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Preliminary Modeling of Moisture Movement in the Tuff Beneath Mortandad Canyon, Los Alamos National Laboratory

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5 August, 1992

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Preliminary Modeling of Moisture Movement in the Tuff Beneath Mortandad Canyon, Los Alamos National Laboratory

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5 August, 1992

Abstract

An area of upper/middle Mortandad Canyon on the Los Alamos National Laboratory is modeled in cross-section. UNSAT2, a finite element model (FEM) is used to predict moisture movement. Hydraulic characteristics of the tuff are described by van Genuchten parameters determined from laboratory tests on cores taken from a borehole within the cross-section. Material properties are distributed horizontal planar in space to cover the solution domain with required initial conditions. An estimate of seepage flux from a thin perched alluvial aquifer into the upper surface of the tuff is taken from a lumped parameter model. Moisture redistribution for a ponded boundary condition and a larger flux is investigated. A composite simulation using material properties from two separate coreholes is also evaluated.

*This study was performed under appointment to the radioactive Waste Management Fellowship program administered by Oak Ridge Associated Universities for the U.S. Department of Energy.

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1. Introduction

Los Alamos National Laboratory (LANL)[1] is located in north central New Mexico, U.S.A. The Laboratory is situated atop the Pajarito Plateau, which is composed of Bandelier tuff. The tuff ranges in thickness from about 1000 ft. along the western edge of the plateau to less than 50 ft. eastward toward the Rio Grande canyon. For the purposes of this study the Bandelier tuff is assumed to consist of three members: the Tshirege, Tsankawi, and Otowi. These materials are described below. The ash flow, ash fall, and pumice of the Bandelier tuff was deposited by a series of volcanic eruptions 1.1 to 1.4 million years ago (Purtymun et al., 1989). The Valle Grande, a remnant expression of the caldera, is directly west of the Laboratory area.

1.1. Physical System

Intermittent streams have cut deep canyons in the Pajarito Plateau. These canyons concentrate surface runoff into thin stream channels in the canyon bottoms. Fig. 1 is a contour map of the portion of Mortandad Canyon containing the study area. The head of the canyon receives National Pollution Discharge Elimination System (NPDES) permitted effluents from the LANL Radioactive Liquid Waste Treatment Plant as well as other permitted discharges and storm-water runoff. The discharge outfall is approximately 1.2 miles up canyon from corehole MCM 5.1 (see Fig. 1). This effluent and natural surface runoff recharge a shallow perched alluvial aquifer. The aquifer is in a thin veneer of sediments that rest on top of the unsaturated tuff. Fig. 2 schematically depicts the relationship between alluvium and tuff in a cross-section perpendicular to the canyon axis.

The alluvium is derived from weathered tuff and consists of clay, silt, sands, and gravels of quartz, sanadine, rock fragments of tuff, pumice, latite, and rhyolite, all generally less than 1-inch in diameter. The sediments west of MCO 5 are dominated by sand, transitional to a silty clay unit near MCO 6 (see Fig. 1). East

[1] This study was performed for EM-8, Environmental Protection Group, LANL

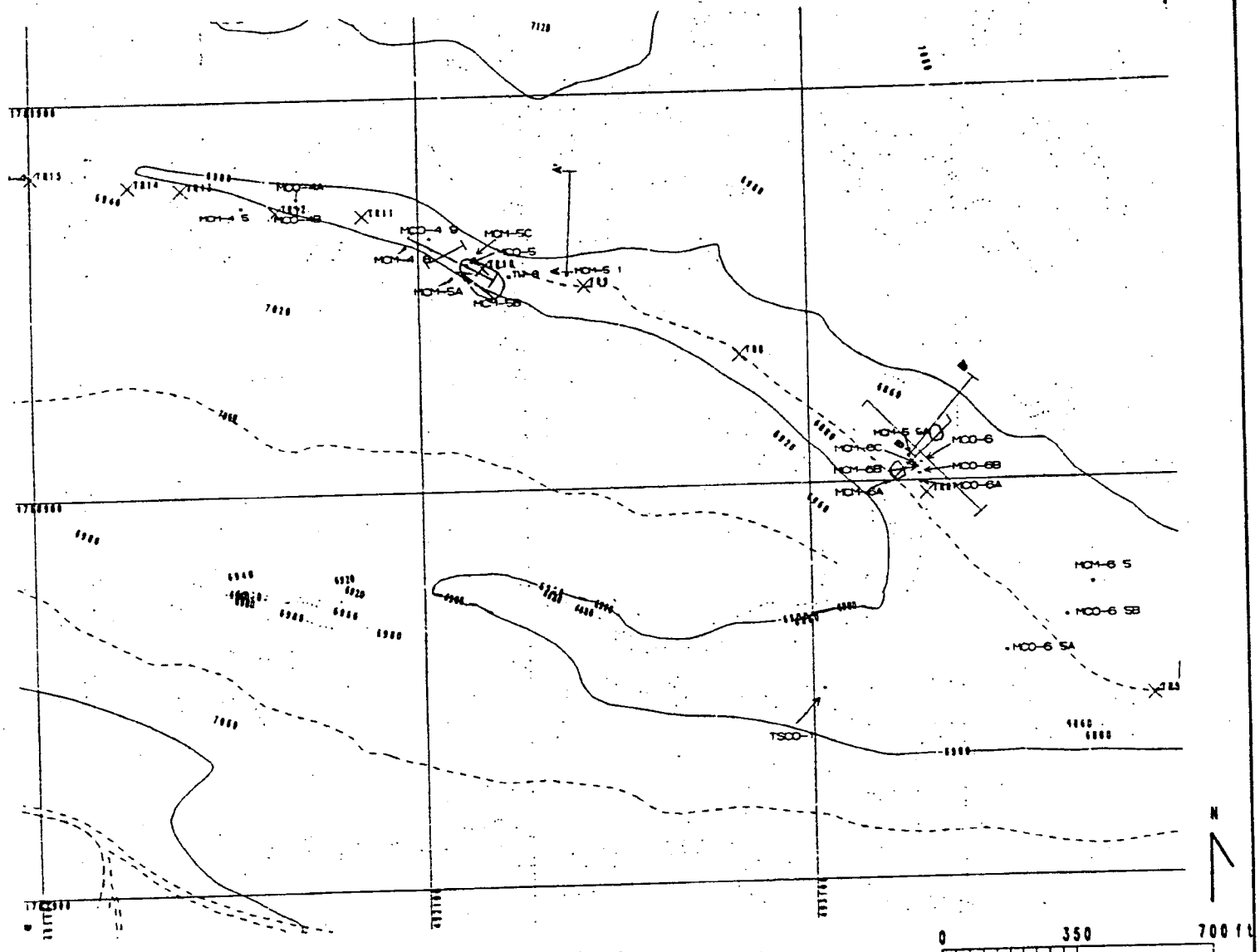

Fig.1: Location Map of Model Area

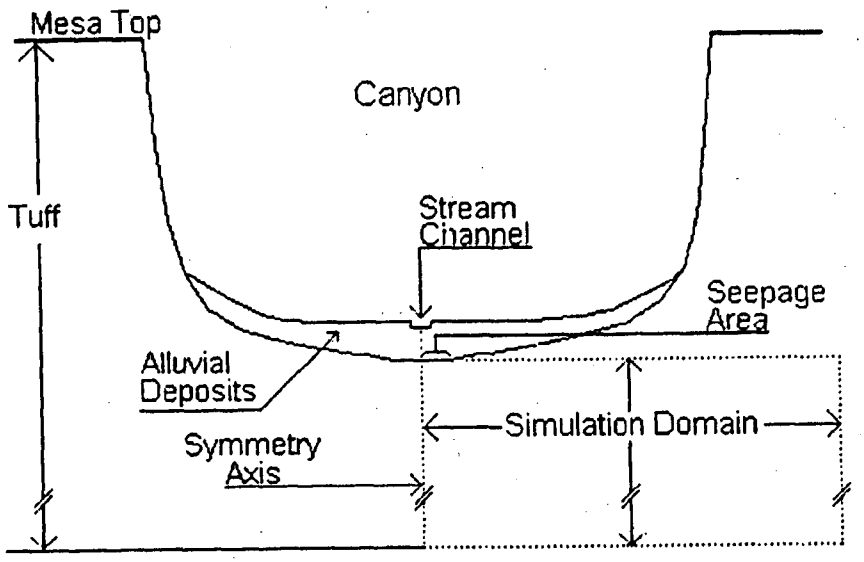

Fig. 2: Schematic cross-section of alluvium - tuff relationship.

of MCO 6 silty clay dominates. Tracer studies have shown the velocity of water in the sand unit to be on the order of 50 ft./day, 20 ft./day in the transitional area, and 6-7 ft./day in the silty clay area (Stoker et al., 1991). Liquid migrates through the alluvial sediments and ponds in places on top of the underlying tuff. Surface flow seldom persists past the first several thousand feet down the five mile long canyon. During the most extreme precipitation events, surface runoff has been observed to flow more than 2 miles down the small stream channel, after which it quickly recedes. In the winter, when stream channel sediments remain frozen, surface flow may continue down canyon farther on average due to a decrease in channel permeability caused by ice (Purtymun, pers. conv.).

The canyon has been conceptually divided into three sections: Upper Canyon, Middle Canyon, and Lower Canyon (Stoker et al., 1991). The hydrologic characteristics of each are slightly different. MCM 5.1 is located in the Upper Canyon which is narrow and filled with underbrush, shrubs, pine, fir, box elder, and oak trees. The alluvium thickens eastward from less than 1 ft. at the NPDES outfall to about 20 ft. near MCM 4.5, and nearly 30 ft. at MCM 5.1 (see Fig. 1). Stream flow in the western half of this section is perennial due to waste water and periodic releases of industrial effluents. The stream channel is entrenched. Major recharge to the shallow alluvial aquifer occurs in the Upper Canyon. Water loss by evapotranspiration also occurs in this section of the canyon due to the large amount of vegetation and shallow extent of the sediments.

MCM 5.9A is in the Middle Canyon which is wider than the Upper Canyon and characterized by thicker sediments. The sediments near MCM 5.9A are 38 ft. thick . The stream channel is well defined, but surface flow is intermittent. The underbrush thins and the canyon floor is littered with pines. The Lower Canyon is wider and has thicker sediments than the Middle Canyon. The stream channel becomes discontinuous, braiding out on the canyon floor. Fig. 3 shows cross-section (BB') near corehole MCM 5.9A (see Fig. 1) including the general location of a typical computer simulation domain used in this study. The corehole penetrates the upper 194 ft. of the profile. Nine core samples were analyzed to determine pertinent hydraulic characteristics (Stoker et al., 1991). Table 1 is a summary of the hydraulic data for these cores, including the important van Genuchten parameters. The sample number denotes the depth at which the core sample was taken. These locations are represented by "pins" through the schematic corehole shown on Fig. 3. Table 2 is a summary of similar data for corehole MCM 5.1, represented by line AA' on Fig. 1.

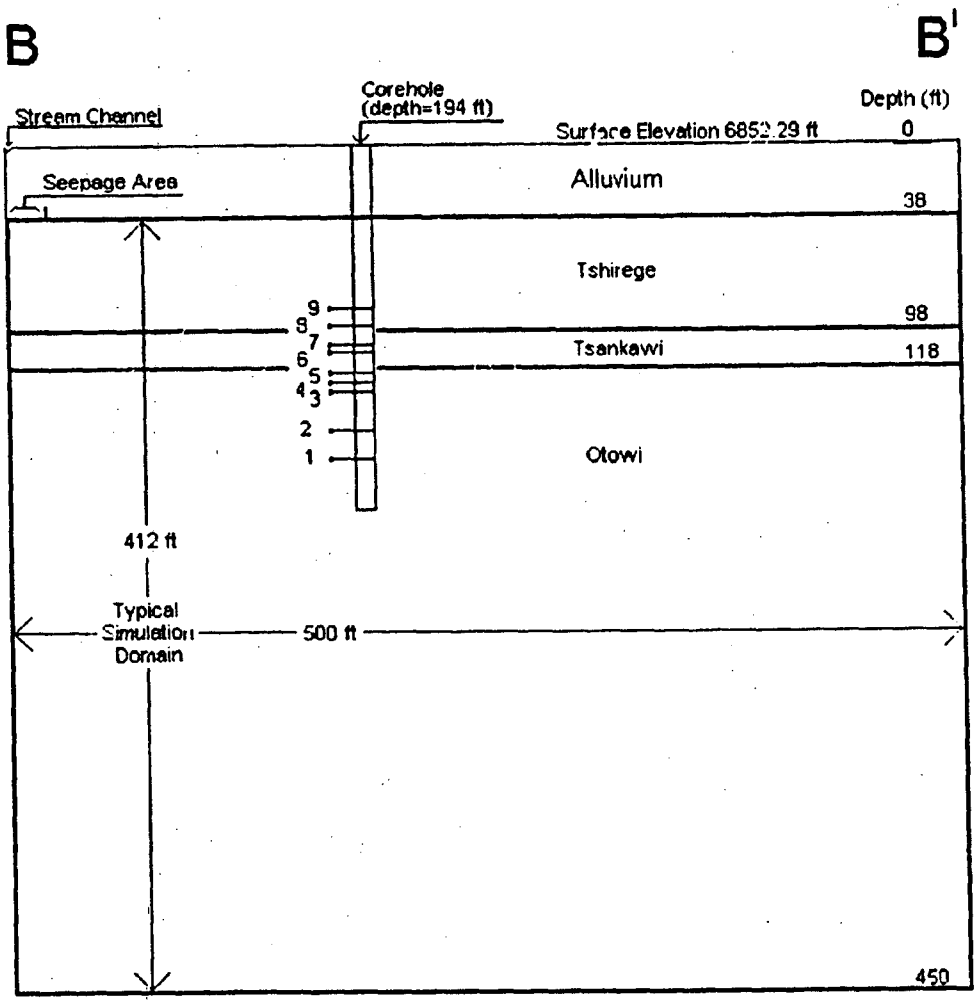

Fig. 3: Conceptual cross-section used for computer simulation domain near corehole MCM 5.9A, middle Mortandad canyon (1 inch = 100 ft., [⟵] = sample location).

Sample Number (Corehole MCM 5.9A)	α (cm^{-1})	N	θ_R ($\frac{cm^3 H_2O}{cm^3 Tuff}$)	θ_S ($\frac{cm^3 H_2O}{cm^3 Tuff}$)	K^S ($\times 10^{-4} \frac{cm}{sec}$)
MCM 5.9A 85.5-86.0	0.10449	1.34112	.209	.686	39.0
MCM 5.9A 94.5-95.0	0.04433	1.47491	.124	.498	11.0
*MCM 5.9A 104.5-105.0	0.00508	1.72981	.329	.537	20.0
*MCM 5.9A 109.0-109.5	0.00818	1.45120	.198	.616	13.0
MCM 5.9A 119.5-120.0	0.01582	1.55108	.052	.435	7.9
MCM 5.9A 124.5-125.0	0.00804	1.86760	.084	.552	2.8
MCM 5.9A 129.5-130.0	0.00555	1.92358	.082	.519	78.0
MCM 5.9A 149.5-150.0	0.00589	1.74058	.091	.538	17.0
MCM 5.9A 164.5-165.0	0.00803	1.68945	.120	.486	2.9

(* = Tsankawi Member).

Table 1: Hydraulic data for cores taken from test hole MCM 5.9A.

Sample Number (Corehole MCM 5.1)	α (cm^{-1})	N	θ_R ($\frac{cm^3 H_2O}{cm^3 Tuff}$)	θ_S ($\frac{cm^3 H_2O}{cm^3 Tuff}$)	K^S ($\times 10^{-4} \frac{cm}{sec}$)
MCM 5.1 43.0-43.5	0.00104	1.77361	.089	.521	2.0
MCM 5.1 53-54 CHEM	0.00873	1.88477	.168	.451	1.5
MCM 5.1 57.5-58.0	0.00972	1.66746	.061	.520	1.8
MCM 5.1 63-64 CHEM	0.01740	1.41385	.089	.533	1.3
MCM 5.1 67.0-67.5	0.01016	1.55430	.049	.520	1.1
MCM 5.1 72.0-72.5	0.01178	1.49131	.040	.515	1.1
MCM 5.1 82.0-82.5	0.01059	1.59133	.220	.589	1.2
MCM 5.1 87.0-87.5	0.00915	1.51023	.049	.512	1.1
MCM 5.1 92.5-93.0	0.00292	1.67116	.102	.472	0.17
*MCM 5.1 94.5-95.0	0.01369	1.50196	.387	.656	6.8
*MCM 5.1 97.0-97.5	0.00073	1.59926	.107	.455	0.58
*MCM 5.1 107.0-107.5	0.02968	1.18191	.150	.178	13.0

(* = Tsankawi Member).

Table 2: Hydraulic data for cores taken from test hole MCM 5.1.

A brief description of the unsaturated Bandelier Tuff beneath the saturated alluvial sediments in the canyon bottom is presented in descending order:

- Tshirege Member: Unit 1A Tuff is non welded to moderately welded, light gray in color, consisting of quartz and sanadine crystals and crystal fragments, rock fragments of pumice, latite, and rhyolite in a matrix of gray ash. It is weathered gray, buff, or light to dark brown in places. The pumice and ash matrix is typically weathered to clay.

- Tsankawi Member: Thin lenses of silt, sand, and gravels, consisting of pumice, quartz, and sanadine crystals, and rock fragments of latite and rhyolite ranging in color from gray to dark brown represent erosion and deposition at the top of a massive ash flow. Ash and some pumice is weathered to clay.

- Otowi Member: Massive non-welded to moderately welded tuff consisting of quartz and sanadine crystals and crystal fragments, numerous pumice fragments up to 2-inches in length, rock fragments of latite and rhyolite in an ash matrix. Tuff is gray to dark brown in color when weathered, ash matrix and some pumice is weathered to silts and clay.

Several hundred feet below these three units lie the Guaje Member, a light tan to light gray pumice, a conglomerate unit, and a basalt layer. The regional water table is approximately 600 feet below the base of the simulation domain, as depicted is Fig. 3. The presence of these units is noted for completeness but they are not included in the modeling effort as no hydraulic data exists for them. Material properties for the Otowi unit are assumed to exist to the base of the simulation domain.

2. Unsaturated Flow Model

The computer model used to describe moisture movement in the tuff is UNSAT2 (Davis et al., 1983), a finite element model (FEM). A source code listing is contained in the appendices. The basic two-dimensional differential equation solved by this model, disregarding storage effects as a result of tuff compressibility or any expansion of water, and any sources or sinks in the flow domain is:

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

where:
h = pressure head or matric potential [L],
$K(h)$ = unsaturated hydraulic conductivity [L/T],
$C(h)$ = specific moisture capacity = $\frac{d\theta}{dh}$ [1/L],
θ = volumetric water content (volume of water per bulk volume of tuff),
x, z = spatial coordinates [L], and
t = time [T].

Basic assumptions needed for the practical numerical solution of (1) are isothermal and isohaline conditions. Solution of (1) at any later time requires that h be known everywhere in space at the beginning of the simulation period, and that any normal fluxes or different h on the boundary of the solution domain be specified. These initial and boundary conditions can be stated mathematically as:

$$h(x,z,0) = h_0 \ , \ h(x,z,t) = h_c \text{ and } v(x,z,t) = v_c. \tag{2}$$

where:
h_0 = prescribed head function of space,
h_c = prescribed head function of space and time, and
v_c = prescribed normal flux function of space and time.

The solution of (1) subject to (2) requires that h be a single valued function of θ. That is, whether a material is wetting or drying, the same one-to-one correspondence between θ and h exists. While this is not rigorously true, at present there is no simple way to account for this type of hysteresis. For the purpose of the present study this last constraint is satisfied by the van Genuchten relationship (van Genuchten, 1980). This relationship is:

$$\theta(h) = \frac{\theta_S - \theta_R}{\left[1 + (\alpha h)^N\right]^M} + \theta_R \tag{3}$$

where:
θ_S = experimentally determined saturated volumetric water content.
θ_R = experimentally determined residual volumetric water content.
α = curve fitting parameter [1/L].
$M = 1 - \frac{1}{N}$, and
N =another curve fitting parameter.

θ or h can be measured in the field and the other calculated after α and N have been determined. To do this, paired values of θ and h are generated experimentally for each material sample, usually while the material is drying. Then α and N are adjusted to minimize the total distance between the experimental data and the theoretical curve described by (3). One may use this information to determine the relative hydraulic conductivity for a corresponding h (*or* θ) according to:

$$K^R(h) = \frac{\left[1 - (\alpha h)^{N-1}\left[1 + (\alpha h)^N\right]^{-M}\right]^2}{\left[1 + (\alpha h)^N\right]^{\frac{M}{2}}} \qquad (4)$$

where:
$K^R(h)$ =relative hydraulic conductivity, and
$0 \leq K^R(h) \leq 1$.
All other variables are as previously defined.

$K(h)$ is then found by the relationship $K(h) = K^R(h)K^S$, where K^S is the experimentally determined saturated hydraulic conductivity [L/T]. The required parameters have all been determined for this study (Stoker, et al., 1991), and are included in Table 1 and 2 above. The laboratory analysis was performed by Daniel B. Stephens & Associates, Inc. of Albuquerque, New Mexico.

2.1. UNSAT2 Flow Equation

The UNSAT2 computer program was developed to analyze isothermal flow in variably saturated porous media (Davis et al., 1983). For the purpose of this project it is used to describe flow in a vertical plane through conceptually layered materials. Conventional prescribed head and prescribed normal flux boundaries are applied to the solution domain. The following equation is solved by UNSAT2, disregarding specific storage effects, and any sources or sinks:

$$C(h)\frac{\partial h}{\partial t} = \sum_{i=1}^{3}\sum_{j=1}^{3}\frac{\partial}{\partial x_i}\left[K^R(h)K_{ij}^S\frac{\partial h}{\partial x_j}\right] + \sum_{i=1}^{3}\frac{\partial}{\partial x_i}K^R(h)K_{i3}^S \qquad (5)$$

where:
x_i = spatial coordinate ($i, j = 1, 2, 3$ with x_3 = vertical coordinate), and
K_{ij}^S =hydraulic conductivity tensor at saturation.
All other variables are as previously defined.

The first term in (5) describes a material's capacity to resist a change in water content for a given change in head, over time. The second term represents advection, and the third term represents drainage. The conductivity tensor is isotropic (here). A solution to (5) is obtained using the Galerkin finite element method (Davis et al., 1983). For this project the storage properties of the simulation domain are considered negligible, which requires the use of a backward difference time integration scheme. The use of finite elements allows specification of irregular domain borders and irregularly layered material. However, the grid developed here is rectangular, with horizontal and vertical spacing that facilitates comparison (of physical and academic significance) with any future finite difference simulations, as the Mortandad canyon modeling effort progresses. The intricacies of the solution procedure can be found in Davis et al. (1983).

3. Lumped Parameter Model

The lumped parameter model is based on a dynamically connected stream-alluvial aquifer system. The structural simplicity of this technique is inherently related to the systems operation approach it takes; the system is described only to the degree that it relates averaged input-output-storage changes over time (Stoker, et. al. 1991). For the stream connected (phreatic) alluvial aquifer system located in Mortandad Canyon, a simple water balance equation may be written as:

$$n\frac{dz}{dt} = q_S - q_O - q_{ET} - q_T \qquad (6)$$

where:
n = average effective aquifer porosity $[\frac{L^3}{L^3}]$,
z = average saturated alluvial aquifer thickness $[L]$,
$\frac{d}{dt}$ = total derivative $[T^{-1}]$,
q_S = stream leakage $[\frac{Vol}{Area \cdot Time}]$,
q_O = net alluvial aquifer outflow $[\frac{Vol}{Area \cdot Time}]$,
q_{ET} = evapotranspiration $[\frac{Vol}{Area \cdot Time}]$, and
q_T = seepage into Tuff $[\frac{Vol}{Area \cdot Time}]$.

The net aquifer outflow term, q_O , is approximated by a linear relationship given as:

$$q_O = a(z - z_O) \tag{7}$$

where:
z_O = stream reference level $[L]$, and
a = a lumped outflow constant $[T^{-1}]$.

Equation (7) is inherently related to Darcy's law. In general, z_O can be a function of time, but is usually assumed constant since fluctuation in z_O are usually much smaller than those for z (Stoker, et. al, 1991). Substituting (7) into (6) yields a differential equation of the form:

$$n\frac{dz}{dt} + a(z - z_O) = E \tag{8}$$

where:
E = represents the lumped time dependent inputs minus output.

The model represented by (8) is a lumped parameter model in the form of a well mixed linear reservoir. The term $\frac{n}{a}$ represents the hydraulic response time (t_h) of the system since it characterizes the average response time of the water balance equation. Typically t_h will vary between one and three months in Mortandad canyon (Stoker, et al., 1991). Numerous analytical solutions for (8) are

available for a wide variety of initial conditions. Parameters for the model have been estimated from a preliminary calibration performed on monthly field data collected in Mortandad canyon from July 1963 to 1965.

The alluvial aquifer can be thought of as a long rectangular volume of saturated sediments that follows the canyon axis under the stream channel, on top of the tuff. This volume of material has a surface area of 40 ft. by 7,200 ft., and a thickness (z) described by (6). The 7,200 ft. distance represents the length of upper/middle Mortandad canyon. The seepage area in each computer simulation domain represents one-half of the 40 ft. wide saturated sediment box. The simulation domain border that extends vertically down beneath the seepage area (see Figs. 2 and 3) can be thought of as a symmetry axis, about which the flow pattern is mirrored. Equation (6) is solved for q_T, which is applied as a flux boundary condition in the seepage area.

4. Computer Simulations

4.1. Boundary and Initial Conditions

Saturation can be defined as the volume of water per volume of pore space, i.e.:

$$S = \frac{\theta_i - \theta_R}{\theta_S - \theta_R} \tag{9}$$

where:
$0 \leq S \leq 1$

For a given S, θ_S, and θ_R, one can solve for the corresponding θ_i, and then compute h using (3), providing α and N have been determined for that material. Initial head configurations for the following simulations are based on an assumed initial saturation value of 0.20 (20 percent). Table 3 shows the matric potential computed for various levels of saturation in corehole MCM 5.9A. Saturation slightly less than 20% produced values for h that represent a very dry condition. This caused convergence problems during run time as a result of steep matric potential gradients in front of the infiltrating water and discontinuities in h across material interfaces. Saturation greater than 20% is essentially a wet system that does not match observations of in-situ water content taken to be similar to those observed at depth in the Otowi. Table 4 is a summary of similar data for corehole MCM 5.1.

Sample Number (Corehole MCM 5.9A)	Material Number	h (-ft) (S=0.05)	h (-ft) (S=0.10)	h (-ft) (S=0.20)
MCM 5.9A 85.5-86.0	9	2016	268	35
MCM 5.9A 91.5-95.0	8	106	91	22
*MCM 5.9A 104.5-105.0	7	391	151	58
*MCM 5.9A 109.0-109.5	6	3067	660	141
MCM 5.9A 119.5-120.0	5	476	135	38
MCM 5.9A 124.5-125.0	4	128	58	26
MCM 5.9A 129.5-130.0	3	151	71	33
MCM 5.9A 149.5-150.0	2	318	121	48
MCM 5.9A 164.5-165.0	1	315	115	42

(* = Tsankawi Member).

Table 3: Matric potential values (h), for cores from MCM 5.9A, calculated using (3), assuming S = 0.05, 0.10, and 0.20.

Sample Number	Material Number	h (-ft) (S=0.05)	h (-ft) (S=0.10)	h (-ft) (S=0.20)
MCM 5.1 43.0-43.5	12	1515	617	219
MCM 5.1 53-54 CHEM	11	111	51	23
MCM 5.1 57.5-58.0	10	300	106	37
MCM 5.1 63-64 CHEM	9	2625	492	92
MCM 5.1 67.0-67.5	8	718	205	58
MCM 5.1 72.0-72.5	7	1233	392	73
MCM 5.1 82.0-82.5	6	491	152	47
MCM 5.1 87.0-87.5	5	1272	327	84
MCM 5.1 92.5-93.0	4	956	341	121
*MCM 5.1 94.5-95.0	3	936	235	59
*MCM 5.1 97.0-97.5	2	6662	2093	654
*MCM 5.1 107.0-107.5	1	554	131	31

(* = Tsankawi Member)

Table 4: Matric potential values (h), for cores from MCM 5.1, calculated using (3), assuming S = 0.05, 0.10, and 0.20.

Material properties as described by van Genuchten parameters are assumed to form planar layers that extend infinitely into space. A point equidistant between core samples was arbitrarily chosen to represent a material boundary, except at the boundary between the Tsankawi member and the material above and below it. The location of this major lithologic contrast was determined from the driller's log.

Corehole MCM 5.9A is 194 ft. deep, and is taken to accurately represent the top 200 ft. of material beneath the surface of the canyon bottom. The uppermost 38 ft. of this material is alluvium, and the remaining 162 ft. is the primary focus of this modeling effort. Table 5 is a summary of gravimetric water content data for MCM 5.9A core samples, with elevation given above this arbitrary 200 ft. depth datum. Daniel B. Stephens & Associates, Inc. determined parameters for the samples indicated. The remaining samples had gravimetric water content determined during a radiochemical analysis performed at LANL. The volumetric water content for these samples was computed using values for bulk density, material density, and porosity from adjacent tested samples. The relationship between these parameters is:

$$\rho_b = \rho_m(1 - \phi) \;\; and \;\; \theta_{vol} = \theta_{grav}\frac{\rho_b}{\rho_l} \tag{10}$$

where:
ρ_b = bulk density $[\frac{M\,Bulk}{L^3\,Bulk}]$,
ρ_m = material density $[\frac{M\,Solid}{L^3\,Solid}]$,
ϕ = porosity $[\frac{L^3\,Pores}{L^3\,Bulk}]$,
θ_{vol} = volumetric water content $[\frac{L^3\,H_2O}{L^3\,Bulk}]$,
θ_{grav} =gravimetric water content $[\frac{M\,H_2O}{M\,Bulk}]$, and
ρ_l = density of water $[\frac{M\,H_2O}{L^3\,H_2O}]$, taken to be 1.0 $\frac{gram}{cm^3}$.

Sample Elevation	θ_{grav} $(\frac{gH_2O}{gBulk})$	ρ_b $(\frac{gBulk}{cm^3Bulk})$	ρ_m $(\frac{gSolid}{cm^3Solid})$	ϕ $(\frac{cm^3Pores}{cm^3Bulk})$	θ_{vol} $(\frac{cm^3H_2O}{cm^3Bulk})$
161	.149	1.00+	2.32+	.569+	.149+
160	.195	1.00+	2.32+	.569+	.195+
156	.189	1.00+	2.32+	.569+	.189+
153	.104	1.00+	2.32+	.569+	.104+
151	.192	1.00+	2.32+	.569+	.192+
146	.238	1.00+	2.32+	.569+	.238+
136	.183	1.00+	2.32+	.569+	.183+
131	.194	1.00+	2.32+	.569+	.194+
129	.181	1.00+	2.32+	.569+	.181+
121	.256	1.00+	2.32+	.569+	.236+
115..	.391	1.00	2.32	.593	.389
111..	.354	1.09	2.32+	.555	.388
111..	.442	0.95	2.32+	.610	.422
106..	.114	1.52	2.32	.381	.172
*98	.065	0.92+	2.48+	.628+	.060+
*96..	.605	0.92	2.48	.624	.558
*91..	.493	0.90	2.48	.632	.445
*86	.248	0.92+	2.48+	.628+	.229+
81..	.214	1.08	2.31+	.557	.232
76..	.161	1.11	2.31	.546	.179
71..	.185	1.05	2.31	.570	.195
66..	.187	1.06+	2.31+	.540+	.199+
61..	.189	1.09+	2.31+	.530+	.205+
56..	.177	1.09+	2.31+	.530+	.193+
51..	.190	1.16	2.31	.525	.221
46..	.174	1.24	2.31	.492	.217
41	.155	1.18+	2.31+	.490+	.183+
36..	.168	1.26	2.31	.485	.212
31..	.158	1.20+	2.31+	.480+	.190+
26..	.159	1.20+	2.31+	.480+	.191+
21..	.159	1.20+	2.31+	.480+	.191+
16..	.165	1.22+	2.31+	.470+	.202+
11	.152	1.22+	2.31+	.470+	.185+

(* = Tsankawi Member, ..= D.B.Stephens, Inc., + = assumed values)

Table 5: Measured gravimetric water content, and calculated volumetric water content where noted. Bulk and material density assumed where noted.

Figure 4 represents observed volumetric water content in MCM 5.9A with distance above the 200 ft. depth datum, using the data from Table 5. An observation made from this figure is that water content generally increases on top of the two material interfaces. The Tshirege Unit 1A has a finer pore structure than the Tsankawi below it, and water content is thought to increase on this interface due to the capillary barrier effect. That is, there is no potential for the finer material to release water to the coarser material below it until the pressure is increased. The pressure increases with an associated increase in water content on the material interface, and the water flows out of the finer material. On the other hand, the Otowi is much less permeable than the Tsankawi above it, and the water content increase on this interface is thought to be a result of this restriction to flow. Fig. 4 shows that the two large increases in water content do not occur exactly at the interfaces. This is attributed to some uncertainty in the exact location of the material boundaries as represented on the figure. If the 20 ft. thick band of material representing the Tsankawi were moved up 5-10 ft., these increases would occur very close to the material interfaces. However, there is no justification to change the location of the interfaces in the references, and this data is used to access the general validity of the computer simulations.

The simulation domain dimensions vary in width and depth to prevent moving water from encountering any prescribed no flow boundaries and to facilitate convergence by keeping grid size to a minimum. All boundaries are no flow except for the seepage area (see Fig. 3), which is present in the upper left-hand corner of all contour plots. This portion of the boundary has three conditions prescribed on it, which are: 1) A downward flux, equal to that predicted by the lumped parameter model, of $q_T = 5.6 \times 10^{-3}$ ft./day (McLin, pers. conv., report in progress); 2) A constant (ponded) head equal to 1.0 ft. of water; 3) An order of magnitude greater downward flux of $q_T = 5.6 \times 10^{-2}$ ft./day. The constant ponded head was chosen to represent the base of the alluvium which is intermittently and variably ponded, but usually saturated in the area near MCM 5.9A.

4.2. Finite Element Simulations

The UNSAT2 input files and source code used to generate the remaining figures are included in the appendix. All finite element simulations were performed on the Integrated Computing Network, Machine Rho, LANL[2]. This is a Cray Y-MP

[2]The author would like to acknowledge the assistance of the C-6 ICN Consulting Office, and Jim Faber for his assitance on porting code to the Cray.

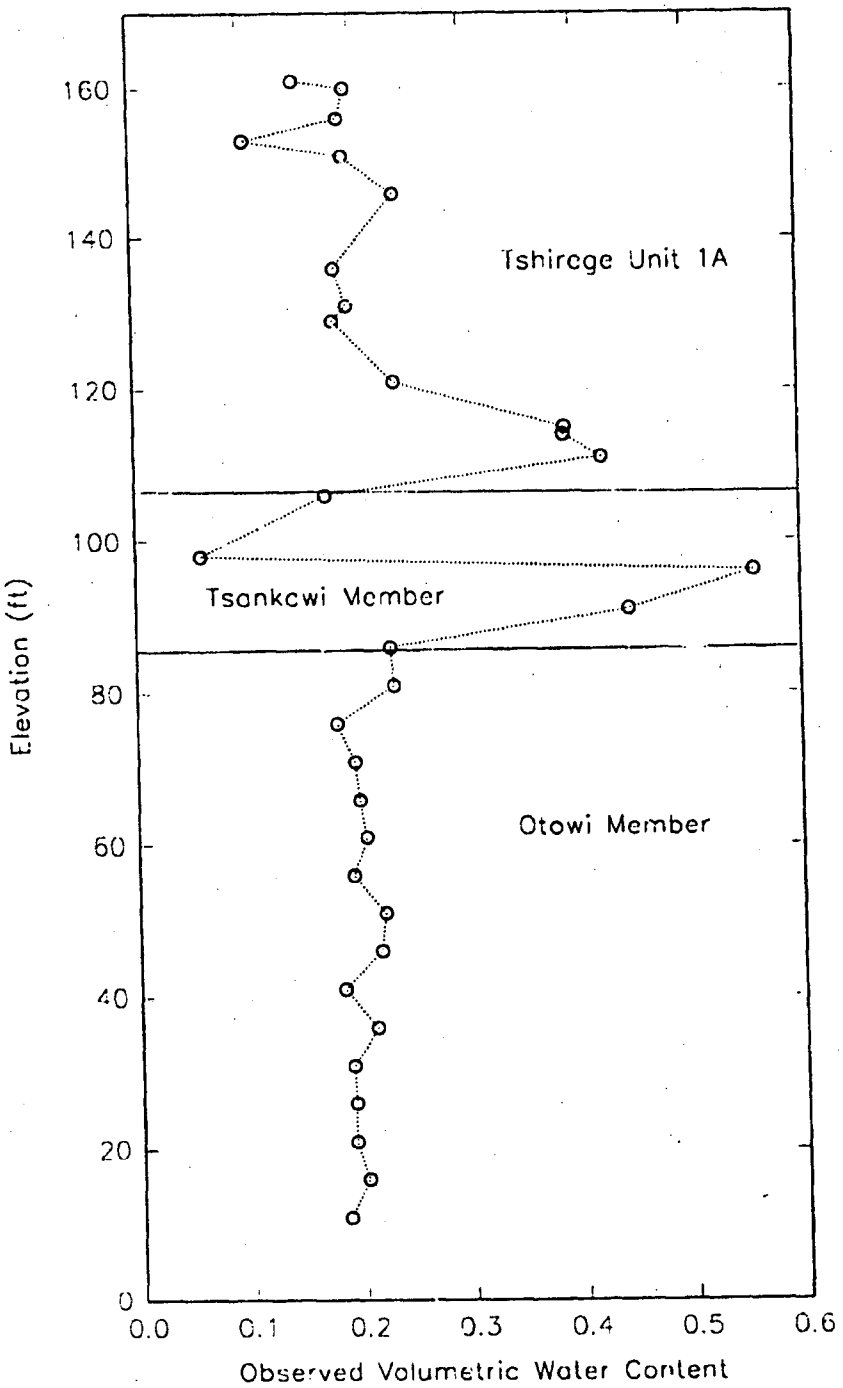

Fig. 4: Observed volumetric water content with elevation in corehole MCM 5.9A, based on data in Table 5.

running UNICOS, ver. 6.0.1. The UNSAT2 finite element grid used to generate Figs. 5, 6, and 7, had 'x' direction nodes spaced 6 at 5.0 ft. apart, 13 at 10.0 ft., and 6 at 15.0 ft. from the symmetry axis, and 'y' direction nodes spaced 250 at 2.0 ft. apart, 100 at 1.0 ft., and 124 at 0.5 ft. from the base of the simulation domain. This configuration defines a grid containing 12,350 nodes (11,850 elements). CPU time was approximately 4000 seconds for the 100 year flux run of Fig. 5, and nearly 10,000 seconds for the ponded head run of Fig. 7, which only simulated 171 days of water movement, using identical time step controls. The large difference in computational effort for two identical grids is a result of the non-linearity of the unsaturated flow equation. Specifically, the capacity term in (1) causes a discontinuity to occur where the change in matric potential (dh) becomes very large. In infiltration problems with several materials this situation will arise across the wetting front of the permeating fluid, and across material interfaces where the matric potential gradient is initially discontinuous.

Fig. 5 & 7 show contours of pressure head (in feet). There are no saturated nodes in the profile of Fig. 5, water movement is entirely by unsaturated flow. Fig. 6 shows predicted and observed water content for the top 162 feet of the Fig. 5 flux run. Comparison of Figs. 5 & 6 is not obvious as a result of the many different materials used. Fig. 5 shows matric potential increasing (becoming less negative) on top of and through the Tsankawi, as we move toward the symmetry axis. The changes are on the order of tens of feet. Fig. 6 shows the associated increase in water content through the Tsankawi, but as a result of material properties, shows the water content dropping off on top of the Tsankawi. This is easily understood if one refers to the data of Table 1. Samples MCM 5.9A 85.5-86.0 and MCM 5.9A 94.5-95.0 are used to represent the Tshirege Unit 1A in these simulations. The porosity (taken as saturated volumetric water content) is 0.686 for MCM 85.5-86.0, and drops off to 0.498 for MCM 94.5-95.0, just on top of the Tsankawi. While neither material is saturated, this decrease in porosity limits the ability to reflect the large change (increase) in water content that may physically occur on the interface. Cumulative inflow for the system at the time of Fig. 5 is 1,200 ft.^{3}.

Fig. 7 is included to demonstrate the questionable validity of a ponded head boundary condition in the seepage area. Observations of water content at the base of the alluvium typically show saturated sediments on the order of several feet thick. Fig. 7 shows that one foot of ponded head on this system saturated nearly 180 ft. of the profile. Cumulative inflow at the time of Fig. 7 (171 days) is 36,110 ft.^{3}. The 0.0 ft. contours represent the saturated part of the profile, and the wetting front was forced to the observed depth as a result of the impermeable

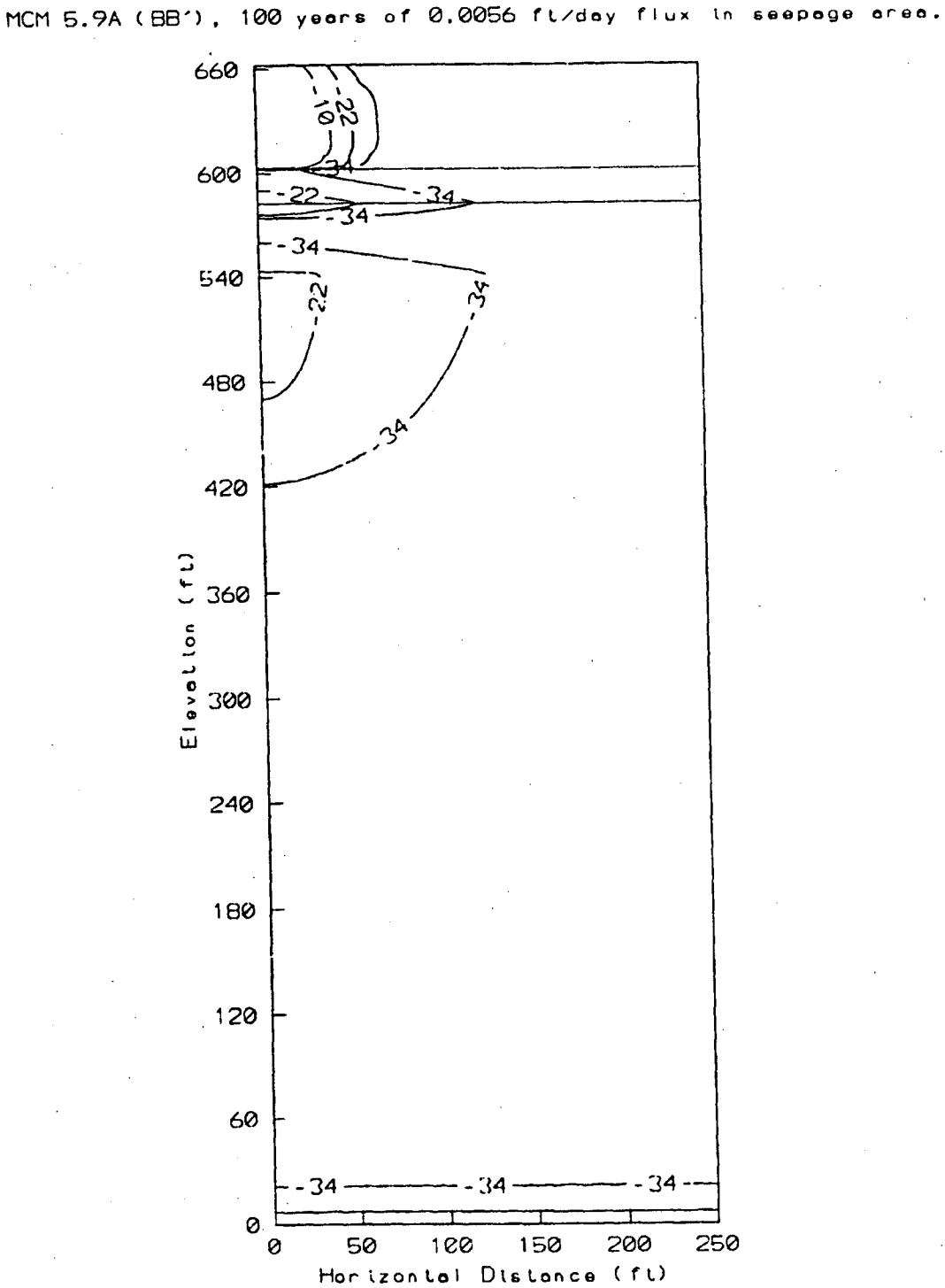

Fig. 5: UNSAT2 simulated matric potential contours (in feet) for 100 years of 0.0056 ft./day flux in seepage area. Cross-section consists of material in Table 1, MCM 5.9A.

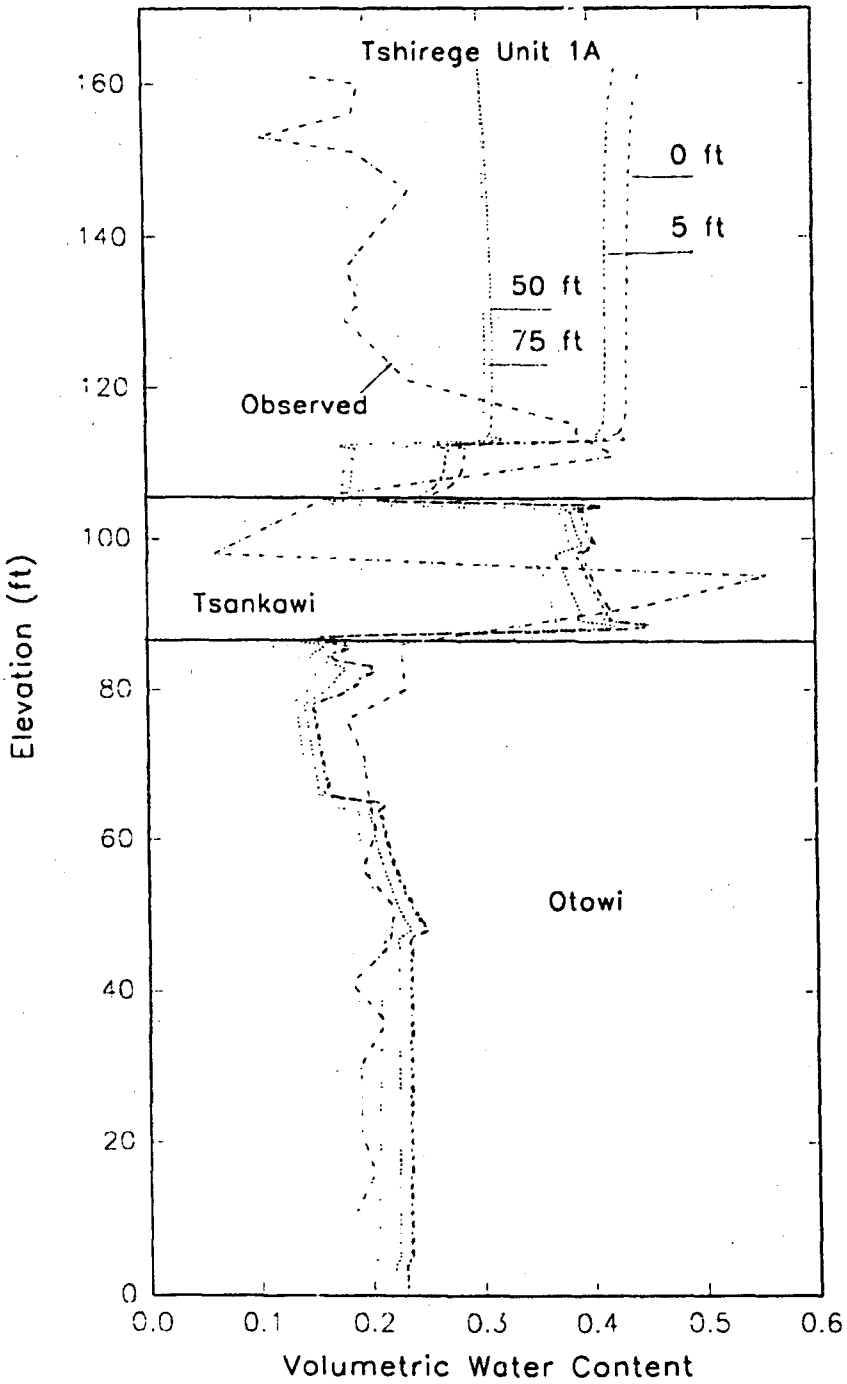

Fig. 6: UNSAT2 simulated water content at x=0,5,50,75 ft. from symmetry axis for upper 162 ft. of Fig. 5, after 100 years of 0.0056 ft/d flux in seepage area.

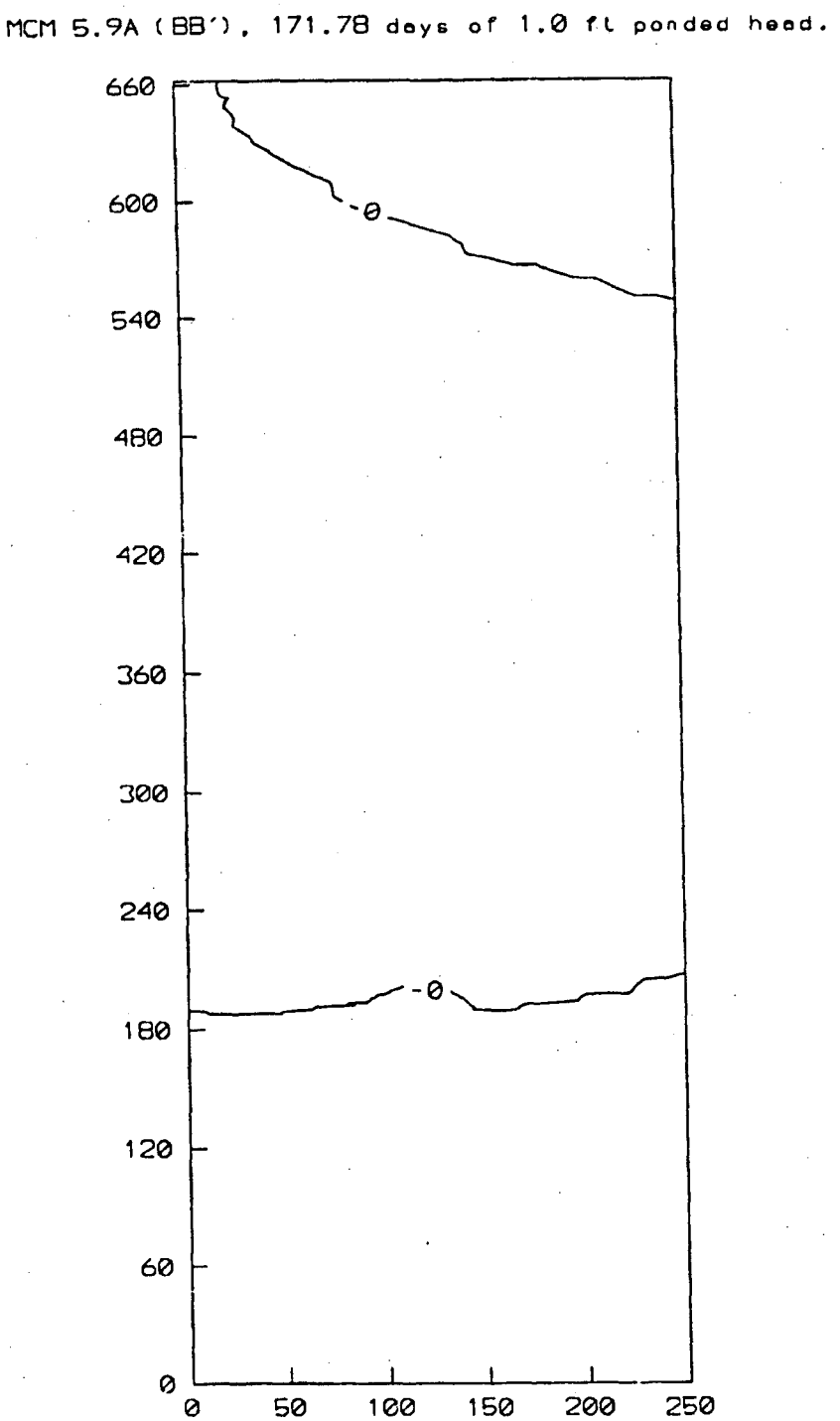

Fig. 7: UNSAT2 simulated matric potential contours (in feet) for 171.78 days of 1.0 ft. ponded head in the seepage area. Zero pressure isobar delineates the saturated region in the profile. Cross-section consists of material in Table 1, MCM 5.9A.

boundary at x=250 ft. from the symmetry axis. At this point in the study several variations in node spacing and grid dimension were tested to arrive at a reasonable solution of the ponded head problem. Many convergence problems occurred as a result of the large number of materials used, and a system where a zero pressure isobar is migrating through an initially unsaturated profile.

Increasing computational time and expense necessitated a simplifying of the conceptual system. Fig. 8 represents the initial water content profile, as predicted by UNSAT2, for a system consisting of three materials. Sample number MCM 5.1 72.0-72.5 (see Tables 1 to 4) was used to represent the Tshirege Unit 1A Member, sample MCM 5.1 107.0-107.5 was used to represent the Tsankawi Member, and sample MCM 5.9A 119.5-120.0 was used to represent the Otowi Member. Stoker (pers. conv.) questions the validity of van Genuchten parameters representing the Tshirege Unit 1A material in MCM 5.9A, as a result of the sampling procedures used during coring. Table 1 shows the the saturated hydraulic conductivity of this material to be much greater and more variable than values at corresponding depths in corehole MCM 5.1 (see Table 2).

Figs. 9, 10, and 11, show ponded head simulations at 1.3, 11.2, and 21.9 years respectively, for the three material system. The node spacing for these simulations is 10 at 5.0 ft. apart, and 15 at 10.0 ft. apart from the symmetry axis, and 112 at 1.0 ft. apart from the base of the simulation domain. This defines a grid of 23,128 nodes (22,660 elements). The infiltrating water in these simulations did not feel the impermeable boundary at x=500 ft. from the symmetry axis. However, the flow field does demonstrate instabilities that manifest themselves as 'bubbles' of positive pressure, most notable in Fig. 10. There is no physical explanation for their occurrence. Behavior of water movement around the material interfaces in the upper part of the profile has the same physical justification as given above for the previous simulations and the observed water content. That is, matric potential increases on top of the Tsankawi (toward the symmetry axis), and through this unit. Cumulative inflow at the time of Fig. 11 is 68,131 $ft.^3$, which is remotely consistent with nearly 125 ft. of saturated sediments at the base of the simulation domain! Fig. 12 is a plot of simulated and observed water content along the symmetry axis in the top 162 ft. of Fig. 11, and also displays the features that have no physical explanation, namely the two large increases in water content near 30 ft. elevation. Observation of water contents at less than saturation through the Tshirege argue against a ponded head upper boundary condition. Unsaturated flow is required to allow this material to remain at less than saturation, as observed, and the ponded boundary condition approach should

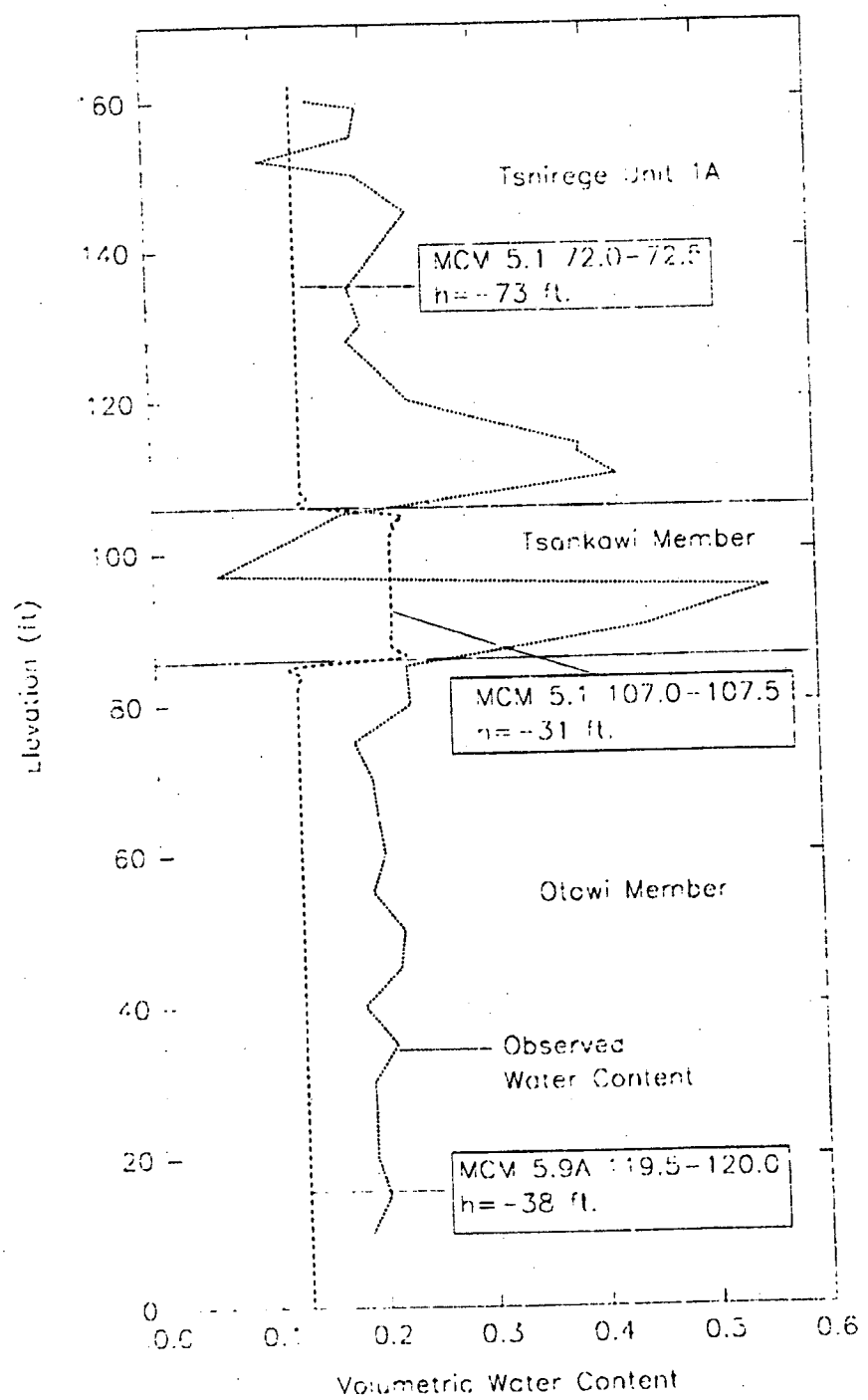

Fig. 8: Initial water content profile for composite cross section (3 materials) at 20% saturation as predicted by UNSAT2.

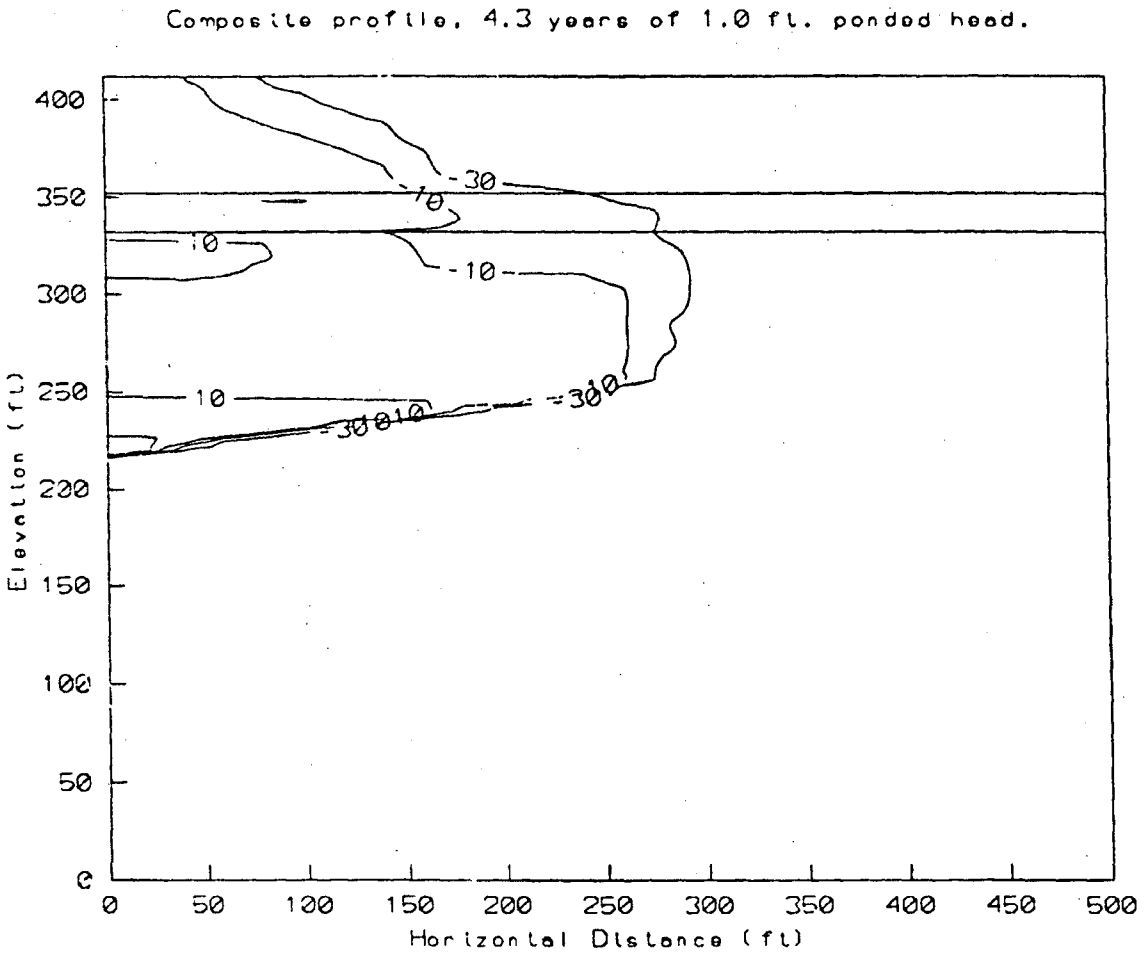

Fig. 9: UNSAT2 simulated matric potential contours (in feet) for 4.3 years of 1.0 ft. ponded head in seepage area. Composite cross-section consists of three materials.

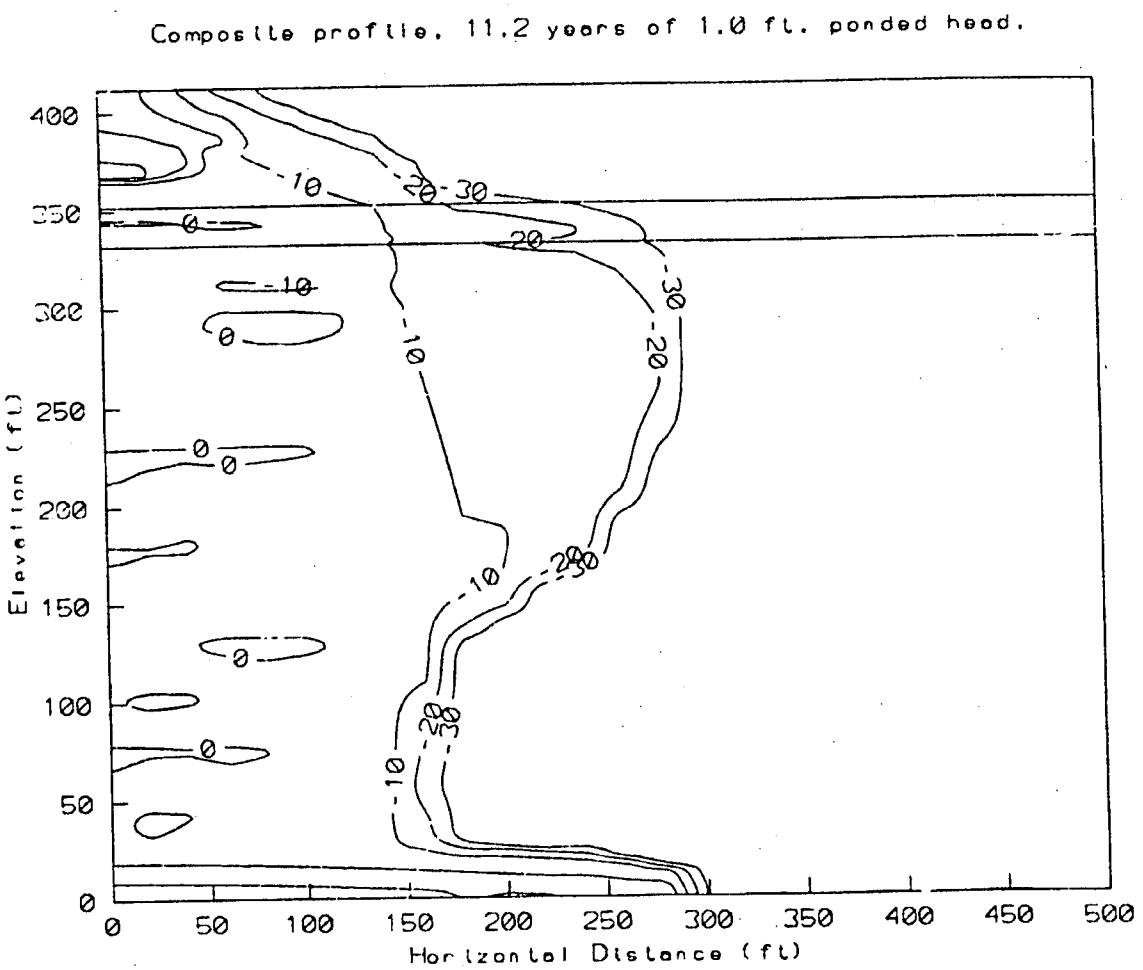

Fig. 10: UNSAT2 simulated matric potential contours (in feet) for 11.2 years of 1.0 ft. ponded head in seepage area. Composite cross-section consists of three materials.

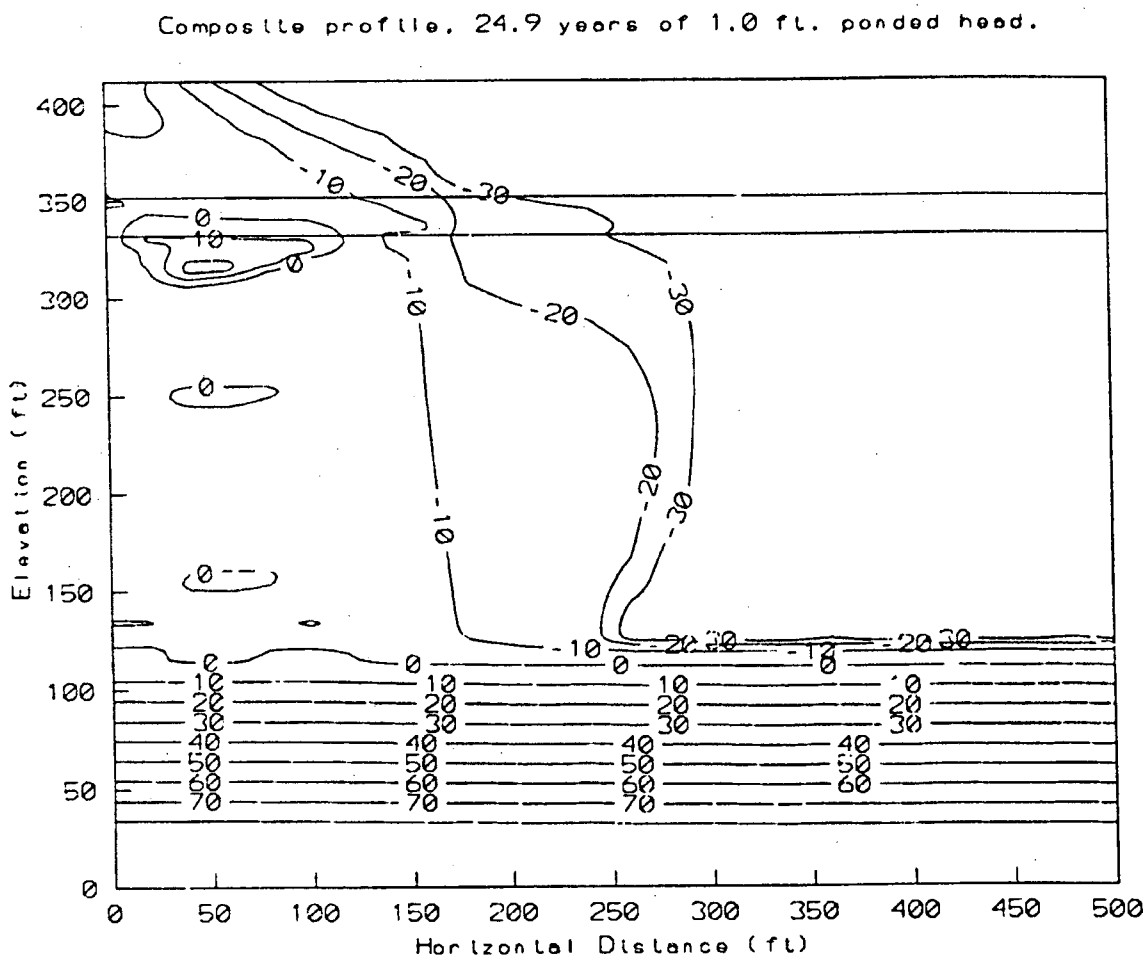

Fig. 11: UNSAT2 simulated matric potential contours (in feet) for 24.9 years of 1.0 ft. ponded head in the seepage area. Composite cross-section consists of three materials.

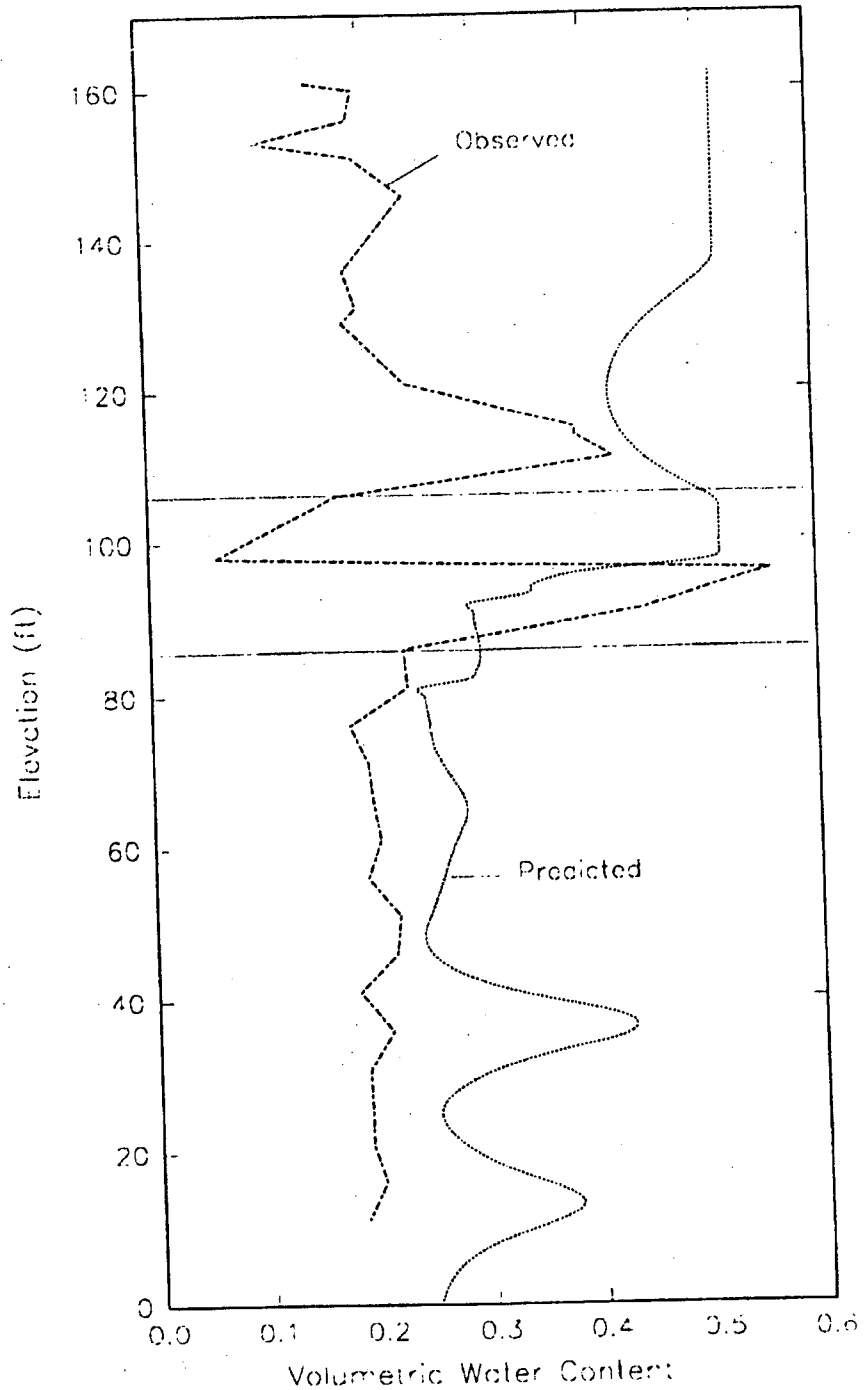

Fig. 12: Predicted and Observed water content for 24.9 years of 1 ft. ponded head, at x = 0 ft. from symmetry axis.

not be pursued.

Figures 13, 14, and 15, show water infiltrating the composite profile at a rate of q_T = 0.056 ft./day. This value represents an order of magnitude increase in the lumped parameter model predicted infiltration rate. Several saturated nodes occur at the base of the simulation domain as a result of redistribution within the profile, otherwise water movement is by unsaturated flow. Gravity appears to play a larger role than capillarity in causing the matric potential contours to migrate downward. Their configuration exhibits very little capillary spreading of the moisture plume. Fig. 16 and 17 show the simulated water content profile in the top 162 feet of Figures 14 and 15 respectively. Cumulative inflow at the time of Fig. 14 was 2,191.5 ft.^{3}, and was 3,171.5 ft.^{3} at the time of Fig. 15. The oscillation of the water content plot for x=0,5, and 15 ft. through the Otowi (on Fig. 17) can only be described as numerical instability.

5. Conclusions and Discussion

Figures 16 and 17 show the migration of a high water content peak through the Tsankawi. A plausible explanation for the occurrence and movement of this peak could be that water leaving the Tshirege does so at a saturated conductivity controlled rate of $K_S = 1.4 \times 10^{-4} \frac{cm}{sec}$, while the Tsankawi is able to move it away from the contact at a faster rate of $K_S = 13.0 \times 10^{-4} \frac{cm}{sec}$, resulting in decreased water content just below the interface. While the Tsankawi is filling with water from above, it is also being drained from below. The peak occurs because the Otowi is able to move water out of the Tsankawi slightly faster than it enters from the Tshirege. (Saturated conductivity of the Otowi is $K_S = 7.9 \times 10^{-4} \frac{cm}{sec}$.) The system dynamics are very complex and the peak could also be attributed to some type of dynamic equilibrium, not allowing the Tsankawi to simply drain. Figure 15 shows a good correspondence between observed (shown on Fig. 15 and in Fig. 4) and simulated water content tendency (increasing and decreasing in tandem) from the top of the Tsankawi Member downward. However, there does not seem to be any way to simulate the observed water contents in the Tshirege with water flowing in from the top of the profile. With any upper boundary contributing water to the simulation domain, the water contents in this region all move toward saturation. The water contents we observe in the Tshirege are near 20% saturation (see for example Fig. 8). This pattern is also observed in MCM 5.1. The amount of water potentially contributed to the system by a ponded

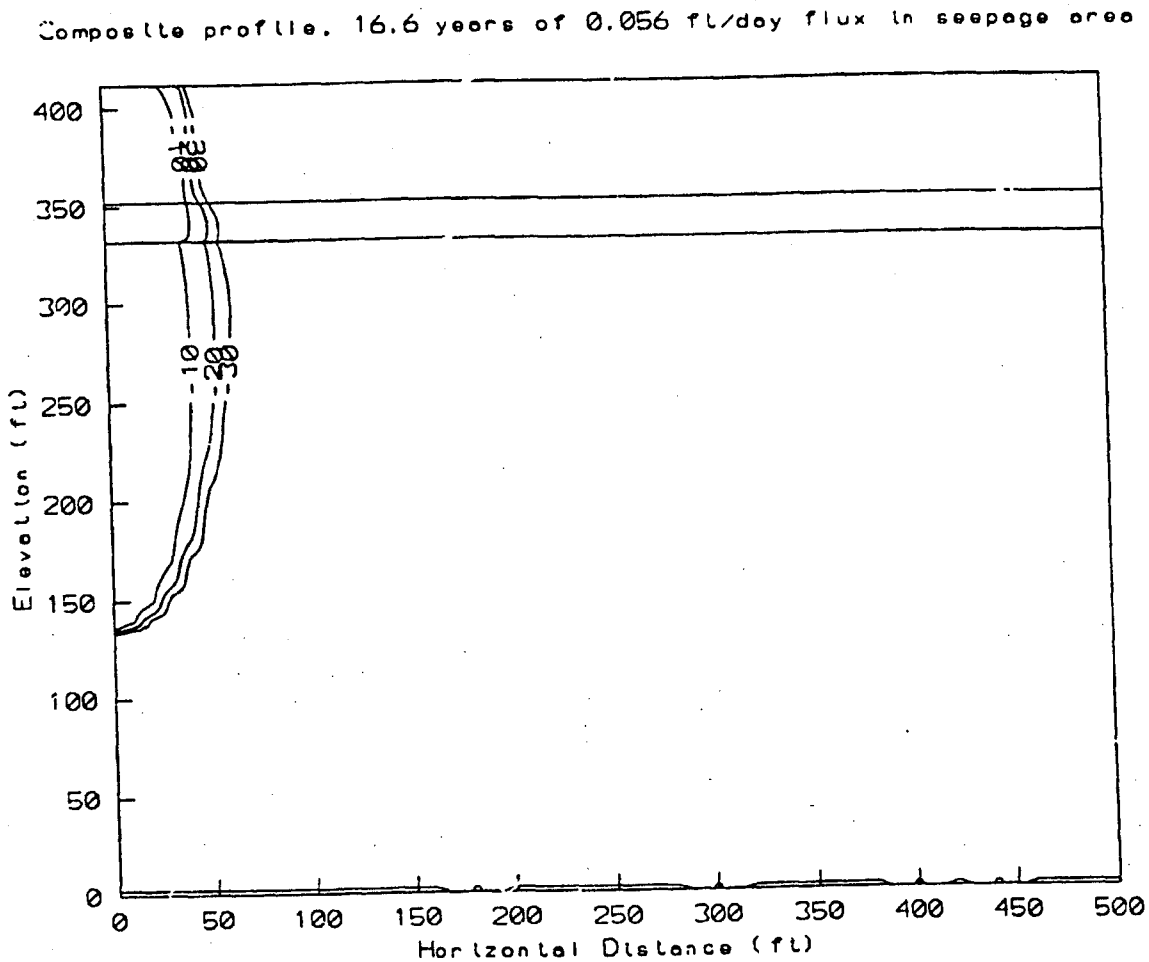

Fig. 13: UNSAT2 simulated matric potential contours (in feet) for 16.6 years of 0.056 ft./day flux in seepage area. Composite cross-section consists of three materials.

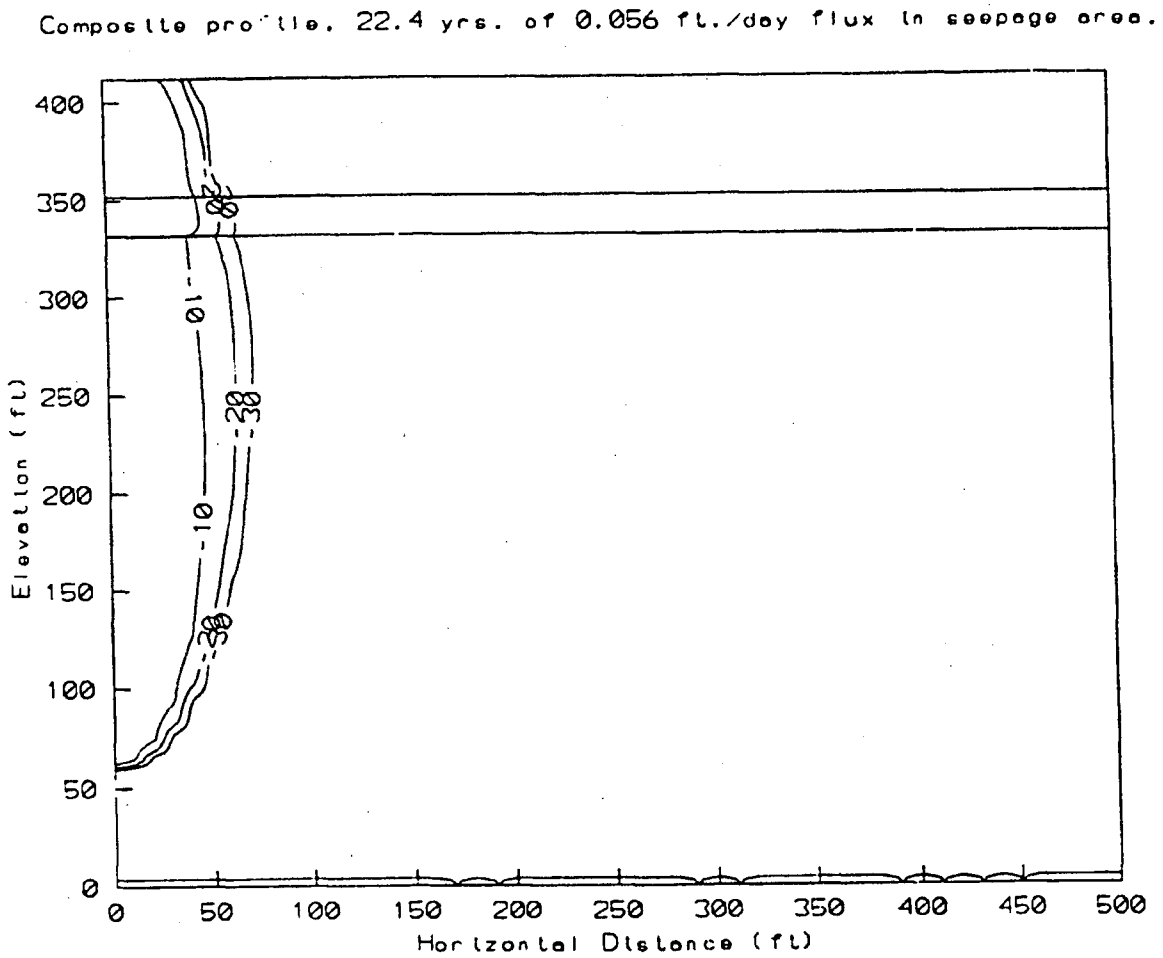

Fig. 14: UNSAT2 simulated matric potential contours (in feet) for 22.4 years of 0.056 ft./day flux in seepage area. Composite cross-section consists of three materials.

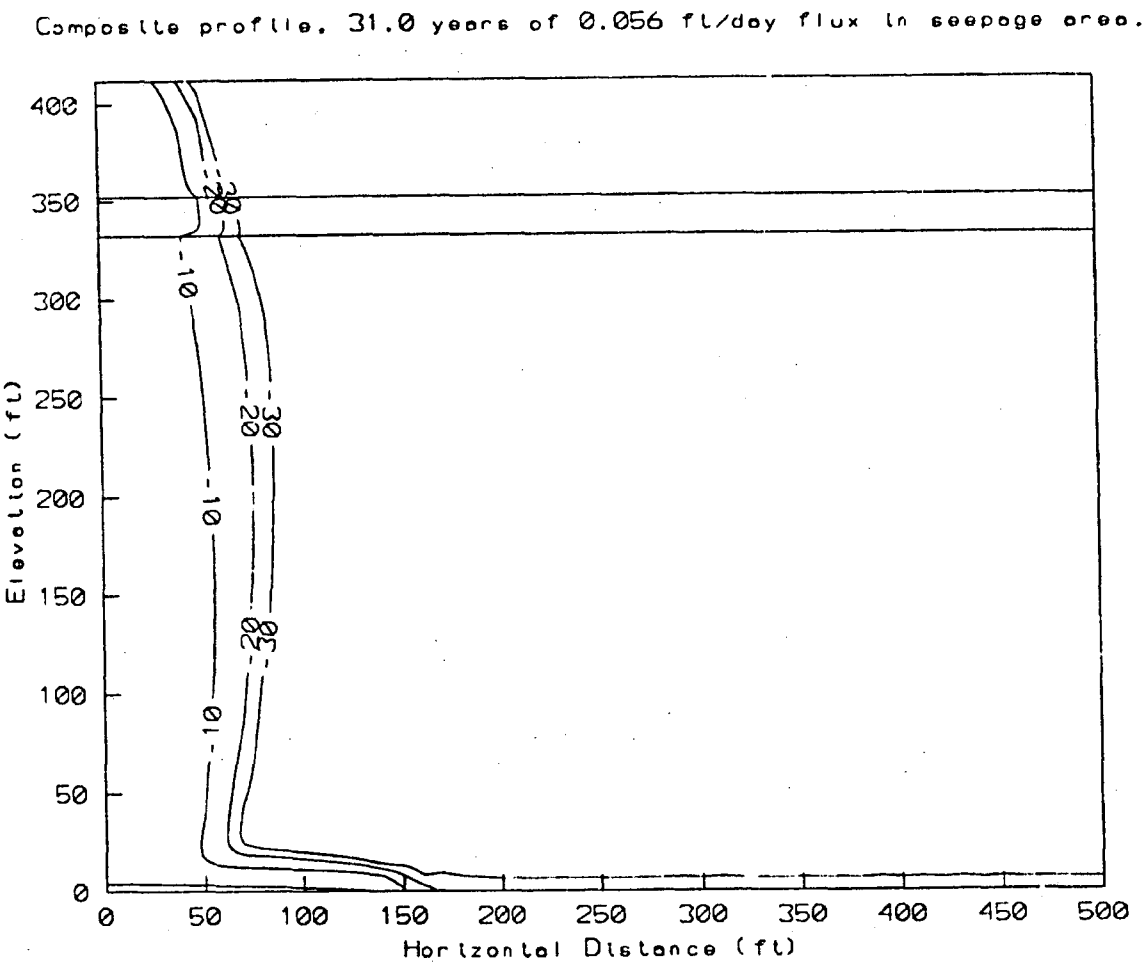

Fig. 15: UNSAT2 simulated matric potential contours (in feet) for 31.0 years of 0.056 ft./day flux in seepage area. Composite cross-section consists of three materials.

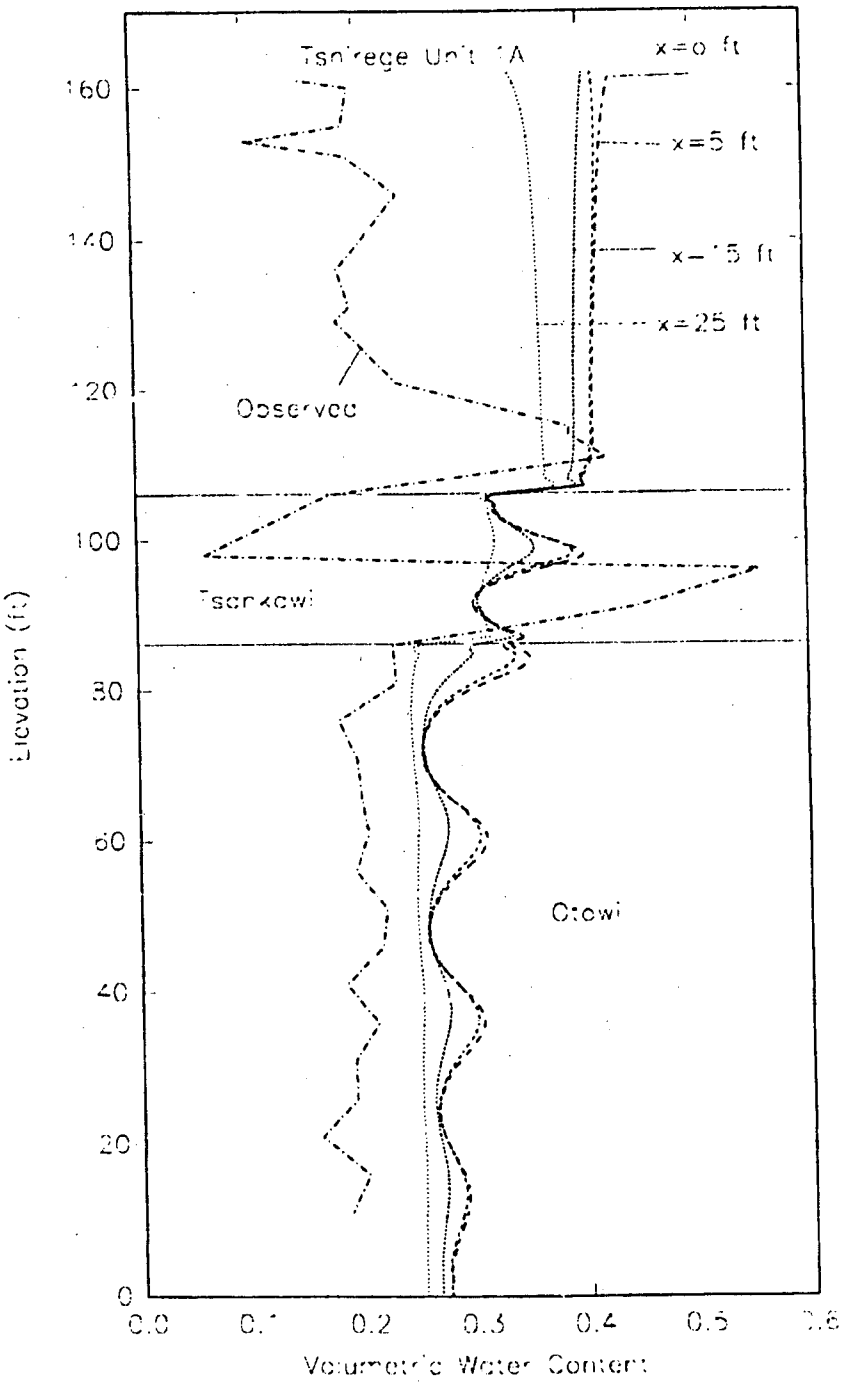

Fig. 16: UNSAT2 simulated water content 22.4 years of 0.0568 ft/day flux in seepage area. Top 162 ft of Fig. 14, at x=0,5,15,25 ft from symmetry axis.

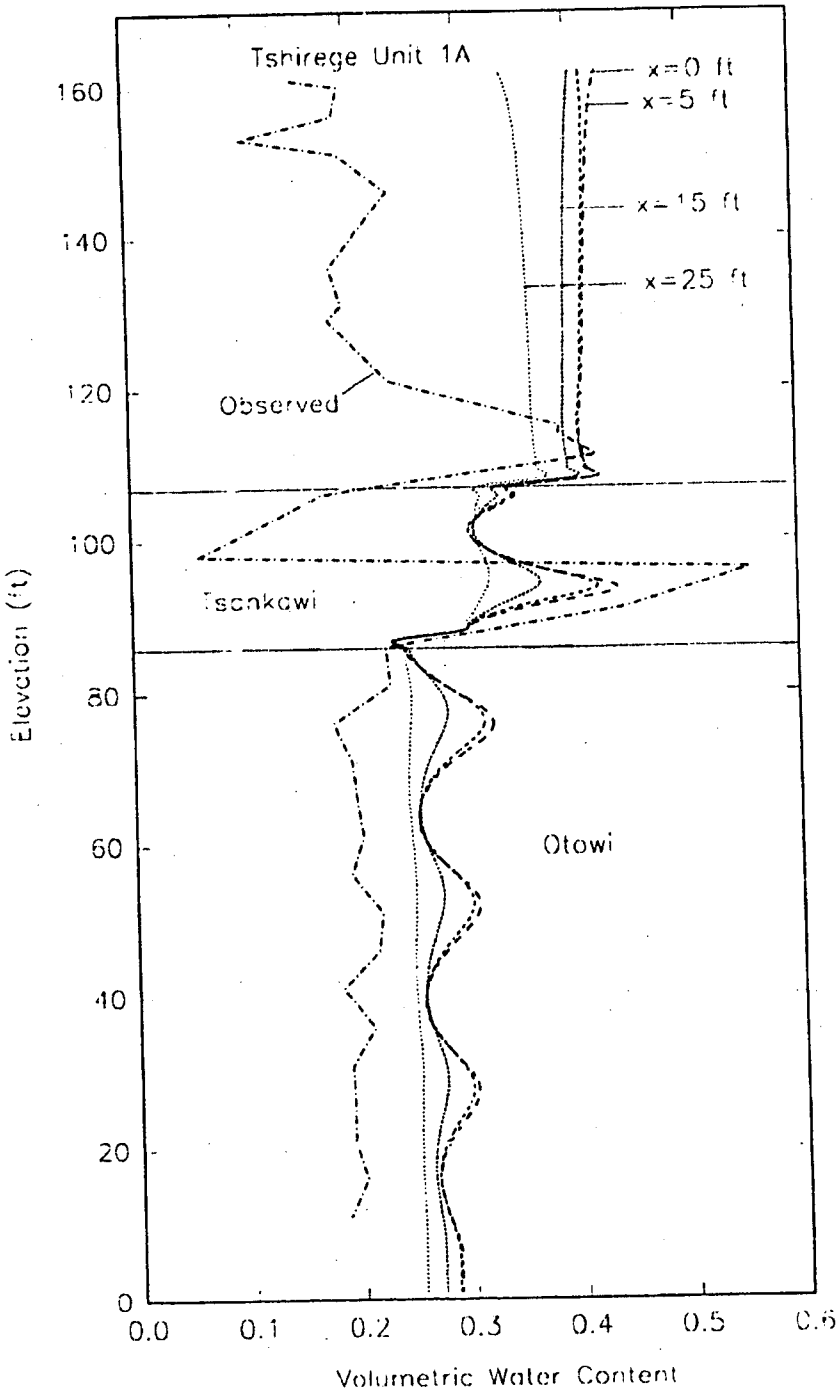

Fig. 17: UNSAT2 simulated water content with elevation for 31.0 years of 0.056 ft/day flux in seepage area for top 162 feet of Fig. 15.

head boundary condition is being reduced. One possible reason is that the highly weathered tuff immediately below the tuff/alluvium interface is restricting flow. The hydraulic characteristic of this material have not yet been evaluated and some sampling in this region should be performed. Also, for the determination of ground water travel time to the regional water table, more hydraulic parameters are needed for material at depth. The Guaje pumice, the conglomerate, and the basalt need to be included in any larger scale modeling effort.

The observed decrease in water content above the upper contact (through the Tshirege) could also be the result of upward diffusion of water vapor from the 'wet' interface. The next step in numerical simulation should include this phenomena, either in a multi-phase analysis, or by diffusion simulation alone. The water content increase on each lithologic contact could be simulated as a planar source for diffusion, allowing water to diffuse downward as well. A numerical solution for the diffusion equation in hydrogeologic systems is listed in the references (Ishii, et al., 1989). Also, the strata in this system are not perfectly horizontal. Tilting the simulation domain to take the principal conductivity off horizontal and assigning some arbitrary anisotropy could provide more enlightening results, possibly causing water to flow along the contacts to a greater extent.

Notably absent from this analysis is an accounting of mass. The balance between prescribed flux rate and change of water content, element by element (or cell by cell), should be evaluated. The canyon has been collecting and seeping water into the tuff for 10's of thousands of years. Water movement for this length of time can not be modeled reliably in the unsaturated zone. Our ability to generate complex numerical computer methods is still more sophisticated than our understanding of physical systems such as this one. The accumulation of moisture on top of the two lithologic contacts could be attributed to a much lower flow rate over this longer time period.

An evaluation of this system by finite difference should be undertaken. VS2DT (Lappala, et. al, 1987, and Healy, 1990) is the suggested code for this purpose. Transport of tritium could then be used as an aid to understanding, as VS2DT is capable of solving the transport problem. Boundary conditions, initial conditions, molecular diffusion coefficient of tritium in tuff, and dispersivity, are easily manipulated in computer simulations, which is the benefit of this type of analysis.

6. References

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7. Appendices

7.1. Input files

```
Input File for UNSAT2 run of Figures 5 & 6.
*******************************************************************
MCM-5.9A, Large Grid (x=250,y=662 feet), 2' to y=500...
12350   2611850    2    9    0   15    1    0    0    1

    0.001      70.0    0.0001       1.1   36525.0      50.0  100
       1.        1.
     .822      .822     0.486       0.0     0.120   0.24475   1.68945    1
    4.819     4.819     0.538       0.0     0.094   0.17953   1.74058    1
   22.110    22.110     0.519       0.0     0.032   0.16916   1.92358    1
    .7937     .7937     0.552       0.0     0.084   0.24506   1.86760    1
    2.239     2.239     0.435       0.0     0.052   0.48219   1.55108    1
   12.189    12.189    0.6465       0.0     0.198   0.24933   1.45120    1
    5.669     5.669     0.537       0.0     0.329   0.15484   1.72981    1
    3.118     3.118    0.4985       0.0     0.124  1.351178   1.47491    1
   11.055    11.055     0.686       0.0     0.209  3.184855   1.34112    1

25,474
1,1
6*5 13*10 6*15
250*2.0 100*1.0 124*0.5
12350*0
12324*0 5*0.0056 21*0
7618*-42.0 468*-48.0 338*-33.0 130*-26.0 104*-38.0
286*-141.0 286*-58.0 416*-22.0 2704*-35.0
7300*1 450*2 325*3 125*4 100*5 275*6 275*7 400*8 2600*9
11850*0.0
END
```

```
Input File for UNSAT2 run of Figure 7.
*************************************************************************
MCM-5.9A, Large Grid (x=250,y=662 feet), 2' to y=500...
12350   2611850    2    9    0   15    1    0    0    1

    0.001      70.0    0.0001       1.1   36525.0      50.0  100
       1.        1.
     .822      .822     0.486       0.0     0.120   0.24475   1.68945    1
    4.819     4.819     0.538       0.0     0.094   0.17953   1.74058    1
   22.110    22.110     0.519       0.0     0.082   0.16916   1.92358    1
    .7937     .7937     0.552       0.0     0.084   0.24506   1.86760    1
    2.239     2.239     0.435       0.0     0.052   0.48219   1.55108    1
   12.189    12.189    0.6465       0.0     0.198   0.24933   1.45120    1
    5.669     5.669     0.537       0.0     0.329   0.15484   1.72981    1
    3.118     3.118    0.4985       0.0     0.124  1.351178   1.47491    1
   11.055    11.055     0.686       0.0     0.209  3.184855   1.34112    1

25,474
1,1
6*5 13*10 6*15
250*2.0 100*1.0 124*0.5
12350*0
12350*0
7618*-42.0 468*-48.0 338*-33.0 130*-26.0 104*-38.0
286*-141.0 286*-58.0 416*-22.0 2678*-35.0 5*1.0 21*-35.0
7300*1 450*2 325*3 125*4 100*5 275*6 275*7 400*8 2600*9
11850*0.0
END
```

```
Input File for UNSAT2 run of Figures 8, 9, 10, 11, and 12.
*****************************************************************
MCM 5.9A, Large Grid (x=500,y=162 feet), delx=5',dely=0.5'
23128   5622660    2    3    0   15    1    0    0    1

     0.01      25.0     0.001       1.2  365250.0      75.0  100
       1.        1.
    2.239     2.239     0.435       0.0     0.052   0.48219   1.55108    1
    3.690     3.690     0.478       0.0     0.150   0.90465   1.48191    1
    0.397     0.397     0.515       0.0     0.040   0.35905   1.49131    1

55,412
1,1
10*5.0 45*10.0
412*1.0
23072*0 5*1 51*0
23072*0 5*0.0 51*0
18648*-38.0 1120*-31 3304*-73.0 5*1.0 51*-73
18260*1 1100*2 3300*3
22660*0.0
END
```

```
Input File for UNSAT2 run of Figures 13, 14, 15, 16, and 17.
*****************************************************************
MCM 5.9A, Large Grid (x=500,y=162 feet), delx=5',dely=0.5'
23128   5622660    2    3    0   15    1    0    0    1

     0.01      25.0     0.001       1.2  365250.0      75.0   70
       1.        1.
    2.239     2.239     0.435       0.0     0.052   0.48219   1.55108    1
    3.690     3.690     0.478       0.0     0.150   0.90465   1.48191    1
    0.397     0.397     0.515       0.0     0.040   0.35905   1.49131    1

55,412
1,1
10*5.0 45*10.0
412*1.0
23128*0
23072*0 5*0.0056 51*0
18648*-38.0 1120*-31 3360*-73
18260*1 1100*2 3300*3
22660*0.0
END
```

7.2. UNSAT2 Source Code

```
**************      LIST OF MODIFICATIONS        *************
September 1986 VERSION OF PROGRAM UNSAT INCLUDING EVAPORATION,
  TRANSPIRATION,AND WELL OPTIONS

Spring 87: MODIFIED TO TAKE Van Genuchten ANALYTICAL EXPRESSIONS
  FOR THE SOIL HYDRAULIC PARAMETERS.  TABULAR INFORMATION IS NOT
  LONGER REQUIRED

Spring 89: MODIFIED TO DISPLAY INFORMATION ABOUT TIME, TIME STEP,
  AND ITERATIONS. THE FREQUENCY OF PRINTOUT IN TERMS OF TIME STEP
  IS CONTROLED BY THE INDEX "INPR"

Spring 90:
  INCLUDE ADDITIONAL SOIL HYDRAULIC PARAMETER MODELS; NOW, THE
  UNSATURATED SOIL PARAMETERS MAY BE REPRESENTED BY THE FOLLOWING
  MODELS:
            IDM(I) = 1: VAN GENUCHTEN MODEL
                   = 2: EXPONENTIAL MODEL
                   = 3: GARDNER-RUSSO MODEL
                   = 4: EXAMPLE OF USER-SPECIFIED MODEL

 Summer 92: To port code to LANL ICN Cray Y-MP running UNICOS 6.0.1
            search for "cmike" and make suggested changes. Otherwise
  this version of the code will run on an IBM PC.
  Automatic time stepping included.  Time step is divided by two if
  convergence is not achieved and simulation restarts from last con-
  vergent time step.

  Automatic Grid Generation for simple geometries is controlled by
  the variable IGG in Group B

  *********      TAPE AND MEMORY REQUIREMENTS          ***********

-----TAPE 1 REQUIRES A STORAGE OF AT LEAST 8*(100+6*NUMNP+7*NUMEL+
     (2*MK+4*MP)*NUMMAT+NDIM*(2+MAXSP)+2*NUMDP+NDIMP*(4+4*MXCOL+2*MXNOD
     )+2*MXNOD) BYTES
-----TAPE 2 REQUIRES A STORAGE OF AT LEAST 8*(IJ+3)*NUMNP BYTES.
---- THE SIZE OF BD MUST BE AT LEAST (IJ+3)*NUMNP
---- THE SIZE OF BS MUST BE AT LEAST 11*NUMNP+7*NUMEL+
     +MAX(1,NSEEP)*(2+MAX(1,NSP(I)))+2*MAX(1,NUMEP)+MAX(1,NPLNT)*(4+4*
     MAX(1,NCOL(J))+2*MAX(1,NSOUR(J))+2*MAX(1,NSOUR(J)))
-----THE SIZE OF EACH ARRAY IN COMMON /MAT/ MUST BE AT LEAST NUMMAT

     UNIT    DESCRIPTION
      1      Stores the necessary information for "RESTART" runs
      2      Contains the A and B matrices (scratch file)
      6      Contains general input/output information
      8      Contains Time versus Cumulative Inflow into the flow domain
     10      Contains X, Y, Pressure Head, Node number and Total Head for
             plotting porpuses

                        LAST MODIFIED  06/29/1990

     PROGRAM U2
cmike HED*4 should be changed to HED* (and END and RESTAR if they are used)
INFILE is deleted where it appears below.
     CHARACTER INFILE*60, HED*4, END*4, RESTAR*4
cmike These arrays must be dimensioned for each run.
     DIMENSION BD(20000),BS(17000)
cmike This line should be commented out, and the variables it contains
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ould be removed from the code.
      INTEGER*4 IHR,IMIN,ISEC,I100,IHRE,IMINE,ISECE,I100E
ike (9) represents nine materials, and must be changed to the number
 materials used
      COMMON /MAT/ CONS1,CONS2,C1(9),C2(9),SS(9),POR(9),ALPHA(9),
     *             BETA(9),WCR(9),IDM(9)
      COMMON /FIX/ HED(20),INIT,MAXIT,KAT,IJ,INTEG,NSEEP
      COMMON /WEL/ NB(3),NE(3),NBW,NPT,NPT1,NPB,NPB1,LW,NEP,NSW,AL,AL1,
     1 QP,QA,RW,RT,ALFA
      DATA END/'END '/,RESTAR/'REST'/
      OPEN(1,FILE='UNS1.DAT',STATUS='UNKNOWN')
      OPEN(2,STATUS='SCRATCH',FORM='UNFORMATTED')
      OPEN(6,FILE='UNSAT.OUT',STATUS='UNKNOWN')
      OPEN(8,FILE='UNS8.DAT',STATUS='UNKNOWN')
      OPEN(10,FILE='UNS10.DAT',STATUS='UNKNOWN')
ike All reads and writes to (*,*) should be removed, here and in
e rest of the code, search for them.
      WRITE(*,*)' TYPE DATA FILE NAME: '
ike Delete the next two lines and open the input file, UNIT=15, with
 standard open statement.
      READ(*,'(A)')INFILE
      OPEN(15,FILE=INFILE,STATUS='OLD')
      NERR=0
ike Remove all calls to GETTIM
      CALL GETTIM(IHR,IMIN,ISEC,I100)
      WRITE(6,8)IHR,IMIN,ISEC
    8 FORMAT(//,5('*'),' STARTING TIME: ',2(I2,':'),I2,1X,5('*'),//)
   10 READ (15,20) HED
   20 FORMAT (20A4)
      IF (HED(1) .EQ. END) THEN
         CALL GETTIM(IHRE,IMINE,ISECE,I100E)
         WRITE(6,19)IHRE,IMINE,ISECE
         CPU = 3600.*(IHRE-IHR)+60.0*(IMINE-IMIN)+FLOAT(ISECE-ISEC)+
     &         0.01*(I100E-I100)
         WRITE(*,21) CPU
         WRITE(6,21) CPU
   19 FORMAT(//,5('*'),' ENDING TIME: ',2(I2,':'),I2,1X,5('*'),//)
   21    FORMAT(' *** CPU TIME = ',E13.5,' SECONDS *** ')
      STOP
      ENDIF
      IF (HED(1) .EQ. RESTAR) GO TO 100
      READ(15,30)NUMNP,IJ,NUMEL,KAT,NUMMAT,INIT,MAXIT,INTEG,NSEEP,MAXS,
     &IGG
      READ(15,30)NBW,NPB,NPT,NEP,LW,NUMEP,NPLNT,MXCOL,MXNOD
   30 FORMAT (16I5)
      NUMDP=NUMEP
      IF (NUMDP .LT. 1) NUMDP=1
      NDIMP=NPLNT
      IF (NPLNT .GT. 0) GO TO 40
      NDIMP=1
      MXCOL=1
      MXNOD=1
   40 NTAPE=0
      NUMRES=0
      MAXSP=1
      NDIM=1
      IF (NSEEP .LT. 1) GO TO 50
      NDIM=NSEEP
      MAXSP=MAXS
   50 MBAND=IJ+2
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 80 M2=1+MBAND*NUMNP
    N2=1+NUMNP
    N3=N2+NUMNP
    N4=N3+NUMNP
    N5=N4+NUMNP
    N6=N5+NUMNP
    N7=N6+NUMNP
    N8=N7+NUMNP
    N9=N8+NUMNP
    N10=N9+NUMNP
    N11=N10+NUMNP
    N12=N11+5*NUMEL
    N13=N12+NUMEL
    N14=N13+NUMEL
    N21=N14+MAXSP*NDIM
    N22=N21+NDIM
    N23=N22+NDIM
    N24=N23+NUMDP
    N25=N24+NUMDP
    N26=N25+NDIMP
    N27=N26+NDIMP
    N28=N27+NDIMP
    N29=N28+NDIMP
    N30=N29+MXCOL*NDIMP
    N31=N30+MXCOL*NDIMP
    N32=N31+MXCOL*NDIMP
    N33=N32+MXCOL*NDIMP
    N34=N33+MXNOD*NDIMP
    N35=N34+MXNOD*NDIMP
    N36=N35+NUMNP
    If(HED(1).ne.RESTAR)then
      TP1 = 8*(100+6*NUMNP+7*NUMEL+NDIM*(2+MAXSP)+
   &        2*NUMDP+NDIMP*(4+4*MXCOL+2*MXNOD)+2*MXNOD)
      TP2 = 4*(IJ+3)*NUMNP
      WRITE(6,1)M2,N36+NUMNP
  1   FORMAT(' ','STORAGE CHECK'//'   THE DIMENSION OF BD SHOULD BE ',
   1  'GREATER THAN',I10/,'   THE DIMENSION OF BS SHOULD BE GREATER ',
   2  'THAN',I10/)
      WRITE(6,2)TP1/1000,TP2/1000
  2   FORMAT(5X,'UNS1.DAT REQUIRES: ',F7.1,' Kb',/
   &         5X,'UNS2.DAT REQUIRES: ',F7.1,' Kb',/)
    ENDIF
 90 CALL FEM (BD(1),BD(M2),BS(1),BS(N2),BS(N3),BS(N4),BS(N5),BS(N6),
   1BS(N7),BS(N8),BS(N9),BS(N10),BS(N11),BS(N12),BS(N13),BS(N14),
   2BS(N21),BS(N22),BS(N23),BS(N24),BS(N25),BS(N26),BS(N27),BS(N28),
   3BS(N29),BS(N30),BS(N31),BS(N32),BS(N33),BS(N34),BS(N35),BS(N36),
   4NUMNP,MBAND,NUMEL,NUMMAT,MK,MP,NERR,NDIM,MAXSP,NTAPE,
   5NUMRES,NUMDP,NUMEP,NPLNT,NDIMP,MXCOL,MXNOD,IGG)
    IF (NERR .GT. 0)THEN
       CALL GETTIM(IHRE,IMINE,ISECE,I100E)
       CPU = 3600.*(IHRE-IHR)+60.0*(IMINE-IMIN)+FLOAT(ISECE-ISEC)+
   &         0.01*(I100E-I100)
       WRITE(6,19)IHRE,IMINE,ISECE
       WRITE(*,21) CPU
       WRITE(6,21) CPU
       STOP
    ENDIF
    GO TO 10
-----RESTART PROCEDURE
100 REWIND 1
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      READ (1,*) NUMNP,MBAND,NUMEL,NUMMAT,MAXSP,NDIM,NSEEP,NUMDP,
     1NUMEP,NPLNT,NDIMP,MXCOL,MXNOD
      GO TO 80
      END
      SUBROUTINE FEM (A,B,KODE,Q,P,P1,T,D,CR,C,X,Y,KX,SANG,CANG,
     1NP,NSP,KODES,WIDTH,BTP,NCOL,NSOUR,PW,TPOT,NRB,NRT,W,PR,RDF,
     2MTR,SAVE,CC,NUMNP,MBAND,NUMEL,NUMMAT,MK,MP,NERR,NDIM,
     3MAXSP,NTAPE,NUMRES,NUMDP,NUMEP,NPLNT,NDIMP,MXCOL,MXNOD,IGG)
      DIMENSION A(MBAND,NUMNP),B(NUMNP),KODE(NUMNP),Q(NUMNP),P(NUMNP),
     1P1(NUMNP),T(NUMNP),D(NUMNP),CR(NUMNP),C(NUMNP),X(NUMNP),
     2Y(NUMNP),KX(NUMEL,5),SANG(NUMEL),CANG(NUMEL),
     3NP(NDIM,MAXSP),NSP(NDIM),KODES(NDIM),WIDTH(NUMDP),BTP(NUMDP),
     4NCOL(NDIMP),NSOUR(NDIMP),PW(NDIMP),TPOT(NDIMP),NRB(MXCOL,NDIMP),
     5NRT(MXCOL,NDIMP),RDF(MXNOD,NDIMP),MTR(MXNOD,NDIMP),W(MXCOL,NDIMP),
     6PR(MXCOL,NDIMP),SAVE(2,MXNOD),CC(NUMNP)
      COMMON /MAT/ CONS1,CONS2,C1(9),C2(9),SS(9),POR(9),ALPHA(9),
     *             BETA(9),WCR(9),IDM(9)
      COMMON /FIX/ HED(20),INIT,MAXIT,KAT,IJ,INTEG,NSEEP
      COMMON /WEL/ NB(3),NE(3),NBW,NPT,NPT1,NPB,NPB1,LW,NEP,NSW,AL,AL1,
     1 QP,QA,RW,RT,ALFA
      DATA RESTAR/4HREST/
      EPSLON=0.
      IF (HED(1) .EQ. RESTAR) GO TO 580
C-----READ SEEPAGE FACE INFORMATION
      IF (NSEEP .LT. 1) GO TO 30
      IF (MAXIT .LT. 4) MAXIT=4
      DO 20 I=1,NSEEP
      READ (15,10) NSP(I),KODES(I)
   10 FORMAT (16I5)
      NS=NSP(I)
      READ (15,10) (NP(I,J),J=1,NS)
   20 CONTINUE
C-----READ POTENTIAL SURFACE FLUX INFORMATION
   30 IF (NUMEP .LT. 1) GO TO 50
      READ (15,91) EI,PL,BTPI
      READ (15,91) (WIDTH(I),I=1,NUMEP)
      DO 40 I=1,NUMEP
      BTP(I)=BTPI
   40 CONTINUE
C-----READ PLANT INFORMATION
   50 IF (NPLNT .LT. 1) GO TO 70
      READ (15,10) (NCOL(J),NSOUR(J), J=1, NPLNT)
      READ (15,91) (PW(J), TPOT(J), J=1, NPLNT)
      DO 60 J=1,NPLNT
      NCJ=NCOL(J)
      NSJ=NSOUR(J)
      READ (15,91) (W(I,J), I=1,NCJ)
      READ (15,10) (NRB(I,J), NRT(I,J), I=1,NCJ)
      NSJ1=NSJ+1
      READ (15,91) (RDF(N,J), N=1,NSJ1)
      READ (15,10) (MTR(N,J), N=1,NSJ)
   60 CONTINUE
C-----READ WELLBORE INFORMATION
   70 AL=0.
      QA=0.
      IF (NBW .LT. 1) GO TO 80
      NSW=NPT-NPB
      NPB1=NPB+1
      NPT1=NPT-1
      READ (15,10) (NB(I),I=1,NBW),(NE(I),I=1,NEP)
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      READ (15,91) RW,RT,QP,AL,ALFA
      IF (ALFA .LE. 0.) ALFA=.8
      AL1=AL
C-----GENERAL INFORMATION
   80 READ (15,90) DT,DTMAX,DTMIN,DMUL,TMAX,TOL,INPR
   90 FORMAT (6E10.3,I5)
      WRITE(6,92)DT,DTMAX,DTMIN,DMUL,TMAX,TOL,INPR
   92 FORMAT(15X,'INITIAL TIME INTERVAL---- =',E12.5,/
     2        15X,'MAXIMUM TIME INTERVAL---- =',E15.5,/
     3        15X,'MINIMUM TIME INTERVAL---- =',E15.5,/
     4        15X,'TIME MULTIPLIER---------- =',E15.5,/
     5        15X,'MAXIMUM SIMULATION TIME-- =',E15.5,/
     6        15X,'MAXIMUM ITERATION ERROR-- =',E15.5,/
     2        15X,'PRINT OUT EVERY',I5,' TIME STEPS'//)
      IF (KAT .EQ. 0)WRITE(6,100)
      IF (KAT .EQ. 1)WRITE(6,110)
      IF (KAT .EQ. 2)WRITE(6,120)
      IF (KAT .EQ. 3)WRITE(6,130)
      IF (KAT .EQ. 3)KAT=1
  100 FORMAT (15X,22H HORIZONTAL PLANE FLOW)
  110 FORMAT (15X,18H AXISYMMETRIC FLOW)
  120 FORMAT (15X,20H VERTICAL PLANE FLOW)
  130 FORMAT (15X,54H AXISYMMETRIC FLOW TO A WELL WITH PRESCRIBED DISCHA
     1RGE//)
      IF (INTEG .EQ. 1)WRITE(6,131)
      IF (INTEG .EQ. 2)WRITE(6,132)
  131 FORMAT (15X,' BACKWARD DIFFERENCE SCHEME '/)
  132 FORMAT (15X,' TIME CENTERED SCHEME '//)
      WRITE(6,140) HED,NUMNP,IJ,NUMEL,NUMMAT,MAXIT
  140 FORMAT(5X,20A4,//,14X,30H NUMBER OF NODAL POINTS-------,I4/
     114X,30H MAX NODES IN A TRNSVRS LINE--,I4/
     214X,30H NUMBER OF ELEMENTS-----------,I4/
     314X,30H NUMBER OF MATERIALS----------,I4/
     414X,30H MAX NUMBER OF ITERATIONS-----,I4///)
      IF (NBW .LT. 1) GO TO 160
      WRITE(6,150) NPB,NPT,RW,RT,AL
  150 FORMAT (22H BOTTOM NODE OF WELL =,I4/
     1        22H TOP NODE OF WELL--- =,I4/
     2        22H RADIUS OF WELL----- =,E11.3/
     3        22H RADIUS OF TUBING--- =,E11.3/
     4        22H INITIAL WATER LEVEL =,E11.3///)
      AA=.5*(RW*RW-RT*RT)
      RW=AA
  160 IF (NPLNT .LT. 1) GO TO 200
      DO 190  J=1,NPLNT
      NCJ=NCOL(J)
      NSJ=NSOUR(J)
      NSJ1=NSJ+1
      WRITE(6,170) J, PW(J), (NRB(I,J),NRT(I,J),I=1,NCJ)
  170 FORMAT ( //// 21H INPUT DATA FOR PLANT, I3 ///23H WILTING PRESSURE
     1HEAD =,E13.5 // 44H LIST OF BOTTOM AND TOP NODES IN ROOT ZONE -//
     210(2I5,3X))
      WRITE(6,180) (RDF(N,J), N=1,NSJ1)
  180 FORMAT (/// 80H ROOT DISTRIBUTION FUNCTION AT EACH NODE IN ROOT ZO
     1NE, STARTING AT BOTTOM NODE -// 10(E13.5))
  190 CONTINUE
C-----READ AND GENERATE MATERIAL INFORMATION
  200 CALL MATIN (NUMMAT)
C-----READ AND GENERATE NODAL POINT INFORMATION
      IF(IGG.NE.0)THEN
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        CALL SGRID(KODE,Q,P,P1,X,Y,WIDTH,NUMNP,INIT,BTPI,EI,KX,SANG,
     &                 NUMDP,CANG,NUMEL)
      ELSE
        CALL NPIN (KODE,Q,P,P1,X,Y,WIDTH,NUMDP,NUMNP,INIT,NERR,BTPI,EI)
        IF (NERR .GT. 0) RETURN
      ENDIF
C-----INITIALIZE PLANT SOURCES
      IF (NPLNT .LT. 1) GO TO 220
      DO 210 J=1,NPLNT
      CALL TRANSP (Q,P,P1,T,CR,Y,NCOL,NSOUR,PW,TPOT,
     1NRB,NRT,W,PR,RDF,MTR,SAVE,NUMNP,NUMMAT,NPLNT,NDIMP,
     2MXCOL,MXNOD,J)
  210 CONTINUE
C-----READ AND GENERATE ELEMENT INFORMATION
  220 IF(IGG.EQ.0)CALL MAFILL (KX,SANG,CANG,NUMEL)
C-----SETUP FOR TIME INTEGRATION
      LA=1
      TIME=DT
      QTOT=0.
      ITER=0
      ITIT=0
      write(*,*)'        Input data has been read !      '
      INDP = 0
  230 WRITE(*,240)HED,TIME,LA,DT
  240 FORMAT (///15X,20A4//10X,6HTIME =,E13.5,3X,11HTIME STEP =,I4,
     &2X,4HDT =,E13.5//)
      EPSLN1=1.0E28
      EPSLN2=1.0E28
      EPSLON=1.0E28
C-----PERTURB WATER LEVEL IN WELL
      IF (NBW .LT. 1) GO TO 250
      CALL WELBOR (KODE,Q,P,Y,NUMNP,DT)
C-----GENERATE TERMS OF MATRIX EQUATION
  250 CALL RESET (KODE,A,B,Q,P,P1,T,D,CR,C,X,Y,KX,SANG,CANG,
     1NUMNP,MBAND,NUMEL,NUMMAT,M,KAT,LA,DT,DT1,ITER,INTEG)
C-----MODIFY FOR CONSTANT PRESSURE HEAD NODES
      CALL CONSTP (A,B,KODE,P,NUMNP,MBAND)
C-----SOLVE BY GAUSS ELIMINATION
      CALL SOLVE (A,B,NUMNP,MBAND)
      DO 260 I=1,NUMNP
      P(I)=B(I)
  260 CONTINUE
C-----DETERMINE BOUNDARY FLUXES
      CALL FIXQ (A,B,KODE,Q,P,P1,D,NUMNP,MBAND,DT,LA,INTEG)
C-----ITERATE TO IMPROVE SOLUTION
  270 IF (MAXIT .LT.1) GO TO 460
      ITER=ITER+1
C-----MODIFY CONDITIONS ON WELLBORE
      IF (NBW .GT. 0) CALL WELBOR (KODE,Q,P,Y,NUMNP,DT)
C-----MODIFY CONDITIONS ON SEEPAGE FACES
      IF (NSEEP .EQ. 0) GO TO 320
      DO 310 I=1,NSEEP
      ICHECK=0
      NS=NSP(I)
      DO 300 J=1,NS
      N=NP(I,J)
      IF (KODE(N) .NE. -2) GO TO 280
      IF (P(N) .LT. 0.) ICHECK=1
      IF (ICHECK .GT. 0) GO TO 300
      KODE(N)=2
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      P(N)=0.
      GO TO 300
  280 IF (KODE(N) .NE. 2) GO TO 300
      IF (ICHECK .GT. 0) GO TO 290
      IF ((Q(N) .LT. 0. .AND. KODES(I) .LT. 0) .OR.
     1    (Q(N) .GT. 0. .AND. KODES(I) .GT. 0)) GO TO 300
  290 KODE(N)=-2
      Q(N)=0.
      ICHECK=1
  300 CONTINUE
  310 CONTINUE
-----MODIFY POTENTIAL SURFACE FLUX BOUNDARIES
  320 IF (NUMEP .LT. 1) GO TO 390
      I=0
      DO 380 N=1,NUMNP
      IF (KODE(N) .NE. 4) GO TO 330
      I=I+1
      IF ((EI .LT. 0. .AND. Q(N) .GE. EI*WIDTH(I)) .OR. (EI .GE. 0. .AND
     1.Q(N) .LE. EI*WIDTH(I)))GO TO 380
      KODE(N)=-4
      Q(N)=EI*WIDTH(I)
      GO TO 380
  330 IF (KODE(N) .NE. -4) GO TO 380
      I=I+1
      IF (EI .GE. 0.) GO TO 350
      IF (P(N) .GT. PL) GO TO 340
      KODE(N)=4
      P(N)=PL
      GO TO 380
  340 IF (ABS(P(N)) .GT. -.001*PL) BTP(I)=BTP(I)*ABS(PL/P(N))
      IF (ABS(P(N)) .LE. -.001*PL) BTP(I)=1.
      GO TO 370
  350 IF (P(N) .LT. 0.) GO TO 360
      KODE(N)=4
      P(N)=0.
      GO TO 380
  360 IF (ABS(P(N)-PL) .GT. -.001*PL) BTP(I)=BTP(I)*ABS(PL/(P(N)-PL))
      IF (ABS(P(N)-PL) .LE. -.001*PL) BTP(I)=1.
      IF(P(N) .LT.PL) BTP(I)=1.
  370 IF (BTP(I) .GT. 1.) BTP(I)=1.
      Q(N)=BTP(I)*EI*WIDTH(I)
  380 CONTINUE
-----MODIFY TRANSPIRATION RATE
  390 IF (NPLNT .LT. 1) GO TO 410
      DO 400 J=1,NPLNT
      CALL TRANSP (Q,P,P1,T,CR,Y,NCOL,NSOUR,PW,TPOT,
     1NRB,NRT,W,PR,RDF,MTR,SAVE,NUMNP,NUMMAT,NPLNT,NDIMP,
     2MXCOL,MXNOD,J)
  400 CONTINUE
-----TEST FOR CONVERGENCE
  410 IF (ITER .EQ. 1) GO TO 450
      EPSLON=0.
      DO 420 I=1,NUMNP
      AA = ABS(P(I)-CC(I))
      IF (AA .LT. EPSLON) GO TO 420
      EPSLON=AA
      NMAX=I
  420 CONTINUE
      WRITE (*,431) ITER,EPSLON,NMAX
  431 FORMAT (13X,'MAX ERROR DURING ITERATION',I2,' WAS',E13.5,' A
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   1T NODE',I4)
    IF (NBW .GT. 0)WRITE(6,440) AL,QA
440 FORMAT (/24H WATER LEVEL IN WELL WAS,E13.5,29H.  DISCHARGE FROM AQ
   1UIFER WAS,E13.5)
    IF (EPSLON .LE. TOL .OR. ITER .GE. MAXIT .OR. EPSLN2 .LE. EPSLON)
   1GO TO 460
450 DO 455 I=1,NUMNP
455     CC(I)=P(I)
    EPSLN2=EPSLN1
    EPSLN1=EPSLON
    GO TO 250
-----PRINT RESULTS
-----QTOT IS UPDATED AND PRINTED ONLY IF THE CURRENT ITER CONVERGED
460 IF(EPSLON.LE.TOL.OR.(ITER.LT.MAXIT.AND.EPSLON.LT.EPSLN2))THEN
        DO 470 N=1,NUMNP
           QTOT=QTOT+Q(N)*DT
470     CONTINUE
        WRITE(8,485) TIME,QTOT
485     FORMAT(5X,2F12.5)
    ENDIF
    IF(NBW .GT. 0)WRITE(6,490)QP,AL
490 FORMAT (//22H DISCHARGE FROM WELL =,E13.5/
   1            22H WATER LEVEL IN WELL =,E13.5/)
    IF (NUMEP .GT. 0) WRITE(6,500) EI,PL
500 FORMAT (//25H POTENTIAL SURFACE FLUX =,E13.5/
   1            32H MINIMUM SURFACE PRESSURE HEAD =,E13.5/)
    IF (NPLNT .LT. 1) GO TO 530
    DO 520 J=1,NPLNT
    NCJ=NCOL(J)
    WRITE(6,510) J, TPOT(J), (PR(I,J), I=1,NCJ)
510 FORMAT (//39H POTENTIAL TRANSPIRATION RATE FOR PLANT,I3,2H =,E13.
   15// 51H PRESSURE HEADS IN ROOTS, FROM LEFT TO RIGHT, ARE-//10(E13.
   25))
520 CONTINUE
530 CONTINUE
    INDP = INDP + 1
-----PRINTS NODE INFORMATION EVERY 'INPR' TIMES
    IF(INDP.EQ.INPR. OR .LA.EQ.1. OR .ABS(TIME-TMAX).LE.0.001*DT)THEN
       WRITE(6,240) HED,TIME,LA,DT
       WRITE(6,430) ITER,EPSLON,NMAX
430  FORMAT (49H MAXIMUM CHANGE IN PRESSURE HEAD DURING ITERATION,I3,
   1 4H WAS,E13.5,8H AT NODE,I5)
       WRITE(6,480) QTOT
480    FORMAT (// 35H CUMULATIVE INFLOW INTO SYSTEM IS =,E13.5)
       CALL PRINTO (Q,P,Y,NUMNP,KAT)
       CALL MOIST (P,P1,T,CR,KX,NUMNP,NUMEL,NUMMAT)
       INDP = 0
    ENDIF
-----SET UP NEW TIME STEP
    LA=LA+1
    IF(EPSLON .LE. TOL .OR.(ITER .LT. MAXIT.AND. EPSLON .LT. EPSLN2))
   1GO TO 540
-----IF CONVERGENCE IS NOT ACHIEVED: LAST DT IS DIVIDED BY TWO AND
-----THE SIMULATION CONTINUES FROM THE LAST CONVERGENT TIME STEP
    DT = DT/2.0
    IF(DT.GT.DTMIN)THEN
       WRITE(6,534)LA-1
534    FORMAT(/,20X,'***** TIME STEP ',I3,' NON CONVERGENT *****',/
   &            20X,'       DT HAS BEEN DIVIDED BY TWO ' )
       WRITE(*,535)
```

```
535     FORMAT(/,20X,'*****   NON CONVERGENT TIME STEP    *****',/
   &            20X,' LAST TIME STEP HAS BEEN DIVIDED BY TWO ' )
        AL1=ALLCI
        TIME=TLCI
           DO 536 I =1,NUMNP
              P(I)=P1(I)
536        CONTINUE
       GOTO 555
      ELSE
       DT = DT*2.0
     ENDIF
     NUMRES=0
     NERR=1
     WRITE(*,538)
     WRITE(6,538)
538  FORMAT(/,10X,'***** SOLUTION DOES NOT CONVERGE *****',/)
     ITIT=ITIT+ITER
     GO TO 560
-----SAVES THE TIME AND WELL LEVEL OF THE LAST CONVERGENT TIME
-----STEP INTO TLCI AND ALLCI RESPECTIVELY
540  TLCI=TIME
     ALLCI=AL
     DT1=DT
     AL1=AL
     IF (ABS(TIME-TMAX) .LE. .001*DT) GO TO 560
     IF (DT .LT. DTMAX. AND. ITER.LT.7) DT=DMUL*DT
550  IF (DT .GT. DTMAX) DT=DTMAX
     IF ((TIME+DT) .GT. TMAX .OR. ABS(TMAX-TIME-DT) .LT. .2*DT) DT=TMAX
    1 -TIME
555  TIME=TIME+DT
     ITIT=ITIT+ITER
     ITER=0
     GO TO 230
-----DUMP ON TAPE
560  NUMRES=NUMRES-1
     WRITE(6,561)ITIT
     WRITE(*,561)ITIT
561  FORMAT(/,15X,'TOTAL NUMBER OF ITERATIONS =',I5,/)
     IF (NUMRES .GE. 0) GO TO 590
     IF (NTAPE .GT. 0) GO TO 570
     REWIND 1
     WRITE (1,*) NUMNP,MBAND,NUMEL,NUMMAT,MAXSP,NDIM,NSEEP,NUMDP,
    1NUMEP,NPLNT,NDIMP,MXCOL,MXNOD
570  WRITE (1,*) KODE,Q,P,P1,X,Y,KX,SANG,CANG,NP,NSP,
    1KODES,WIDTH,BTP,NCOL,NSOUR,PW,TPOT,NRB,NRT,W,RDF,MTR,CONS1,CONS2,
    2C1,C2,SS,POR,LA,ITER,DT,TIME,DT1,KAT,INTEG,NE,NB,
    3NPT,NPT1,NPB,NPB1,NBW,LW,NEP,NSW,AL,AL1,QP,QA,RW,QTOT,PR,
    4WCR, ALPHA, BETA, IDM
     LAG = LA -1
     WRITE(10,571)LAG, TIME, DT, QTOT
571  FORMAT(2X,'TIME STEP NO. = ',I5,/,
    12X,'TOTAL TIME = ',E10.5,/,
    22X,'TIME INTERVAL = ',E10.5,/,
    32X,'CUMULATIVE INFLOW INTO THE SYSTEM = ',E12.5,/)
     WRITE(10,574)
574  FORMAT(5X,'      X          Y       PRESS. HEAD    N    TOTAL HEAD')
     DO 573 I = 1,NUMNP
        DUM = Y(I) + P(I)
        WRITE(10,572) X(I), Y(I), P(I), I, DUM
572     FORMAT(5X,2F10.2,F12.5,I5,F12.5)
```

```
573 CONTINUE
    IF (NTAPE .GT. 0) RETURN
    NTAPE=1
    GO TO 570
-----RESTART FROM TAPE
580 READ (15,10) NTAPE,NUMRES
    READ (1,*) KODE,Q,P,P1,X,Y,KX,SANG,CANG,NP,NSP,
   1KODES,WIDTH,BTP,NCOL,NSOUR,PW,TPOT,NRB,NRT,W,RDF,MTR,CONS1,CONS2,
   2C1,C2,SS,POR,LA,ITER,DT,TIME,DT1,KAT,INTEG,NE,NB,
   3NPT,NPT1,NPB,NPB1,NBW,LW,NEP,NSW,AL,AL1,QP,QA,RW,QTOT,PR,
   4WCR, ALPHA, BETA, IDM
    IF (NTAPE .EQ. 1) GO TO 590
    READ (1,*) KODE,Q,P,P1,X,Y,KX,SANG,CANG,NP,NSP,
   1KODES,WIDTH,BTP,NCOL,NSOUR,PW,TPOT,NRB,NRT,W,RDF,MTR,CONS1,CONS2,
   2C1,C2,SS,POR,LA,ITER,DT,TIME,DT1,KAT,INTEG,NE,NB,
   3NPT,NPT1,NPB,NPB1,NBW,LW,NEP,NSW,AL,AL1,QP,QA,RW,QTOT,PR,
   4WCR, ALPHA, BETA, IDM
    REWIND 1
    WRITE (1,*) NUMNP,MBAND,NUMEL,NUMMAT,MAXSP,NDIM,NSEEP,NUMDP,
   1NUMEP,NPLNT,NDIMP,MXCOL,MXNOD
    WRITE (1,*) KODE,Q,P,P1,X,Y,KX,SANG,CANG,NP,NSP,
   1KODES,WIDTH,BTP,NCOL,NSOUR,PW,TPOT,NRB,NRT,W,RDF,MTR,CONS1,CONS2,
   2C1,C2,SS,POR,LA,ITER,DT,TIME,DT1,KAT,INTEG,NE,NB,
   3NPT,NPT1,NPB,NPB1,NBW,LW,NEP,NSW,AL,AL1,QP,QA,RW,QTOT,PR,
   4WCR, ALPHA, BETA, IDM
590 READ (15,600) MAXIT,DD,DTMAX,DTMIN,DMUL,TMAX,TOL,QP,ALFA,INPR
    IF (ALFA .LE. 0.) ALFA=.8
600 FORMAT (I5,8E10.3,I5)
    IF (DD .GT. 0.) DT=DD
    IF (DD .LE. 0.) DT=DMUL*DT
    IF (NUMEP .LT. 1) GO TO 620
    READ (15,91) EI,PL,BTPI
    I=0
    DO 610 N=1,NUMNP
    IF (KODE(N) .EQ. 4) KODE(N)=-4
    IF (KODE(N) .NE. -4) GO TO 610
    I=I+1
    BTP(I)=BTP(I)*BTPI
    IF (BTP(I) .GT. 1.) BTP(I)=1.
    Q(N)=BTP(I)*EI*WIDTH(I)
610 CONTINUE
620 IF (NPLNT .LT. 1) GO TO 670
    DO 660 J=1,NPLNT
    NSJ=NSOUR(J)
    NSJ1=NSJ+1
    VALUE=TPOT(J)
    READ (15,630) NCJ,TPOT(J)
630 FORMAT (I5,E10.3)
    IF (NCJ .LT. 1) GO TO 650
    READ (15,91) (RDF(N,J), N=1,NSJ1)
 91 FORMAT (8E10.3)
    WRITE(6,640) J,(RDF(N,J),N=1,NSJ1)
640 FORMAT (41H NEW ROOT DISTRIBUTION FUNCTION FOR PLANT, I3,27H, STAR
   1TING AT BOTTOM NODE -// 10(E13.5))
650 IF (ABS(VALUE-TPOT(J)).LE. 1.0E-15) GO TO 660
    CALL TRANSP (Q,P,P1,T,CR,Y,NCOL,NSOUR,PW,TPOT,
   1NRB,NRT,W,PR,RDF,MTR,SAVE,NUMNP,NUMMAT,NPLNT,NDIMP,
   2MXCOL,MXNOD,J)
660 CONTINUE
670 IF (NSEEP .LT. 1) GO TO 680
```

```
      IF (MAXIT .LT. 4) MAXIT=4
----READ IN NEW BOUNDARY CONDITIONS
680 READ (15,690) N,NEWKOD,VALUE
690 FORMAT (2I5,E10.3)
      IF (N .LT. 1) GO TO 550
      KODE(N)=NEWKOD
      IF (KODE(N) .LT. 1) GO TO 700
      P(N)=VALUE
      P1(N)=VALUE
      GO TO 680
700 Q(N)=VALUE
      GO TO 680
      END
      SUBROUTINE ELEM (CMUL,KODE,A,B,P,P1,T,D,CR,C,X,Y,KX,SANG,CANG,
     1NUMNP,MBAND,NUMEL,NUMMAT,M,KAT,N)
      DIMENSION E(3,3),S(4,4),A(MBAND,NUMNP),B(NUMNP),P(NUMNP),T(NUMNP),
     1D(NUMNP),CR(NUMNP),C(NUMNP),X(NUMNP),Y(NUMNP),KX(NUMEL,5),
     2P1(NUMNP),SANG(NUMEL),CANG(NUMEL),LM(4),IX(3),KODE(NUMNP)
      COMMON /MAT/ CONS1,CONS2,C1(9),C2(9),SS(9),POR(9),ALPHA(9),
     *             BETA(9),WCR(9),IDM(9)
----DETERMINE CONDUCTIVITY TENSOR
      SIN2=SANG(N)*SANG(N)
      COS2=CANG(N)*CANG(N)
      CONDI=C1(M)*COS2+C2(M)*SIN2
      CONDJ=C1(M)*SIN2+C2(M)*COS2
      CONDK=(C1(M)-C2(M))*SANG(N)*CANG(N)
      DO 20 I=1,4
      DO 20 J=1,4
         S(I,J)=0.
 20 CONTINUE
      DO 30 I=1,4
         LM(I)=KX(N,I)
 30 CONTINUE
      NUS=4
      IF (LM(3) .EQ. LM(4)) NUS=3
----DETERMINE UNSATURATED VARIABLES FOR CORNER NODES
      IWET=0
      DO 60 K=1,NUS
         I=LM(K)
         IF (CR(I) .GE. 0.) GO TO 50
         IF (P(I) .GE. 0.0)THEN
             CR(I) = 1.0
             T(I)= POR(M)
             C(I) = 0.0
           ELSE
 40          IF (KODE(I) .LT. 1) CM=P(I)
             IF (KODE(I).GE. 1) CM=.5*(P(I)+P1(I))
             CR(I)=XK(CM,M)
             C(I)=XCM(CM,M)
         ENDIF
 50      IF (P(I) .LT. 0.) IWET=1
 60 CONTINUE
      QSTORE=0.
----LOOP ON SUBELEMENTS
      KK=2
      IF(NUS .LT. 4) KK=1
      DO 120 K=1,KK
         I=LM(1)
         J=LM(K+1)
         L=LM(K+2)
```

```
70      CI=X(L)-X(J)
        CJ=X(I)-X(L)
        CK=X(J)-X(I)
        BI=Y(J)-Y(L)
        BJ=Y(L)-Y(I)
        BK=Y(I)-Y(J)
        XMUL=1.
        IF (KAT .NE. 1) GO TO 80
        XMUL = (X(I)+X(J)+X(L))/3.
80      DEL2=CK*BJ-CJ*BK
     OPEN(8,file='areas.dat',status='unknown')
     write(8,'(10x,i5,3x,e15.3)')n,del2
        CM=(CR(I)+CR(J)+CR(L))/3.
        COMM=.5*XMUL*CM/DEL2
        QSTORE=.5*DEL2*XMUL
        IF (KAT .GE. 1) THEN
           AA=.5*CM*XMUL
           B(I)=B(I)+AA*(CONDK*BI+CONDJ*CI)
           B(J)=B(J)+AA*(CONDK*BJ+CONDJ*CJ)
           B(L)=B(L)+AA*(CONDK*BK+CONDJ*CK)
        ENDIF
        E(1,1)=CONDI*BI*BI+2.*CONDK*BI*CI+CONDJ*CI*CI
        E(1,2)=CONDI*BI*BJ+CONDK*(BI*CJ+CI*BJ)+CONDJ*CI*CJ
        E(1,3)=CONDI*BI*BK+CONDK*(BI*CK+CI*BK)+CONDJ*CI*CK
        E(2,1)=E(1,2)
        E(2,2)=CONDI*BJ*BJ+2.*CONDK*BJ*CJ+CONDJ*CJ*CJ
        E(2,3)=CONDI*BJ*BK+CONDK*(BJ*CK+BK*CJ)+CONDJ*CJ*CK
        E(3,1)=E(1,3)
        E(3,2)=E(2,3)
        E(3,3)=CONDI*BK*BK+2.*CONDK*BK*CK+CONDJ*CK*CK
        IX(1)=1
        IX(2)=K+1
        IX(3)=K+2
        DO 110 I=1,3
           II=IX(I)
           IJ=LM(II)
           BB=0.
           IF (IWET .EQ. 0) BB=T(IJ)*CMUL
           AA=C(IJ)+BB
           DO 100 J=1,3
              JJ=IX(J)
              JI=LM(JJ)
              BB=0.
              IF (IWET .EQ. 0) BB=T(JI)*CMUL
              AA=AA+C(JI)+BB
              S(II,JJ)=S(II,JJ)+E(I,J)*COMM
100        CONTINUE
           D(IJ)=D(IJ)+AA*QSTORE/12.
110     CONTINUE
120  CONTINUE
-----ADD ELEMENT CONTRIBUTION TO A MATRIX
     DO 140 L=1,4
     I=LM(L)
     DO 130 K=1,4
     J=LM(K)-I+1
     IF (J .LT. 1) GO TO 130
     A(J,I)=A(J,I)+S(L,K)
130  CONTINUE
140  CONTINUE
     RETURN
```

```
      END
      SUBROUTINE RESET (KODE,A,B,Q,P,P1,T,D,CR,C,X,Y,KX,SANG,CANG,
     1 NUMNP,MBAND,NUMEL,NUMMAT,M,KAT,LA,DT,DT1,ITER,INTEG)
      DIMENSION A(MBAND,NUMNP),B(NUMNP),Q(NUMNP),P(NUMNP),P1(NUMNP),
     1T(NUMNP),D(NUMNP),CR(NUMNP),C(NUMNP),X(NUMNP),Y(NUMNP),
     2KX(NUMEL,5),SANG(NUMEL),CANG(NUMEL),KODE(NUMNP)
      COMMON /MAT/ CONS1,CONS2,C1(9),C2(9),SS(9),POR(9),ALPHA(9),
     *             BETA(9),WCR(9),IDM(9)
      IF (LA .GT. 1) DTT=.5*DT/DT1
C-----INITIALIZATION AND EXTRAPOLATION OF P VALUES
      DO 40 I=1,NUMNP
      B(I)=0.
      D(I)=0.
      IF(ITER.GT.0) GO  TO 10
      IF (LA .LE.1) PP  =P1(I)
      IF (LA .GT.1) PP  =P(I)+DTT*(P(I)-P1(I))
      P1(I)=P(I)
      IF (KODE(I) .LT. 1) P(I)=PP
      GO TO 20
   10 PP=.5*(P(I)+P1(I))
      IF (KODE(I) .LT. 1) P(I)=PP
   20 DO 30 J=1,MBAND
      A(J,I)=0.
   30 CONTINUE
   40 CONTINUE
      DO 70 M=1,NUMMAT
         CMUL=CONS1*SS(M)/POR(M)
         DO 50 I=1,NUMNP
            CR(I)=-1.
   50    CONTINUE
         DO 60 N=1,NUMEL
            IF (KX(N,5) .NE. M) GO TO 60
            CALL ELEM (CMUL,KODE,A,B,P,P1,T,D,CR,C,X,Y,KX,SANG,CANG,
     1      NUMNP,MBAND,NUMEL,NUMMAT,M,KAT,N)
   60    CONTINUE
   70 CONTINUE
      REWIND 2
      WRITE (2)A,B
C-----COMPLETE CONSTRUCTION OF RHS VECTOR AND FORM EFFECTIVE MATRIX
      PP=2.
      IF (LA .EQ. 1 .OR. INTEG .EQ. 1) PP=1.
      DO 110 I=1,NUMNP
      B(I)=PP*(CONS2*Q(I)-B(I)+D(I)*P1(I)/DT)
      IF (PP .EQ. 1.) GO TO 100
      DO 90 J=1,MBAND
      K=I+J-1
      IF (K .GT. NUMNP) GO TO 80
      B(I)=B(I)-A(J,I)*P1(K)
   80 K=I-J+1
      IF (J .EQ. 1 .OR. K .LT. 1) GO TO 90
      B(I)=B(I)-A(J,K)*P1(K)
   90 CONTINUE
  100 A(1,I)=A(1,I)+PP*D(I)/DT
  110 CONTINUE
      RETURN
      END
      SUBROUTINE MATIN (NUMMAT)
      COMMON /MAT/ CONS1,CONS2,C1(9),C2(9),SS(9),POR(9),ALPHA(9),
     *             BETA(9),WCR(9),IDM(9)
      CHARACTER*13 MDL(10)
```

```
      DATA MDL/'van Genuchten ',' Exponential ','Gardner-Russo','  User-s
     *up.  ',6*'              '/
      READ (15,10) CONS1,CONS2
   10 FORMAT (2E10.3)
      WRITE(6,20) CONS1,CONS2
   20 FORMAT (///50H  UNITS ARE CONTROLED BY THE FOLLOWING CONSTANTS -//
     1 9H  CONS1 =,E12.3,3X,7HCONS2 =,E12.3////9H MATERIAL,7X,2HK1,13X,
     2 2HK2,10X,8HPOROSITY,10X,2HSS,12X,3HRWC,12X,5HALPHA,11X,4HBETA,
     3 11X,6HMODEL /)
      DO 50 M=1,NUMMAT
      READ (15,30)C1(M),C2(M),POR(M),SS(M),WCR(M),ALPHA(M),BETA(M)
     1              ,IDM(M)
   30 FORMAT (7E10.3,I5)
      WRITE(6,40)M,C1(M),C2(M),POR(M),SS(M),WCR(M),ALPHA(M),BETA(M),
     1MDL(IDM(M))
   40 FORMAT (I6,E17.5,6E15.5,4X,A13)
   50 CONTINUE

      RETURN
      END
      SUBROUTINE NPIN (KODE,Q,P,P1,X,Y,WIDTH,NUMDP,NUMNP,INIT,NERR,BTPI,
     1                 EI)
      DIMENSION KODE(NUMNP),Q(NUMNP),P1(NUMNP),X(NUMNP),Y(NUMNP),
     1P(NUMNP),WIDTH(NUMDP)
      NERR=0
      WRITE(6,10)
   10 FORMAT (////24H NODAL POINT INFORMATION //10H  NODE NO.,6X,4HKODE,
     1 7X,3HX,R,12X,3HY,Z,11X,5H.PSI.,12X,1HQ/)
      NPR=0
      L=0
   20 L=L+1
   30 READ (15,40) N,KODE(N),X(N),Y(N),P1(N),Q(N)
   40 FORMAT (2I5,4E10.3)
      P1(N)=P1(N)-INIT*Y(N)
      IF (N-L) 50,90,70
   50 WRITE(6,60) N
   60 FORMAT (20H ERROR IN NPIN AT N=, I5)
      NERR=1
      RETURN
   70 DENO=N-L+1
      DX=(X(N)-X(NPR))/DENO
      DY=(Y(N)-Y(NPR))/DENO
      DP=(P1(N)-P1(NPR))/DENO
   80 X(L)=X(L-1)+DX
      Y(L)=Y(L-1)+DY
      P1(L)=P1(L-1)+DP
      KODE(L)=KODE(L-1)
      Q(L)=Q(L-1)
      L=L+1
      IF (L .LT. N) GO TO 80
   90 NPR=N
      IF (L .LT. NUMNP) GO TO 20
      I=0
      DO 110 N=1,NUMNP
      WRITE(6,100) N,KODE(N),X(N),Y(N),P1(N),Q(N)
  100 FORMAT (2I10,4E15.6)
      P(N)=P1(N)
      IF (KODE(N) .NE. -4) GO TO 110
      I=I+1
      Q(N)=BTPI*EI*WIDTH(I)
```

```
110 CONTINUE
    RETURN
    END
    SUBROUTINE MAFILL (KX,SANG,CANG,NUMEL)
    DIMENSION KX(NUMEL,5),SANG(NUMEL),CANG(NUMEL)
    NUM=0
    WRITE(6,10)
 10 FORMAT (////20H ELEMENT INFORMATION//55H ELEMENT   C O R N E R   N
   1 O D E S    MATERIAL    ANGLE/)
    DO 60 N=1,NUMEL
    IF (NUM-N) 20,60,40
 20 READ (15,30) NUM,(KX(NUM,I),I=1,5),SANG(NUM)
 30 FORMAT (6I5,E10.3)
    IF (KX(NUM,4) .EQ. 0) KX(NUM,4)=KX(NUM,3)
    IF (NUM .EQ. N) GO TO 60
 40 DO 50 I=1,4
    KX(N,I)=KX(N-1,I)+1
 50 CONTINUE
    KX(N,5)=KX(N-1,5)
    SANG(N)=SANG(N-1)
 60 CONTINUE
    AA=3.141592654/180.
    DO 80 N=1,NUMEL
    BB=AA*SANG(N)
    WRITE(6,70) N,KX(N,1),KX(N,2),KX(N,3),KX(N,4),KX(N,5),SANG(N)
 70 FORMAT (I6,I9,3I6,I10,E14.3)
 71 FORMAT (' ',6I5,E10.3)
    CC= SIN(BB)
    SANG(N)=CC
    CC= COS(BB)
    CANG(N)=CC
 80 CONTINUE
    RETURN
    END
    SUBROUTINE CONSTP (A,B,KODE,P,NUMNP,MBAND)
    DIMENSION A(MBAND,NUMNP),B(NUMNP),KODE(NUMNP),P(NUMNP)
    DO 70 N=1,NUMNP
    IF (KODE(N) .LT. 1) GO TO 70
 10 DO 60 M=2,MBAND
    K=N-M+1
    IF (K) 30,30,20
 20 B(K)=B(K)-A(M,K)*P(N)
    A(M,K)=0.
 30 L=N+M-1
    IF (NUMNP-L) 50,40,40
 40 B(L)=B(L)-A(M,N)*P(N)
 50 A(M,N)=0.
 60 CONTINUE
    A(1,N)=1.
    B(N)=P(N)
 70 CONTINUE
    RETURN
    END
    SUBROUTINE FIXQ (A,B,KODE,Q,P,P1,D,NUMNP,MBAND,DT,LA,INTEG)
    DIMENSION A(MBAND,NUMNP),B(NUMNP),KODE(NUMNP),Q(NUMNP),P(NUMNP),
   1P1(NUMNP),D(NUMNP)
    COMMON /MAT/ CONS1,CONS2,C1(9),C2(9),SS(9),POR(9),ALPHA(9),
   *             BETA(9),WCR(9),IDM(9)
    REWIND 2
    READ (2)A,B
```

```
      PPP=1.
      PP=2.
      IF (LA .NE. 1 .AND. INTEG .NE. 1) GO TO 10
      PPP=0.
      PP=1.
   10 DO 40 N=1,NUMNP
      IF (KODE(N) .LT.1) GO TO 40
      QN=PP*(B(N)+D(N)*(P(N)-P1(N))/DT)+A(1,N)*(P(N)+P1(N)*PPP)
      DO 30 J = 2,MBAND
      K=N-J+1
      IF (K .LT. 1) GO TO 20
      QN=QN+A(J,K)*(P(K)+P1(K)*PPP)
   20 K=N+J-1
      IF (K .GT. NUMNP) GO TO 30
      QN=QN+A(J,N)*(P(K)+P1(K)*PPP)
   30 CONTINUE
      QN=QN/(CONS2*PP)
      Q(N)=QN
   40 CONTINUE
      RETURN
      END
      SUBROUTINE MOIST (P,P1,T,T1,KX,NUMNP,NUMEL,NUMMAT)
      DIMENSION P(NUMNP),P1(NUMNP),T(NUMNP),T1(NUMNP),KX(NUMEL,5),
     1 NN(8),TT(8)
      COMMON /MAT/ CONS1,CONS2,C1(9),C2(9),SS(9),POR(9),ALPHA(9),
     *             BETA(9),WCR(9),IDM(9)
      DO 130 M=1,NUMMAT
          DO 10 I=1,NUMNP
             T(I)=-1.
   10     CONTINUE
          AWC=POR(M)-WCR(M)
          DO 60 N=1,NUMEL
             IF (KX(N,5) .NE. M) GO TO 60
             NUS=4
             IF (KX(N,3) .EQ. KX(N,4)) NUS=3
             DO 50 J=1,NUS
                I=KX(N,J)
                IF (T(I) .GT. 0.) GO TO 50
                IF (P1(I) .LT. 0.) GO TO 20
                T1(I)=POR(M)
                GO TO 30
   20           T1(I)=WCR(M)+AWC*SE(P1(I),M)
   30           IF (P(I) .LT. 0.0) GO TO 40
                T(I)=POR(M)
                GO TO 50
   40           T(I)=WCR(M)+AWC*SE(P(I),M)
   50        CONTINUE
   60     CONTINUE
          WRITE(6,70) M
   70 FORMAT (//' MOISTURE CONTENT AT UNSATURATED NODES CORRESPONDING TO
     1 MATERIAL',I3/)
          J=0
          N=0
   80     DO 90 K=1,6
             NN(K)=0
             TT(K)=0.
   90     CONTINUE
  100     N=N+1
          IF (N .GT. NUMNP) GO TO 110
          IF (T(N) .EQ. POR(M) .OR. T(N) .LT. 0.) GO TO 100
```

```
      J=J+1
      NN(J)=N
      TT(J)=T(N)
      IF (J .LT. 6) GO TO 100
110   WRITE(6,120) (NN(K),TT(K),K=1,6)
120   FORMAT (I7,E13.5)
      J=0
      IF (N .LT. NUMNP)GO TO 80
130 CONTINUE
      RETURN
    END
    SUBROUTINE WELBOR (KODE,Q,P,Y,NUMNP,DT)
    DIMENSION KODE(NUMNP),Q(NUMNP),P(NUMNP),Y(NUMNP)
    COMMON /MAT/ CONS1,CONS2,C1(9),C2(9),SS(9),POR(9),ALPHA(9),
   *             BETA(9),WCR(9),IDM(9)
    COMMON /WEL/ NB(3),NE(3),NBW,NPT,NPT1,NPB,NPB1,LW,NEP,NSW,AL,AL1,
   1 QP,QA,RW,RT,ALFA
C-----CALCULATE TOTAL DISCHARGE INTO WELL
    QA1=QA
    QA=0.
    DO 10 I=1,NBW
    N=NB(I)
    QA=QA-Q(N)
 10 CONTINUE
    DO 20 N=NPB1,NPT
    QA=QA-Q(N)
 20 CONTINUE
    QA=.5*(QA+QA1)
C-----CALCULATE WATER LEVEL IN WELL
 30 AA=DT*(QP-QA)/RW*CONS2/CONS1
    AL=ALFA*AL+(1.-ALFA)*(AL1-AA)
C-----DETERMINE CORRESPONDING NODE
    DO 50 N=NPB,NPT1
    IF (AL .GT. Y(N)) GO TO 50
    IF (N .GT. NPB) GO TO 40
    LW=-1
    GO TO 60
 40 LW=N-1
    GO TO 60
 50 CONTINUE
C-----MODIFY BOUNDARY CONDITIONS BELOW WATER LEVEL
 60 DO 70 I=1,NBW
    N=NB(I)
    IF (KODE(N) .EQ. 0) GO TO 70
    IF (LW .LT. 0) GO TO 65
    P(N)=AL-Y(NPB)
    GO TO 70
 65 P(N)=0.
 70 CONTINUE
    IF (LW .LT. 0) GO TO 90
    DO 80 N=NPB1,LW
    IF (KODE(N) .EQ. 0) GO TO 80
    KODE(N)=2
    P(N)=AL-Y(N)
 80 CONTINUE
C-----MODIFY BOUNDARY CONDITIONS ABOVE WATER LEVEL
 90 IF (LW .LT. 0) LW=NPB
    DO 130 J=1,NEP
    NF=NE(J)
    NL=NPT
```

```
      IF (J .LT. NEP) NL=NE(J+1)-1
      ICHECK=0
      DO 120 N=NF,NL
      IF (N .LE. LW) GO TO 120
      IF (KODE(N) .NE. -2) GO TO 100
      IF (P(N) .LT. 0.) ICHECK=1
      IF (ICHECK .GT. 0) GO TO 120
      KODE(N)=2
   95 P(N)=0.
      GO TO 120
  100 IF (KODE(N) .NE. 2) GO TO 120
      IF (ICHECK .GT. 0) GO TO 110
      IF (Q(N) .GE. 0.) GO TO 110
      GO TO 95
  110 KODE(N)=-2
      Q(N)=0.
      ICHECK=1
  120 CONTINUE
  130 CONTINUE
  140 RETURN
      END
      SUBROUTINE PRINTO (Q,P,Y,NUMNP,KAT)
      DIMENSION Q(NUMNP),P(NUMNP),Y(NUMNP),NN(3),PP(3),HH(3),QQ(3)
      WRITE(6,10)
   10 FORMAT (////1H0,3(43H NODE     HEAD      PRESS HEAD   DISCHARGE )
     1//)
      J=0
      N=0
   20 N=N+1
      J=J+1
      IF (N .GT. NUMNP) GO TO 30
      NN(J)=N
      PP(J)=P(N)
      HH(J)=PP(J)
      IF (KAT .GT. 0) HH(J)=HH(J)+Y(N)
      QQ(J)=Q(N)
      GO TO 40
   30 NN(J)=0
      PP(J)=0.
      HH(J)=0.
      QQ(J)=0.
   40 IF (J .LT. 3) GO TO 20
      WRITE(6,50) (NN(J),HH(J),PP(J),QQ(J),J=1,3)
   50 FORMAT (1X,3(I4,3E13.5))
      J=0
      IF (N. LT. NUMNP) GO TO 20
      RETURN
      END
      SUBROUTINE SOLVE (A,B, NUMNP,MBAND)
      DIMENSION A(MBAND,NUMNP),B(NUMNP)
      REDUCTION
      DO 30 N = 1,NUMNP
      DO 20 M=2,MBAND
      IF (A(M,N) .EQ.0.) GO TO 20
      C = A(M,N)/A(1,N)
      I = N + M - 1
      IF (I .GT. NUMNP) GO TO 20
      J = 0
      DO 10 K = M,MBAND
      J = J + 1
```

```
10 IF (A(K,N) .NE. 0.) A(J,I) = A(J,I) - C*A(K,N)
   A(M,N) = C
   B(I) = B(I) - A(M,N)*B(N)
20 CONTINUE
   B(N) = B(N)/A(1,N)
30 CONTINUE
   BACK SUBSTITUTION
   N = NUMNP
40 DO 50 K = 2,MBAND
   L = N + K - 1
   IF (L .GT. NUMNP) GO TO 60
50 IF (A(K,N) .NE. 0.) B(N)=B(N)-A(K,N)*B(L)
60 N = N - 1
   IF (N .GT. 0) GO TO 40
   RETURN
   END
   SUBROUTINE TRANSP (Q,P,P1,T,CR,Y,NCOL,NSOUR,PW,TPOT,
  1NRB,NRT,W,PR,RDF,MTR,SAVE,NUMNP,NUMMAT,NPLNT,NDIMP,
  2MXCOL,MXNOD,J)
   DIMENSION Q(NUMNP),P(NUMNP),P1(NUMNP),T(NUMNP),CR(NUMNP),Y(NUMNP),
  1NCOL(NDIMP),NSOUR(NDIMP),PW(NDIMP),TPOT(NDIMP),NRB(MXCOL,NDIMP),
  2NRT(MXCOL,NDIMP),RDF(MXNOD,NDIMP),W(MXCOL,NDIMP),PR(MXCOL,NDIMP),
  3MTR(MXNOD,NDIMP),SAVE(2,MXNOD)
   COMMON /MAT/ CONS1,CONS2,C1(9),C2(9),SS(9),POR(9),ALPHA(9),
  *             BETA(9),WCR(9),IDM(9)
   NCJ=NCOL(J)
   NSJ=NSOUR(J)
   NSJ1=NSJ-1
   DO 90 I=1,NCJ
      PR(I,J)=PW(J)
      IF(TPOT(J) .GE. 0.) PR(I,J)=0.
      NB=NRB(I,J)
      NT=NRT(I,J)
      ND=(NT-NB)/(NSJ-1)
      NC=0
      Q(NB)=0.
      PNN=.5*(P(NB)+P1(NB))
      DO 30 NK=1,NSJ1
         N=NB+(NK-1)*ND
         N1=N+ND
         Q(N1)=0.
         IF (TPOT(J) .GE. 0.) GO TO 30
         PN=PNN
         PNN=.5*(P(N1)+P1(N1))
         NC=NC+1
         M=MTR(NC,J)
         IF (NC .EQ. 1) GO TO 10
         IF (NC .GT. 1 .AND. M .EQ. MTR(NC-1,J)) GO TO 20
 10      CR(N)=XK(PN,M)
 20      CR(N1)=XK(PNN,M)
         CC = (Y(N1)-Y(N))*C1(M)
         CM = CC*RDF(NC,J)*CR(N)
         SAVE(1,NC)=CM
         CM=CC*RDF(NC+1,J)*CR(N1)
         SAVE(2,NC)=CM
 30   CONTINUE
      IF (TPOT(J) .GE. 0.0) GO TO 90
      NC=0
      PNN=0.5*(P(NB)+P1(NB))
      DO 40 NK=1,NSJ1
```

```
         N=NB+(NK-1)*ND
         N1=N+ND
         PN=PNN
         PNN=0.5*(P(N1)+P1(N1))
         NC=NC+1
         CM=Q(N)+W(I,J)*(SAVE(1,NC)*(PR(I,J)-PN)/3.+SAVE(2,NC)*(PR(I,
  1         J)-PNN)/6.)
         Q(N)=CM
   CM=W(I,J)*(SAVE(1,NC)*(PR(I,J)-PN)/6.+SAVE(2,NC)*(PR(I,J)-PNN)/3.)
         Q(N1 )=CM
40     CONTINUE
       QCUM=0.
       DO 50 NK=1,NSJ
         N=NB+(NK-1)*ND
         IF (Q(N) .GT. 0.) Q(N)=0.
         QCUM=QCUM+Q(N)
50     CONTINUE
       WT=W(I,J)*TPOT(J)
       WT=WT/QCUM
       IF(WT .GE. 1.) GO TO 90
       DO 60 NK=1,NSJ
         N=NB+(NK-1)*ND
         IF (Q(N) .LT. 0.) Q(N)=WT*Q(N)
60     CONTINUE
       QCUM=WT*QCUM
       NC=0
       AA=0.
       BB=0.
       PNN=.5*(P(NB)+P1(NB))
       DO 80 NK=1,NSJ1
         N=NB+(NK-1)*ND
         N1=N+ND
         PN=PNN
         PNN=.5*(P(N1)+P1(N1))
         NC=NC+1
         IF(Q(N) .GE. 0.) GO TO 70
         AA=AA+SAVE(1,NC)/3.+SAVE(2,NC)/6.
         BB=BB+SAVE(1,NC)*PN/3.+SAVE(2,NC)*PNN/6.
70       IF(Q(N1) .GE. 0.) GO TO 80
         AA=AA+SAVE(1,NC)/6.+SAVE(2,NC)/3.
         BB=BB+SAVE(1,NC)*PN/6.+SAVE(2,NC)*PNN/3.
80     CONTINUE
       PR(I,J)=(QCUM/W(I,J)+BB)/AA
       IF(PR(I,J) .LT. PW(J)) PR(I,J)=PW(J)
90 CONTINUE
   RETURN
   END
--- FUNCTION TO EVALUATE DIMENSIONLESS SATURATION
   FUNCTION SE(H,M)
   COMMON /MAT/ CONS1,CONS2,C1(9),C2(9),SS(9),POR(9),ALPHA(9),
  *             BETA(9),WCR(9),IDM(9)

   SE=1.0
   IF(H.GE.0.0) RETURN
   IF(IDM(M).EQ.1)THEN
      SE=(1.0+ABS(ALPHA(M)*H)**BETA(M))**(-(1.0-1.0/BETA(M)))
    ELSE IF(IDM(M).EQ.2)THEN
      SE=EXP(ALPHA(M)*H)
    ELSE IF(IDM(M).EQ.3)THEN
      EE=0.5*ALPHA(M)*H
```

```
      SE=EXP(EE)*(1.0+ABS(EE))**(2.0/(BETA(M)+2.0))
    ELSE IF(IDM(M).EQ.4)THEN
      SE=1.0/(1.0+(ALPHA(M)*H)**2.0)
   ENDIF
   RETURN
   END

--- FUNCTION TO SPECIFIC MOISTURE CAPACITY
   FUNCTION XCM(H,M)
   COMMON /MAT/ CONS1,CONS2,C1(9),C2(9),SS(9),POR(9),ALPHA(9),
  *             BETA(9),WCR(9),IDM(9)

   XCM=0.0
   IF(H.GE.0.0) RETURN
   IF(IDM(M).EQ.1)THEN
      GAMMAT=1.0-1.0/BETA(M)
      S=(1.0+ABS(ALPHA(M)*H)**BETA(M))**(-GAMMAT)
      GAMMA1=1.0/GAMMAT
      XCM=ALPHA(M)*(BETA(M)-1.0)*(POR(M)-WCR(M))*S**GAMMA1*
  *       (1.0-S**GAMMA1)**GAMMAT
    ELSE IF(IDM(M).EQ.2)THEN
      XCM=(POR(M)-WCR(M))*ALPHA(M)*EXP(ALPHA(M)*H)
    ELSE IF(IDM(M).EQ.3)THEN
      HA=0.5*ALPHA(M)
      XCM=SE(H,M)*HA*(POR(M)-WCR(M))*(2.0/((BETA(M)+2.0)*
  *         (1.0+HA*H))-1.0)
    ELSE IF(IDM(M).EQ.4)THEN
      XCM=-2.0*H*(POR(M)-WCR(M))*(ALPHA(M)*SE(H,M))**2.0
   ENDIF
   RETURN
   END

  FUNCTION TO EVLAUTE RELATIVE CONDUCTIVITY
   FUNCTION XK(H,M)
   COMMON /MAT/ CONS1,CONS2,C1(9),C2(9),SS(9),POR(9),ALPHA(9),
  *             BETA(9),WCR(9),IDM(9)

   XK=1.0
   IF(H.GE.0.) RETURN
   IF(IDM(M).EQ.1)THEN
      GAMMAK=1.0-1.0/BETA(M)
      GAMMA1=1.0/GAMMAK
      S=(1.0+ABS(ALPHA(M)*H)**BETA(M))**(-GAMMAK)
      XK=SQRT(S)*(1.0-(1.0-S**(GAMMA1))**GAMMAK)**2
    ELSE IF(IDM(M).EQ.2. OR .IDM(M).EQ.3)THEN
      XK=EXP(ALPHA(M)*H)
    ELSE IF(IDM(M).EQ.4)THEN
      XK=SE(H,M)**4.0
   ENDIF
   RETURN
   END

   AUTOMATIC GRID GENERATION
   SUBROUTINE SGRID(KODE,Q,P,P1,X,Y,WIDTH,NUMNP,INIT,BTPI,EI,KX,SANG,
  &                 NUMDP,CANG,NUMEL)
   DIMENSION KODE(NUMNP),Q(NUMNP),P1(NUMNP),X(NUMNP),Y(NUMNP),
  1P(NUMNP),WIDTH(NUMDP),KX(NUMEL,5),SANG(NUMEL),CANG(NUMEL)
ike The next two arrays should be dementioned correctly
r each problem.
   DIMENSION DX(50),DY(50)
```

```
   Reads number of columns and rows for grid
   READ(15,*)NC,NR
   Reads index which indicates if the DX and DY are constant
   READ(15,*)ICDX,ICDY
   If ICDX .eq. 0 indicates that DX is constant and only one value
               is needed;
   If ICDX .ne. 0 indicates varying DX and NC values need to be
               supplied.

   IF(ICDX.NE.0)THEN
      IRC = NC
     ELSE
      IRC = 1
   ENDIF

   READ(15,*)(DX(I),I=1,IRC)
   IF(IRC.EQ.1)THEN
      DO 10 I=1,NC
10       DX(I)= DX(1)
   ENDIF
   IF(ICDY.NE.0)THEN
      IRR = NR
     ELSE
      IRR = 1
   ENDIF

   READ(15,*)(DY(I),I=1,IRR)
   IF(IRR.EQ.1)THEN
      DO 20 I=1,NR
20       DY(I)= DY(1)
   ENDIF

   Figures out which value is larger; NC or NR, to decide the
   direction in which the grid will be numbered, (i.e., horizon-
   tally or vertically).
   IF(NC.GE.NR)THEN
      CALL NODIN(NR,NC,DY,DX,Y,X,NUMNP)
     ELSE
      CALL NODIN(NC,NR,DX,DY,X,Y,NUMNP)
   ENDIF

   NTN = (NC + 1) * (NR + 1)
   NEL = NC * NR
   IF(NTN.NE.NUMNP. OR .NEL.NE.NUMEL)THEN
      WRITE(*,99)
      WRITE(6,99)
   ENDIF

   Reads the code, flow rate and pressure for each node
   READ(15,*)(KODE(I),I=1,NUMNP)
   READ(15,*)(Q(I),I=1,NUMNP)
   READ(15,*)(P1(I),I=1,NUMNP)
   DO 25 I=1,NUMNP
      P1(I)=P1(I)-INIT*Y(N)
      P(I)=P1(I)
25 CONTINUE

   Writes the nodal information to unit 6 (unsat.out)
   WRITE(6,60)
```

```
      J=0
      DO 50 I = 1,NUMNP
         WRITE(6,100)I,KODE(I),X(I),Y(I),P1(I),Q(I)
         IF(KODE(I).NE.-4)GOTO 50
         J=J+1
         Q(I)=BTPI*EI*WIDTH(J)
   50 CONTINUE

      Reads the material and the angle (degrees) between K11 and the
      coordinate axis to be used for each element
      READ(15,*)((KX(I,J),J=5,5),I=1,NUMEL)
      READ(15,*)(SANG(I),I=1,NUMEL)

      Assigns element numbers and corresponding corner nodes
      IF(NC.GE.NR)THEN
         CALL ELEM1(NR,NC,KX,NUMEL)
        ELSE
         CALL ELEM2(NC,NR,KX,NUMEL)
      ENDIF

      Writes the element information to unit 6 (unsat.out)
      WRITE(6,70)
      AA=3.141592654/180.
      DO 80 N=1,NUMEL
         BB=AA*SANG(N)
         WRITE(6,71)N,KX(N,1),KX(N,2),KX(N,3),KX(N,4),KX(N,5),SANG(N)
         CC= SIN(BB)
         SANG(N)=CC
         CC= COS(BB)
         CANG(N)=CC
   80 CONTINUE

   60 FORMAT (////24H NODAL POINT INFORMATION //10H  NODE NO.,6X,4HKODE,
     1 7X,3HX,R,12X,3HY,Z,11X,5H.PSI.,12X,1HQ/)
   70 FORMAT (///20H ELEMENT INFORMATION,//,' ELEMENT   C O R N E R   N
     1 O D E S    MATERIAL    ANGLE'/)
   71 FORMAT (I6,I9,3I6,I10,E14.3)
   72 FORMAT (6I5,E10.3)
   99 FORMAT(/,' *** ERROR IN SGRID: NUMBER OF GENERATED NODES OR ELEMEN
     &TS IS NOT EQUAL TO SPECIFIED NUMNP OR NUMEL *** ',/)
  100 FORMAT(2I10,4E15.6)
      RETURN
      END

      This subroutine numbers the grid and generates node coordinates
      SUBROUTINE NODIN(IFAST,ISLOW,DX1,DX2,X1,X2,NUMNP)
      DIMENSION X1(NUMNP),X2(NUMNP)
      DIMENSION DX1(1),DX2(1)

      N = 0
      X2L = 0.0
      DO 30 I = 1,ISLOW+1
         X1L = 0.0
         DO 25 J = 1,IFAST+1
            N = N + 1
            X2(N) = X2L
            X1(N) = X1L
            X1L = X1L + DX1(J)
   25    CONTINUE
         X2L = X2L + DX2(I)
```

```
30 CONTINUE
   RETURN
   END
```

The following subroutines create element information

```
   SUBROUTINE ELEM1(IF,IS,KX,NUMEL)
   DIMENSION KX(NUMEL,5)

   M = IF + 1
   K = 0
   L = 0
   DO 40 J = 1,IS
      DO 35 I = 1,IF
         K = K + 1
         KX(K,1) = L + I
         KX(K,2) = M + I
         KX(K,3) = KX(K,2) + 1
         KX(K,4) = KX(K,1) + 1
35    CONTINUE
      L = M
      M = L + IF + 1
40 CONTINUE
   RETURN
   END

   SUBROUTINE ELEM2(IF,IS,KX,NUMEL)
   DIMENSION KX(NUMEL,5)
   M = IF + 1
   K = 0
   L = 0
   DO 40 J = 1,IS
      DO 35 I = 1,IF
         K = K + 1
         KX(K,1) = L + I
         KX(K,2) = KX(K,1) + 1
         KX(K,4) = M + I
         KX(K,3) = KX(K,4) + 1
35    CONTINUE
      L = M
      M = L + IF + 1
40 CONTINUE
   RETURN
   END
```