of macroporosity were assigned to be higher in the B-horizon than in the A-horizon. This was based on observations from the field study site: macropores in the B-horizon were more numerous and continuous than those in the A-horizon.


INPUTS
IF PONDING
YES
FILL MACROPORES IN TOP TWO LAYERS
NO
FLOW WITHIN SOIL LAYERS
IF MESOPORES SATURATED
IF WATER IN MACROPORES
YES
FLOW FROM MESO(I) → MACRO(I)
FLOW FROM MACRO(I) → MESO(I)
NO
FLOW BETWEEN SOIL LAYERS
MESOPORE FLOW IF WATER IN MACROPORES
YES
MESO(I) → MESO(I + 1)
MACRO(I) → MACRO(I + 1)
NO
WATER CONTENT ADJUSTMENT
IF MESOPORES OVERFILLED
YES
ADD EXCESS TO MACROPORES
MACRO EXCESS → LATERAL FLOW
NO
SOIL WATER CONTENT
EVAPOTRANSPIRATION
PLANT WATER STATUS
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AT
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PROSPR SUBROUTINE
MODIFIED FOR MACROPORES
DATE 4-28-80
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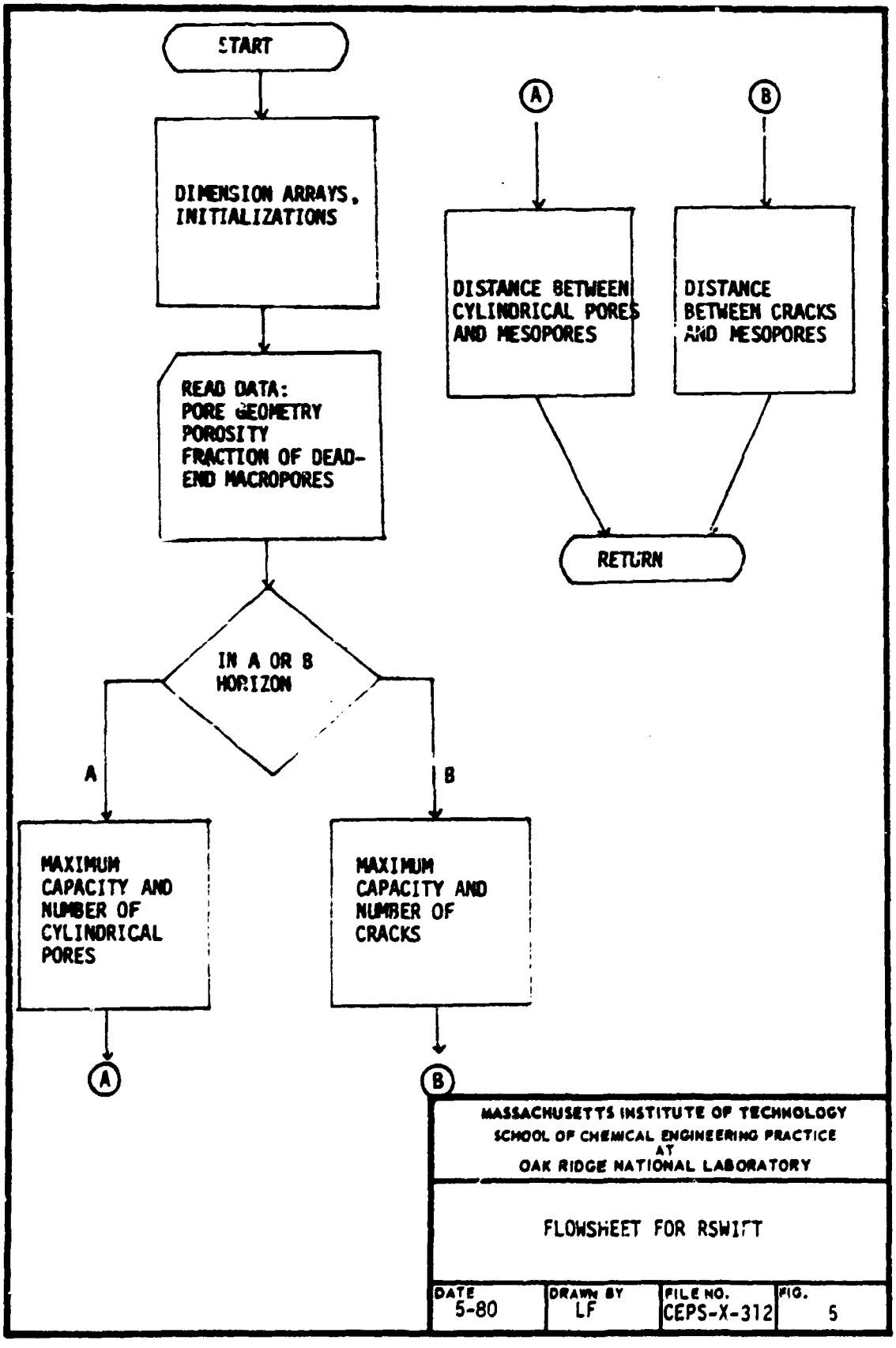
FILE NO. CEPS-X-312
FIG. 4


START
DIMENSION ARRAYS, INITIALIZATIONS
READ DATA: PORE GEOMETRY POROSITY FRACTION OF DEAD-END MACROPORES
IN A OR B HORIZON
A
B
MAXIMUM CAPACITY AND NUMBER OF CYLINDRICAL PORES
MAXIMUM CAPACITY AND NUMBER OF CRACKS
A
B
A
B
DISTANCE BETWEEN CYLINDRICAL PORES AND MESOPORES
DISTANCE BETWEEN CRACKS AND MESOPORES
RETURN
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AT
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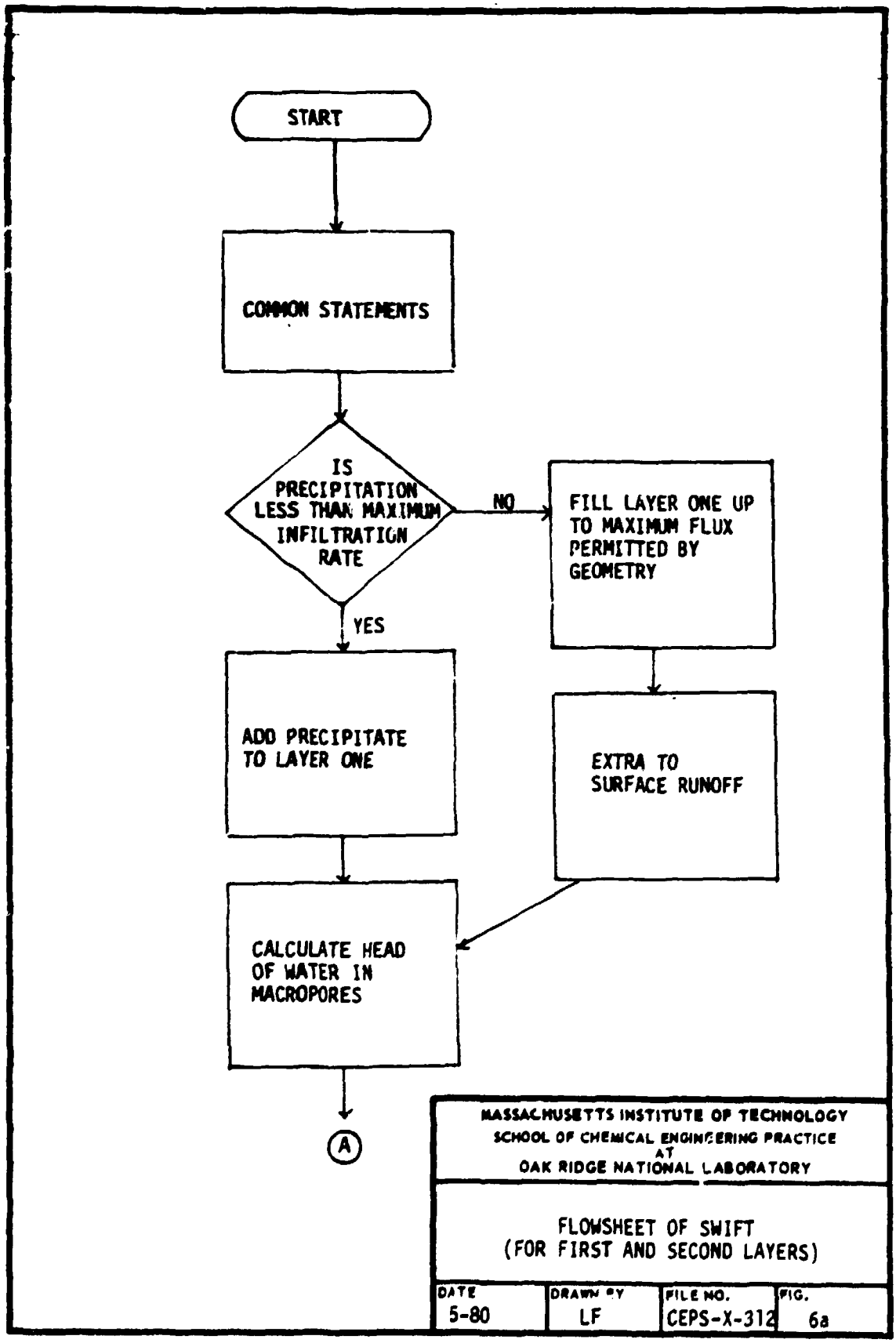
FLOWSHEET FOR RSWIFT
DATE 5-80
DRAWN BY LF
FILE NO. CEPS-X-312
FIG. 5


START
COMMON STATEMENTS
IS PRECIPITATION LESS THAN MAXIMUM INFILTRATION RATE
NO
YES
FILL LAYER ONE UP TO MAXIMUM FLUX PERMITTED BY GEOMETRY
ADD PRECIPITATE TO LAYER ONE
EXTRA TO SURFACE RUNOFF
CALCULATE HEAD OF WATER IN MACROPORES
A
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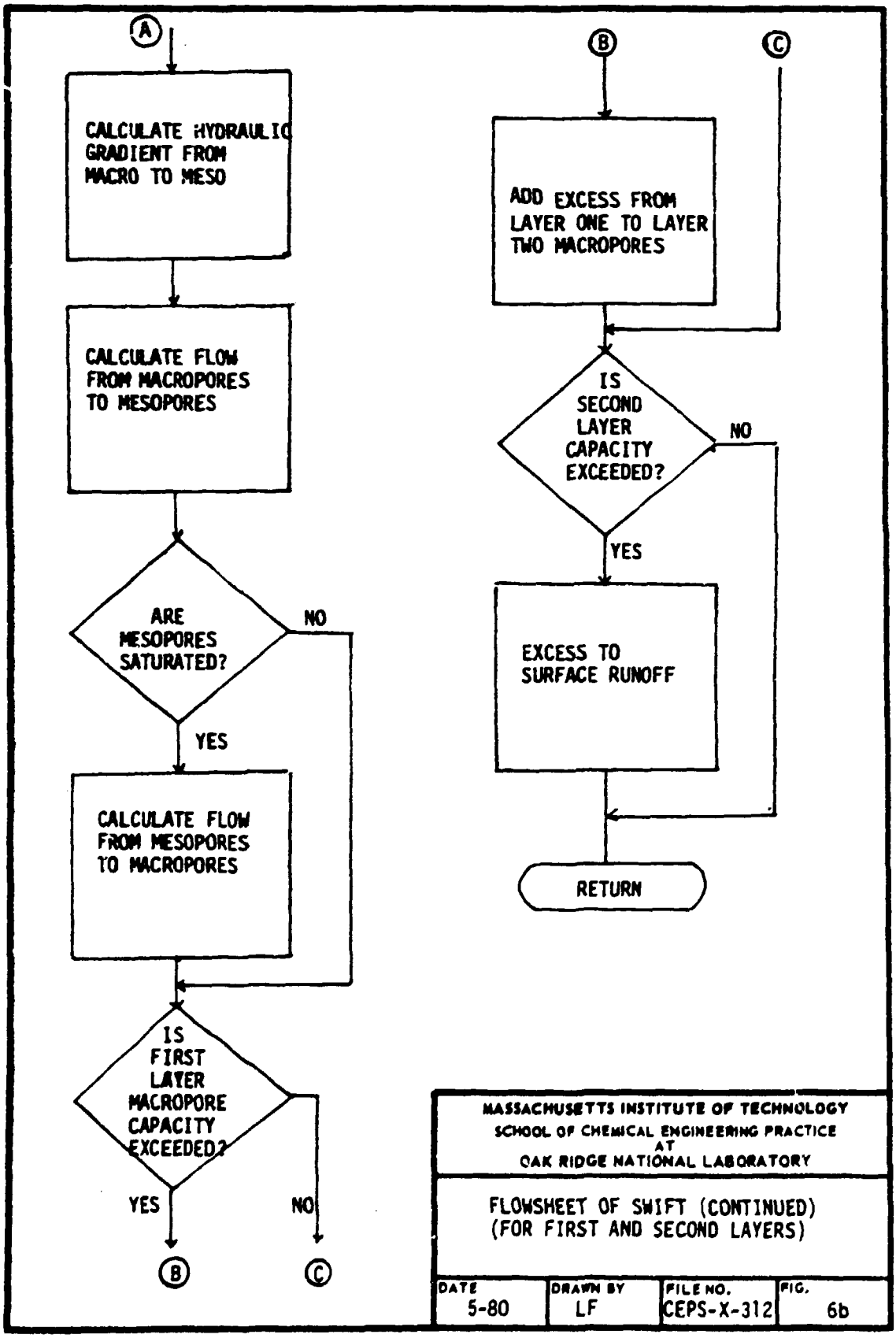
AT
OAK RIDGE NATIONAL LABORATORY
FLOWSHEET OF SWIFT
(FOR FIRST AND SECOND LAYERS)
DATE 5-80
DRAWN BY LF
FILE NO. CEPS-X-312
FIG. 6a


A
CALCULATE HYDRAULIC GRADIENT FROM MACRO TO MESO
CALCULATE FLOW FROM MACROPORES TO MESOPORES
ARE MESOPORES SATURATED?
NO
YES
CALCULATE FLOW FROM MESOPORES TO MACROPORES
IS FIRST LAYER MACROPORE CAPACITY EXCEEDED?
YES
NO
B
C
B
C
ADD EXCESS FROM LAYER ONE TO LAYER TWO MACROPORES
IS SECOND LAYER CAPACITY EXCEEDED?
NO
YES
EXCESS TO SURFACE RUNOFF
RETURN
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AT
OAK RIDGE NATIONAL LABORATORY
FLOWSHEET OF SWIFT (CONTINUED)
(FOR FIRST AND SECOND LAYERS)
DATE 5-80
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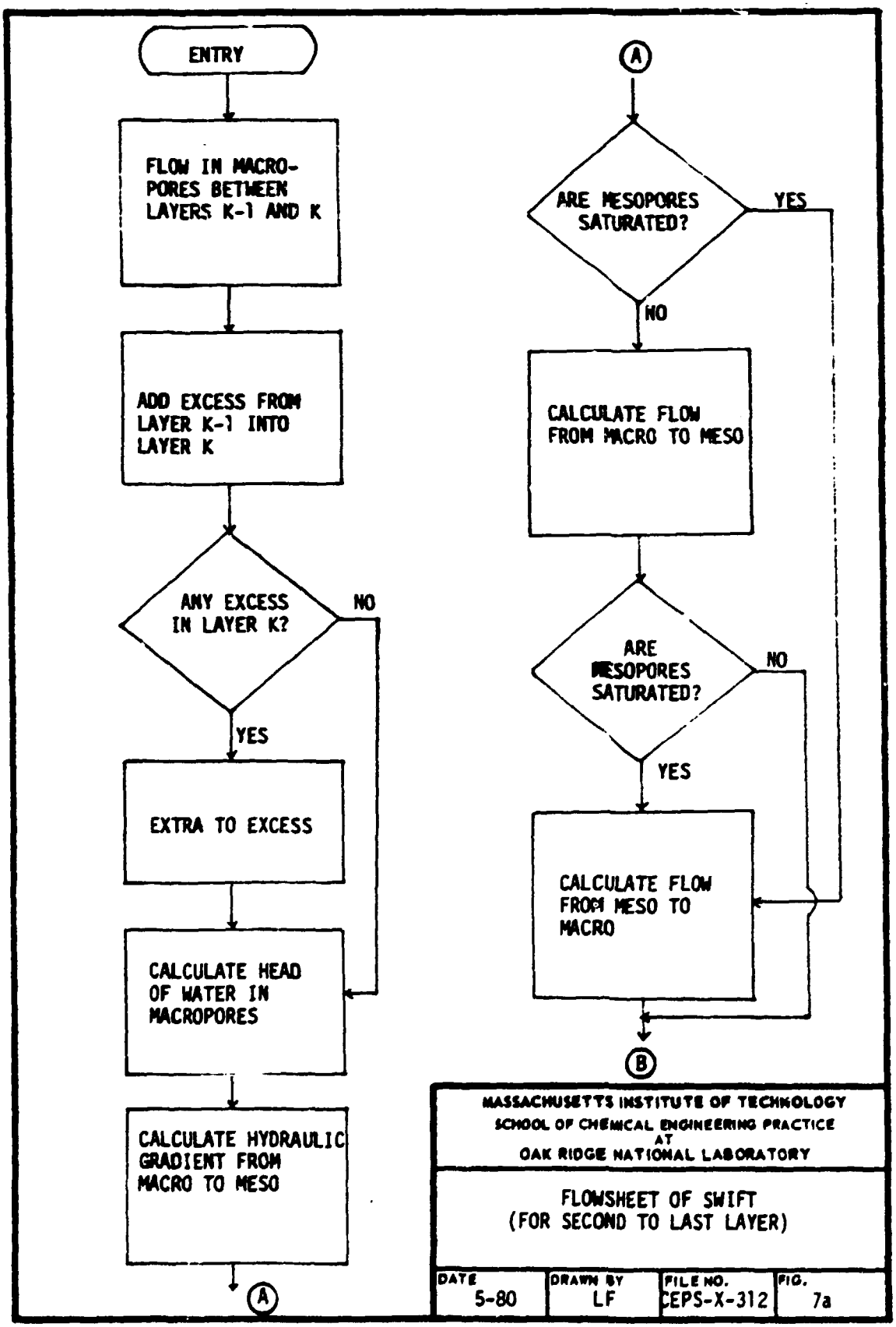
FILE NO. CEPS-X-312
FIG. 6b


ENTRY
FLOW IN MACRO-PORES BETWEEN LAYERS K-1 AND K
ADD EXCESS FROM LAYER K-1 INTO LAYER K
ANY EXCESS IN LAYER K?
NO
YES
EXTRA TO EXCESS
CALCULATE HEAD OF WATER IN MACROPORES
CALCULATE HYDRAULIC GRADIENT FROM MACRO TO MESO
A
A
ARE MESOPORES SATURATED?
YES
NO
CALCULATE FLOW FROM MACRO TO MESO
ARE MESOPORES SATURATED?
NO
YES
CALCULATE FLOW FROM MESO TO MACRO
B
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AT
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FLOWSHEET OF SWIFT
(FOR SECOND TO LAST LAYER)
DATE 5-80
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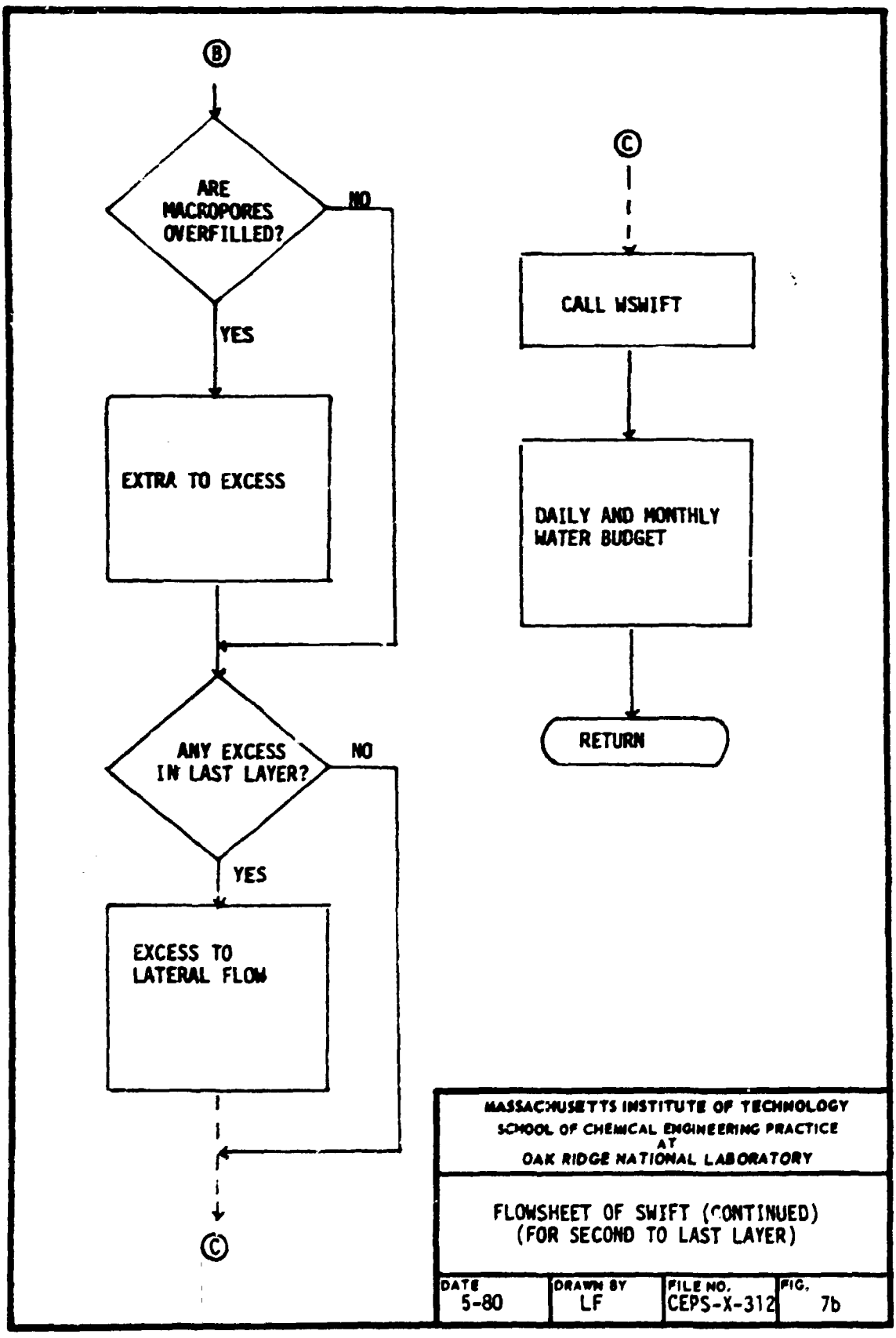
FILE NO. CEPS-X-312
FIG. 7a


B
ARE MACROPORES OVERFILLED?
NO
YES
EXTRA TO EXCESS
ANY EXCESS IN LAST LAYER?
NO
YES
EXCESS TO LATERAL FLOW
C
C
CALL WSWIFT
DAILY AND MONTHLY WATER BUDGET
RETURN
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OAK RIDGE NATIONAL LABORATORY
FLOWSHEET OF SWIFT (CONTINUED)
(FOR SECOND TO LAST LAYER)
DATE 5-80
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FIG. 7b

Two major runs were carried out for soils of high and low hydraulic conductivities and for varying macroporosities. Hydraulic conductivity and macroporosity are the two most important parameters for flow through macropores. The results, in the form of monthly water budgets, for soils of high and low hydraulic conductivities, are shown respectively in Figs. 8 and 9. A water budget shows:

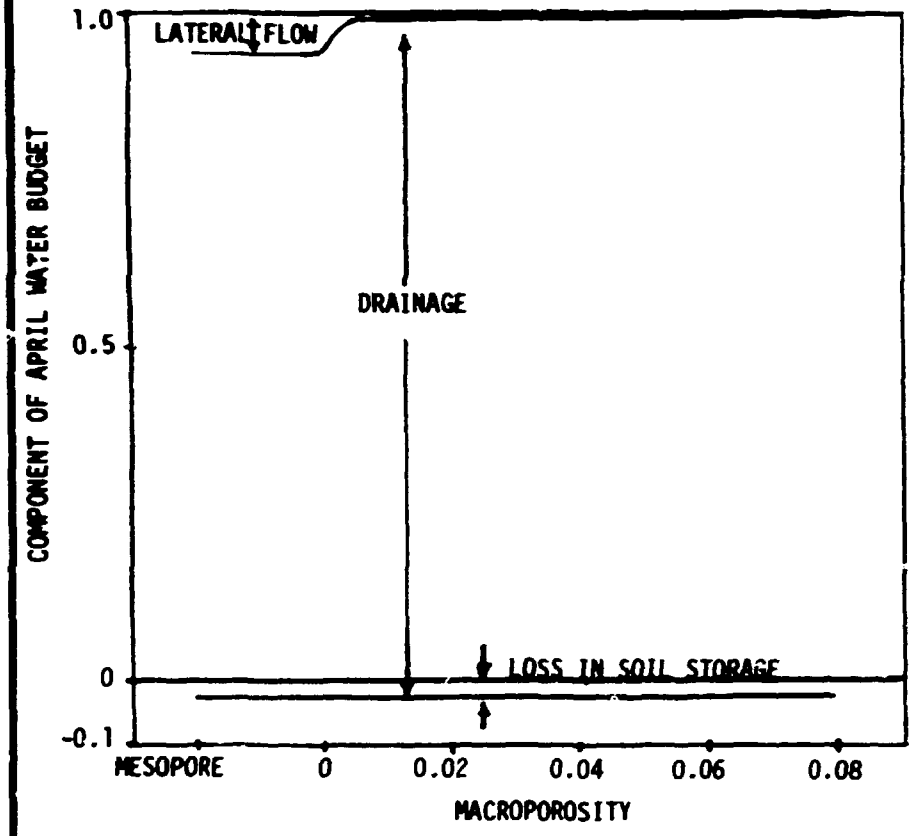
$$\text{infiltration} = \text{drainage} + \text{lateral flow} + \text{surface runoff} + \Delta\text{storage}$$

where Δstorage is the change in water content in the soil. For soil of high hydraulic conductivity, a value of 240 cm/d was used for the first layer and 120 cm/d for the subsequent layers. The different values represented the actual change in conductivity from the A-horizon, where the soil is mostly sandy, to the B-horizon, where more clay is found. The soil with lower conductivity had values of 9.6 cm/d for the first layer and 4.8 cm/d for the remaining layers. Both high and low hydraulic conductivity values are realistic and have been actually recorded for field soils. The monthly infiltration for both cases was 98 cm with no ponding. Hence, the water entered the mesopores, rather than the macropores, in the first layer.

For soil of higher hydraulic conductivity, the macropore effect was not significant, even for a macroporosity of 0.08 ml/ml (Fig. 8). Most of the water flowed through the mesopores and finally appeared in drainage. The excess, a small amount from the saturated mesopores, was transferred to the macropores. The macropores did not reach their saturation limit, and there was no lateral flow. Surface runoff was also not observed from the simulation results. A negative value was obtained for Δstorage; the soil layers decreased in water content by the end of the month relative to the start of the month. On the abscissa "mesopore" indicates that subroutines for macropore effects were not called, while a macroporosity of zero represents the case where the subroutines were called but zero macroporosity was used. For both cases when the mesopores were saturated, their excess water was immediately treated as lateral flow.

In soil of low hydraulic conductivity, macropores played a much more significant role. There was a sizeable amount of both drainage and lateral flow. The drainage arose from the mesopores while the lateral flow was the excess from the macropores. The low conductivity of soil did not allow mesopores to drain water rapidly. Hence, there was a significant amount of excess from the saturated mesopores. This was transferred to the macropores, with the excess from the macropores appearing in lateral flow. Some of the water in macropores of the lower layers was transferred back to mesopores in those layers, providing a bypass around an upper saturated zone. Thus drainage from mesopores increased with increase in macroporosity for the case with low soil hydraulic conductivity (Fig. 9), and there was a corresponding decrease in lateral flow. Again, as in soil of high hydraulic conductivity, there was a loss in soil water storage. It is interesting to note the change in runoff from the case of "mesopore" to that of zero macroporosity. In the mesopore case, any excess from the first layer was

INFILTRATION = DRAINAGE + LATERAL FLOW + RUNOFF + STORAGE



INFILTRATION = 977.39 MM

HYDRAULIC CONDUCTIVITY: FIRST LAYER - 240 CM/D
2nd TO 5th LAYER - 120 CM/D

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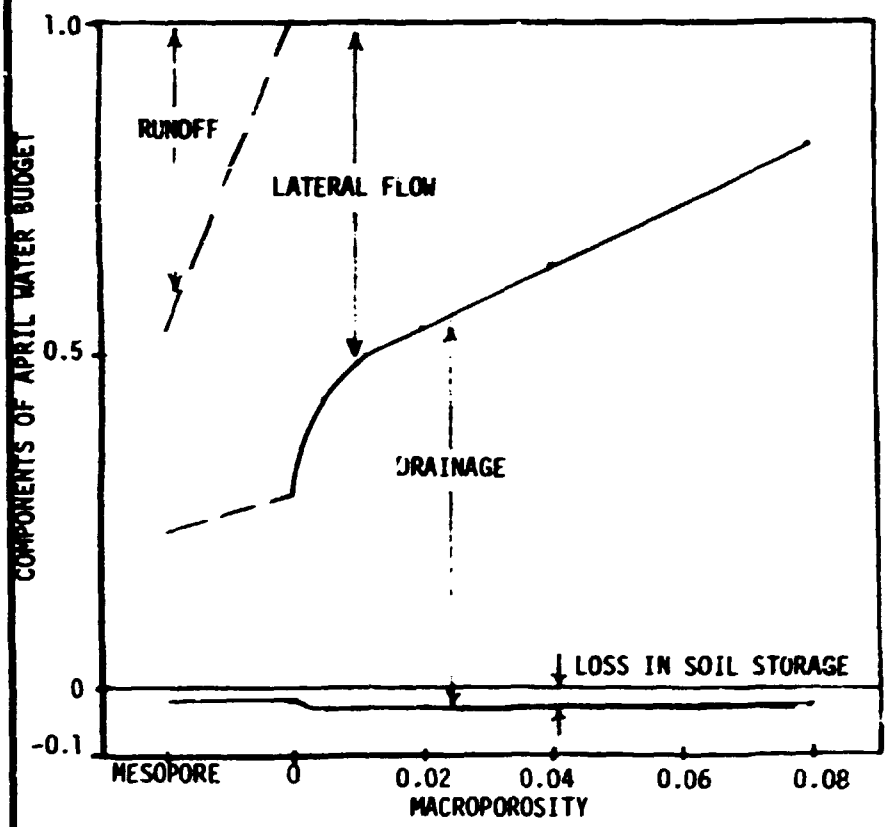
COMPONENTS OF APRIL WATER BUDGET
AS A FUNCTION OF MACROPOROSITY
(HIGH HYDRAULIC CONDUCTIVITY)

DATE	DRAWN BY	FILE NO.	FIG.
5-80	HRA	CEPS-X-312	8



INFILTRATION = 977.39 MM

HYDRAULIC CONDUCTIVITY: 1st LAYER - 9.6 CM/D

2nd - 5th LAYER - 4.8 CM/D

MASSACHUSETTS INSYITUTE OF TECHNOLOGY SCHOOL OF CHEMICAL ENGINEERING PRACTICE AT OAK RIDGE NATIONAL LABORATORY			
COMPONENTS OF APRIL WATER BUDGET AS A FUNCTION OF MACROPOROSITY (LOW HYDRAULIC CONDUCTIVITY)			
DATE 5-80	DRAWN BY HRA	FILE NO. CEPS-X-312	FIG. 9

sent to surface runoff. However, in the zero macroporosity case, since there was no ponding, additional runoff was not calculated. The excess was transferred to the negligible macropores and eventually to lateral flow instead.

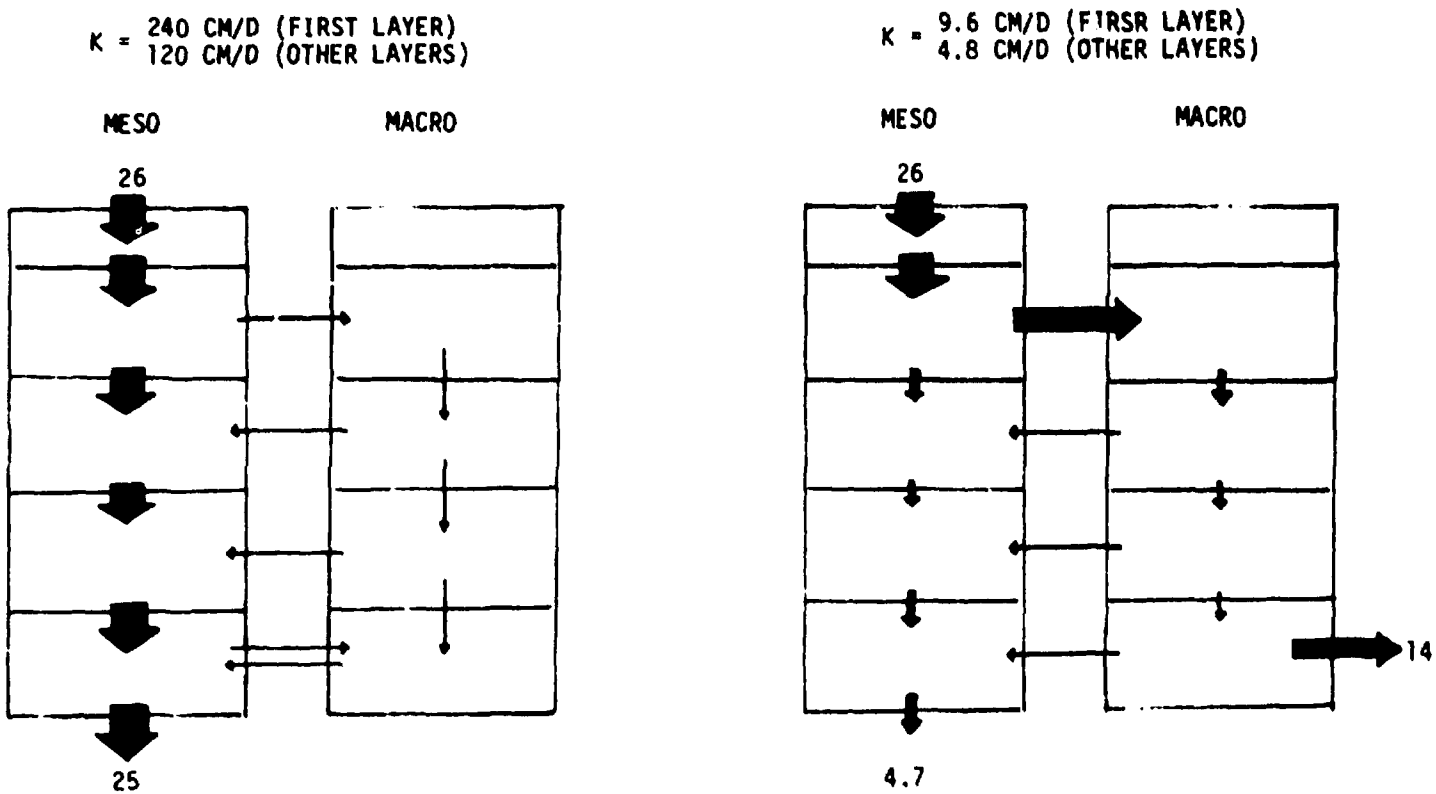
The macropore flow effects are more clearly shown in Fig. 10. Daily flows, for a day with high infiltration (26 cm), are compared for soils of different hydraulic conductivities. The macroporosity was 0.04 ml/ml. The width of the arrows are proportional to the amount of flow. The first layer was 30-cm deep, with the subsequent layers being twice as thick. For soil of high conductivity the water was mainly transferred in mesopores, with a drainage of 25 cm and no lateral flow. On the other hand, the mesopores were quickly saturated (in the second layer) in soil of low conductivity. The excess was diverted to macropores and most of it appeared in the lateral flow (14 cm). The difference between the input and output values of the soil layers was the daily change in water content.

Macropore effects are more apparent when daily flows rather than monthly flows were analyzed. As macropores have significant effects during short duration, study of hourly flows are suggested.

A summary of the comparison of the two major flows, drainage and lateral flow, for soils of different hydraulic conductivity and macroporosity is shown in Table 1. Macropore effects are a strong function of hydraulic conductivity and a weaker function of macroporosity.

Table 1. Summary of Results

	Drainage (cm/d)	Lateral Flow (cm/d)
Low Conductivity		
Mesoporosity = 0.0	3.1	19.5
Macroporosity = 0.01	4.3	16.5
Macroporosity = 0.08	4.7	5.2
High Conductivity		
Mesoporosity = 0.0	23.5	1.5
Macroporosity = 0.01	24.8	0.6
Macroporosity = 0.08	25.1	0.0



F:g. 10. MACROPORE FLOW EFF..TS COMPARED IN SOILS OF HIGH VS LOW CONDUCTIVITY

Infiltration and mesopore water-content profiles were also compared for heavy and light precipitation. In the absence of macropores, the water-content curve had a similar profile to the infiltration curve. Corresponding peaks were observed. With the macropore effect, most of the water drained rapidly through macropores during heavy precipitation. Thus, the peaks in the water-content curve were much reduced. This indicates that the effect of high infiltration was greatly dampened in the presence of macropores. On the other hand, the macropore effect was expectedly insignificant during light precipitation.

A detailed sensitivity analysis on the other input parameters (pore shape and dimensions, percentage of dead-end pores) was not completed. However, preliminary results suggest that pore shape had an insignificant effect on drainage, whereas the proportion of dead-end macropores had a slight effect, especially on decreasing macropore-to-macropore flow and on increasing the excess water in macropores.

7. CONCLUSIONS

The presence of macropores:

1. Is important during heavy precipitation.

2. Is significant in soil of low hydraulic conductivity.

3. Increased drainage for soil of low hydraulic conductivity.

4. Decreased lateral flow for soil of low hydraulic conductivity.

8. RECOMMENDATIONS

1. The logic of subroutines SWIFT, RSWIFT, and WSWIFT should be verified.

2. A detailed sensitivity analysis should be carried out for the other input parameters: macroporosity, pore shape and dimensions, percentage of dead-end pores.

3. The importance of macropores for different soil hydraulic conductivities should be investigated, and the range of conductivity where macropores are most important should be determined. Beven and Germann concluded from their model that the presence of macropores is most significant in soil of intermediate hydraulic conductivity.

4. The programs should be tested with data from soil-block drainage study, which allows comparison with the water content profiles obtained from the soil-block facility (Fig. 13).

5. A storm analysis, which gives hourly flow information, should be carried out with our model.

9. ACKNOWLEDGMENTS

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10. APPENDIX

10.1 Computer Logic

Three additional subroutines were used to simulate macropore phenomena. These routines executed all reading, calculating, and printing of macropore flow information. The following explanation outlines the computer calculations. Continuous and dead-end macropores were treated as separate but parallel cases so that the discussion applies to either unless otherwise stated.

Subroutine RSWIFT was called whenever a new watershed segment was simulated. All data required for the additional macropore calculations were read and initialized, then transferred to a TEHM output file. These parameters that remained constant for a soil layer were calculated. These parameters include the number and capacity of macropores, and the distance from the center of a macropore to the center of an aggregate. In addition, the number of layers in the A-horizon was calculated from the input data by assuming that only cylindrical pores were present in the A-horizon.

Water entered the mesopores unless there was ponding, in which case subroutine SWIFT was called. Precipitation entered the macropores, its rate being limited to the maximum flux, FLXMAX, permitted by the macropore geometry. Any excess from the uppermost two layers would be treated as surface runoff. It was assumed that dead-end macropores in the first layer were open to the surface. Differences in pore geometry must be considered; otherwise similar flows would be calculated for all soil layers.

In a soil layer, continuous macropore flow from the upper layer, MAFBL, was received until the capacity of the current layer was exceeded. The excess from the upper layer was then added, if possible; otherwise it would be stored in the EXCESS account and put into each subsequent layer. Excess from the last layer was considered to be lateral flow. To determine macropore-to-mesopore flow the hydraulic gradient from macropores to mesopores was calculated as the difference between mesopore water potential and the height of water (hydraulic potential) in macropores. If mesopores were saturated, they could not receive additional flow; any excess from the mesopores was transferred into the macropores. Macropore-to-mesopore flow was modeled using a Darcy-type equation:

flow = (area of interaction)(hydraulic conductivity)(hydraulic gradient)

where flow was assumed to be mesopore-controlled by using the mesopore hydraulic conductivity. The area of interaction was the total area in a layer with water at a macropore/mesopore interface. The maximum amount of water that could flow into the mesopores was the water content of the macropores. Again, if the mesopores were overfilled, the excess was returned to the macropores. The macropores were then checked to see if they

were filled beyond capacity. Any excess was added to the EXCESS account, which was totalled daily in MACEX(K) for each soil layer (K).

The WSWIFT subroutine was called once during each simulated day. A daily and monthly summary of the flow history was produced. Daily flows between macropores and between macropores and mesopores were written and counters were reinitialized. The water contents of the mesopores and macropores were checked daily in addition to the total excess. Monthly accounts were also maintained for the flows and excess. They were initialized before further calculation in TEHM was initiated.

10.2 Computer Programs and Sample Ouput

Listings for subroutines SWIFT, RSWIFT, and WSWIFT follow and also a sample of the output.

10.3 Definition of Calculated Terms in Programs

Capacity of continuous macropores (cm)

B(K) = (macroporosity)(soil layer length)(fraction of continuous macropores)

Capacity of dead end macropores (cm):

BD(K) = (macroporosity)(soil layer length)(fraction of dead-end macropores)

Average macropore potential (cm water):

$^{+}$HWAT(K)/2 = average head of water in macropores

Distance from macropore to mesopores (cm):

A-horizon: DX(K) = length of soil layer/[(total number of pores)(FRAC)(2)]

FRAC = length of macropore/length of layer = CSC(angle of pore to vertical)

B-horizon: DX(K) = (2)(breadth of crack + aggregate length)/6

Flow from macropores to mesopores (cm/time increment):

SWIFT (Main Program) Flow Calculations

```
LEVEL 21.8 ( JUN 74 )                    OS/360  FORTRAN H

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,XREF
  ISN 0002            SUBROUTINE SWIFT(K,DTIN)
                C     THIS POLTINE ACCOUNTS FOR MACROPORE FLOW EFFECTS
  ISN 0003            IMPLICIT REAL*8 (A-H,O-Z)
  ISN 0004            REAL*8 MCPOR,NPOR,MAPBL,MACEX
  ISN 0005            COMMON/INPTS/MCPOR(8),PP(8),WP(8),PL(8),PERC(8),AGSIZE(8)
  ISN 0006            COMMON/UITS/B(8),HWAT(8),FLOW(8),NPOR(8),DX(8)
                     1,OFLOW(8),DHWAT(8),BO(8),IATCB
  ISN 0007            COMMON/BOOKS/DMEMA(8),DMAME(8),DMAMA(8),MACEX(8),BETA(8),DBET(8)
  ISN 0008            COMMON/GEOMET/DL(8),AT(2),ARAT(2),FC(8),THETA(8),SWT(8)
  ISN 0009            COMMON/FORES/VP(8),F,S(8),SEV,ETGW,DNPAC,WF1,WP2,NSL,NBL,NS
  ISN 0010            COMMON/CHMOS/SWPBL(8),CHETA(8),SWRF1,SWRF2,RLAT(8)
  ISN 0011            COMMON/PIECES/TRUNO,ZS(8),PRE,POND,TBET(8),YESMAC,PSM(8)
  ISN 0012            DATA TWOPI/6.28318531/,EXCESS/0.0/,FLXMAX/0.0/
  ISN 0013            DATA BYES/.5/,FRAC/1.414213562/
                C     DTIN=TIME STEP IN FRACTIONAL DAYS
                C     DATA, AS IN PROSPR, ARE PER CM**2
                C
                C     FIRST LAYER MACROPORES
                C     SURFACE INFILTRATION AND RUNOFF ACCOUNTED FOR
  ISN 0014            RAIN=PRE
                C     FLXMAX=MAX INFILTRATION RATE (CM/TIME STEP)
  ISN 0015            FLXMAX=12250.*RP(1)**2*NCPOR(1)*86400.*DTIN
  ISN 0016            IF(POND.EQ.0.0)RAIN=0.0
                C     IF FLXMAX EXCEEDED ALLOW RUNOFF
  ISN 0018            IF(RAIN.LE.FLXMAX)GO TO 250
                C     ASSUME ALL DEAD END MACROPORES IN FIRST LAYER OPEN TO SURFACE
  ISN 0020            BETA(1)=BETA(1)+FLXMAX*(1.-PERC(1))
  ISN 0021            DBET(1)=DBET(1)+FLXMAX*PERC(1)
  ISN 0022            TRUNO=TRUNO+RAIN-FLXMAX
  ISN 0023            GO TO 300
  ISN 0024     250    DBET(1)=DBET(1)+RAIN*PERC(1)
  ISN 0025            BETA(1)=BETA(1)+RAIN*(1.-PERC(1))
  ISN 0026     300    HWAT(1)=BETA(1)/(MCPOR(1)*(1.-PERC(1)))
  ISN 0027            DHWAT(1)=DBET(1)/(MCPOR(1)*PERC(1))
  ISN 0028            HGRAD1=(PSM(1)+HWAT(1)/2.)/(RP(1)*DLOG(DX(1)/RP(1)))
  ISN 0029            DHGRAD=(PSM(1)+DHWAT(1)/2.)/(RP(1)*DLOG(DX(1)/RP(1)))
                C     DMEMA KEEPS TRACK OF DAILY MESO TO MACROPORE FLOW
  ISN 0030            IF(THETA(1).LE.S(1))GO TO 302
  ISN 0032            DMEMA(1)=DMEMA(1)+(THETA(1)-S(1))
  ISN 0033            FLOW(1)=0.0
  ISN 0034            DFLOW(1)=0.0
  ISN 0035            GO TO 305
                C     CALCULATE MACROPORE TO MESOPORE FLOW
  ISN 0036     302    FLOW(1)=TWOPI*RP(1)*FRAC*HWAT(1)*ZS(1)*DTIN*HGRAD1*NPOR(1)
                     1*(1.-PERC(1))
  ISN 0037            DFLOW(1)=TWOPI*RP(1)*FRAC*DHWAT(1)*ZS(1)*DTIN*DHGRAD*NPOR(1)
                     1*PERC(1)
  ISN 0038            IF(FLOW(1).GT.BETA(1))FLOW(1)=BETA(1)
  ISN 0040            IF(DFLOW(1).GT.DBET(1))DFLOW(1)=DBET(1)
                C     DMAME KEEPS TRACK OF DAILY MACRO TO MESOPORE FLOW
  ISN 0042            DMAME(1)=DMAME(1)+FLOW(1)+DFLOW(1)
  ISN 0043            THETA(1)=THETA(1)+FLOW(1)+DFLOW(1)
  ISN 0044            BETA(1)=BETA(1)-FLOW(1)
  ISN 0045            DBET(1)=DBET(1)-DFLOW(1)
  ISN 0046            IF(THETA(1).LE.S(1))GO TO 310
  ISN 0048            DMAME(1)=DMAME(1)-(THETA(1)-S(1))
```

SWIFT (continued)

```
                C     FLOW FROM MESOPORE TO MACROPORE
ISN 0048        305   BETA(I)=BETA(I)+(THETA(I)-S(I))*(1.-PERC(I))
ISN 0050              DBET(I)=DBET(I)+(THETA(I)-S(I))*PERC(I)
ISN 0051              THETA(I)=S(I)
ISN 0052        310   CONTINUE
ISN 0053              IF(BETA(I).LE.B(I))GO TO 315
                C     IF EXCEED CAPACITY ADD TO SECOND LAYER
ISN 0055              BETA(2)=BETA(2)+BETA(I)-B(I)
ISN 0056              DMAMA(2)=DMAMA(2)+(BETA(I)-B(I))
ISN 0057              BETA(I)=B(I)
ISN 0058        315   IF(DBET(I).LE.BD(I))GO TO 320
                C     IF EXCEED CAPACITY ALLOW RUNOFF
ISN 0060              TRUNO=TRUNO+DBET(I)-BD(I)
ISN 0061              DBET(I)=BD(I)
ISN 0062        320   IF(BETA(2).LE.B(2))GO TO 350
ISN 0064              TRUNO=TRUNO+BETA(2)-B(2)
ISN 0065              BETA(2)=B(2)
ISN 0066        350   EXCESS=0.0
ISN 0067              TBET(I)=BETA(I)+DBET(I)
ISN 0068              RETURN
ISN 0069              ENTRY SLBONE(K,DTIM)
                C
                C     MACROPORE FLOW BETWEEN LAYERS (K-1) AND (K)
ISN 0070              MAFBL=BETA(K-1)
ISN 0071              IF(MAFBL.LE.(B(K)-BETA(K)))GO TO 370
ISN 0073              MAFBL=B(K)-BETA(K)
ISN 0074              BETA(K-1)=BETA(K-1)-MAFBL
ISN 0075              BETA(K)=B(K)
ISN 0076              GO TO 380
ISN 0077        370   BETA(K)=BETA(K)+MAFBL
ISN 0078              BETA(K-1)=0.0
ISN 0079        380   CONTINUE
ISN 0080              DMAMA(K)=DMAMA(K)+MAFBL
                C     ACCOUNTING FOR FLOW WITHIN LAYERS
                C     FLOW(K)=FLOW FROM MACROPORES TO MESOPORES
ISN 0081              BETA(K)=BETA(K)+EXCESS
ISN 0082              EXCESS=0.0
ISN 0083              IF(BETA(K).LE.B(K))GO TO 400
ISN 0085              EXCESS=BETA(K)-B(K)
ISN 0086              BETA(K)=B(K)
ISN 0087        400   HWAT(K)=BETA(K)/(MCPOR(K)*(1.-PERC(K)))
ISN 0088              DHWAT(K)=DBET(K)/(MCPOR(K)*PERC(K))
ISN 0089              DHGRAD=(PSM(K)+DHWAT(K)/2.)/DX(K)
ISN 0090              HGRAD=(PSM(K)+HWAT(K)/2.)/DX(K)
ISN 0091              IF(THETA(K).LE.S(K))GO TO 450
ISN 0093              FLOW(K)=0.0
ISN 0094              OFLOW(K)=0.0
ISN 0095              DMEMA(K)=DMEMA(K)+(THETA(K)-S(K))
ISN 0096              GO TO 510
ISN 0097        450   IF(K.GT.IATOB) GO TO 500
ISN 0099              DHGRAD=(PSM(K)+DHWAT(K)/2.)/(RP(K)*DLOG(DX(K)/RP(K)))
ISN 0100               HGRAD=(PSM(K)+HWAT(K)/2.)/(RP(K)*DLOG(DX(K)/RP(K)))
                C     FLOW FROM MACROPORE CYLINDERS
ISN 0101              FLOW(K)=TWOPI*RP(K)*FRAC*HWAT(K)*ZS(K)*DTIM*HGRAD*NPOR(K)*
                     1(1.-PERC(K))
ISN 0102              OFLOW(K)=TWOPI*RP(K)*FRAC*DHWAT(K)*ZS(K)*DTIM*DHGRAD*NPOR(K)
                     1*PERC(K)
ISN 0103              GO TO 510
```

SWIFT (continued)

```
ISN 0104      500   X=BYPS**4GSIZE(K)
                    C     FLOW FROM MACROPORE CRACKS
ISN 0105            FLOW(K)=2.*(WP(K)+PL(K))*(X*FRAC+(1.-X))
                   1*HWAT(K)*ZS(K)*DTI**HGRAD*NPCR(K)*(1.-PERC(K))
ISN 0106            DFLOW(K)=2.*(WP(K)+PL(K))*(X*FRAC+1.-X)*NPCR(K)*PERC(K)
                   1*DHWAT(K)*ZS(K)*DTI**DHGRAD
ISN 0107      550   IF(FLOW(K).GT.BETA(K))FLOW(K)=BETA(K)
ISN 0108            IF(DFLOW(K).GT.DBET(K))DFLOW(K)=DBET(K)
ISN 0111            DNAME(K)=DNAME(K)+FLOW(K)+DFLOW(K)
ISN 0112            THETA(K)=THETA(K)+FLOW(K)+DFLOW(K)
ISN 0113            IF(THETA(K).LT.0.0) CALL ERROR
ISN 0114            BETA(K)=BETA(K)-FLOW(K)
ISN 0116            DBET(K)=DBET(K)-DFLOW(K)
ISN 0117            IF(THETA(K).LE.S(K)) GO TO 590
ISN 0118            DNAME(K)=DNAME(K)-(THETA(K)-S(K))
                    C     FLOW FROM MESO TO MACROPORE (IF MESOPORES OVERFILLED)
ISN 0120      570   BETA(K)=BETA(K)+(THETA(K)-S(K))*(1.-PERC(K))
ISN 0121            DBET(K)=DBET(K)+(THETA(K)-S(K))*PERC(K)
                    C      WRITE(6,707)THETA(K),BETA(K),DBET(K),K
                    C707   FORMAT(' SWFT121 ',3G16.5,I3)
ISN 0122            THETA(K)=S(K)
ISN 0123            IF(DBET(K).LE.BD(K))GO TO 580
ISN 0125            EXCESS=EXCESS+DBET(K)-BD(K)
                    C      WRITE(6,750)EXCESS,DBET(K),BD(K),K
                    C750   FORMAT(' SWFT122 ',3G16.5,I3)
ISN 0126            DBET(K)=BD(K)
ISN 0127      580   CONTINUE
ISN 0128            IF(BETA(K).LE.B(K))GO TO 590
ISN 0130            EXCESS=EXCESS+BETA(K)-B(K)
                    C      WRITE(6,775)EXCESS,BETA(K),B(K),K
                    C775   FORMAT(' SWFT134 ',3G16.5,I3)
ISN 0131            BETA(K)=B(K)
                    C     BETA(NSL) ENTERS MESOPORES
ISN 0132      590   MACEX(K)=MACEX(K)+EXCESS
                    C     IF(MACEX(K).GT.0.0) WRITE(6,777) K,MACEX(K),EXCESS,BETA(K),DBET(K)
                    C    1,THETA(K),FLOW(K),DFLOW(K),DNAMA(K),DNEMA(K),DNAME(K),
                    C    2RLAT(K),TRUNO,FLXMAX
                    C 777 FORMAT(' ',I1,I3D10.3)
ISN 0133            IF(MACEX(K).GT.100.) CALL ERROR
ISN 0135            IF(K.NE.NSL)GO TO 600
ISN 0137            RLAT(K)=RLAT(K)+EXCESS
ISN 0138            EXCESS=0.0
ISN 0139      600   TBET(K)=BETA(K)+DBET(K)+EXCESS
ISN 0140            RETURN
ISN 0141            END
```

RSWIFT (Read Data, Initializations)

```
LEVEL 21.8 ( JUN 74 )                          OS/360  FORTRAN H

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                                   SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,XREF
  ISN 0002            SUBROUTINE RSWIFT
                  C   THIS ROUTINE READS AND INITIALIZES FOR SWIFT
                  C   SWIFT ROUTINE ACCOUNTS FOR MACROPORE FLOW EFFECTS
  ISN 0003            IMPLICIT REAL*8 (A-H,O-Z)
  ISN 0004            REAL*8 MCPOR,MPOR,MFBL,MACEX,MMACEX,MMEME
  ISN 0005            REAL*8 MMEMA,MMAME,MMAMA
  ISN 0006            COMMON/INPTS/MCPOR(8),RP(8),WP(8),PL(8),PERC(8),AGSIZE(8)
  ISN 0007            COMMON/EITS/ B(8),HWAT(8),FLOW(8),MPOR(8),DX(8)
                     1,DFLOW(8),DHWAT(8),BD(8),IATOB
  ISN 0008            COMMON/BOOKS/DMEMA(8),DMAME(8),DMAMA(8),MACEX(8),BETA(8),DBET(8)
  ISN 0009            COMMON/GEOMET/DL(8),AT(2),ARAT(2),FC(8),THETA(8),SWT(8)
  ISN 0010            COMMON/PORES/VP(8),F,S(8),SEV,ETGW,DNFAC,WF1,WP2,NSL,NBL,NS
  ISN 0011            COMMON/CHNNOS/SWFBL(8),CHETA(8),SWRF1,SWFF2,PLAT(8)
  ISN 0012            COMMON/PIECES/TRUNO,ZS(8),PRE,POND,TBET(8),YESMAC,PSM(8)
  ISN 0013            COMMON/MONTHS/MMAME(8),MMEMA(8),MMAMA(8),MMACEX(8),MMEME(8)
  ISN 0014            COMMON/MESOP/DMEME(8)
                  C   VARIABLES IN COMMONS BOOKS & MONTHS DEFINED IN MSWIFT
  ISN 0015            DATA PI/3.1415926535E9979/
  ISN 0016            DATA FRAC/1.4142135E2/
                  C   DATA INPUTS
                  C   VALUES ARE FOR A 1-CM**2 CROSS SECTION
                  C   FRAC=COSEC(ANGLE OF A PORE TO THE VERTICAL)
                  C   I REFERS TO A SOIL LAYER
                  C   MCPOR(I)=TOTAL MACROPOROSITY (ML/ML)
                  C   RP(I)=RADIUS OF CYLINDRICAL PORE (CM)
                  C   WP(I)=WIDTH OF RECTANGULAR CRACK (CM)
                  C   PL(I)=BREDTH OF RECTANGULAR CRACK (CM)
                  C   AGSIZE(I)=AVG LENGTH OF AGGREGATE (CM)
                  C   PERC(I)=FRACTION OF MACROPORES WHICH ARE DEAD END
                  C   BETA(I)=WATER CONTENT OF CONTINUOUS MACROPORES (CM/LAYER)
                  C   B(I)=MAX CAPACITY OF CONTINUOUS MACROPORES(SATURATED CM/LAYER)
                  C   DBET(I)=WATER CONTENT OF DEAD END MACROPORES (CM/LAYER)
                  C   BD(I)=MAX CAPACITY OF DEAD END MACROPORES (CM/LAYER)
                  C   HWAT(I)=HEAD OF WATER IN CONT. MACROPORES (CM OF WATER)
                  C   DHWAT(I)=HEAD OF WATER IN DEAD END MACROPORES (CM OF WATER)
                  C   MPOR(I)=TOTAL NUMBER OF MACROPORES (#/LAYER)
                  C   TBET(I)=TOTAL WATER CONTENT OF MACROPORES(CM/LAYER)
                  C   DX(I)=DISTANCE FROM MACROPORES TO MESOPORES (CM)
                  C   FOLLOWING VARIABLES ORIGINATE IN PROSPR
                  C   DL(I)=DEPTH OF SOIL LAYER (CM)
                  C   THETA(I)=WATER CONTENT OF MESOPORES (CM/LAYER)
                  C   S(I)=MAX CAPACITY OF MESOPORES (CM/LAYER)
                  C   NSL=NUMBER OF SOIL LAYERS
                  C   PLAT(I)=LATERAL FLOW (CM/TIME STEP)
                  C   TRUNO=SURFACE RUNOFF (CM/TIME STEP)
                  C   ZS(I)=HYDRAULIC CONDUCTIVITY (CM/DAY)
                  C   DTIM=TIME STEP (FRACTIONAL DAYS)
                  C   PRE=PRECIPITATION (CM/TIME STEP)
                  C   POND=SWITCH SET TO 1 IF THERE IS SURFACE PONDING
                  C   YESMAC=SWITCH SET TO 0 IF NEGLECTING MACROPORES
                  C   PSM(I)=PATRIC POTENTIAL IN MESOPORES (CM OF WATER)
                  C   IATOB=NUMBER OF SOIL LAYERS IN A HORIZON
                  C   NOMINAL VALUES ARE USED FOR ZERO INPUT DATA OF MCPOR,RP,WP,
                  C   PL,PERC AND AGSIZE
  ISN 0017            IATOB=0
  ISN 0018            POND=0.
```

RSWIFT (continued)

```
ISN 0015            WRITE(6,100)
ISN 0020      100   FORMAT(' LEVEL POROSITY  PORE RADIUS   WIDTH   LENGTH
                   1PERCENTAGE   AGSIZE ')
ISN 0021            DO 170 I=1,NSL
ISN 0022            READ(5,150)NCPOP(I),RP(I),WP(I),PL(I),PERC(I),AGSIZE(I)
ISN 0023      150   FORMAT(6F10.4)
              C     IATOB=NUMBER OF LAYERS IN "A" HORIZON
ISN 0024            IF(PL(I).LE.1.00-10) IATOB=IATOB+1
              C     SET NOMINAL VALUES FOR ZERO INPUT DATA
ISN 002E            IF (NCPOR(I).EQ.0.)  NCPOR(I)=1.D-12
ISN 002F            IF (RP(I).EQ.0.)  RP(I)=1.D-12
ISN 0030            IF (WP(I).EQ.0.)  WP(I)=1.D-12
ISN 0032            IF (PL(I).EQ.0.)  PL(I)=1.D-12
ISN 0034            IF (PERC(I).EQ.0.)  PERC(I)=1.D-12
ISN 0036            IF (AGSIZE(I).EQ.0.)  AGSIZE(I)=1.D-12
ISN 0038            WRITE(6,160)I,NCPOR(I),RP(I),WP(I),PL(I),PERC(I),AGSIZE(I)
ISN 0039      160   FORMAT(2X,I2,2X,6F10.4)
ISN 0040      170   CONTINUE
ISN 0041            DO 200 I=1,NSL
              C     INITIALIZING WATER BUDGET ACCOUNTS
ISN 0042            BETA(I)=0.0
ISN 0043            DBET(I)=0.0
ISN 0044            TBET(I)=0.0
ISN 0045            DMEME(I)=0.0
ISN 0046            DMEMA(I)=0.0
ISN 0047            DMAME(I)=0.0
ISN 0048            DMAMA(I)=0.0
ISN 0049            MACEX(I)=0.0
ISN 0050            MMEME(I)=0.0
ISN 0051            MMEMA(I)=0.0
ISN 0052            MMAME(I)=0.0
ISN 0053            MMAMA(I)=0.0
ISN 0054            MMACEX(I)=0.0
ISN 0055            B(I)=NCPOR(I)*DL(I)*(1.-PERC(I))
ISN 0056            BD(I)=NCPOR(I)*DL(I)*PERC(I)
ISN 0057            IF(I.GT.IATOB)GO TO 190
              C     NO. OF CYLINDERS IN "A" HORIZON LAYER
ISN 0059            NPOR(I)=NCPOR(I)/(PI*RP(I)**2.*FRAC)
              C     ASSUMES MACROPORE LENGTH=FRAC*DL(I)
ISN 0060            DX(I)=DL(I)/(NPOR(I)*2.*FRAC)
ISN 0061            GO TO 200
              C     NO. OF CRACKS IN "B" HORIZON LAYER
ISN 0062      190   NPOR(I)=NCPOR(I)*DL(I)/(WP(I)*PL(I)*AGSIZE(I))
ISN 0063            DX(I)=(2.*DL(I)+AGSIZE(I))/6.
ISN 0064      200   CONTINUE
ISN 0065            RETURN
ISN 0066            END
```

WSWIFT (Write Results)

```
LEVEL 21.8 ( JUN 74 )                    CS/360  FORTRAN H

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,XREF
  ISN 0002            SUBROUTINE WSWIFT
                  C   ROUTINE TO PRINT OUT DAILY/MONTHLY WATER STATUS
  ISN 0003            IMPLICIT REAL*8 (A-H,O-Z)
  ISN 0004            REAL*8 MACEX,MMEMA,MMAME,MMAMA,MMACEX,MMEME
  ISN 0005            DIMENSION DBETA(8),DDBET(8),DTHET(8)
  ISN 0006            COMMON/MONTHS/MMAME(8),MMEMA(8),MMAMA(8),MMACEX(8),MMEME(8)
  ISN 0007            COMMON/MESOP/DMEME(8)
  ISN 0008            COMMON/GEOMET/DL(8),AT(2),ARAT(2),PC(8),THETA(8),SWT(8)
  ISN 0009            COMMON/FORES/VP(8),P,S(8),SEV,ETGW,ONPAC,WP1,WP2,NSL,NBL,NS
  ISN 0010            COMMON/BOOKS/DMEMA(8),DMAME(8),DMAMA(8),MACEX(8),BETA(8),DBET(8)
                  C   DMEMA(J)=DAILY MESOPORE TO MACROPORE FLOW
                  C   DMEME(J)=DAILY MESOPORE TO MESOPORE FLOW
                  C   DMAME(J)=DAILY MACROPORE TO MESOPORE FLOW
                  C   DMAMA(J)=DAILY MACROPORE TO MACROPORE FLOW
                  C   MACEX(J)=DAILY MACROPORE EXCESS
                  C   MMAME(J)=MONTHLY MACROPORE TO MESOPORE FLOW
                  C   MMEMA(J)=MONTHLY MESOPORE TO MACROPORE FLOW
                  C   MMEME(J)=MONTHLY MESOPORE TO MESOPORE FLOW
                  C   MMAMA(J)=MONTHLY MACROPORE TO MACROPORE FLOW
                  C   MMACEX(J)=MONTHLY MACROPORE EXCESS
  ISN 0011            DO 111 J=1,NSL
  ISN 0012            DBETA(J)=BETA(J)/DL(J)
  ISN 0013            DDBET(J)=DBET(J)/DL(J)
  ISN 0014            DTHET(J)=THETA(J)/DL(J)
                  C   DAILY WATER STATUS
  ISN 0015    111     CONTINUE
  ISN 0016            WRITE(6,100)(DMAME(I),I=1,NSL)
  ISN 0017    100     FORMAT(' DMAME (CM/DAY) ',8(E12.4,2X))
  ISN 0018            WRITE(6,200)(DMEMA(I),I=1,NSL)
  ISN 0019    200     FORMAT(' DMEMA (CM/DAY) ',8(E12.4,2X))
  ISN 0020            WRITE(6,300)(DMAMA(I),I=1,NSL)
  ISN 0021    300     FORMAT(' DMAMA (CM/DAY) ',8(E12.4,2X))
  ISN 0022            WRITE(6,400)(MACEX(I),I=1,NSL)
  ISN 0023    400     FORMAT(' MACEX (CM/DAY) ',8(E12.4,2X))
  ISN 0024            WRITE(6,450)(DMEME(I),I=1,NSL)
  ISN 0025    450     FORMAT(' DMEME (CM/DAY) ',8(E12.4,2X))
  ISN 0026            WRITE(6,500)(DBETA(I),I=1,NSL)
  ISN 0027    500     FORMAT(' BETA/DL(ML/ML) ',8(E12.4,2X))
  ISN 0028            WRITE(6,600)(DDBET(I),I=1,NSL)
  ISN 0029    600     FORMAT(' DBET/DL(ML/ML) ',8(E12.4,2X))
  ISN 002A            WRITE(6,700)(DTHET(I),I=1,NSL)
  ISN 0031    700     FORMAT(' THETA/DL(ML/ML)',8(E12.4,2X))
                  C   SET UP MONTHLY WATER ACCOUNTS
  ISN 0032            DO 800 J=1,NSL
  ISN 0033            MMAME(J)=MMAME(J)+DMAME(J)
  ISN 0034            DMAME(J)=0.0
  ISN 0035            MMEME(J)=MMEME(J)+DMEME(J)
  ISN 0036            DMEME(J)=0.0
  ISN 0037            MMEMA(J)=MMEMA(J)+DMEMA(J)
  ISN 0038            DMEMA(J)=0.0
  ISN 0039            MMAMA(J)=MMAMA(J)+DMAMA(J)
  ISN 0040            DMAMA(J)=0.0
  ISN 0041            MMACEX(J)=MMACEX(J)+MACEX(J)
  ISN 0042            MACEX(J)=0.0
  ISN 0043    800     CONTINUE
  ISN 0044            RETURN
```

WSWIFT (Continued)

```
                C       MONTHLY WATER STATUS
ISN 0044                ENTRY IMONTH
ISN 0045                WRITE(6,105)
ISN 0046        105     FORMAT(16X,'  MONTHLY WATER BUDGETS    ')
ISN 0047                WRITE(6,110)(WNAME(I),I=1,NSL)
ISN 0048        110     FORMAT(' WNAME (CM/MTH) ',8(E12.4,2X))
ISN 0049                WRITE(6,210)(WMENA(I),I=1,NSL)
ISN 0050        210     FORMAT(' WMENA (CM/MTH) ',8(E12.4,2X))
ISN 0051                WRITE(6,310)(WMANA(I),I=1,NSL)
ISN 0052        310     FORMAT(' WMANA (CM/MTH) ',8(E12.4,2X))
ISN 0053                WRITE(6,410)(WMACEX(I),I=1,NSL)
ISN 0054        410     FORMAT(' WMACEX(CM/MTH) ',8(E12.4,2X))
ISN 0055                WRITE(6,510)(WMENE(I),I=1,NSL)
ISN 0056        510     FORMAT(' WMENE (CM/MTH) ',8(E12.4,2X))
ISN 0057                DO 900 J=1,NSL
ISN 0058                WNAME(J)=0.0
ISN 0059                WMENA(J)=0.0
ISN 0060                WMENE(J)=0.0
ISN 0061                WMANA(J)=0.0
ISN 0062                WMACEX(J)=0.0
ISN 0063        900     CONTINUE
ISN 0064                RETURN
ISN 0065                END
```

```
THETA/DL(ML/ML)  0.22740 00    0.23410 00    0.28550 00    0.28870 00    0.29070 00
 117  0.0        0.0        0.29930 00 0.77880-02 0.0        0.64670-01    0.84060-02 -.73740 01   0.23690 000.23370 000.29010 00
DNAME (CM/DAY)   0.0           0.0           0.0           0.0           0.0
DNEMA (CM/DAY)   0.0           0.0           0.0           0.0           0.0
DNAMA (CM/DAY)   0.0           0.0           0.0           0.0           0.0
MACEX (CM/DAY)   0.0           0.0           0.0           0.0           0.0
DNEMF (CM/DAY)   0.21340-01    0.64570-01    0.14110 00    0.21690 00    0.0
BETA/DL(ML/ML)   0.0           0.0           0.0           0.0           0.0
DBET/DL(ML/ML)   0.0           0.40000-02    0.0           0.10000-02    0.0
THETA/DL(ML/ML)  0.22650 00    0.23340 00    0.28420 00    0.28740 00    0.28950 00
 118  0.750 01   0.0        0.14860 01 0.52290-02 0.0        0.15450 01    0.66110-02 -.69680 01   0.24430 000.23310 000.28890 00
DNAME (CM/DAY)   0.0           0.0           0.10260 01    0.88280 00    0.84930 00
DNEMA (CM/DAY)   0.0           0.45130 01    0.0           0.0           0.32360-01
DNAMA (CM/DAY)   0.0           0.0           0.40610 01    0.34270 01    0.27240 01
MACEX (CM/DAY)   0.0           0.45130 00    0.0           0.0           0.0
DNEME (CM/DAY)   0.67050 01    0.15450 01    0.15180 01    0.15100 01    0.0
BETA/DL(ML/ML)   0.0           0.0           0.0           0.0           0.25880-01
DBET/DL(ML/ML)   0.0           0.40000-02    0.0           0.81890-07    0.15730-02
THETA/DL(ML/ML)  0.25110 00    0.24420 00    0.30170 00    0.30230 00    0.30390 00
 119  0.0        0.0        0.14180 01 0.98610-02 0.0        0.66240 00    0.40000-02 -.11860 02   0.24110 000.24130 000.30390 00
DNAME (CM/DAY)   0.0           0.0           0.0           0.0           0.15870 01
DNEMA (CM/DAY)   0.0           0.0           0.0           0.0           0.0
DNAMA (CM/DAY)   0.0           0.0           0.0           0.0           0.0
MACEX (CM/DAY)   0.0           0.0           0.0           0.0           0.0
DNEMF (CM/DAY)   0.48180 00    0.66240 00    0.10050 01    0.12620 01    0.0
BETA/DL(ML/ML)   0.0           0.0           0.0           0.0           0.0
DBET/DL(ML/ML)   0.0           0.40000-02    0.0           0.81890-07    0.0
THETA/DL(ML/ML)  0.23740 00    0.23980 00    0.29600 00    0.29800 00    0.29940 00
 120  0.0        0.0        0.83260 00 0.86140-02 0.0        0.24700 00    0.40000-02 -.10760 02   0.23470 000.23860 000.29760 00
DNAME (CM/DAY)   0.0           0.0           0.0           0.0           0.0
DNEMA (CM/DAY)   0.0           0.0           0.0           0.0           0.0
DNAMA (CM/DAY)   0.0           0.0           0.0           0.0           0.0
MACEX (CM/DAY)   0.0           0.0           0.0           0.0           0.0
DNEME (CM/DAY)   0.12000 00    0.24700 00    0.47100 00    0.65660 00    0.0
BETA/DL(ML/ML)   0.0           0.0           0.0           0.0           0.0
DBET/DL(ML/ML)   0.0           0.40000-02    0.0           0.81890-07    0.0
THETA/DL(ML/ML)  0.23310 00    0.23770 00    0.29230 00    0.29490 00    0.29650 00

MONTHLY WATER BUDGET (CM)

TOTAL INFILTRATION, EVAPOTRANSPIRATION, RUNOFF, DRAINAGE, LATERAL FLOW, SOIL WATER CHANGE AND BALANCE (CM)
        97.73884       0.19083C8       0.0             64.64435       15.26679       -2.403133       0.49134760-05
ROOT WATER UPTAKE (CM) LAYER 1   0.64315390-07 LAYER 2   0.82212180-06
                 MONTHLY WATER BUDGETS
MNAME (CM/MTH)   0.0           0.0           0.16060 02    0.23100 01    0.16170 02
MNEMA (CM/MTH)   0.0           0.68960 02    0.0           0.0           0.83870 00
MNAMA (CM/MTH)   0.0           0.0           0.31590 02    0.18420 02    0.16110 02
MNACEX(CM/MTH)   0.0           0.37370 02    0.34490 02    0.34490 02    0.38270 02
MNEMF (CM/MTH)   0.99130 02    0.29570 02    0.44210 02    0.48990 02    0.0
FILE KEY =    >| 715
```

$^{+}$FLOW(K) = (surface area of macropore)(height of water in macropore)(hydraulic conductivity)(hydraulic gradient)(number of (macropores)*

Height of water in macropores (cm):

$^{+}$HMAT(K) = macropore water content*/(macroporosity)(fraction of macropores*)

Hydraulic gradient from macropore to mesopores (cm water/cm):

cylindrical pore: $^{+}$HGRAD(K) = (mesopore matric potential + average macropore potential)/[macropore radius · ln(distance from macropore to mesopores/macropore radius)]

rectangular crack: $^{+}$HGRAD(K) = (mesopore matric potential + average macropore potential)/(distance from macropore to mesopores)

Total number of macropores:

NPOR(K) = macroporosity(length of soil layer)/macropore volume

macropore volume: A-horizon = $(\pi)(\text{pore radius})^2(\text{length of macropore})$

B-horizon = (width)(breadth)(length of crack)

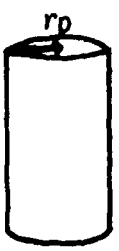
$^{+}$Similar for dead-end macropores.

*Either continuous or dead-end macropores, depending on calculation.

10.4 Calculation of Maximum Flow Rate Through Macropores

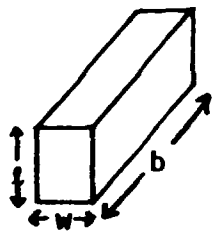
From Poiseuille's Law, the flow in a cylinder is given by:

$$q_p = \frac{\pi \rho g}{8\mu}(r_p^4) \qquad (2)$$



Similarly, flow in slits may be expressed as:

$$q_c = \frac{2}{3}\frac{\rho g}{\mu} w^3 b \qquad (3)$$



where

ρ = density of fluid

g = acceleration due to gravity

μ = dynamic viscosity of fluid

q_p = flux in cylindrical pores

q_c = flux in cracks

r_p = radius of a cylindrical pore

w = width of a rectangular crack

b = breadth of a rectangular crack

Tables 2 and 3 show the flux through macropores of different dimensions for cylindrical pores and rectangular cracks, respectively.

Table 2. Flow Through Cylindrical Pores as Determined by Poiseuille's Law

r_p (cm)	Number of Macropores N_p	q_p (cm^3/h)	Macroporosity
0.04	1	355	0.005
0.04	10	355×10^1	0.05
0.40	1	355×10^4	0.50

Table 3. Flow Through Cracks as Determined by Poiseuille's Law

w (cm)	b (cm)	ℓ (cm)	N_p	q_c (cm^3/h)	Macroporosity
0.005	1.0	1.0	1	29.4	0.005
0.05	1.0	1.0	1	29.4×10^3	0.05
0.05	1.0	1.0	10	29.4×10^4	0.50

Note that macroporosity does not enter into the calculation of q_p or q_c. It is shown here only for comparison.

The precipitation rate was compared with the maximum flow rate possible through macropores. Precipitation records have shown rainfall rates up to 30 cm^3-cm^{-2}-h^{-1} in some tropical regions; however, these rates are exceptional and a more typical high rainfall rate would be 6 cm^3-cm^{-2}-h^{-1}. These high rainfall rates are much lower than the maximum flow rates (q_p, q_c) shown in Tables 2 and 3. Therefore, the flow in macropores will not be limited by pore geometry but rather by macropore capacity.

10.5 Pore Size Distribution

Macropores are pores where capillary forces are negligible or flow is not appreciably affected by these forces. Macropores are somewhat arbitrarily defined to be pores which are filled with water at suctions less than 10 cm of water. The radius corresponding to 10 cm of suction is calculated using the expression for capillary pressure (7):

$$P = \frac{2\delta \cos \alpha}{R} \tag{4}$$

where δ is the surface tension, α is the contact angle in a capillary, and R is the radius of the capillary, which leads to,

$$R = \frac{2\delta \cos \alpha}{\rho g H} \tag{5}$$

where ρ is the density of manometer fluid and H is the height of the fluid. Some calculations for different heights of suction are shown in Table 4.

Table 4. Radius of Pores for Different Heights of Suction

H (cm)	R (cm)
0.05	3.00
5	0.03
10	0.015
20	0.0075

A minimum macropore radius of 0.015 cm is obtained for a suction of 10 cm of water in soil. Although apparently small, this value for a radius will account for the few small macropores. The mesopores should be of a much smaller size. For rectangular cracks, 1/w is substituted for 2/R, giving a minimum crack width of 0.0075 cm.

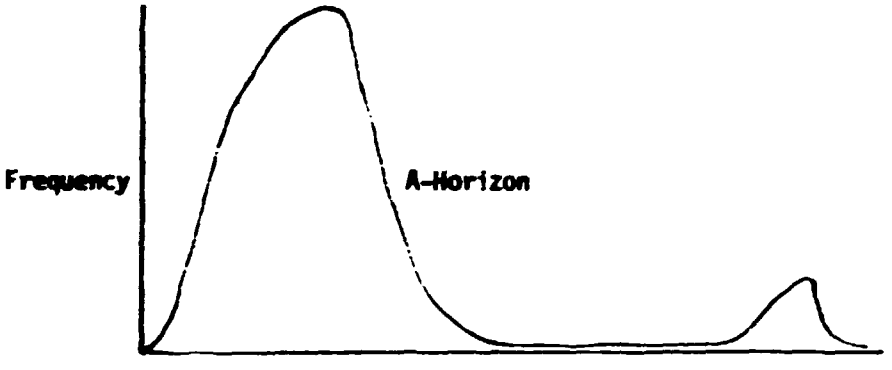
A Gaussian-type of distribution with separate peaks for mesopores and macropores was assumed for the pore sizes in each horizon. A schematic diagram of the expected frequency distribution is shown in Fig. 11.

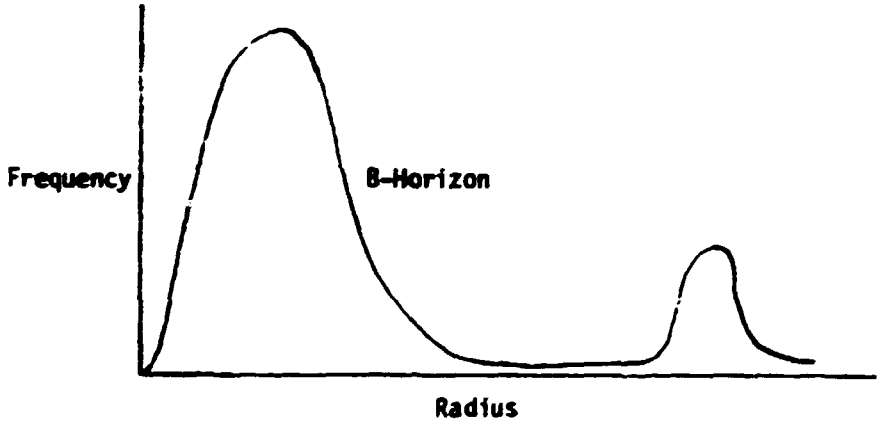
In the A-horizon, the mesopore distribution may be skewed towards higher radii because of the larger size of soil particles than those found in the B-horizon (1). The same tilt may occur for macropores, since the few of them which arise from biological forces are generally larger than those which arise from physical forces.

From drainage tests conducted at the field soil-block facility, mesopore size distributions at different depths into the soil were derived. The field facility was a 2x2-m soil block, with rubber lining down to 2 m on three sides and a concrete wall down to 3 m on the fourth side, as shown in Fig. 12. Soil moisture content was measured by neutron scattering from a neutron probe placed at selected positions within each of two access tubes located 1 m apart. On the concrete wall, access ports were situated at different depths for tensiometers that measured soil water potential. From the data of the two types of instruments obtained during drainage of the flooded soil block, the relationships between water content and water potential (retention curves) were developed for selected depths. A distinctive change in drainage from the A- to B-horizon (37-cm depth), as seen in Fig. 13, may account for surface ponding or the perched water table during winter. The water content-potential curve showed a discrepancy between the field and the laboratory data (Fig. 14). This may be attributed to entrapped air in the field soil sample. In the field, the soil is flooded from the top while the soil in the laboratory is wetted upward from the bottom.

Mesopore size distributions were calculated from the field data with the assumption that the mesopores were spherical. A comparison between the distributions for the same location but at different depths is shown in Fig. 15.

Contrary to expectations, the normalized distribution curve at the higher level skewed towards higher radii. Another comparison between the distributions for the same depth (10 cm), but two locations one meter apart (different reps) is shown in Fig. 16. From these two figures, we can conclude that a wide variation in the frequency distribution not only exists between different locations in the soil, but also between different levels in the same profile. It is obvious from the two figures that the distribution did not cover the entire pore size range. Exclusion of the macropore distributions resulted from calculations of the radii which were based on the rise of water in the manometer due to capillary effects. Small pores of radii less than $\sim$0.004 cm were not analyzed in this method because they had not drained in the time interval considered ($\sim$55 days).

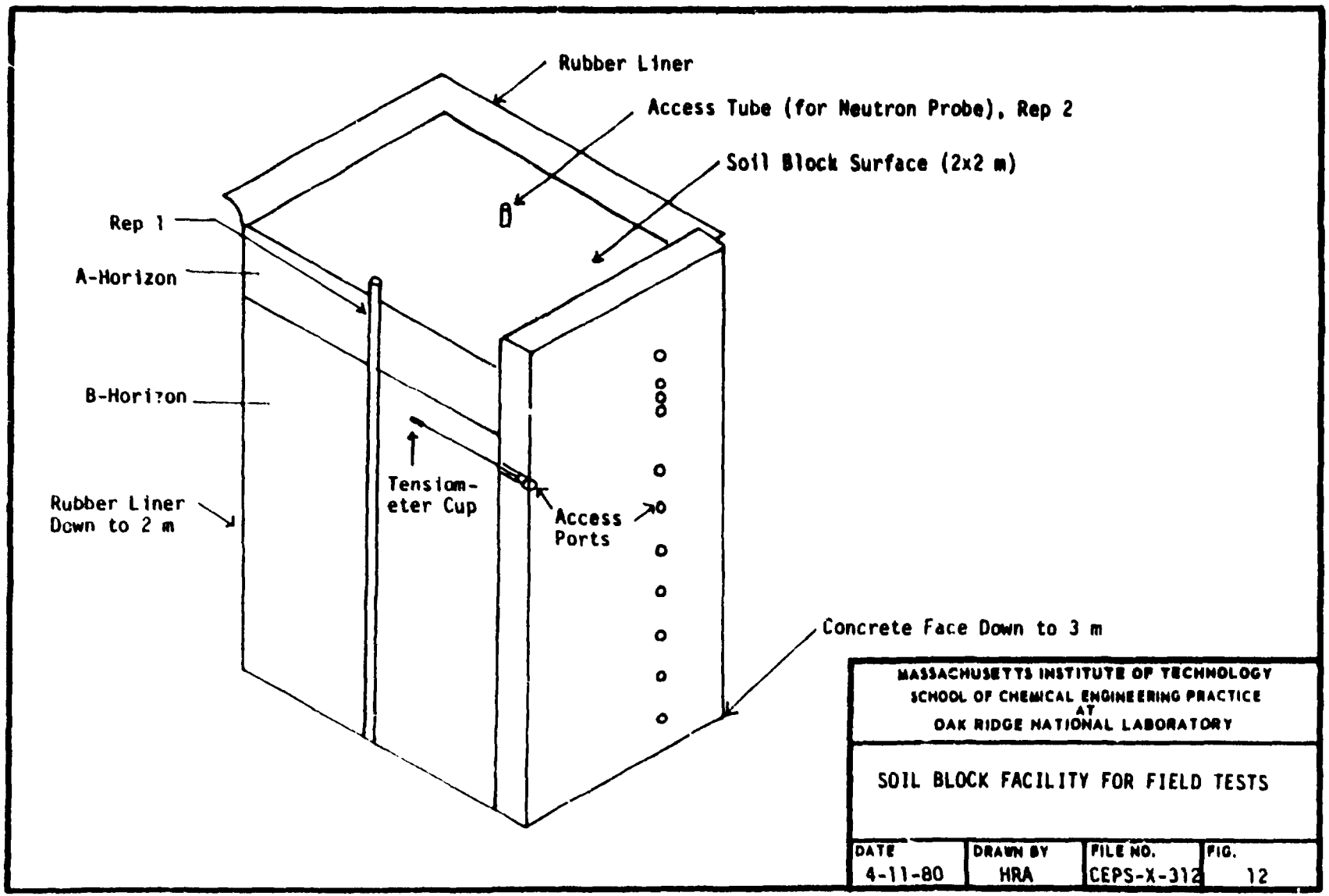




MASSACHUSETTS INSTITUTE OF TECHNOLOGY
SCHOOL OF CHEMICAL ENGINEERING PRACTICE
AT
OAK RIDGE NATIONAL LABORATORY

EXPECTED RELATIVE PORE SIZE
DISTRIBUTIONS IN A- AND B-HORIZONS

DATE	DRAWN BY	FILE NO.	FIG.
4-14-80	MKA	CEPS-X-312	11


Rubber Liner
Access Tube (for Neutron Probe), Rep 2
Soil Block Surface (2x2 m)
Rep 1
A-Horizon
B-Horizon
Tensiom-
eter Cup
Rubber Liner
Down to 2 m
Access
Ports
Concrete Face Down to 3 m
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
SCHOOL OF CHEMICAL ENGINEERING PRACTICE
AT
OAK RIDGE NATIONAL LABORATORY
SOIL BLOCK FACILITY FOR FIELD TESTS
DATE 4-11-80
DRAWN BY HRA
FILE NO. CEPS-X-312
FIG. 12

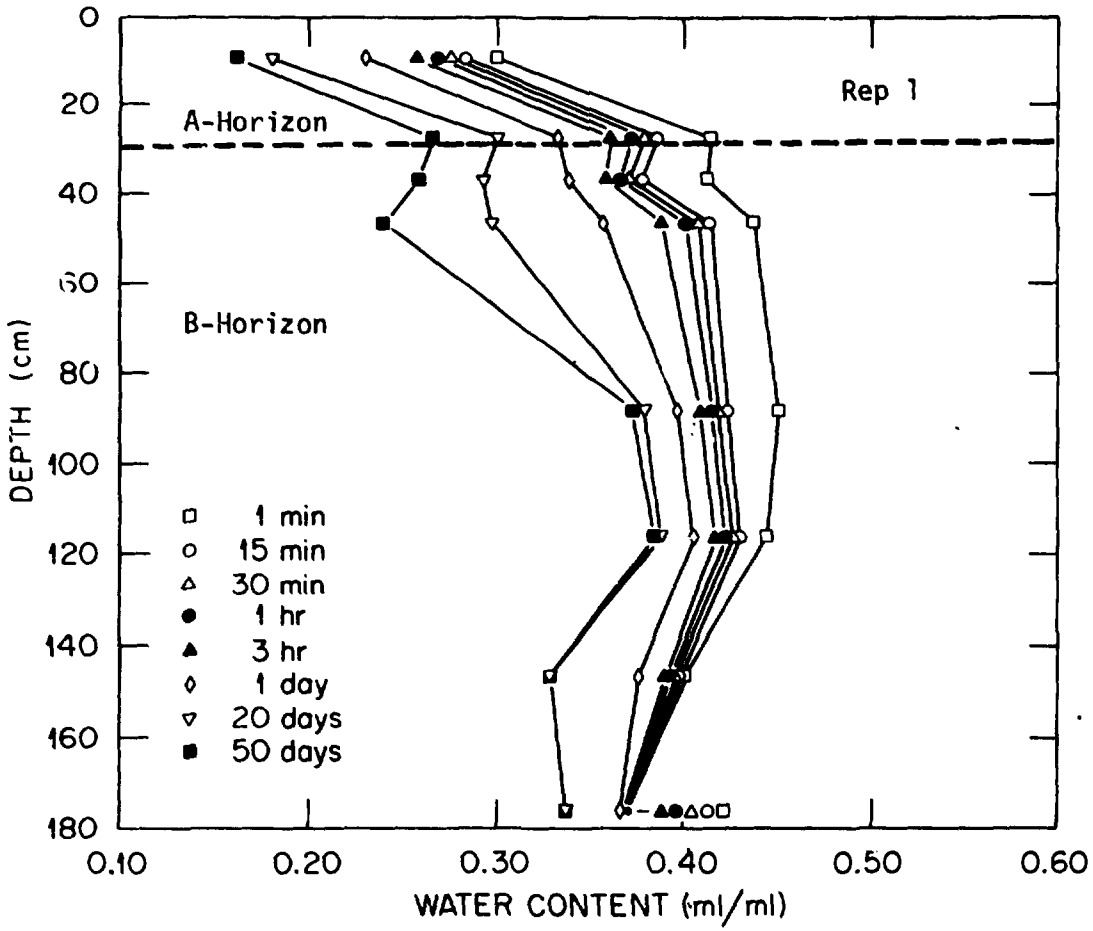
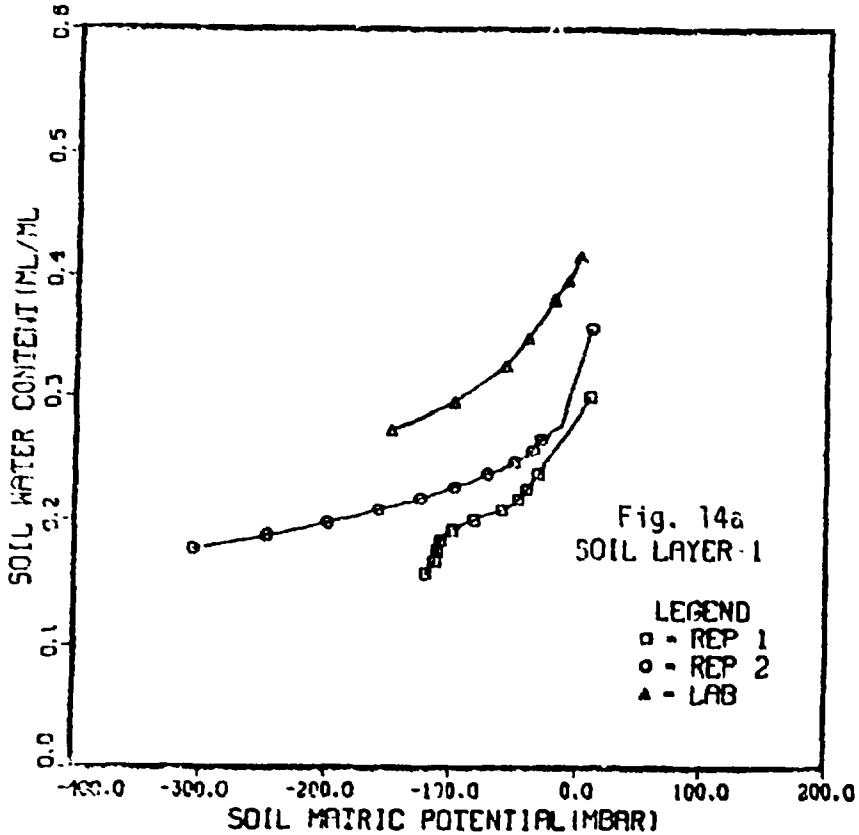


Fig. 13. Water Content Profile (11)



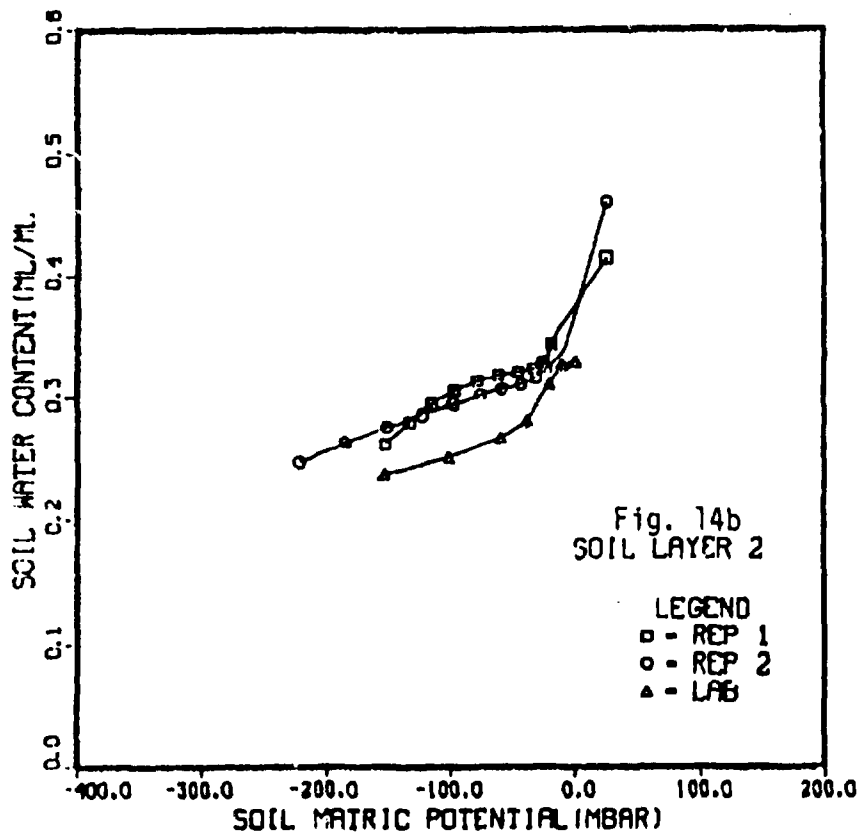


Fig. 14. COMPARISON OF LABORATORY AND BLOCK FACILITY WATER RETENTION DATA (11)

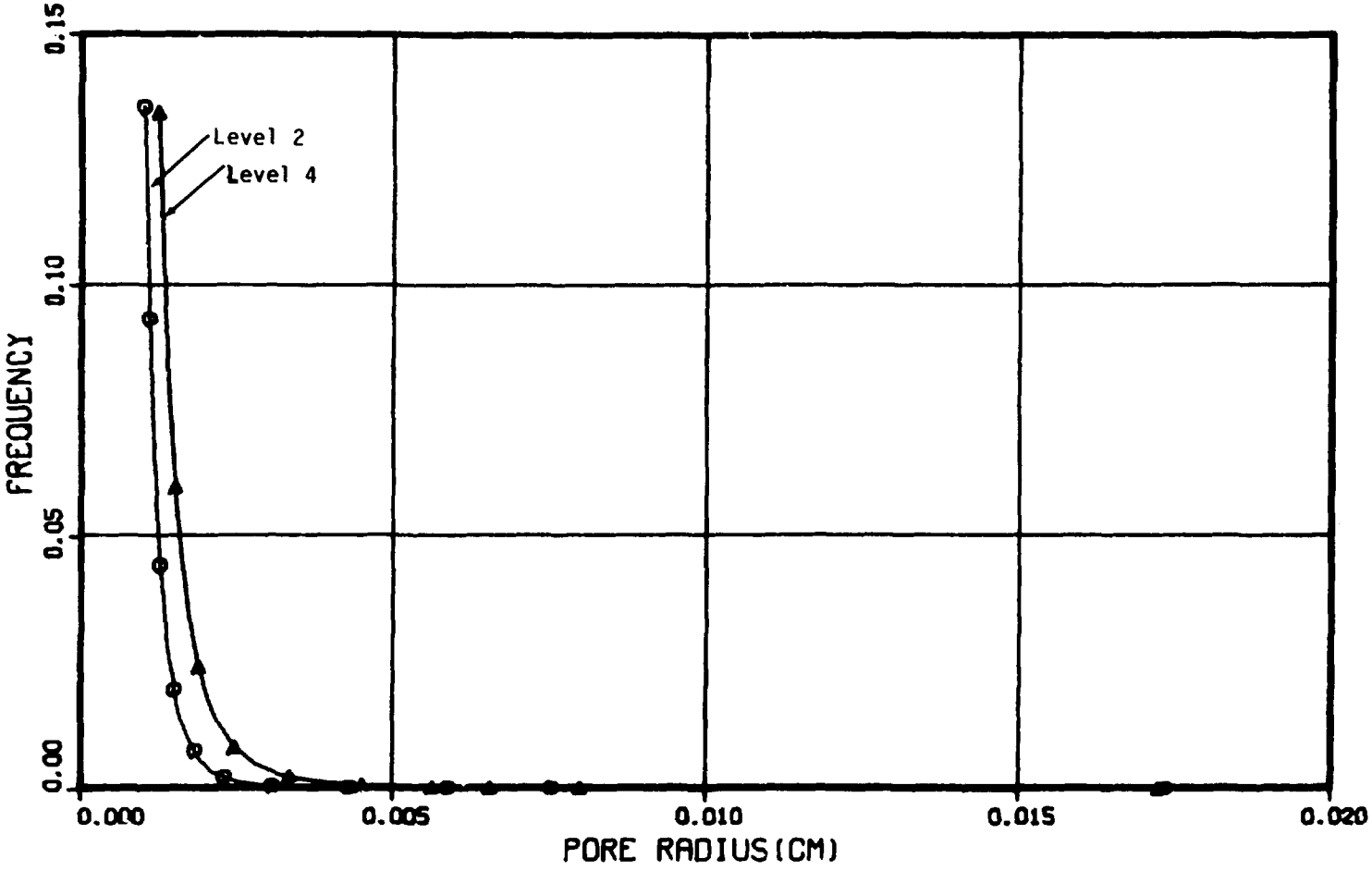


Fig. 15. MESOPORE SIZE DISTRIBUTION AT DIFFERENT DEPTHS (Rep 1)

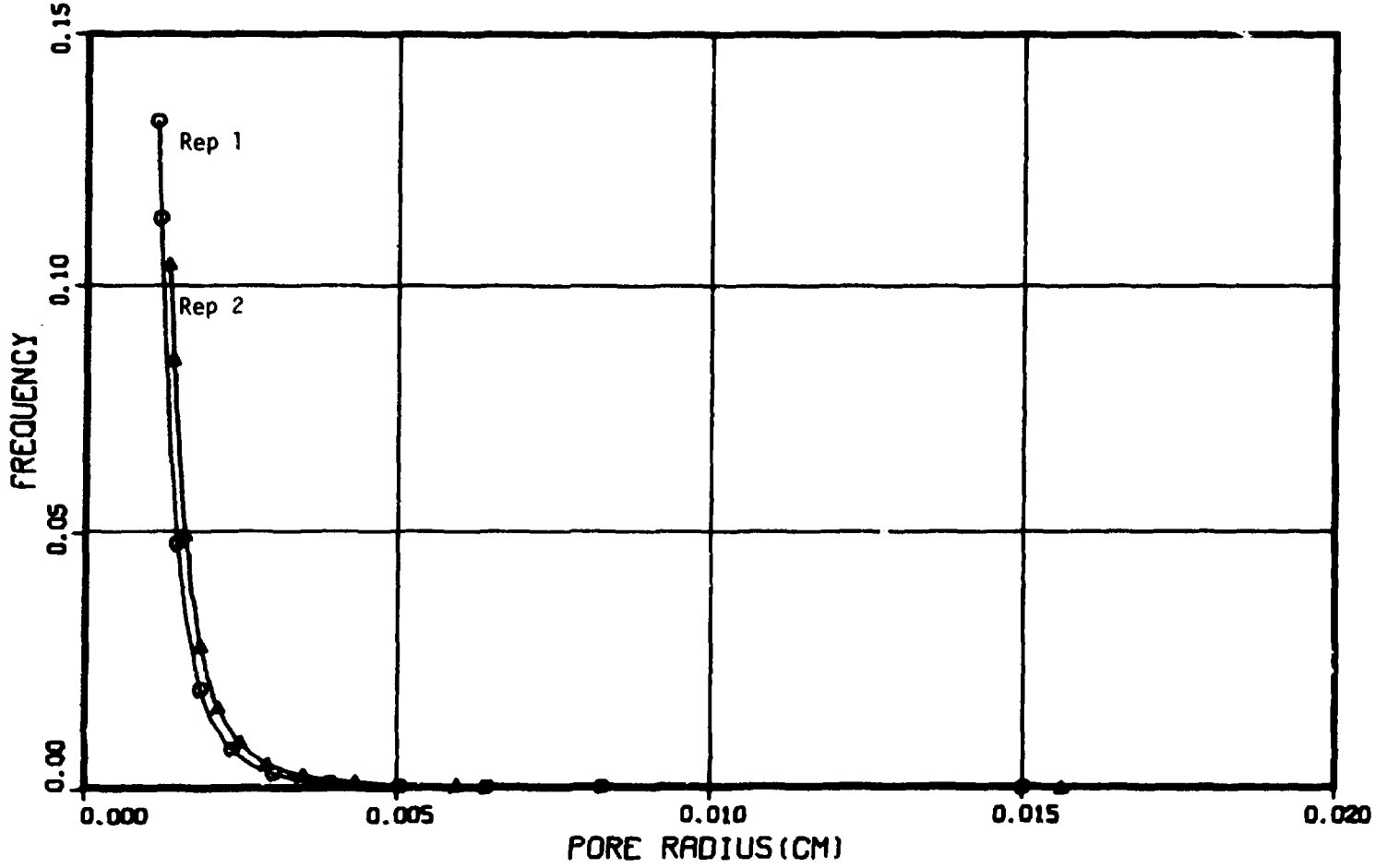


Fig. 16. Mesopore Size Distribution at Different Lateral Positions (Level 3)

A flowchart of the algorithm used for calculating mesopore size distributions is given in Fig. 17, with the diagram being followed by the FORTRAN logic employed.

The pore size frequency distributions for 6 levels (10, 28, 37, 47, 89, and 117-cm depth) at two locations (Rep 1 and Rep 2) (Figs. 18 and 19) in Fullerton cherty silt loam soil were calculated by the method reported by Marshall (12) from soil water content-potential relationships obtained from the field soil (11). The results showed that there were very few pores with radius greater than 0.01 cm and that the smallest pore size was the most frequent class.

10.6 Documentation of Inputs

Additional inputs into TEHM:

macroporosity (MCPOR)

proportion of dead-end macropores (PERC)

radius of cylindrical pores (RP)

width of cracks (WP)

breadth of cracks (PL)

length of aggregate (AGSIZE)

flag for YESMAC:

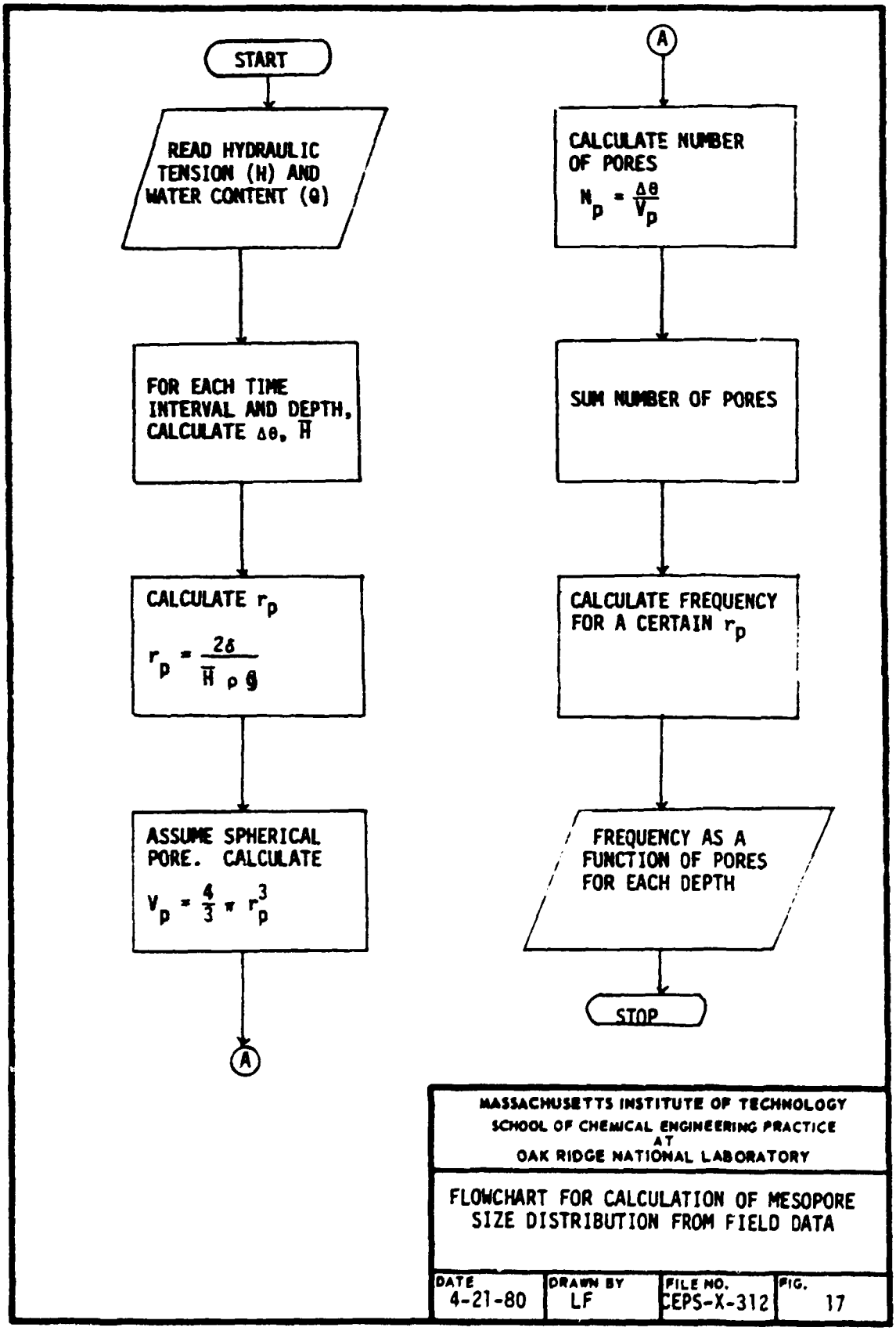
YESMAC = 0 for no macropore effects

YESMAC = 1 for macropore effects

A section of a sample input data file is given on page 47.

Documentation:

Subroutine	Card Number	Columns	Description of Input Data
READIN	7.11	30 - 40	FORMAT (2G10.3, 2I5, F10.0) YESMAC; flag for macropore flow effects YESMAC = 0 for no macropores YESMAC = 1 for macropores
RSWIFT	7.33		FORMAT (6F10.4) One card per soil layer for NSL soil layers
(called from READIN)	to 7.32 + NSL	1 - 10 11 - 20	MCPOR; macroporosity in that layer, ml/ml RP; radius of cylindrical pores if in A-horizon, cm (put 0.0 for B-horizon)


START
READ HYDRAULIC TENSION (H) AND WATER CONTENT (θ)
FOR EACH TIME INTERVAL AND DEPTH, CALCULATE Δθ, $\overline{H}$
CALCULATE r_p
$r_p = \frac{2\delta}{\overline{H}\,\rho\,g}$
ASSUME SPHERICAL PORE. CALCULATE
$V_p = \frac{4}{3}\pi r_p^3$
A
A
CALCULATE NUMBER OF PORES
$N_p = \frac{\Delta\theta}{V_p}$
SUM NUMBER OF PORES
CALCULATE FREQUENCY FOR A CERTAIN r_p
FREQUENCY AS A FUNCTION OF PORES FOR EACH DEPTH
STOP
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
SCHOOL OF CHEMICAL ENGINEERING PRACTICE
AT
OAK RIDGE NATIONAL LABORATORY
FLOWCHART FOR CALCULATION OF MESOPORE SIZE DISTRIBUTION FROM FIELD DATA
DATE 4-21-80
DRAWN BY LF
FILE NO. CEPS-X-312
FIG. 17

PORE SIZE DISTRIBUTION FORTRAN PROGRAM

```
        COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                           SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
                C       CALCULATION OF MESOPORE SIZE DISTRIBUTION ASSUMING SPHERICAL
                C       PORES
ISN 0002                DIMENSION THETA(51,8),H(51,8)
ISN 0003                DIMENSION PN(51,8),RP(51,8),RNP(51,8),T(51),TIME(51),SUM(8)
ISN 0004                DATA SIGMA,PHO/73.5,1.0/
ISN 0005                G=980.1
ISN 0006                PHI=3.1416
                C
                C       READ HYDRAULIC TENSION AND WATER CONTENT DATA
ISN 0007                DO 2  I=1,51
ISN 0008        2       READ(5,100) T(I),(H(I,J),J=1,6)
ISN 0009        100     FORMAT(2X,F8.4,6F6.1)
ISN 0010                DO 4  I=1,51
ISN 0011        4       READ(5,200) T(I),(THETA(I,J),J=1,8)
ISN 0012        200     FORMAT(1X,F9.5,8F5.4)
                C
                C       WRITE HEADINGS FOR OUTPUT DATA
ISN 0013                DO 10  J=1,8
ISN 0014                WRITE(6,500)
ISN 0015                WRITE(6,600) J
ISN 0016        600     FORMAT(30X,'LEVEL ',I2)
ISN 0017                WRITE(6,300)
ISN 0018        300     FORMAT(8X,'TIME',9X,'PORE RADIUS',7X,'FREQUENCY',10X,'NUMBER')
ISN 0019                WRITE(6,500)
ISN 0020        500     FORMAT(' ')
                C
ISN 0021                SUM(J)=0.0
ISN 0022                DO 6  I=1,50
                C       SKIP NEGATIVE OR INCONSISTENT DATA
ISN 0023                IF (H(I,J).LT.0.0)  GO TO 6
ISN 0025                IF (THETA(I+1,J).GE.THETA(I,J))  GO TO 12
ISN 0027                DTHETA=THETA(I,J)-THETA(I+1,J)
ISN 0028                GO TO 14
ISN 0029        12      DTHETA=0.0
ISN 0030        14      AVH=(H(I+1,J)+H(I,J))/2.0-1.5
                C
                C       CALCULATE RADIUS OF PORE CORRESPONDING TO THAT HYDRAULIC TENSION
ISN 0031                RP(I,J)=(2*SIGMA)/(AVH*RHO*G)
ISN 0032                VP=4.0/3.0*PHI*RP(I,J)**3
                C
                C       CALCULATE NUMBER OF PORES CORRESPONDING TO THAT RADIUS
ISN 0033                PN(I,J)=DTHETA/VP
ISN 0034                SUM(J)=SUM(J)+PN(I,J)
ISN 0035        6       TIME(I)=(T(I+1)+T(I))/2.0
                C
                C       WRITE PORE RADIUS, FREQUENCY AND PORE NUMBER
ISN 0036                DO 8  I=1,50
ISN 0037                RNP(I,J)=PN(I,J)/SUM(J)
ISN 0038        8       WRITE(6,400) TIME(I),RP(I,J),RNP(I,J),PN(I,J)
ISN 0039        400     FORMAT(F13.4,9X,F8.6,8X,E10.4,9X,E10.4)
ISN 0040        10       CONTINUE
ISN 0041                STOP
ISN 0042                END
```

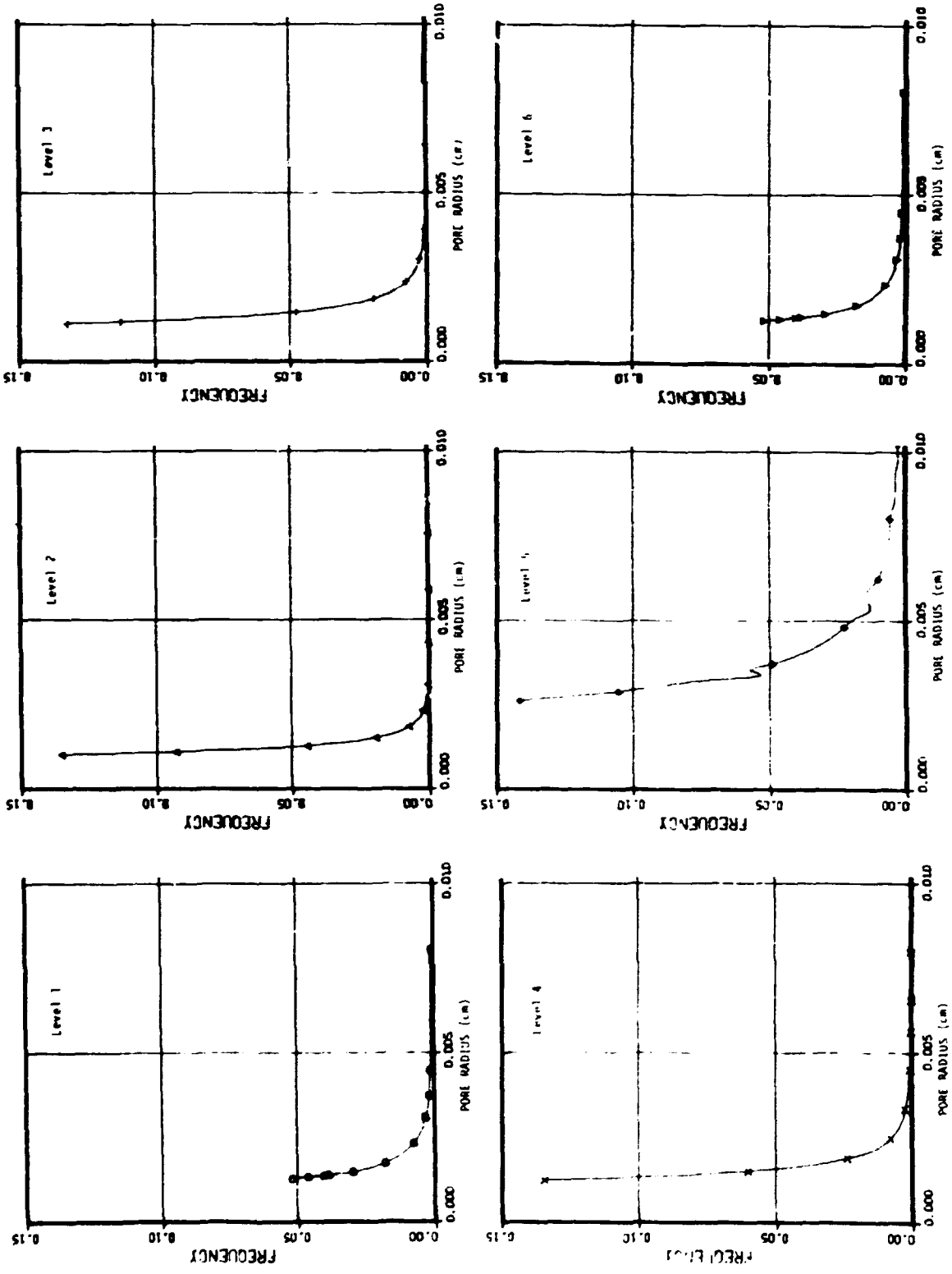


Fig. 18. Mesopore Size Distribution for Six Levels of Map 1

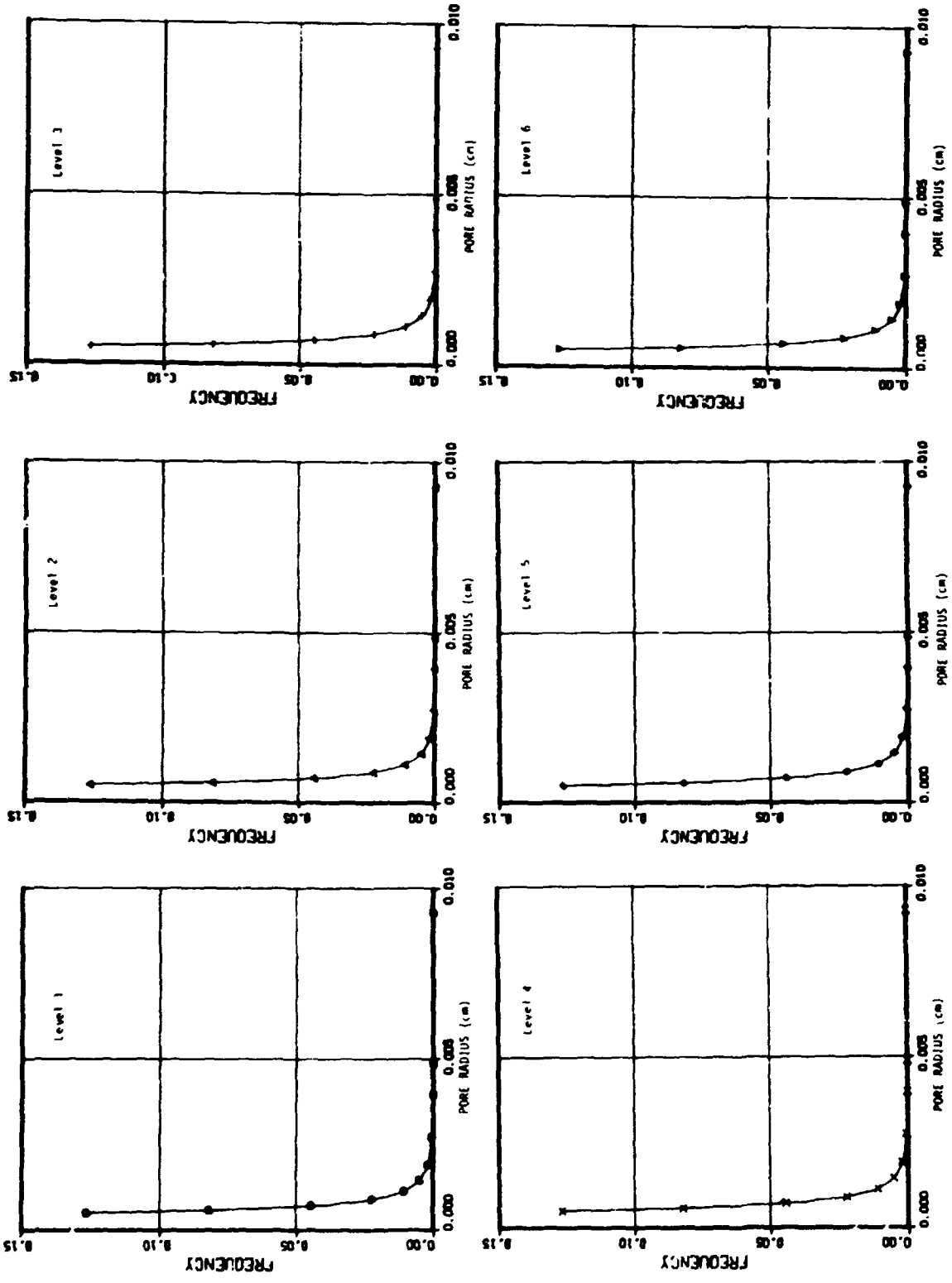


Fig. 19. Mesopore Size Distribution for Six Levels of Rep 2

Sample Input Data

```
 7 PROSPER READIN ----- ANALYSIS:  MACROPOROSITY(0.04)
1   DATA AND SIMULATION OF WALKER BRANCH WATERSHED
   30.0       60.0       60.0       60.0       60.0
     .1591      .2086      .2466      .2466      .2466
      .308
   1.0132      .24       10.        100.       1.0
    .2         .01         .6         .4        20.        400.     5000.0
     0.001       6.3        0.0  20.
500000.        .001       .001
   129.      130.       260.       306.
     2.0       8.0        2.         1.         .12        .16
     0.6       0.48       5    3          1.
  34.         0.        250.       250.       -0.5       -0.5
       0.0       180.       36.0

FULLERTON  A2/E   WALKER BRANCH
 9          50          .27         9.6        0.0
73.49       0.999       .01138     15.        980.
2.0
.125.143.159.170.187.210.240.263.270
11900.  3950.   790.   527.   263.   79.0   19.8   3.95     0.
FULLERTON  B21/6  WALKER BRANCH
 9          50          .246        4.8        0.0
73.49       0.999       .01138     15.        980.
2.0
.166.177.187.193.201.211.225.236.246
11900.  3950.   790.   527.   263.   79.0   19.8   3.95     0.
FULLERTON  B22T/6 WALKER BRANCH
 5          50          .304        4.8        0.0
73.49       0.999       .01138     15.        980.
2.0
.184.198.211.218.226.257.278.298.304
11900.  3950.   790.   527.   263.   79.0   19.8   3.95     0.
INFILTRATION CURVE/6  FOREST SOIL
  15.         0.0         0.0        25
0.    .324 .648 .949 1.26 1.57 1.89 2.20 2.51 2.82 3.14 3.45 3.76 4.07 4.38 4.69
4.99 5.30 5.60 5.91 6.22 6.52 6.82 7.12 7.41
0.   2.47 4.94 7.41 9.88 12.4 14.8 17.3 19.8 22.2 24.7 27.2 29.6 32.1 34.6 37.0
39.5 42.0 44.5 46.9 49.4 51.9 54.3 56.8 59.3
    0.04       0.25       0.00       0.00       0.10       0.00
    0.04       0.25       0.00       0.00       0.10       0.00
    0.04       0.00       0.0625     1.00       0.05       2.00
    0.04       0.00       0.0625     1.00       0.05       2.00
    0.04       0.00       0.0625     1.00       0.05       2.00
 8 SUBSURFACE PARAMETERS
    0.00      10.       1.0       0.0       2.
    180.      180.
    .212      .212
    .29:4536730.228.06886202.134142.1391  700.00104.5259   0.210    0.233
      0.02       0.12       0.00
16 GO
  7   1 99 99
 6 LANPAP          COL 9-80 FOR COMMENTS, SEE M26
  1.0 0.00  25. 0.24  0.4
     0.12v      0.072                      11 1
    1 4    2
 7 PROSPER READIN ----- ANALYSIS:  MESOPORES ONLY(YESMAC=0.0)
1   DATA AND SIMULATION OF WALKER BRANCH WATERSHED
   30.0       60.0       60.0       60.0       60.0
     .1591      .2086      .2466      .2466      .2466
      .308
```

Input for MCPOR, RP, WP, PL, PERC, AGSIZE (in order)

Documentation (continued):

Subroutine	Card Number	Columns	Description of Input Data
RSWIFT		21 - 30	WP; width of cracks if in B-horizon, cm (put 0.0 for A-horizon)
		31 - 40	PL; breadth of cracks if in B-horizon, cm (put 0.0 for A-horizon)
		41 - 50	PERC; proportion of dead-end macropores
		51 - 60	AGSIZE; average length of aggregate size, cm

10.7 Input Data Sets

Standard Case

Layer	Porosity	Radius	Width	Breadth	Proportion of Dead-End Pores	Length
1	0.05	0.25	0.00	0.00	0.10	0.0
2	0.05	0.25	0.00	0.00	0.10	0.0
3	0.10	0.00	0.0625	1.00	0.05	2.0
4	0.10	0.00	0.0625	1.00	0.05	2.0
5	0.10	0.00	0.0625	1.00	0.05	2.0

Each of the following data sets contains seven cases with one parameter being varied from the standard value for each case.

For Hydraulic Conductivity and Porosity Study

SENYES.DAT Hydraulic Conductivity: Layer 1 - 240 cm/d; Layers 2-5 - 120 cm/d

Macroporosity

1	0.04	5	0.02
2	0.00	6	0.08
3	0.005	7	YESMAC = 0 (ignore macropores)
4	0.01		

SLOW.DAT Hydraulic conductivity: Layer 1 - 9.6 cm/d, Layers 2-5, 4.8 cm/d

Macroporosity

1	0.00	5	0.02
2	0.08	6	0.04
3	0.005	7	YESMAC = 0 (ignore macropores)
4	0.01		

Additional Sensitivity Analysis

TEST.DAT Hydraulic conductivity: Layer 1 - 9.6 cm/d; Layers 2-5, 4.8 cm/d

Macroporosity = 0.04 for each case

1	width = 0.10	5	proportion of dead end = 0.0
2	standard macroporosity = 0.04	6	radius = 0.025
3	macroporosity = 0.16	7	width = 0.01
4	proportion of dead end = 0.20 + 0.10		

For Detailed Sensitivity Analysis (suggested)

ANAL1.DAT

Macroporosity		Proportion of dead-end pores	
1	0.04	5	0.00
2	0.08	6	0.05
3	0.12	7	0.25
4	0.16		

ANAL2.DAT

Proportion of dead-end pores		Radius		Width	
1	0.50	2	0.015	5	0.0075
		3	0.150	6	0.0750
		4	1.500	7	0.7500

ANAL3.DAT

Breadth		Length		Macroporosity	
1	0.5	4	0.50	7	0.10, 0.05
2	2.0	5	1.00		
3	5.0	6	5.00		

ANAL4.DAT

Macroporosity		Proportion of Dead-End Pores	
1	0.00	7	0.50
2	0.001		
3	0.005		
4	0.01		
5	0.02		
6	0.04		

10.8 Computer Variables

AGSIZE(K)	average length of an aggregate, cm
B(K)	capacity of continuous macropores, cm/layer
BD(K)	capacity of dead-end macropores, cm/layer
BETA(K)	water content of continuous macropores, cm/layer
BYPS	fraction of non-vertical flow through aggregates
DBET(K)	water content of dead-end macropores, cm/layer
DBETA(K)	daily water content of continuous macropores, ml/ml
DDBET(K)	daily water content of dead-end macropores, ml/ml
DFLOW(K)	flow from dead-end macropores to mesopores, cm/time increment
DHGRAD(K)	hydraulic gradient - mesopores to dead-end macropores, dimensionless
DHWAT(K)	height of water in dead-end macropores, cm
DL(K)	length of soil layer, cm

DMAMA(K)	daily macropore-to-macropore flow, cm/d
DMAME(K)	daily macropore-to-mesopore flow, cm/d
DMEMA(K)	daily mesopore-to-macropore flow, cm/d
DX(K)	distance from macropore to mesopore, cm
EXCESS	excess water from macropores, cm
FRAC	fraction of pore length over vertical distance, dimensionless
FLOW(K)	flow from continuous macropores to mesopore, cm/time increment
FLXMAX	maximum infiltration rate for first soil layer, cm/time increment
HGRAD(K)	hydraulic gradient - mesopores to continuous macropores, dimensionless
HWAT(K)	height of water in continuous macropores, cm
MACEX(K)	daily total of macropore excess, cm
MCPOR(K)	macroporosity, dimensionless
MFBL	macropore flow between layers, cm
MMAMA(K)	monthly macropore-to-macropore flow, cm/month
MMACEX(K)	monthly macropore excess, cm
MMAME(K)	monthly macropore-to-mesopore flow, cm/month
MMEMA(K)	monthly mesopore-to-macropore flow, cm/month
NPOR(K)	number of macropores
NSL	number of soil layers
PERC(K)	fraction of dead-end macropores, dimensionless
PI	π
PL(K)	breadth of rectangular crack, cm
POND	flag set to 1 if there is surface ponding
PRE	precipitation, cm/time increment
PSM(K)	matric potential in mesopores, cm
RAIN	precipitation which enters macropores or is runoff, cm/time increment

RLAT(K)	lateral flow, cm/time increment
RP(K)	radius of cylindrical macropore, cm
S(K)	capacity of mesopores, cm/layer
TBET(K)	total water content of macropores, cm/layer
THETA(K)	water content of mesopores, cm/layer
TRUNO	surface runoff, cm/time increment
TWOPI	2π
WP(K)	width of rectangular crack, cm
YESMAC	flag set to zero if ignoring macropores
ZS(K)	hydraulic conductivity, cm/d
I, J, K	denotes I^{th}, J^{th}, or K^{th} soil layer

10.9 Nomenclature

A	area of interaction, cm^2
b	breadth of rectangular crack, cm
g	gravitational constant, cm/s^2
H	height in a capillary, cm
K	hydraulic conductivity, cm/d
ℓ	length of aggregate, cm
N_p	number of pores
P	capillary pressure
q_c	flux in cracks, cm^3/s
q_p	flux in cylindrical pores, cm^3/s
Q	flux of water in mesopore, cm^3/s
R	radius of a capillary, cm
r_p	radius of a pore, cm

V_p volume of pores, cm^3

w width of a rectangular crack, cm

x average distance between macropores and mesopores, cm

α contact angle in a capillary, degrees

δ surface tension, g/s^2

θ water content in mesopore, cm^3/layer

μ dynamic viscosity, g/s-cm

ρ density, g/cm^3

ψ hydraulic potential, cm water

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