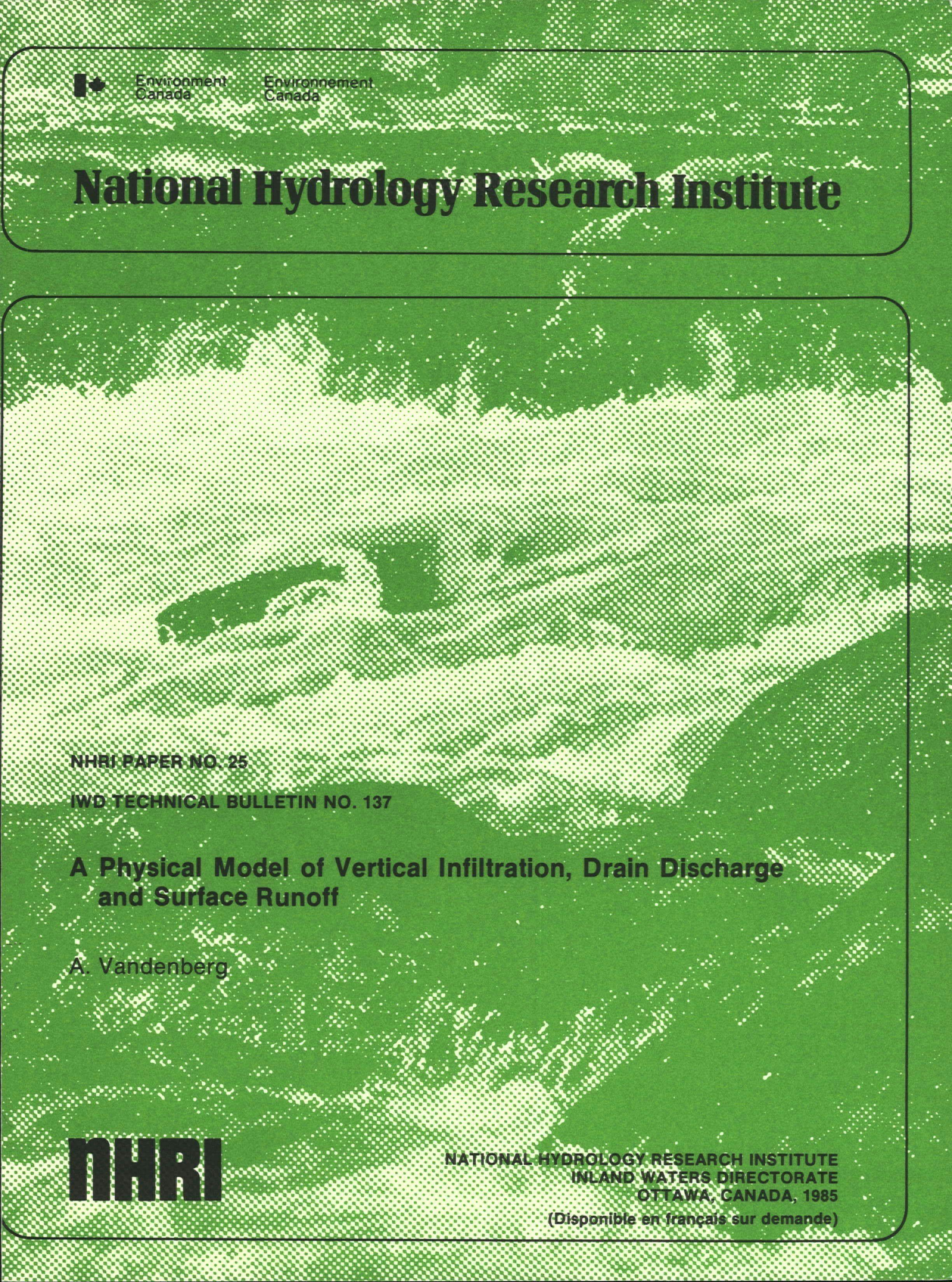

Environment Canada Environnement Canada

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A Physical Model of Vertical Infiltration, Drain Discharge and Surface Runoff

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OTTAWA, CANADA, 1985

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Abstract

The author identifies the elements of the hydrological cycle and their interrelationships which are directly influenced by soil and surface drainage improvements. A model of this partial cycle is constructed, permitting the assessment of the effect of drainage improvement on the total discharge from a drained plot for a given precipitation input. Total discharge is composed of surface runoff and drain discharge.

Particular emphasis is placed on the soil moisture component, infiltration and percolation to the ground-water table. All components except the unsaturated zone are treated as lumped systems, but the unsaturated zone is represented in the model by a stack of up to 50 layers, the moisture transfer between layers being calculated by a forward-finite difference type of calculation based on the physical characteristics of the soil.

The effects of the parameters of the model are described and discussed by means of approximately 90 sample runs. The parameters determining storage capacity of the soil influence the shape and peak value of discharge much more than those determining velocity of flow.

In the course of the drainage history of originally waterlogged areas, increased peak flows can be expected in the early stages owing to improved surface drainage; subsequently, improvement in soil drainage and aeration will cause peak flows to diminish.

Users are cautioned that the model is only a crude representation of the real world, being single-layered and one-dimensional, and representing only one level of drainage.

Key words: Drainage, flooding, discharge peak, infiltration, percolation, unsaturated zone, surface runoff, digital model.

Résumé

L'auteur indique les éléments du cycle hydrologique, ainsi que leurs interrelations, qui sont directement touchés par des améliorations du sol et du drainage de surface. Il présente un modèle décrivant ce cycle partiel, qui permet d'évaluer l'effet de l'amélioration du drainage sur l'écoulement total provenant d'une parcelle drainée recevant une précipitation de volume connu. L'écoulement total est constitué du ruissellement de surface et de l'écoulement des drains.

Une attention particulière est accordée à la composante de l'humidité du sol, à l'infiltration et à la percolation jusqu'à la nappe phréatique. Toutes les composantes à l'exception de la zone insaturée sont traitées comme des systèmes globaux («lumped»), mais la zone insaturée est représentée dans le modèle par une cinquantaine de couches, le passage de l'humidité entre les couches étant déterminé par un calcul du type progressif aux différences finies à partir des caractéristiques physiques du sol.

L'effet des paramètres du modèle est décrit et examiné à partir des résultats d'environ 90 essais. Les paramètres déterminant la capacité d'emmagasinement du sol influent beaucoup plus sur la forme et le niveau de pointe de l'écoulement que ceux qui déterminent la vitesse d'écoulement.

Sur les terrains qui étaient saturés d'eau, l'amélioration du drainage de surface devrait entraîner dans les premiers temps un accroissement du débit de pointe, puis l'amélioration du drainage du sol et de l'aération le fera diminuer.

Les utilisateurs sont prévenus que le modèle est seulement une représentation grossière de la réalité, étant monocouche et unidimensionnel et ne représentant qu'un seul niveau de drainage.

Mots clés: Drainage, inondation, débit de pointe, infiltration, percolation, zone insaturée, ruissellement de surface, modèle numérique.

List of Symbols

A	Drainage intensity = $8 K_0 d/L^2$	(day^{-1})	Eq. 13
A_b	Coefficient in surface runoff equation	(cm^{-1} day^{-1})	Eq. 18
a	Exp ($\alpha \Delta z$)	-	Eq. 6
a'	$a^{1/2}$ = exp ($\alpha \Delta z/2$)	-	Eq. 12
D	Drain discharge to ditch	(cm/day)	Introduction
d	Equivalent depth of aquifer	(cm)	Eq. 13
E_{pot}	Potential evaporation rate	(cm/day)	Precipitation, P
E_{Soil}	Actual evaporation from upper soil layer	(cm/day)	Precipitation, P
F	Implicit function of Z_w	-	Eq. 17
F'	Derivative of F with respect to Z_w	-	-
G	Ground-water discharge to drain	(cm/day)	Introduction
I	Infiltration rate	(cm/day)	Introduction
$K, K(\theta), K(\psi)$	Conductivity of soil, function of θ and of ψ	(cm/day)	Eq. 1
K_i	Conductivity of ith soil layer	(cm/day)	Eq. 4
K_0	Saturated conductivity	(cm/day)	Eq. 2
L	Distance between drains	(cm)	Eq. 13
m	Number of soil layers	-	-
n_s (or ns as a subscript)	Number of saturated layers	-	Eq. 16
P	Precipitation rate	(cm/day)	Introduction
P_{max}	Depth of water on surface below which no surface runoff takes place	(cm)	Surface runoff, R
Q_i	Flow rate from layer i to layer (i + 1)	(cm/day)	Eq. 4

q	Upward vector of internal moisture flow	(cm/day)	Eq. 1
R	Surface runoff rate	(cm/day)	Introduction
S_1	Storage element 1, the atmosphere	(cm)	Introduction
S_2	Storage element 2, the surface ponding	(cm)	Introduction
S_3	Storage element 3, the soil	(cm)	Introduction
$S_{3,i}$	Storage in ith soil layer	(cm)	-
S_4	Storage in drain	(cm)	Introduction
S_5	Storage in ditch	(cm)	Introduction
t	Time	(days)	-
Z	Elevation above the drain	(cm)	Eq. 1
Z_i	Elevation of centre of the ith soil layer above the drain	(cm)	Eq. 4
Z_w	Elevation of water table above drain	(cm)	Eq. 14
α	Constant in the $K(\psi)$ relation	(cm^{-1})	Eq. 2
Δt	Small time interval between successive inventories	(days)	Eq. 7
ΔZ	Thickness of a soil layer	(cm)	Eq. 4
θ	Volumetric moisture content	(cm/cm)	-
θ_{sat}	Moisture content of soil at saturation	(cm/cm)	Eq. 10
θ_m	Moisture content of mth soil element	(cm/cm)	Eq. 11
θ_m'	Moisture content of mth soil element at end of time step	(cm/cm)	Eq. 10, 11
θ_o	Minimum soil moisture content on the ψ-θ curve of the model	(cm/cm)	-
ψ	Pressure head	(cm)	Eq. 1
ψ_D	Pressure head at depth of drain midway between drains	(cm)	Eq. 13

A Physical Model of Vertical Infiltration, Drain Discharge and Surface Runoff

A. Vandenberg

INTRODUCTION

Any part of the hydrological cycle can be defined as a set of storage reservoirs between which water transfers take place at rates governed by the laws of physics. In general, these physical laws relate the transfer between two adjacent reservoirs to the physical state of the two reservoirs. Once all the transfer functions have been established, the changing state of the system as a whole can be followed through time by a system of double bookkeeping, provided entries to the ledger are made at frequent enough intervals that the state just after the transfers have been entered provides the basis for calculating the transfer rates during the small time until the next entry is made.

The part of the hydrological cycle that is of primary interest in determining the transformation of a precipitation event over a basin into the corresponding discharge event is shown in Figure 1, where the storage reservoirs are represented by rectangular boxes, and the transfer functions by triangles suggesting the prevalent direction of the transfer.

Drainage works, when installed in parts of a basin, will primarily alter transfer functions, such as runoff rate and ground-water discharge rate, but secondarily affect storages, such as surface ponding and soil moisture. In particular, if we wish to study the effect of drainage improvements on the shape of the time series of basin outflow, we can limit ourselves to a smaller subsection of Figure 1, including only those transfer functions and storages most directly altered by drainage improvement. Figure 2 shows such a partial cycle, including the storage reservoirs S_1 to S_5 and the transfer functions P, I, G, D and R, where

S_1 = precipitation reservoir
S_2 = surface ponding
S_3 = soil moisture storage
S_4 = storage in the drains
S_5 = storage in the ditch
P = precipitation
I = infiltration
G = ground-water discharge to drain
D = drain discharge to ditch
R = runoff over the surface into the ditch.

Figure 2 also indicates how the partial cycle for one plot is connected to other plots through the section of ditch, S_5; each section of the ditch receives inputs R and D, as well as input from at least one

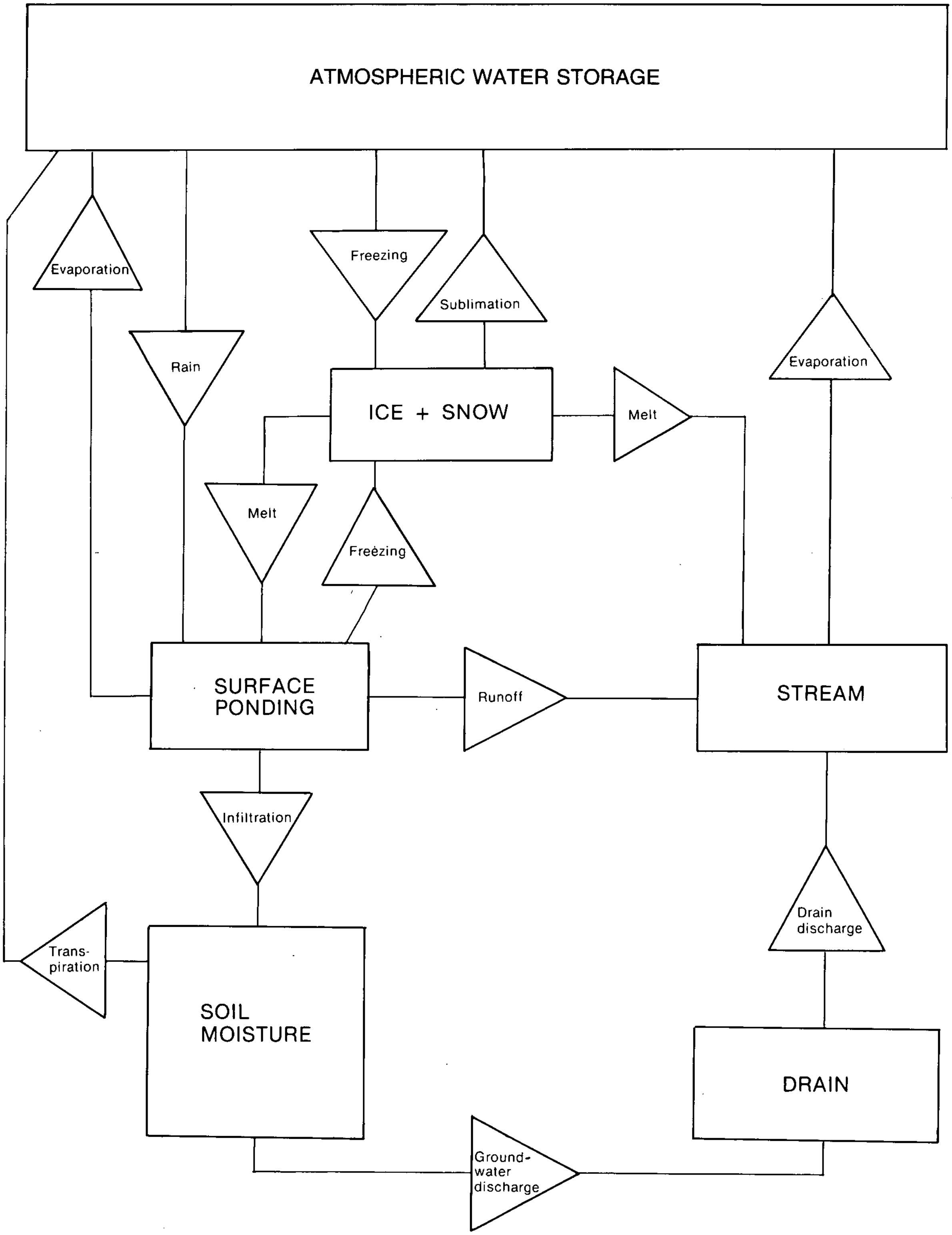

Figure 1. Part of the hydrological cycle affecting streamflow.

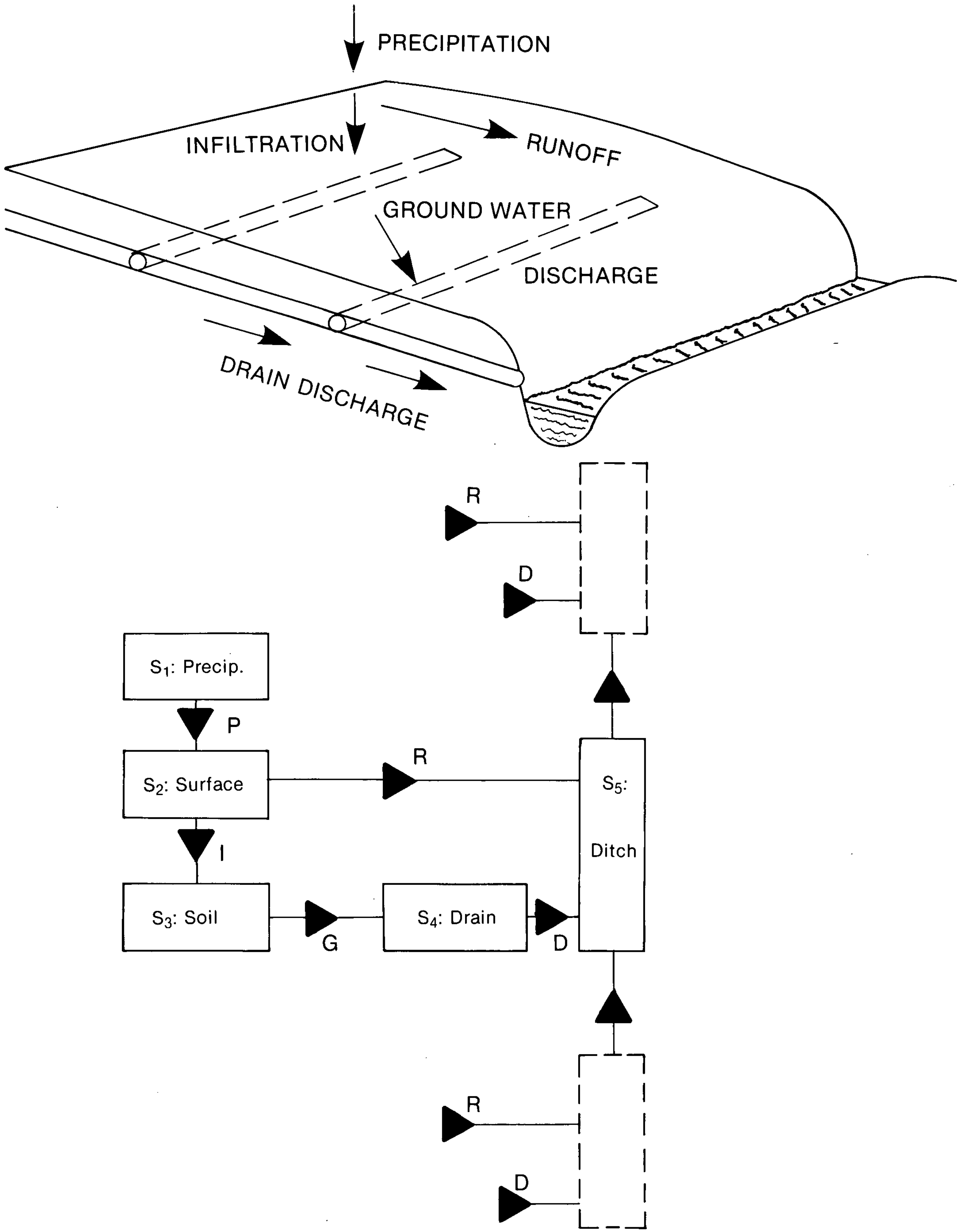

Figure 2. Section of the hydrological cycle affected by drainage improvements.

other section, and discharges into at least one other section. Therefore the state of the section of the ditch cannot be calculated unless the states of the adjoining sections are also known. This has the further consequence that if R and D are sensitive to changes in S_5, all other storages in the system will also be affected and a workable model must include all parcels of drained land which discharge into the same ditch.

Fortunately, in most instances both R and D discharge into the ditch or stream above the water level and therefore do not depend on the water level in the ditch. Only in cases of extreme flooding, i.e., when the outlet of S_5 becomes blocked, will the drain outlet be under water, in which case the direction of D may be reversed. We will not consider such extreme cases here but limit ourselves to the one plot, assuming that R and D are independent of S_5, which will be maintained for bookkeeping purposes only. Thus, with the addition of S_1 at the input end, we are dealing with a closed system for which the sum of all the storages must remain constant.

In the next two sections, a detailed analysis is given of the transfer functions: the soil-related functions I and G and the remaining functions P, D and R. Then the model, basically a moisture-accounting process, is described in its entirety. Some of the model results are shown and the effect of the various parameters on the discharge time series are discussed.

INTERNAL SOIL MOISTURE MOVEMENT, INFILTRATION AND GROUND-WATER DISCHARGE

In the previous section, and in Figures 1 and 2, we have tacitly assumed that for each of the storage elements shown, under isothermal conditions, the state of the element can be equated to the total amount of water in the element, a unique number. Specifically in the case of soil storage, however, soil moisture is typically a function of its position in the element, notably of its elevation. But the infiltration rate, I, does not depend on the moisture content at some depth, but only on the moisture content near the surface; similarly, the ground-water discharge, G, does not depend on the moisture content near the surface or some intermediate depth, but rather on the hydraulic head and therefore the water content at the depth of the drain. Thus the lumped system of Figures 1 and 2 can introduce large errors, since soil moisture is distributed unevenly throughout the soil column. Thus we come to consider the model of Figure 3, with distributed ground-water storage, which is derived from Figure 2 by subdividing S_3 into m smaller storage elements $S_{3,i}$, i = 1 to m, and introducing the (m-1) internal transfer functions Q_i, i = 1 to (m-1).

Internal Transfer Functions, Q_i

The internal transfer functions can be derived from Darcy's law as modified for vertical flow in unsaturated soil:

$$q = -K(\psi)(d/dZ)(\psi + Z) = -K(\psi)(d\psi/dZ + 1) \quad (1)$$

where q = volume of water moving upward through a horizontal plane of unit area per unit of time (dimension L/T)

K = conductivity, which is a function of pressure head ψ (dimension L/T)

ψ = pressure head, negative in unsaturated soil, positive in saturated soil (dimension L)

Z = vertical coordinate increasing upward (dimension L).

Pressure head is related to moisture content, θ, but the relation strictly speaking is not unique, showing hysteresis, i.e., the $\psi(\theta)$ curve for a drying soil is different from the $\psi(\theta)$ curve for a moistening soil. Although it is difficult to assess the error introduced in doing so, we will nevertheless base our model on an average $\psi(\theta)$ curve, where θ is the moisture content by volume, which uniquely relates θ and ψ independent of past history. This relation must be determined for each soil in the laboratory or in the field by measuring ψ at different values of θ.

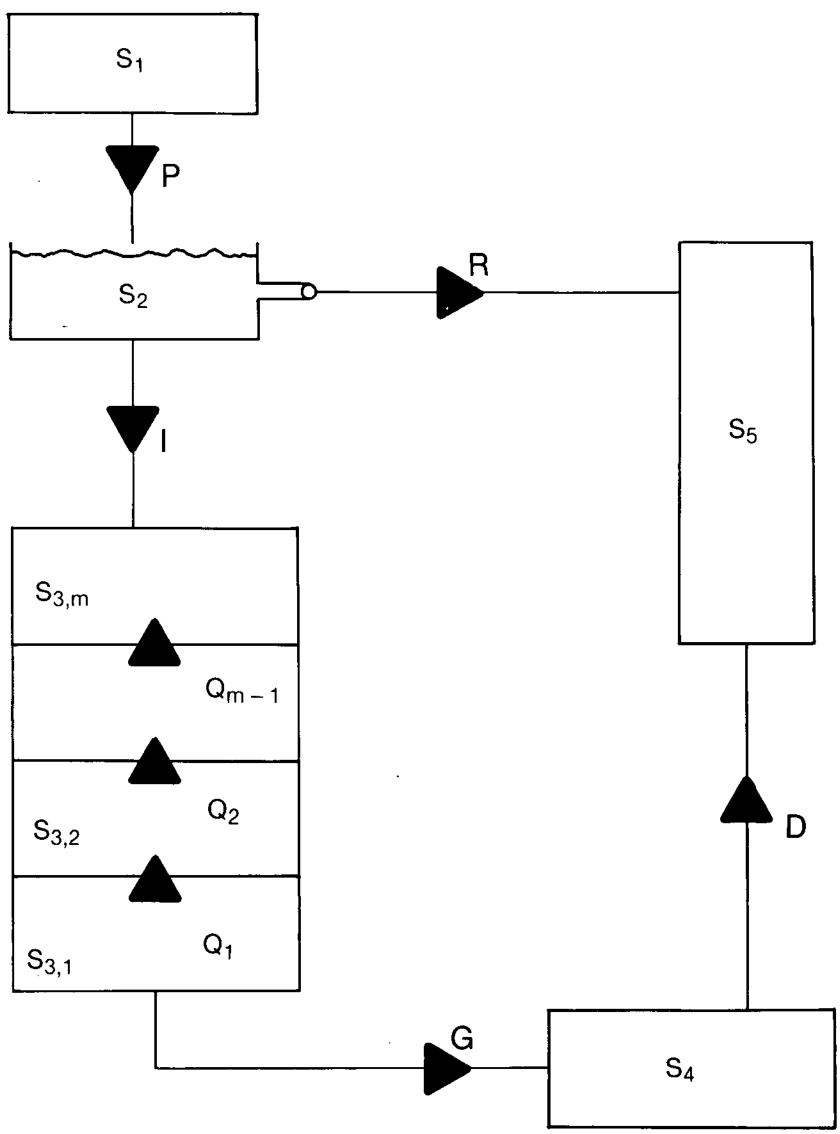

Figure 3. Drainage model with distributed soil moisture storage.

On the other hand, the relationship between K and ψ is unique and for not too dry soils can be approximated by an exponential expression:

$$K = K_0 \exp(\alpha\psi) \tag{2}$$

where K_0 = conductivity of the saturated soil (dimension L/T)
α = a constant (dimension L^{-1}).

From Equation 2 we have

$$d\psi/dK = 1/(\alpha K)$$

which, substituted in (1), gives

$$dK/dZ = -\alpha(q + K) \tag{3}$$

For the flow Q_i between two thin adjacent soil elements Z_i and Z_{i+1} (Fig. 4) Q may be taken as constant, and integration of Equation 3 then results in:

$$\ln[(Q_i + K_i)/(Q_i + K_{i+1})] = \alpha(Z_{i+1} - Z_i) \tag{4}$$

or

$$Q_i + K_i = (Q_i + K_{i+1})e^{\alpha\Delta Z} \tag{5}$$

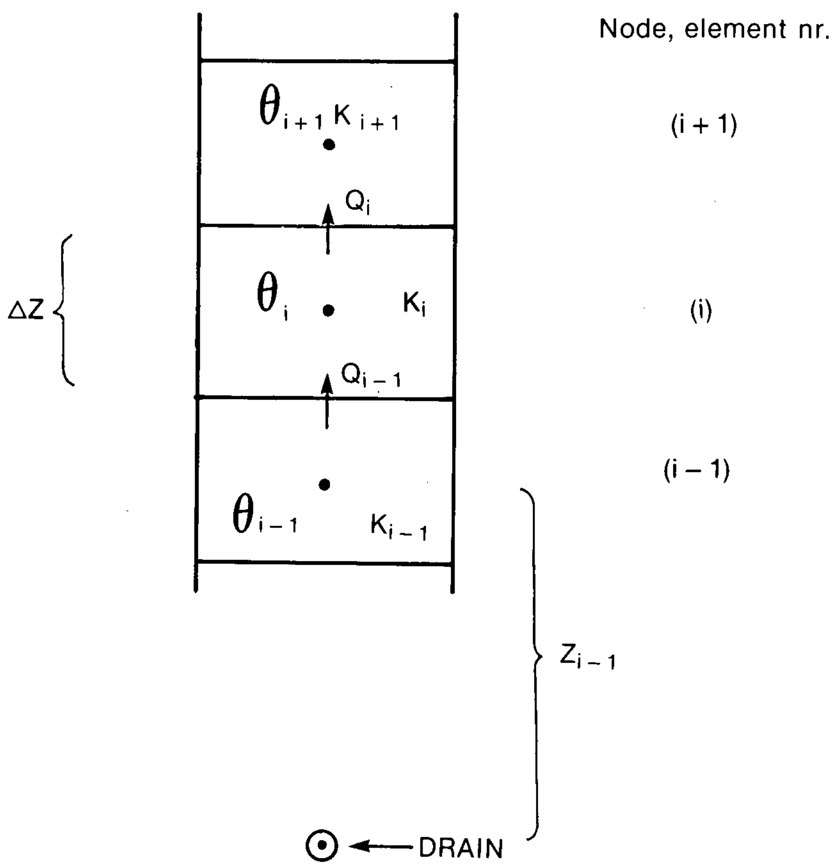

Figure 4. Internal moisture movement and symbol definitions.

where ΔZ = $Z_{i+1} - Z_i$, positive
K_i = conductivity of the ith element
Z_i = the elevation of the centrepoint of the lower (ith) element
Z_{i+1} = the elevation of the centrepoint of the higher element
Q_i = moisture flow from the ith element to the (i+1)th element.

Equation 5 can be written explicitly for Q_i:

$$Q_i = (K_i - aK_{i+1})/(a-1) \tag{6}$$

where $a = \exp(\alpha\Delta Z)$

Now, a flow of moisture Q_i out of the ith element results in a decrease $\Delta(\theta\Delta Z)$ in the total moisture $\theta\Delta Z$ of the ith:

$$\Delta(\theta\Delta Z) = Q_i\Delta t$$

where Δt = an increment of time between two bookkeeping entries. Since K_i, K_{i+1} and K_{i-1} are known functions $K[\psi(\theta)]$ of θ, the change in moisture content of an element during Δt can be calculated (Fig. 4) from:

$$\Delta(\theta_i\Delta Z) = \Delta t(Q_{i-1} - Q_i) \tag{7}$$

or, using (6)

$$\Delta\theta_i = (\Delta t/\Delta Z)[K_{i-1} - (a+1)\ K_i + aK_{i+1}]/(a - 1) \tag{8}$$

Equations 7 or 8 can be used to simulate the future state of all the internal elements with moisture content below saturation. But for the upper element of S_3, the flux through the upper surface, that is infiltration or evaporation, must be calculated by other means, since it is controlled by the state of the storage element S_2, the pooled water, as well as by the state of $S_{3,m}$, the uppermost soil layer. And in the case of the lowermost unsaturated element, the flow through its lower surface is determined by saturated flow conditions in the underlying element, and must therefore also be determined separately.

Infiltration, I

Instantaneous infiltration rate into a soil depends primarily on the moisture content of the uppermost soil element, but is limited by the amount of water stored on the surface S_2,

$$I\Delta t \leq S_2 \tag{9}$$

and by the storage capacity of the upper soil layer

$$I\Delta t \leq \Delta Z\ (\theta_{sat} - \theta_m') \tag{10}$$

where θ_{sat} = saturated moisture content of the soil

θ'_m = the moisture content of the mth or upper soil storage element $S_{3,m}$, taking into account that its water content at the end of the timestep may be taken, thus

$$\theta'_m = \theta_m + Q_{m-1} \Delta t/\Delta z. \tag{11}$$

Furthermore, it must be taken into consideration that if the level of S_2 is above the level of the outflow (Fig. 3), surface runoff R will be generated, competing with infiltration for the total available surface storage (ponding).

Within these limits the infiltration rate can be calculated on the assumption that as long as $S_2>0$ the surface of the soil is saturated and has conductivity K_0. Then, from Equation 6,

$$-I = (K_m - a'K_0)/(a' - 1) \tag{12}$$

where $a' = \exp(\alpha \Delta Z/2)$

since $(Z_2 - Z_1)$ is now $\Delta Z/2$, the distance between the surface and the centre of the uppermost element, and I designates downward flow in keeping with the direction of the arrow in Figure 3.

<u>Ground-Water Discharge, G</u>

For the simulation of ground-water discharge, G, we use the linear approximation first given by Hooghoudt (1937), and also described in Hillel (1980):

$$G = A\psi_D \tag{13}$$

where ψ_D = pressure head at the depth of the drains, midway between two parallel drains
A = drainage intensity = $8K_0d/L^2$ (dimension 1/T)
L = distance between drains
d = the equivalent depth of the aquifer below the drains.

From Equation 13 we can derive an expression for G in terms of Z_w, the height of the water table above the drains midway between the drains, instead of in terms of ψ_D (Van Wyk, 1980):

$$G = AZ_wK_0/(AZ_w + K_0) \tag{14}$$

and the equivalent equation for Z_w:

$$Z_w = GK_0/[A(K_0 - G)] \tag{15}$$

Equations 14 and 15 contain the two unknowns, G and Z_w. However, since the saturated zone does not allow for any storage changes, we must assume that the flow from the lowermost unsaturated element to the water table must also be equal to G (Fig. 5) and with the use of

Equation 4 can be expressed as:

$$G = -q_{ns} = -[K_0 - K_{ns+1} \exp(\alpha(n_s\Delta Z - Z_w))]/[\exp(\alpha(n_s\Delta Z - Z_w))-1] \quad (16)$$

where n_s = number of saturated elements.

Eliminating G between Equations 15 and 16 and rearranging finally gives the implicit equation:

$$Z_w - C_1 + C_2 \exp(\alpha Z_w) = 0 \quad (17)$$

where $C_1 = K_0 K_{ns+1}/[A(K_0 - K_{ns+1})]$

$C_2 = K_0^2 \exp(-\alpha n_s \Delta Z)/[A(K_0 - K_{ns+1})]$.

Equation 17 was first given by Wind and Van Doorne (1975); it can be solved iteratively for Z_w with Newton's method:

$$Z_w^{(n+1)} = Z_w^{(n)} - F(Z_w)/F'(Z_w)$$

where $Z_w^{(n)}$ and $Z_w^{(n+1)}$ are the nth and (n+1)th approximation of Z_w and

$$F(Z_w) = Z_w - C_1 + C_2 \exp(\alpha Z_w)$$

$$F'(Z_w) = 1 + \alpha C_2 \exp(\alpha Z_w).$$

Once Z_w has been determined, G follows from Equation 14.

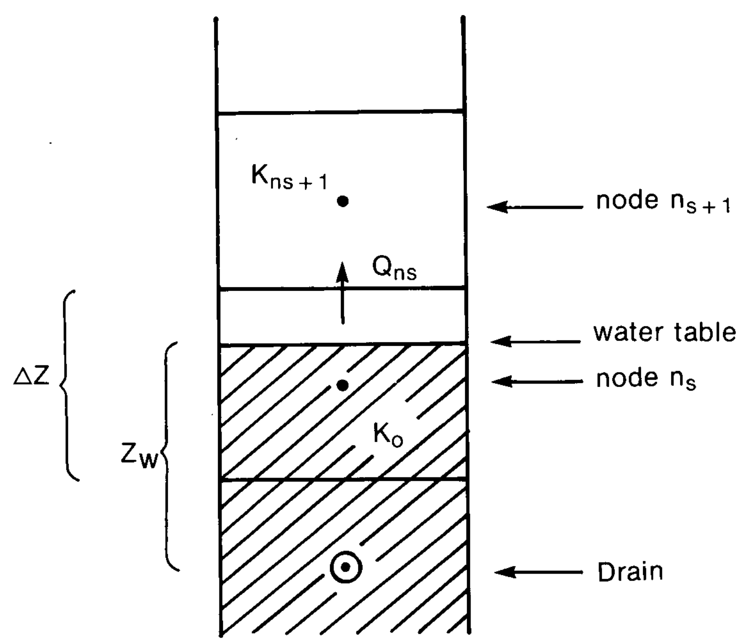

Figure 5. Moisture displacement at the water table.

OTHER TRANSFER FUNCTIONS

Precipitation, P

Comparison of Figures 2 and 3 indicates that the transfer function labelled P, the input to the surface reservoir, S_2, is in reality composed of a number of transfers: mainly those shown in Figure 2 as rain, melt, evaporation and freezing, the latter two being negative inputs to S_2. At present, the construction of the model does not distinguish between these inputs but presumes that their algebraic sum is known from other sources and presented at each timestep as input to the model. The construction of the model, however, permits the insertion of additional routines for these functions as they become available.

Whenever there is no precipitation, evaporation may take place from ponded water, or from the uppermost soil layer if S_2 is empty; P may thus be negative. In the model, transpiration, which takes place in the leaves of plants, is not considered, although it transfers moisture from the soil, sometimes at considerable depth, through the root system to the atmosphere. Soil moisture accounting models which do include transpiration exist (i.e. Feddes _et al_., 1978), but it is our opinion that the theory is not well enough established and the necessary data are generally not available for practical application in discharge modelling. Thus the model accounts only for evaporation from the ponded water S_2 at potential evaporation rate or, if no ponding is present, from the top layer at a reduced rate. At present we have simply put

$$E_{soil} = E_{pot}(\theta_m - \theta_o)/(\theta_{sat} - \theta_o)$$

where
- E_{soil} = actual evaporation from the upper soil layer (L/T)
- E_{pot} = potential evaporation, as specified in input to model (L/T)
- θ_m = moisture content of top layer
- θ_o = minimum soil moisture content on the $\psi - \theta$ curve
- θ_{sat} = moisture content at saturation.

Thus, actual evaporation will be equal to potential evaporation for a saturated top layer, to decrease linearly with decreasing soil moisture content, becoming zero when the soil is at minimum moisture content.

Drain Discharge, D

In the present version of the model the small storage changes in the drains are not taken into account, and D is assumed to be equal to G at all times. If future applications so warrant, the transfer function $D(S_4)$ can easily be inserted into the model.

Surface Runoff, R

Surface runoff will be generated whenever the depth of water on the surface, S_2, exceeds a certain value, designated by the constant P_{max} in the model. The constant P_{max} is usually in the order of a few millimetres.

The runoff velocity $R(S_2)$ is calculated by

$$R = A_b (S_2 - P_{max})^2 \quad (18)$$

where A_b is a constant; R, however, is restricted by the following inequalities:

$$(1): \quad R\Delta t < S_2 - P_{max}$$

and

$$(2): \quad (R + I)\Delta t < S_2$$

Condition (2) requires that I and R be determined in conjunction, that is, both I and R are first calculated separately, R being limited by condition (1). Then the sum $(R + I)\Delta t$ is calculated and compared with the available storage S_2; if condition (2) is not met, the available storage will be prorated over R and I, that is, both R and I are multiplied by the factor

$$S_2/[(R + I)\Delta t]$$

The threshold value P_{max} can have a strong effect on the peak flow. If the threshold value is low, as with good surface drainage, the soil cannot absorb and pass the incoming precipitation, and most of it will run off over the surface. Surface runoff is relatively fast and thus creates a large peak. If the threshold value is high, as with poor surface drainage and swamp conditions, the excess water cannot run off, and either evaporates or slowly runs off through the soil and drains.

If, however, not only the surface drainage but subsequently also the subsurface drainage is improved, the peak will become smaller again (Wind and Vandenberg, 1984). Such a course of events is depicted in Figure 6, showing a possible drainage history of a swamp on a sandy loam. In the natural state, drain intensity A and the coefficient of surface drainage, A_b, are extremely low, the threshold value is 6 cm, and the soil is initially completely saturated with 5 cm of water on the surface; existing natural drainage channels are shallow (0.5 m). At the start of the simulation precipitation sets in at 6 mm/day, lasting 15 days for a total of 9 cm; under these conditions the outflow from the swamp (trace 1) does not reach 1 mm/day.

If the surface runoff coefficient is increased and the threshold value is reduced to 5 mm, the outflow, practically all surface flow, increases to 6 mm/day (trace 2). Only a slight reduction in peak flow is achieved by increasing the drain intensity, leaving the drain depth at 0.5 m (trace 3). Increasing the depth of the drains to 1.5 m drastically reduces the peak outflow to 3 mm.

MOISTURE ACCOUNTING

Once the transfer rates between storage elements have been calculated, the new stored volumes can be calculated by adding the inflows and subtracting the outflows from the previous stored volumes for each element according to the schematic of Figure 3. Since for the soil elements the total volume stored equals the product of moisture content

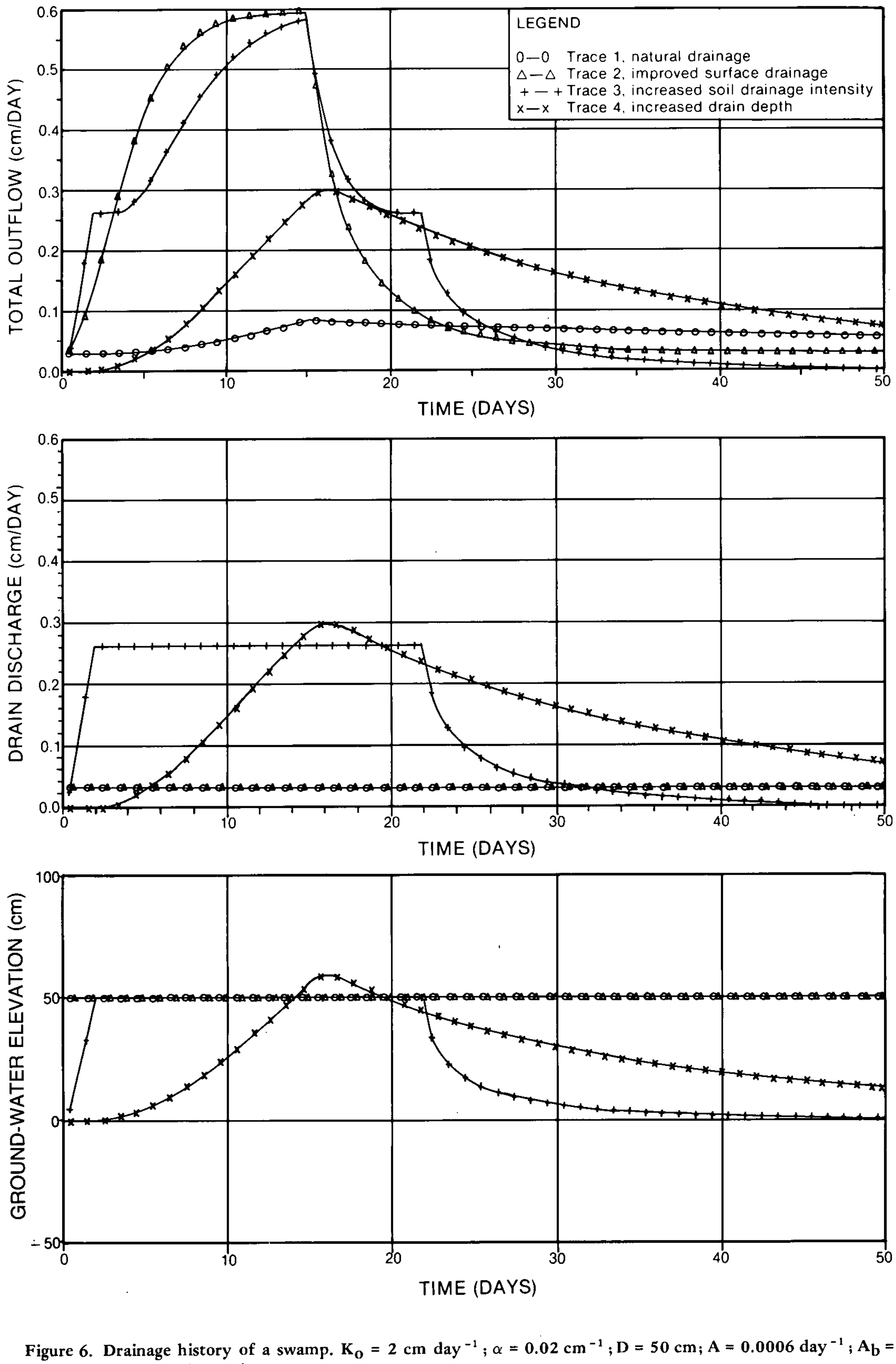

Figure 6. Drainage history of a swamp. K_o = 2 cm day^{-1}; α = 0.02 cm^{-1}; D = 50 cm; A = 0.0006 day^{-1}; A_b = 0.001 cm^{-1} day^{-1}; P_{max} = 6 cm; Pool = 5 cm.

and thickness, the new moisture content will be

$$\theta_i(t + \Delta t) = \theta_i(t) + (Q_{i-1} - Q_i)\Delta t/\Delta Z \quad (19)$$

$$\text{for } i = 2, m - 1$$

for all the internal elements. For the upper (mth) element

$$Q_m = -I$$

and for the lowermost unsaturated element

$Q_{i-1} = -G$, the ground-water discharge.

From Figure 3 we can read directly:

$$S_1(t + \Delta t) = S_1(t) - P\Delta t \quad (20)$$
$$S_2(t + \Delta t) = S_2(t) + (P - R - I)\Delta t \quad (21)$$
$$S_5(t + \Delta t) = S_5(t) + (R + G)\Delta t \quad (22)$$

Equation 22 occurs in this form, since we have assumed for the moment that

$$D = G$$

In the case of evaporation, i.e. negative P, the value of P in (20) is not necessarily the value of potential evaporation given, with negative sign, on input, but depends on the presence or absence of pooled water on the surface, and in the absence of surface water, on the moisture content of the upper soil element.

EFFECT OF DRAINAGE AND SOIL PARAMETERS ON DISCHARGE RATE

In this section simulations carried out with the model are discussed. Table 1 is an overview of the parameters that determine the outflow hydrograph of a given precipitation input, showing their Fortran names, the symbols used in this report, the categories indicating to which part of the hydrologic cycle they belong, and a brief description.

For most of the simulations a standard rainfall pattern was used: 15 days of precipitation at 0.6 cm/day, followed by a dry period of 35 days. Three different pF curves, roughly representative of a sand, a sandy loam and a clay loam were used. These pF curves are shown in Figure 7, and in tabular form, as they are input to the program, in Table 2.

Of the other variables, K_0 and α are soil-dependent, as are the $\Psi(\theta)$ curves, and therefore not primarily affected by drainage improvements, although they may be affected secondarily in the course of time. Truly drainage-dependent variables are A, the drain intensity, D, the depth of drains below surface, and A_b, which might be called the surface drain intensity. Other factors affecting the shape of the discharge time series are the potential evaporation and the initial moisture content.

The simulations will be presented in the following manner: four simulations are normally shown in each figure, showing the responses of one particular soil type to four different values of one of the parameters. Each figure shows the height of the water table, the drain discharge and the combined surface runoff and drain discharge; three successive figures show the effect of the variable parameter in the sand,

Table 1. Model Parameters

Fortran name	Symbol used in this report	Remarks on use	Category
TT(I), PP(I)	Ψ (θ)-Curve	Table values defining the Ψ (θ)-curve, standardized to represent 3 basic soil types (Fig. 7) TT = moisture PP = pressure	Soil, unsaturated
AKO	K_0	Saturated conductivity	Soil, unsaturated
ALF	α	Coefficient in: $K = K_0 \exp(\alpha\psi)$	Soil, unsaturated
DEPTH	D	Depth of drain below surface	Soil drainage
A	A	Drain intensity $g = A\Psi_0$	Soil drainage
AB	A_b	Surface drainage efficiency $R = A_b(P - P_{max})^2$	Surface drainage
PMAX	P_{max}	Pool height above which surface runoff occurs	Surface drainage
QD	G	As an input parameter, the equilibrium ground-water outflow determining antecedent moisture	Initial or antecedent moisture content
RATE (positive)	P	Precipitation rate	Atmospheric
RATE (negative)	E_{pot}	Potential evaporation	Atmospheric

the sandy loam and the clay loam, respectively. Initial moisture content for the bulk of these simulations is the equilibrium moisture distribution with no vertical movement and a ground-water table at the depth of the drain, or the equilibrium distribution at the very low constant downward flow of 0.1 cm/day. The program can accept initial moisture, or initial pressure, in tabular form, but this option was not used except in Figure 6, already discussed. Thus, in the examples, the initial moisture content is always raised or lowered by increasing or decreasing the initial value of the drain discharge.

<u>Effect of Drain Intensity A (Figs. 8, 9, 10)</u>

In this set of three figures, A was given the four values 0.001, 0.002, 0.005 and 0.01 day^{-1}; other parameter values are given in the captions.

In the sand, with its high storage capacity, no surface runoff occurs for any value of A; in the sandy loam, no surface runoff is generated with A = 0.01 day^{-1}, a very small amount for A = 0.005 day^{-1}, and slightly more than half the peak flow is surface runoff at

Table 2. Representative pF-Curves for Sand, Sandy Loam and Clay Loam

θ	Sand ψ (cm)	Sandy loam ψ (cm)	Clay loam ψ (cm)
0.28	-217	-295	-280
0.29	-127	-265	-272
0.30	-97	-237	-264
0.31	-78	-210	-255
0.32	-65	-186	-245
0.33	-55	-163	-234
0.34	-51	-138	-223
0.35	-47	-118	-211
0.36	-43	-102	-199
0.37	-39.5	-88	-186
0.38	-36	-77	-172
0.39	-33	-68	-157
0.40	-30	-60	-142
0.41	-27.3	-52	-123
0.42	-19.7	-43	-101
0.43	-13.2	-33	-77
0.44	-6.5	-19	-45
0.445	-3.1	-10	-26
0.45	0	0	0

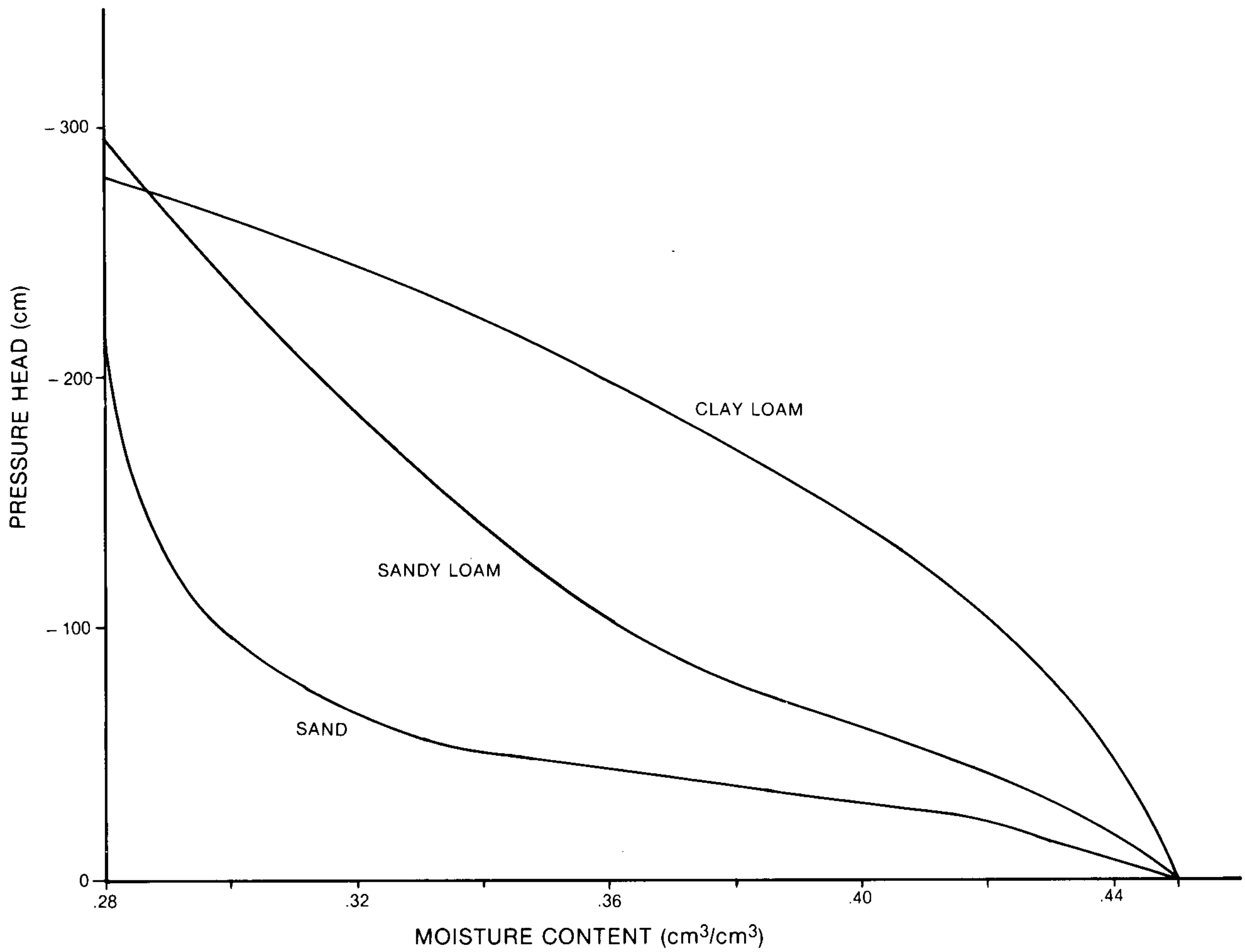

Figure 7. The pF-curves representative of a sand, a sandy loam and a clay loam, as used in the examples.

the lowest value of A. Because in this set of simulations the maximum pool depth was set rather high, surface runoff begins (points B) relatively long after the soil becomes saturated (points A), but sooner for the less intensively drained soil, since the maximum drain discharge is, according to Equation 14,

$$q = ADK_0/(AD + K_0)$$

since D is the maximum height of the water table above the drain. Furthermore, when the soil is completely saturated, the infiltration equals the drain discharge, since no more change in the soil moisture storage can take place.

Thus for this set of simulations

Infiltration at saturation = 200A/(2 + 100A) and

Maximum infiltration ($A = 0.005$ day^{-1}) = 0.4 cm/day

Maximum infiltration ($A = 0.001$ day^{-1}) = 0.095 cm/day

Thus for $A = 0.005$ day^{-1} it takes $0.4/(0.6 - 0.4) = 2$ days for the pool to fill to overflow and 0.8 days for $A = 0.001$ day^{-1}.

Also for $A = 0.005$ day^{-1}, the pool is depleted in 5 days, whereas for $A = 0.001$, the pool was just barely depleted at the end of the model run.

In the clay loam, only for the highest value of A no surface runoff is generated and the maximum discharge is limited by the rate of rainfall and equal to it, the soil not being entirely saturated. Surface runoff is by far the most important component at the lowest drain intensity, its importance decreasing with increasing drain intensity.

Comparing the three figures, the effect of the soil is very noticeable. The effect of decreasing storage capacity in the sequence from sand to clay loam is immediately apparent in the increasing steepness of the rising limb. In the sand the water from 15 days of rain is not sufficient to saturate the soil and cause surface ponding at either drainage intensity, and the maximum drain discharge is not attained. In the sandy loam the maximum drain discharge is reached after approximately 8 days ($A = 0.001$ day^{-1}) to 9.5 days ($A = 0.005$ day^{-1}) of rain, and in the clay loam already after 2 to 3 days. And obviously, the longer the time between points A and C (end of rain), the higher the pooled water will rise above P_{max}, and the higher the surface discharge peak and the longer the time between points C and D (pool empty).

In summary, for all three soil types the increased drain intensity results in an increased peak flow.

Effect of Drain Intensity A, Low K_0 (Figs. 11, 12, 13)

These three figures are the same as Figures 8, 9 and 10, but with the saturated conductivity for all simulations reduced by a factor of 10. The results show a drastic reduction in drain discharge in all 12 simulations. Surface discharge occurs in all 12 simulations; noticeable is how in the sand the surface runoff has already ceased when the drain discharge is still increasing. Moreover, this surface runoff occurs without the soil being completely saturated, since K_0 is substantially less than the precipitation rate. The reduced peak in the total discharge may be misleading, if we do not realize that when the drain discharge is low, the infiltration will in general be low, and the peak discharge is determined largely by the parameters of surface flow, A_b and P_{max}. In the simulations the A_b is generally assigned the rather low value of 0.01 cm^{-1} day^{-1}, causing surface to be spread over a long period with a low peak.

Effect of Drain Depth D (Figs. 14, 15, 16)

For all three soil types, drainage at 50 cm causes the soil to saturate completely and surface runoff occurs, although at a rate considerably less than 0.1 cm/day. Saturation is complete after 1 day in the clay loam and after 2 days in the sandy loam, whereas in the sand it takes 7 days before the water will collect on the surface. The maximum drain discharge is 0.4 cm for all soils, since drain discharge in a completely saturated soil depends only on A and D.

Deepening the drains to 100 cm below surface results in lower peak discharge for the sand, but peak discharge is increased in the sandy loam and the clay loam. Deepening of the drains to 200 cm results in reduced peak flow in all soils; in the sand and the sandy loam the peak is furthermore delayed to about 5 days after the end of the rain. Further deepening to 300 cm results in more pronounced lowering of the peak discharge, and longer delays of respectively 15, 25 and 35 days after the end of the storm for the sand, sandy loam and clay loam.

Effect of Saturated Conductivity, K_0 (Figs. 17, 18, 19)

At the lower conductivity, K_0 = 0.1 cm/day, no drain discharge is generated in the sand, and in the sandy loam drain discharge is only a fraction of a millimetre at the end of the simulation, although still rising. In the clay loam, however, the water table suddenly begins to rise 15 days after the beginning of the storm and becomes saturated in about 11 days.

Raising K_0 to 0.5 cm/day causes the clay loam to become saturated after 6 days of rain and the drain discharge to stabilize at 0.32 cm/day, and only a small surface runoff component remains. Increasing K_0 still further to 2 and 10 cm/day causes rapid drain discharge, incomplete saturation and disappearance of the surface runoff.

Effect of alpha (Figs. 20, 21, 22)

Apparently the effect of alpha has little effect on the timing and the size of the peak discharge. Small values of alpha indicate relatively little change in K with pressure and therefore with moisture content, whereas large values of alpha indicate a strong decline in K with decreasing moisture content. Thus high values of alpha tend to delay the percolation to the water table and therefore the onset of drain discharge, but by the same mechanism the moisture content and conductivity will rise rapidly, and the water table will rise suddenly. Once the soil becomes moist, however, the effect of alpha is very small, as shown in the falling limb, specifically in the sand. Higher alphas tend to limit the storage capacity of the soil, that is, the storage is there, but the moisture cannot get there and as a consequence reinforces the tendency of a soil to pass the input undistorted, but with a noticeable delay in the rising limb.

A High-Intensity Short-Duration Event (Figs. 23, 24, 25)

The effect of soil and drainage parameters on the discharge hydrograph has been described in the previous three figures. Figures 23 to 25 show how the response of the different soils is affected if the total amount of precipitation (9 cm) of the previous simulation is concentrated in two days at a rate of 4.5 cm/day. Four drain intensities are shown. Noticeable are the steep rising limbs, and the absence of surface runoff in the sand and the sandy loam, where only 50 cm and 100 cm, respectively, of the available 150 cm above the drain are saturated. Only 0.3 cm/day and 0.55 cm/day discharge is generated from the 4.5 cm/day input peak at the most intensive drainage. In the clay loam, surface discharge is generated at all drain intensities, and the influence of drainage and of the soil as a buffer in discharge generation is much less, the discharge hydrograph being to a large extent dependent on the surface drainage efficiency.

Three Heavy One-Day Storms, One Week Apart (Figs. 26, 27, 28)

Figures 26 to 28 show how the sandy soil, the sandy loam and the clay loam respond to a series of three separate rainstorms: 3 cm/day on day 1, day 7 and day 14, for a total of 9 cm; potential evaporation was 0.2 cm/day from day 2 to day 6 and from day 8 to day 13, and 0.1 cm/day from day 15 to the end of the simulation. The four traces correspond to the four values of A:0.001, 0.002, 0.005 and 0.01 day^{-1}. The sand responds almost as if the rain were continuous over the 15 days at 0.6 cm/day, with only small ripples in the hydrograph to show for the uneven distribution of rain in time. For the sandy loam the ripples have become waves, but the effectiveness of the drained soil in buffering the heavy storm events is obvious for both soils. This is not the case with the clay loam, where a high drainage intensity, 0.01 day^{-1}, is needed to keep the water table at 60 cm below the surface, but causing a very high discharge peak. The next lowest drain intensity, 0.005 day^{-1}, has a slightly smaller discharge peak, and soil becomes waterlogged for only approximately 1 day, which could still be acceptable agriculturally. The smallest peak is produced by the next lowest drain intensity, and waterlogging occurs for approximately one day after the second rainstorm, and for 3.5 days after the third. This is not ideal, but much better than at the lowest drainage intensity, where these periods of waterlogging are 3 and 7 days, respectively. It might well prove to be the optimum choice for fixed drain depth, if both waterlogging and discharge peaks are to be minimized.

CONCLUSIONS

A total of 88 simulations were carried out, which are shown in Figure 6 and Figures 8 to 28 and discussed in the text. If we consider the number of parameters needed to describe even what must be considered a basic and crude model of discharge generation, the number of simulations needed to give a complete coverage of the field of possible combinations of parameters is enormous. There are the five scalar parameters, K_0, α, A, A_b, P_{max}, the two composite "parameters" initial moisture and Ψ (θ) curve, and the pattern - peak and duration - of the precipitation input. If, for each of these eight variables on which the output depends, only a minimum, average and maximum value were to be represented in combination with each of three values of the other parameters, a total of 3^8, or 6561 simulations, would be needed, and this would represent the sparsest possible coverage of the domain of possible cases.

It seems then that estimating the discharge response of a specific precipitation event, for a specific soil and a specific drainage configuration from "known" responses such as presented in these pages, will forever remain unreliable, and modelling based on parameters established for the area will be the only means by which predictions will be at all possible.

Nevertheless, a few general statements can be made on the effect of the different parameters. These general remarks have been made elsewhere (Wind and Vandenberg, 1984) and are repeated here for completeness only:

1. The three factors determining storage capacity of the soil, which are, in order of significance, drain depth, pF-curve, and the coefficient α, influence the shape and peak value of the discharge considerably: the lower the storage capacity, the higher the peak flow and the closer the output shape resembles the input.

2. Of less importance seem to be those factors determining velocity of flow: hydraulic conductivity and drain intensity. The lower these are, the higher the peak discharges, provided no surface discharge is generated.

3. In the course of the drainage improvement history of originally swampy or waterlogged areas, initial drainage improvements are likely to be mostly improvements in surface drainage, causing relatively large increases in peak flows. Subsequent drainage improvement will then be directed more to improving soil drainage and aeration, increasing the available storage and diminishing peak flows.

The present model has been termed basic and crude, and it is perhaps useful here to specify in more detail what is meant by these derogatory descriptors. At least three major areas can be distinguished in which the model may differ significantly from actual discharge generated in the real world:

1. The soil is assumed to be homogeneous to at least the depth of the drains. However, the presence of even one thin layer of relatively low conductivity drastically alters the internal flow and moisture conditions. Extension to a multilayered model is a realistic possibility, but drastically increases the amount of physical data needed, a very costly and time consuming requirement.

2. The one-dimensional structure of the model is used to represent what is really a two- or even three-dimensional problem; thus results can only be interpreted as average values over a large area. Even in the present computer age, however, two- and three-dimensional models are too costly for routine analysis, and have the same drawback of needing a large and costly data base to fully justify their use.

3. The model represents only <u>one level of drainage</u>, with only one characteristic value of drain depth and drain intensity. In nature this is seldom the case. For example in the Mannis and Domain Drain areas of the Red River Valley, Manitoba, where the National Hydrology Research Institute is presently developing a research program, three levels of drainage can be distinguished: (1) the very shallow, on-farm drainage system, with the higher drain intensity and the lesser drain depth; (2) the municipal system of roadside ditches, which is fairly deep but of much smaller intensity than the on-farm system; and (3) the systems composed by the main drains and their drainage basins. When the soil is saturated to some level above the on-farm drains, all three drainage systems will be operating and contributing to drain discharge in the main drain. As soon as the water table midway between the on-farm drains drops below the level of the on-farm drains, only the municipal and main drains will contribute to discharge, and so on. Such a multilevel drainage system could possibly be modelled with only slight modifications.

ACKNOWLEDGMENTS

To acquire knowledge of soil physics for the NHRI program on the "Effect of Drainage on Streamflow," D.H. Lennox, Director of NHRI, and J.A. Gilliland, Head of the Ground Water Division, asked the author to obtain additional schooling in soil physics and moisture movement in the unsaturated zone. Thus it was their initiative which resulted in my six-month secondment at ICW, the Institute for Land and Water Management Research, Wageningen, The Netherlands. For their encouragement, and for the cordial way in which my request for this secondment was met by Ir. G.A. Oosterbaan, Director of ICW, my sincere thanks.

Most of my education as a soil physicist fell to Dr. G.P. Wind, without whose continuous interest and active help I would still be floundering in the dark. In fact, the theoretical background and much of the computer code for this report is based on his work, following closely the concepts of hydraulic-analog, numerical and electrical analog modelling of unsaturated flow of moisture described in Wind (1972), Wind and Van Doorne (1975), and Wind and Mazee (1979). I therefore dedicate this report to you, Geek.

It was a pleasure to share the room at ICW with you, Jan Beuving, and to learn from you with what painstaking care soil samples must be taken in the field, transported to and analyzed in the laboratory.

I must refrain from mentioning by name all with whom I had contacts at ICW; may I say to all of you that you made me feel welcome and contributed to make my stay at Wageningen both pleasurable and rewarding.

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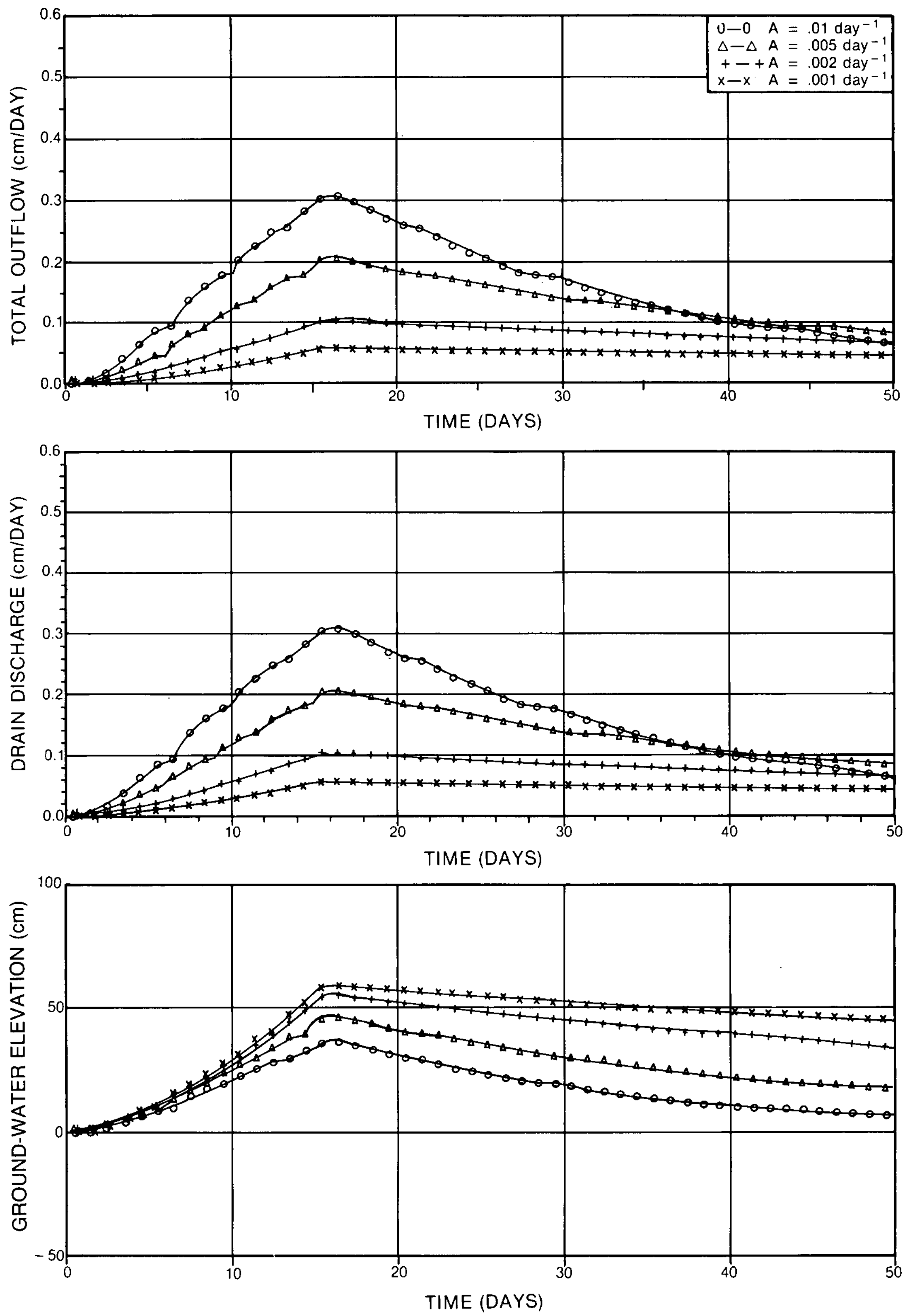

Figure 8. Effect of drain intensity A: sand. K_o = 2 cm day^{-1}; α = 0.02 cm^{-1}; D = 100 cm; A_b = 0.01 cm^{-1} day^{-1}; P_{max} = 0.4 cm.

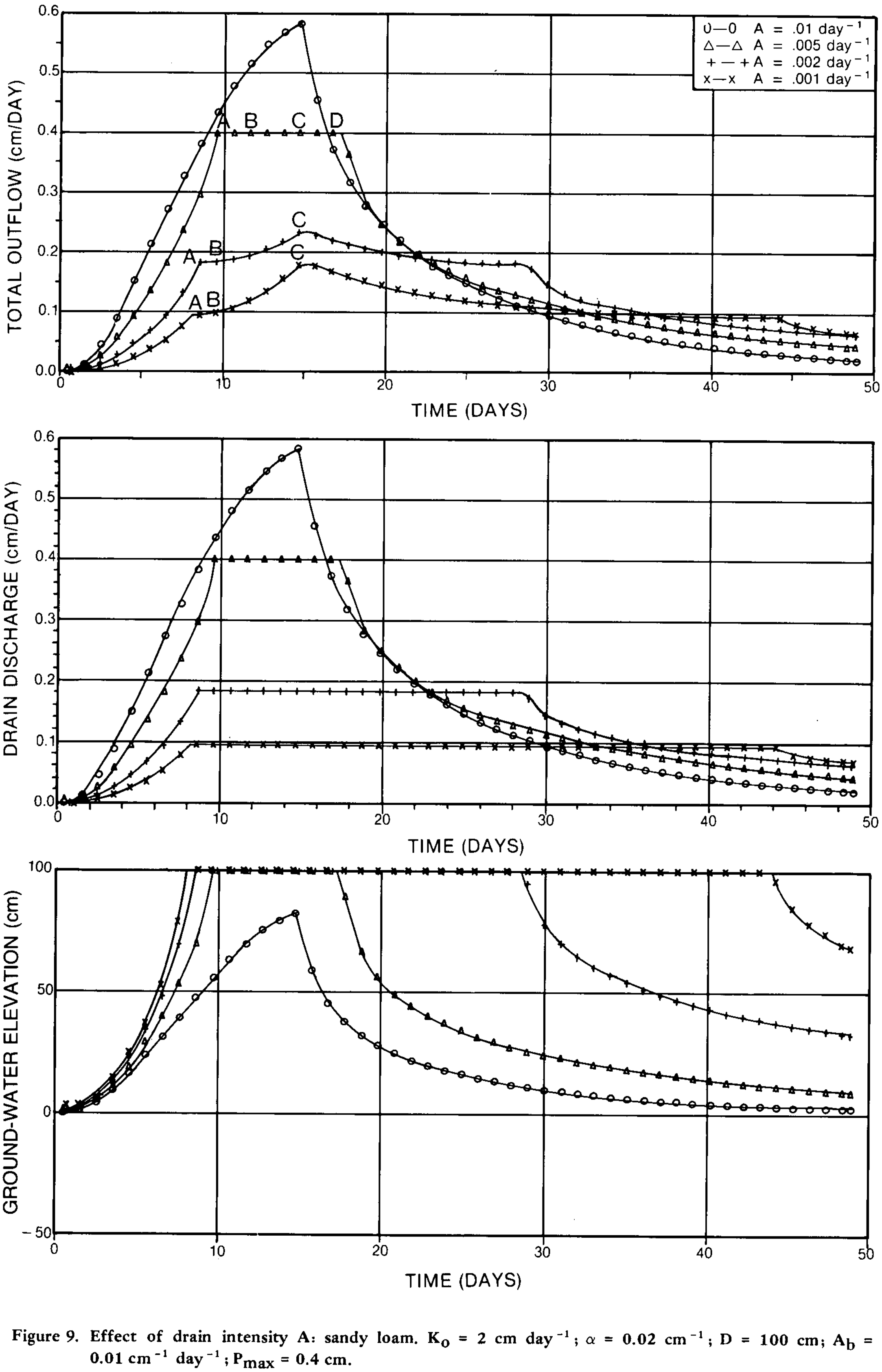

Figure 9. Effect of drain intensity A: sandy loam. K_0 = 2 cm day^{-1}; α = 0.02 cm^{-1}; D = 100 cm; A_b = 0.01 cm^{-1} day^{-1}; P_{max} = 0.4 cm.

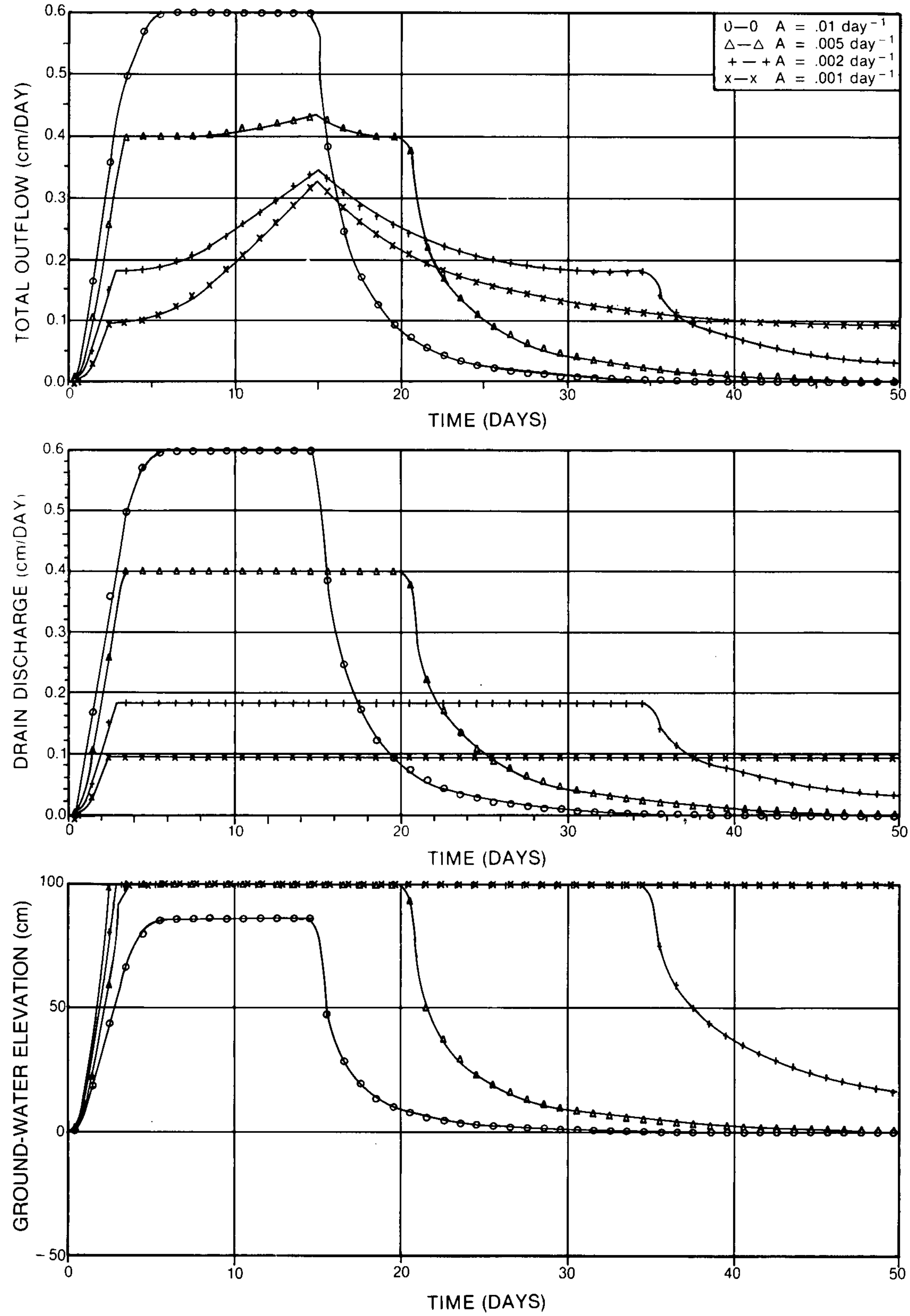

Figure 10. Effect of drain intensity A: clay loam. K_o = 2 cm day^{-1}; α = 0.02 cm^{-1}; D = 100 cm; A_b = 0.01 cm^{-1} day^{-1}; P_{max} = 0.4 cm.

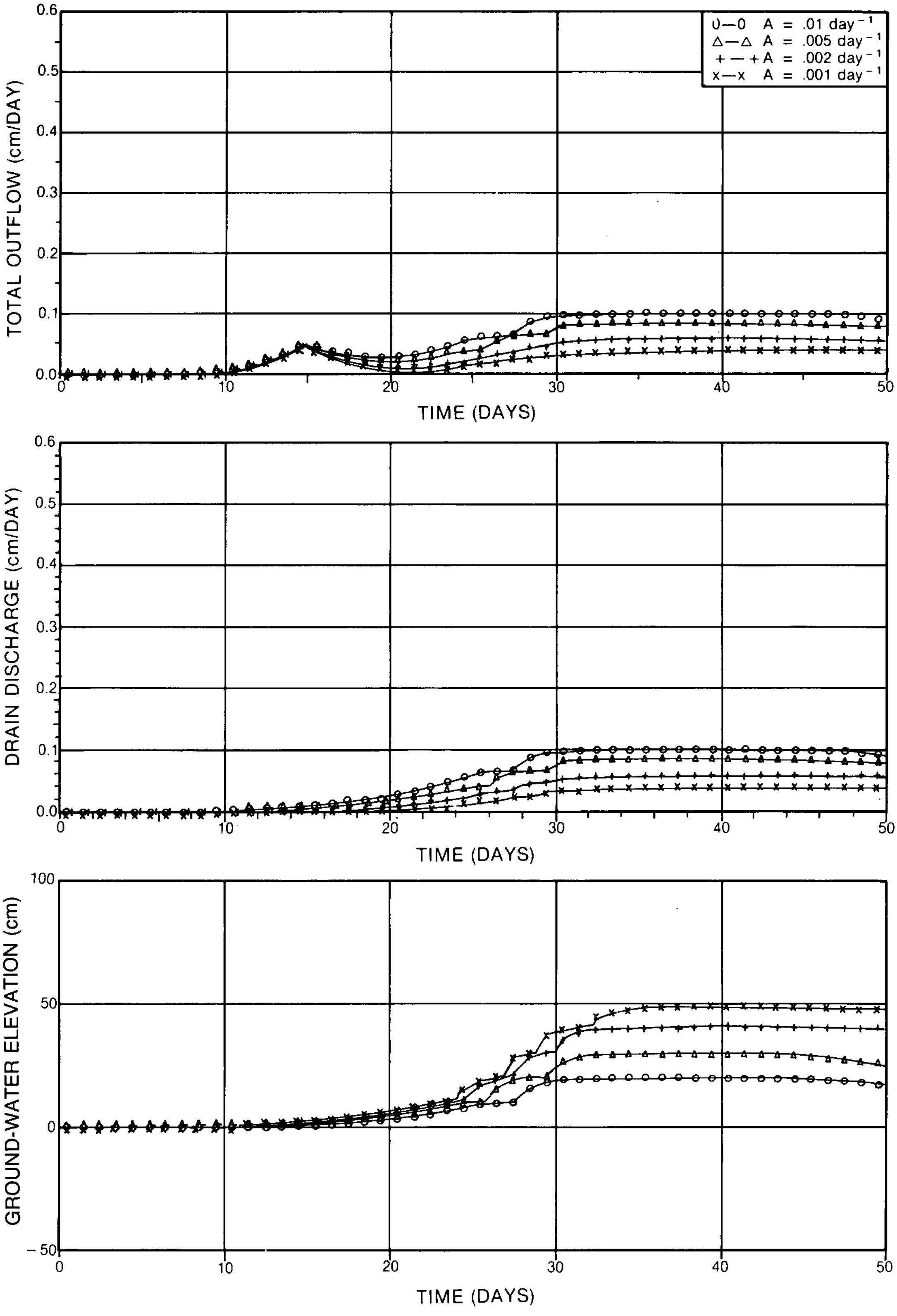

Figure 11. Effect of drain intensity A: sand, low K_o. K_o = 0.2 cm day^{-1}; α = 0.02 cm^{-1}; D = 100 cm; A_b = 0.01 cm^{-1} day^{-1}; P_{max} = 0.4 cm.

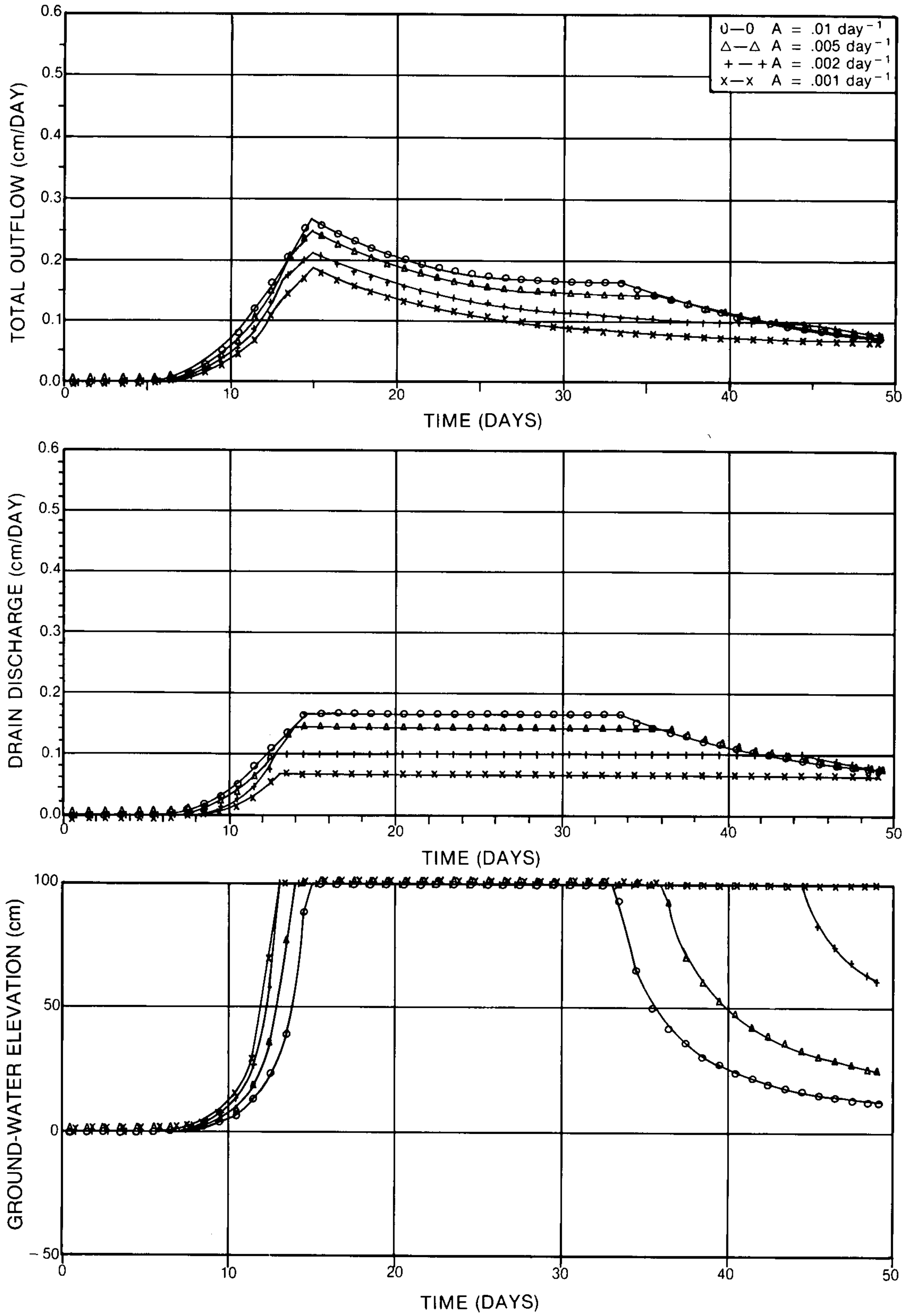

Figure 12. Effect of drain intensity A: sandy loam, low K_0. K_0 = 0.2 cm day^{-1}; α = 0.02 cm^{-1}; D = 100 cm; A_b = 0.01 cm^{-1} day^{-1}; P_{max} = 0.4 cm.

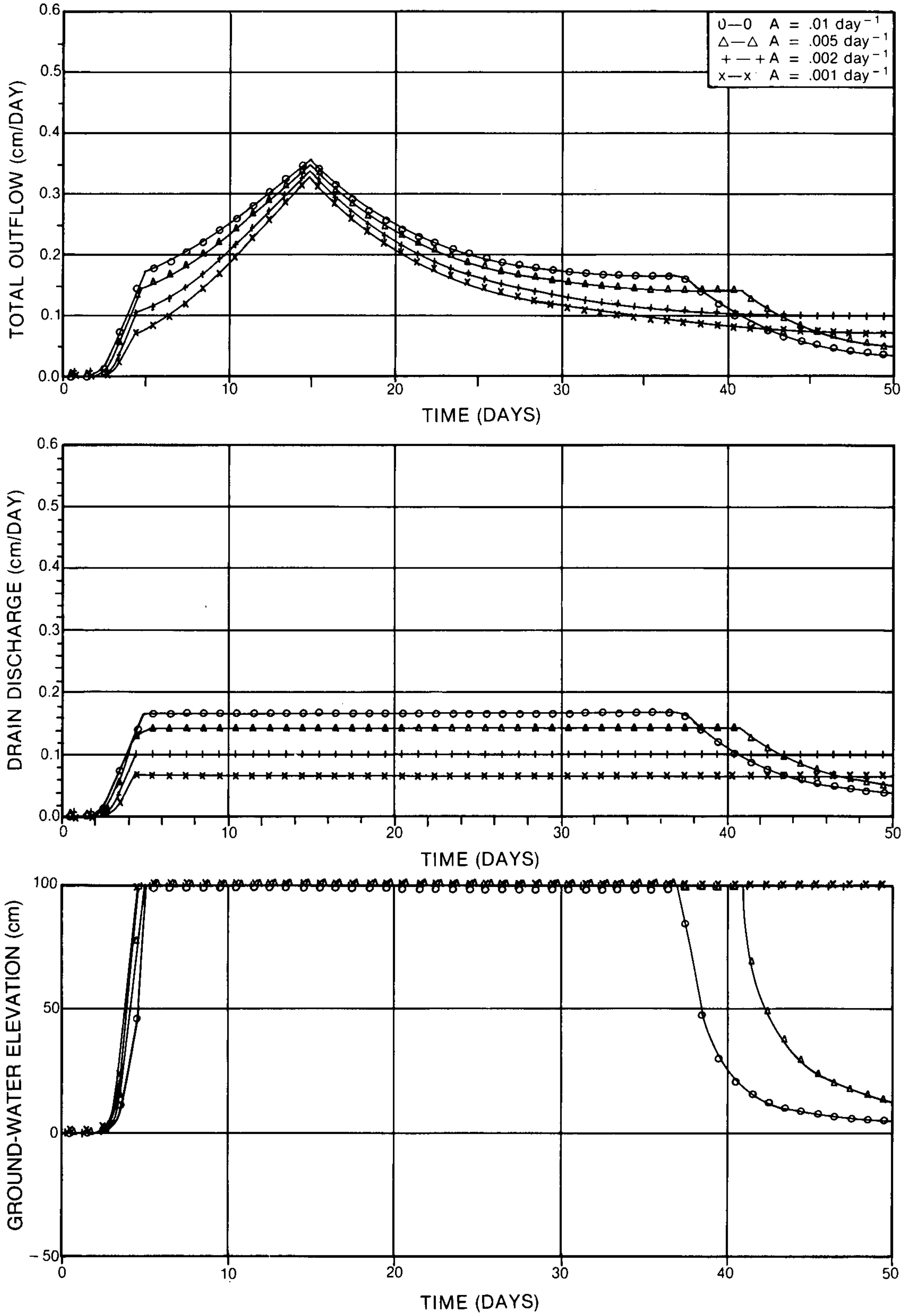

Figure 13. Effect of drain intensity A: clay loam, low K_o. K_o = 0.2 cm day^{-1} ; α = 0.02 cm^{-1} ; D = 100 cm; A_b = 0.01 cm^{-1} day^{-1} ; P_{max} = 0.4 cm.

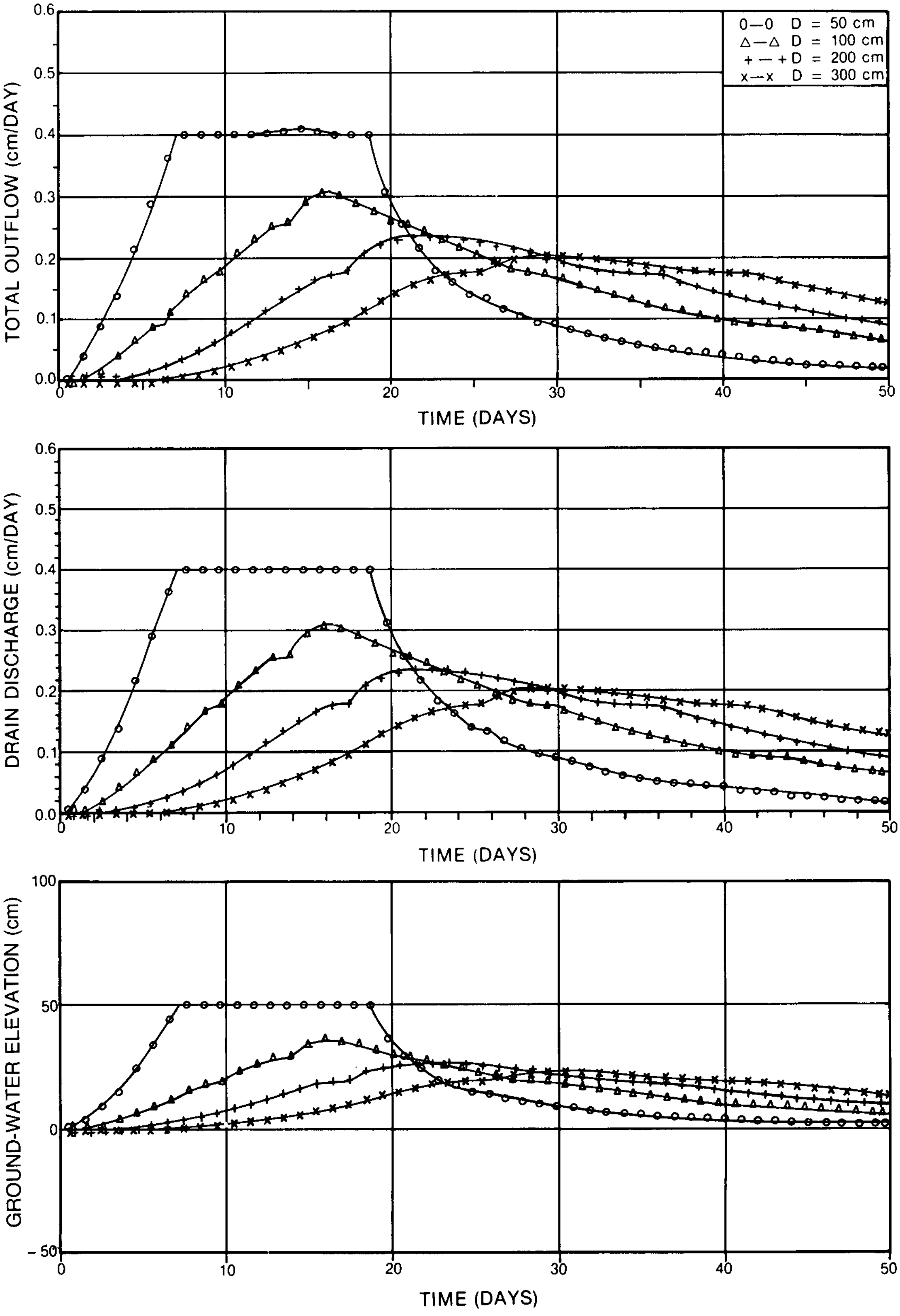

Figure 14. Effect of drain depth D: sand. K_0 = 2 cm day^{-1}; α = 0.02 cm^{-1}; A = 0.01 day^{-1}; A_b = 0.01 cm^{-1} day^{-1}; P_{max} = 0.4 cm.

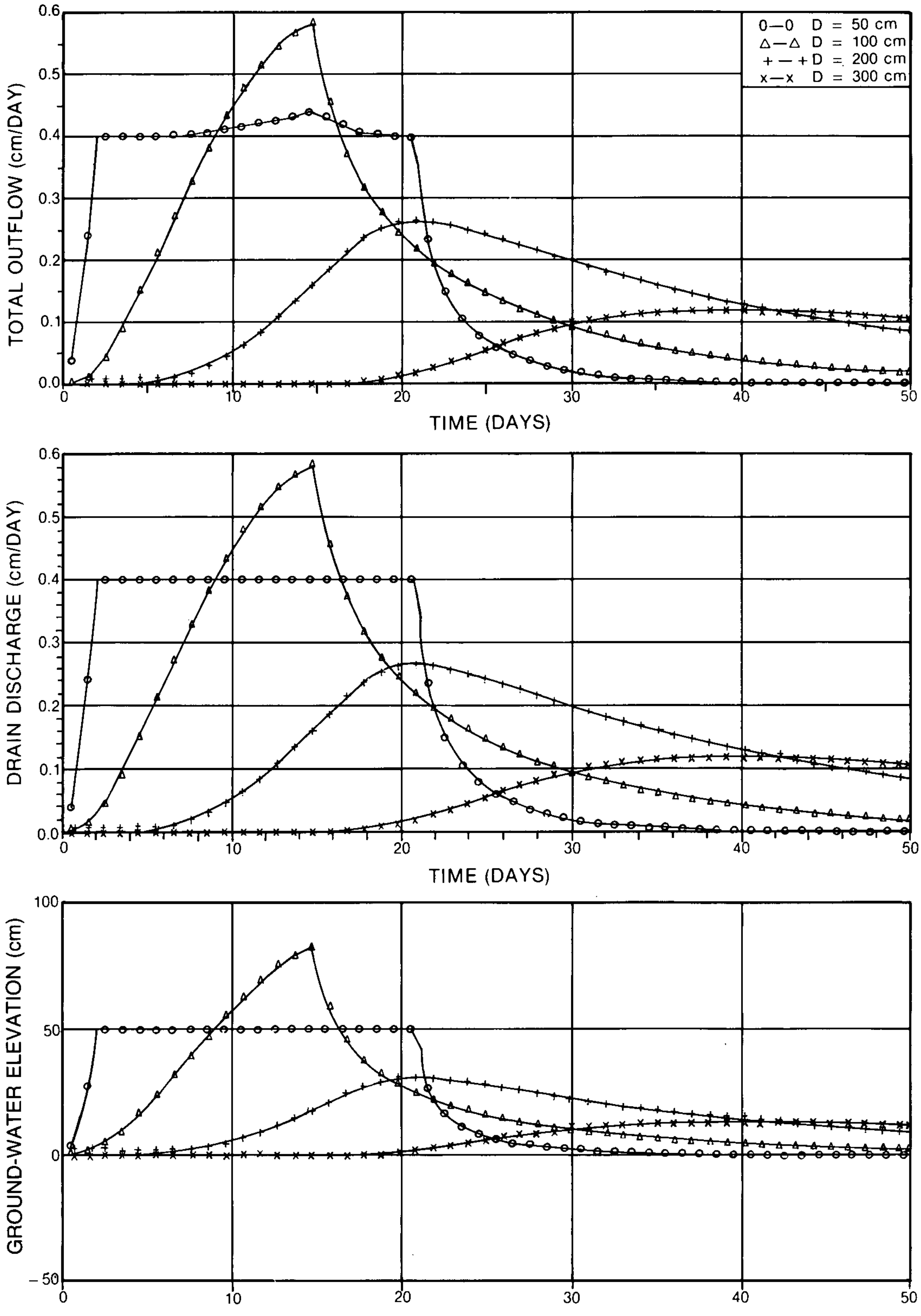

Figure 15. Effect of drain depth D: sandy loam. K_0 = 2 cm day^{-1}; α = 0.02 cm^{-1}; A = 0.01 day^{-1}; A_b = 0.01 cm^{-1} day^{-1}; P_{max} = 0.4 cm.

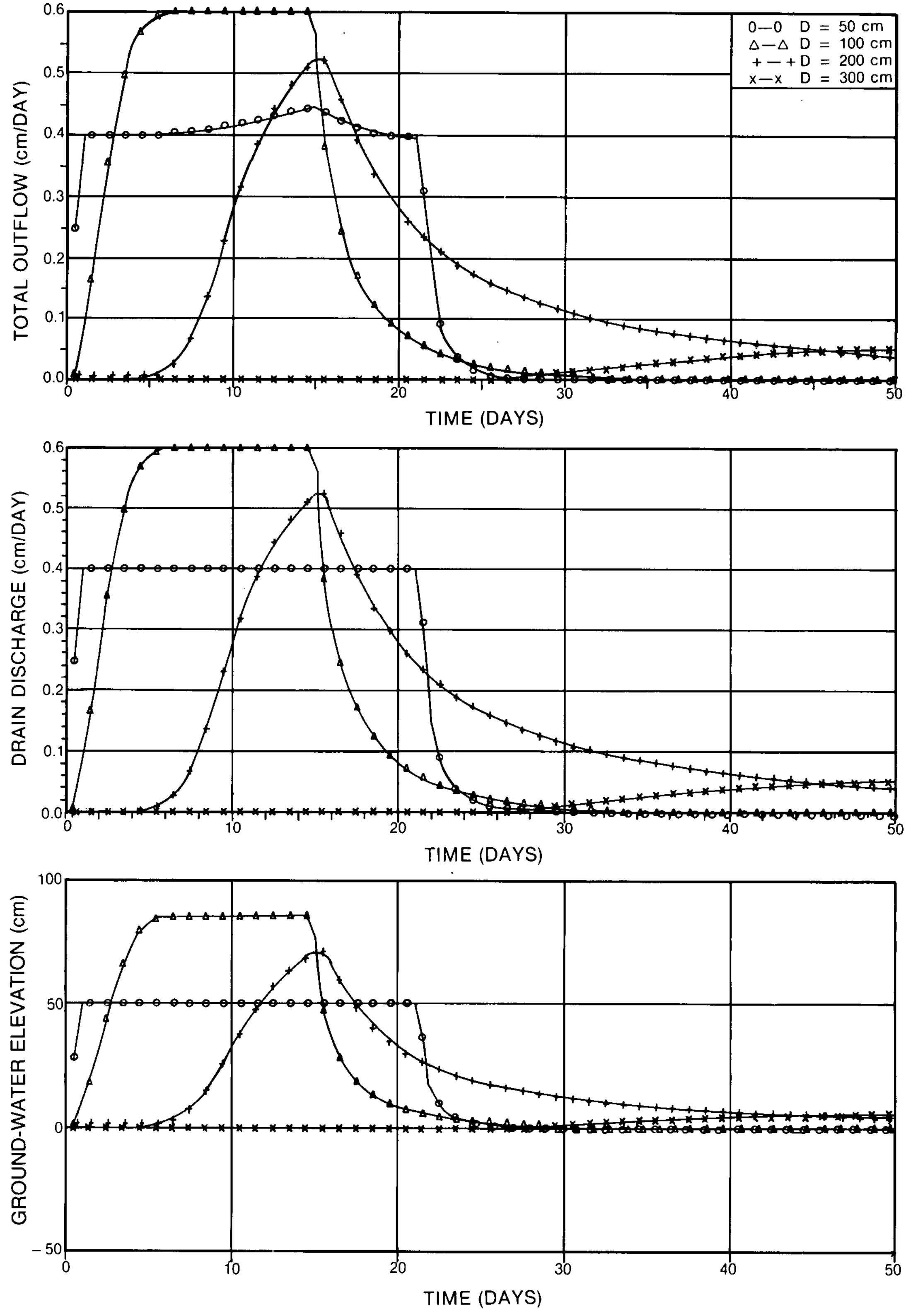

Figure 16. Effect of drain depth D: clay loam. $K_0 = 2$ cm day^{-1}; $\alpha = 0.02$ cm^{-1}; $A = 0.01$ day^{-1}; $A_b = 0.01$ cm^{-1} day^{-1}; $P_{max} = 0.4$ cm.

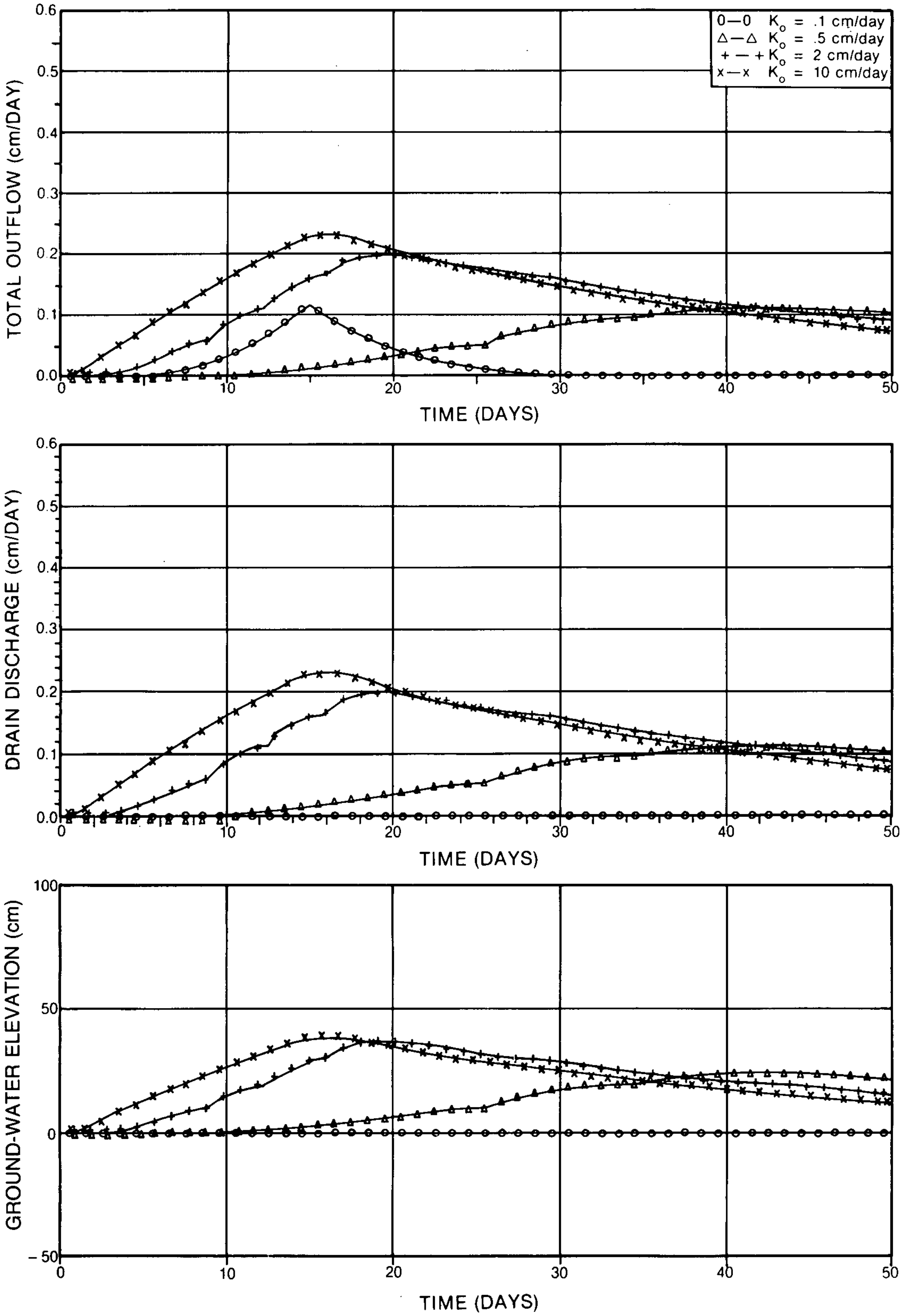

Figure 17. Effect of saturated conductivity K_0: sand. α = 0.02 cm^{-1}; D = 150 cm; A = 0.006 day^{-1}; A_b = 0.01 cm^{-1} day^{-1}; P_{max} = 0.4 cm.

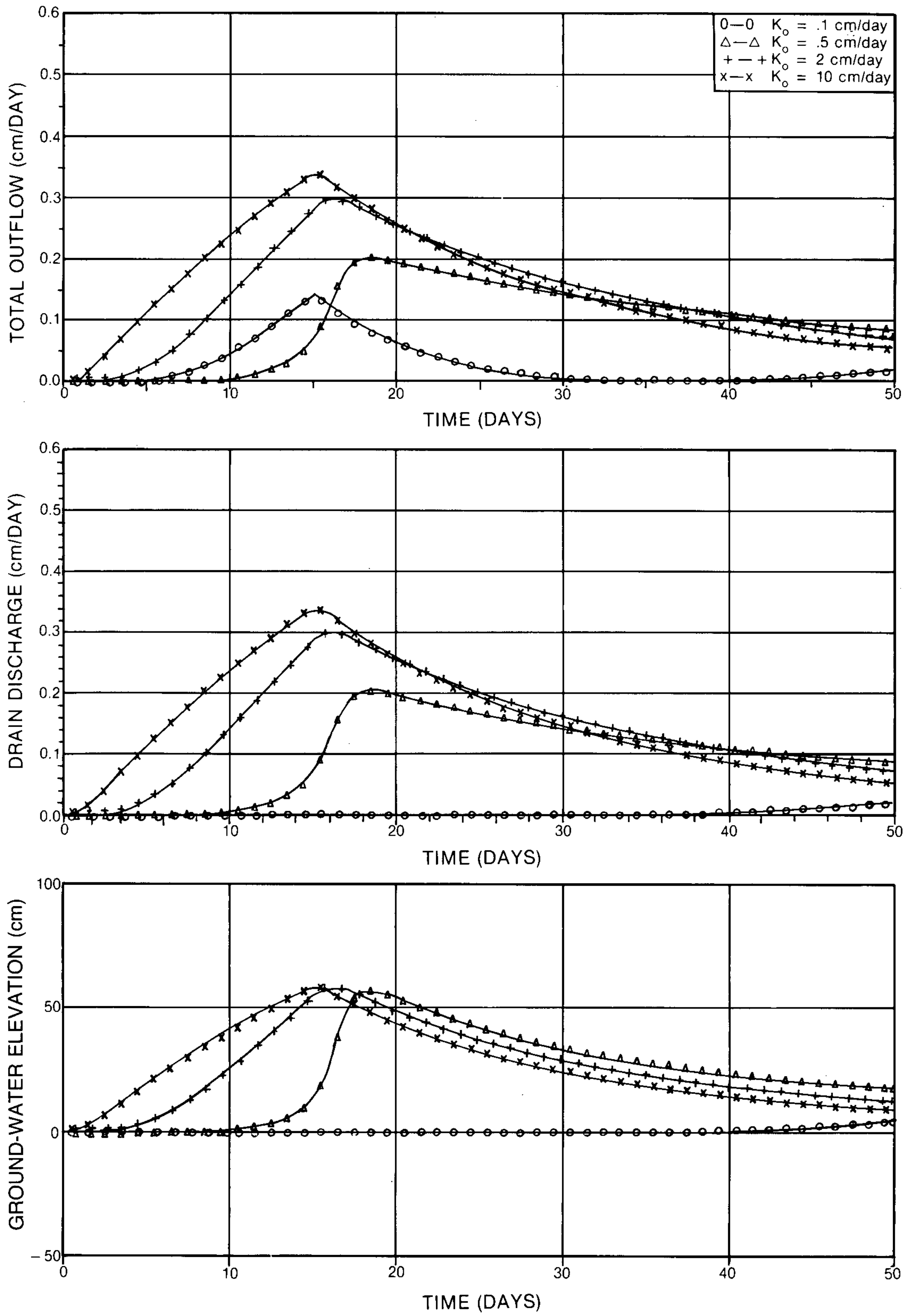

Figure 18. Effect of saturated conductivity K_o: sandy loam. $\alpha = 0.02\ cm^{-1}$; D = 150 cm; A = 0.006 day^{-1}; $A_b = 0.01\ cm^{-1}\ day^{-1}$; $P_{max} = 0.4$ cm.

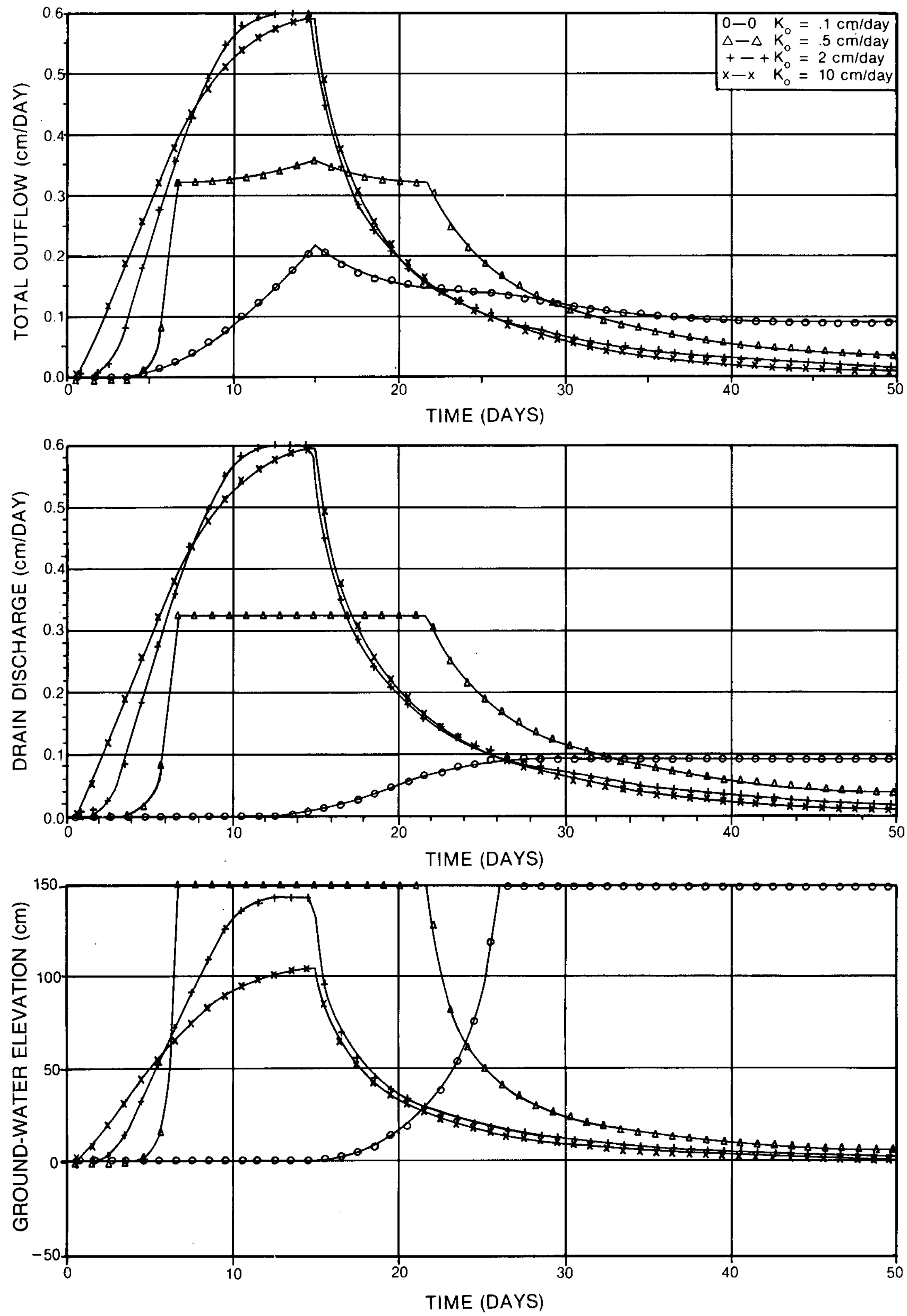

Figure 19. Effect of saturated conductivity K_0: clay loam. $\alpha = 0.02\ cm^{-1}$; D = 150 cm; $A = 0.006\ day^{-1}$; $A_b = 0.01\ cm^{-1}\ day^{-1}$; $P_{max} = 0.4$ cm.

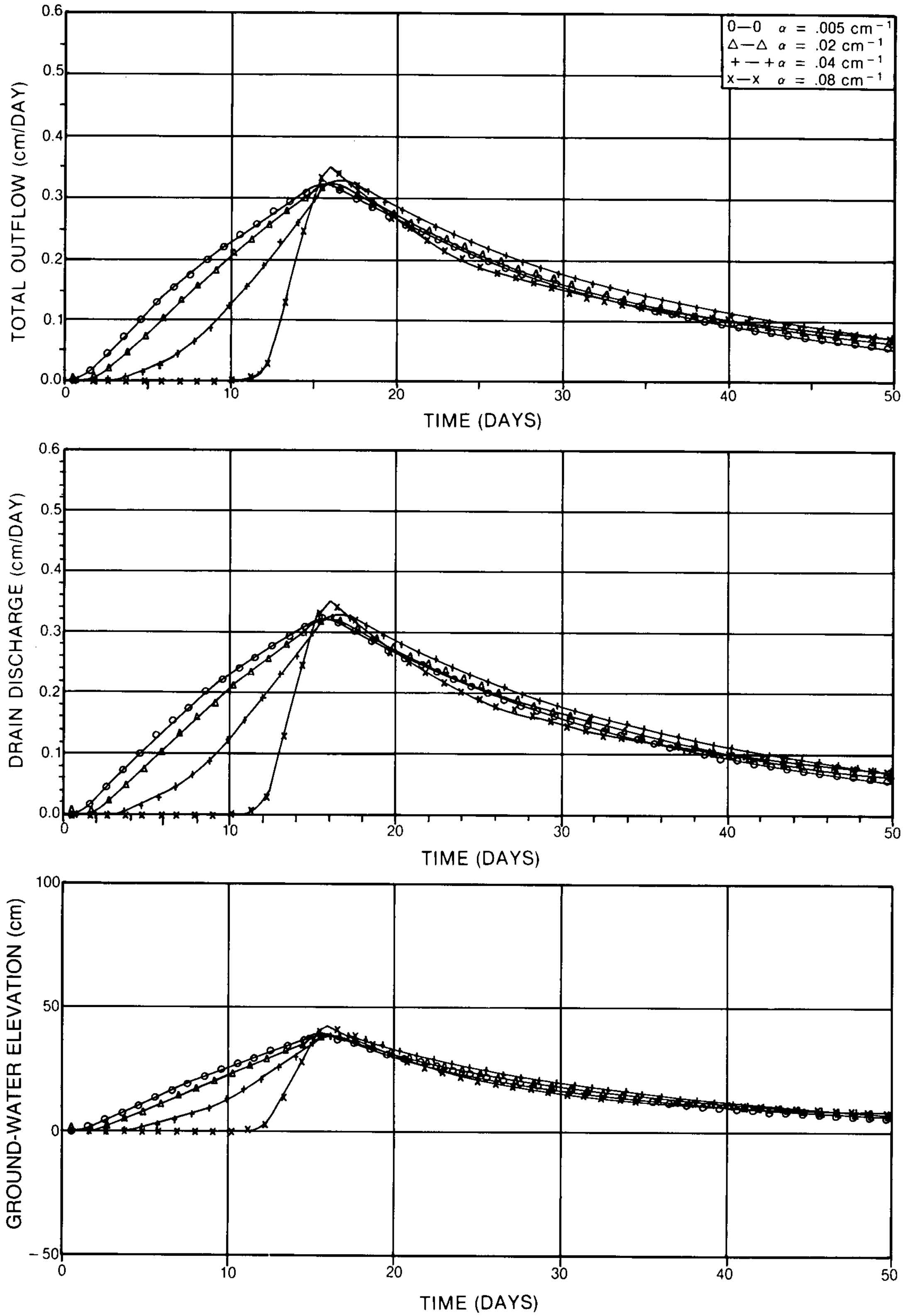

Figure 20. Effect of alpha: sand. K_0 = 2 cm day^{-1}; D = 100 cm; A = 0.01 day^{-1}; A_b = 0.01 cm^{-1} day^{-1}; P_{max} = 0.4 cm.

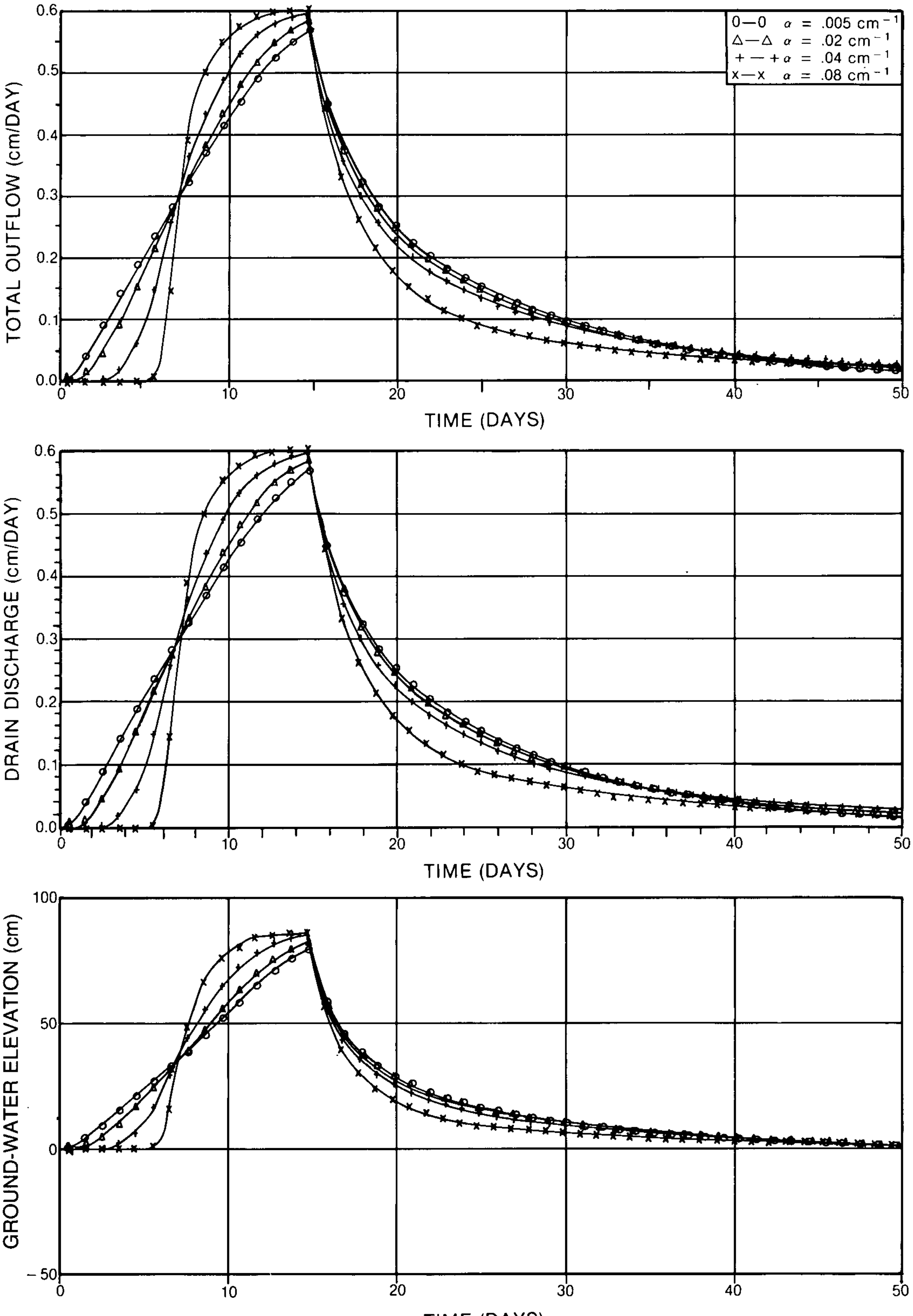

Figure 21. Effect of alpha: sandy loam. K_0 = 2 cm day^{-1}; D = 100 cm; A = 0.01 day^{-1}; A_b = 0.01 cm^{-1} day^{-1}; P_{max} = 0.4 cm.

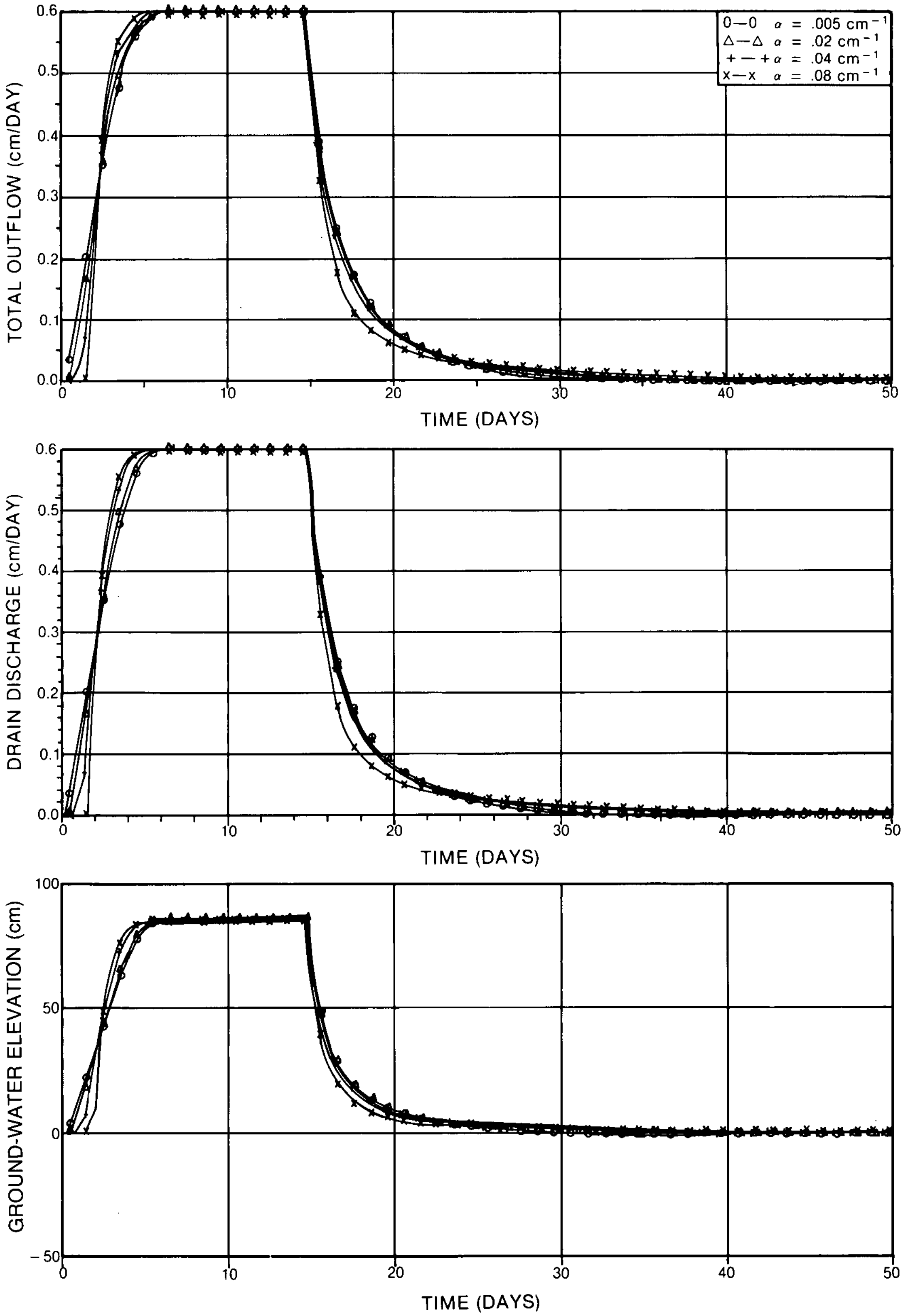

Figure 22. Effect of alpha: clay loam. K_o = 2 cm day^{-1}; D = 100 cm; A = 0.01 day^{-1}; A_b = 0.01 cm^{-1} day^{-1}; P_{max} = 0.4 cm.

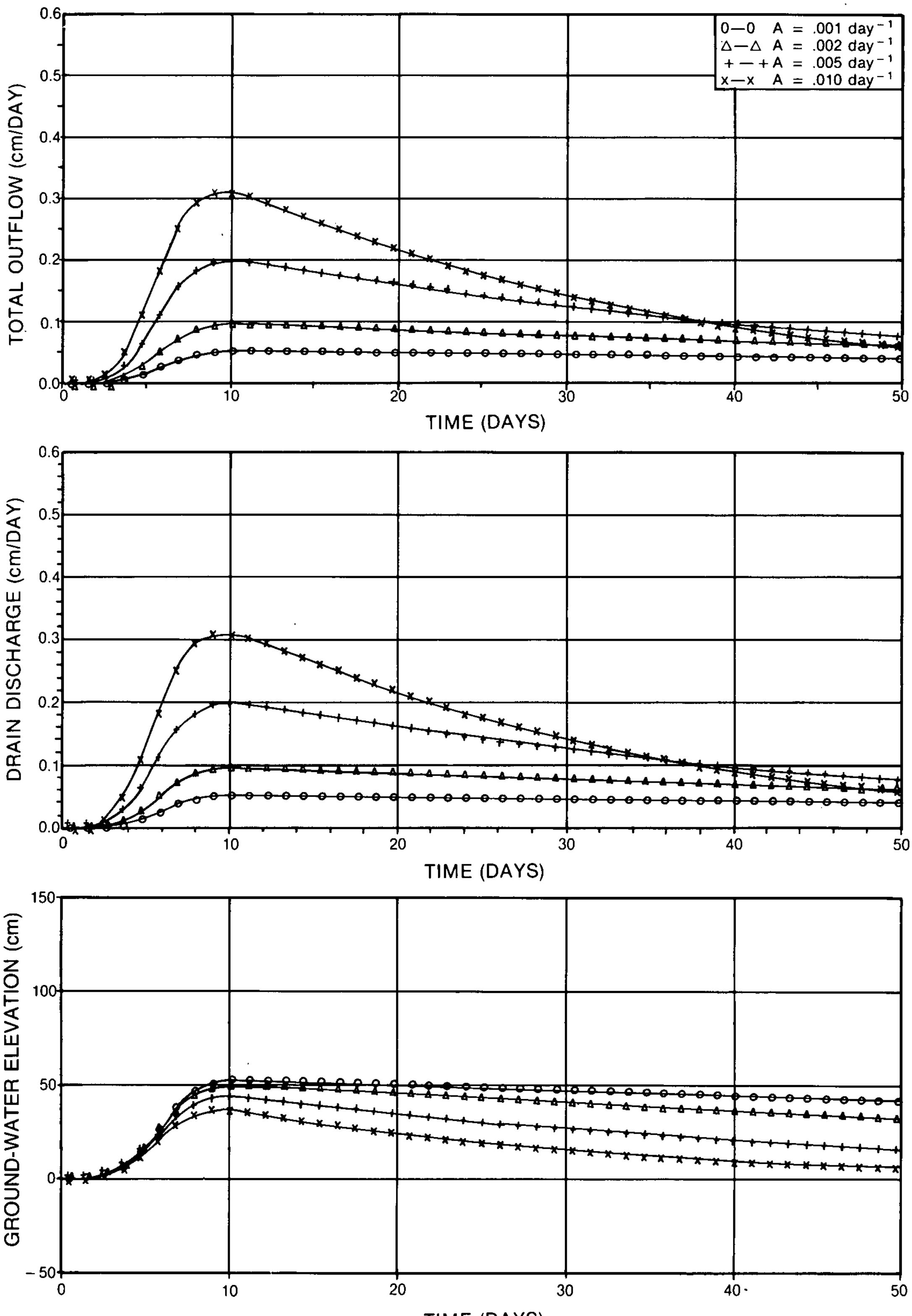

Figure 23. A high-intensity short-duration event: sand. K_o = 2 cm day^{-1}; α = 0.02 cm^{-1}; D = 150 cm; A_b = 0.01 cm^{-1} day^{-1}; P_{max} = 0.4 cm.

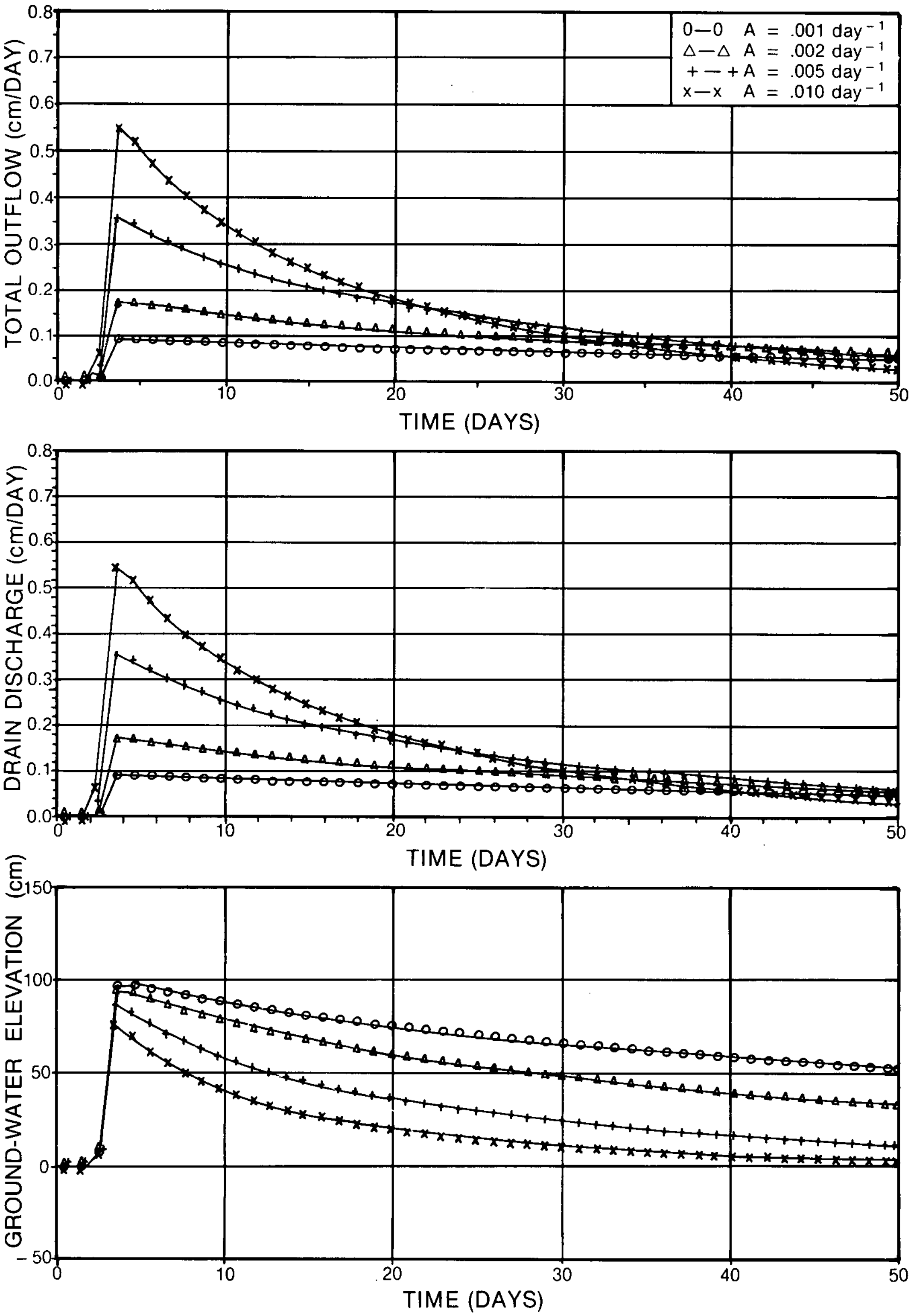

Figure 24. A high-intensity short-duration event: sandy loam. K_0 = 2 cm day^{-1} ; α = 0.02 cm^{-1}; D = 150 cm; A_b = 0.01 cm^{-1} day^{-1}; P_{max} = 0.4 cm.

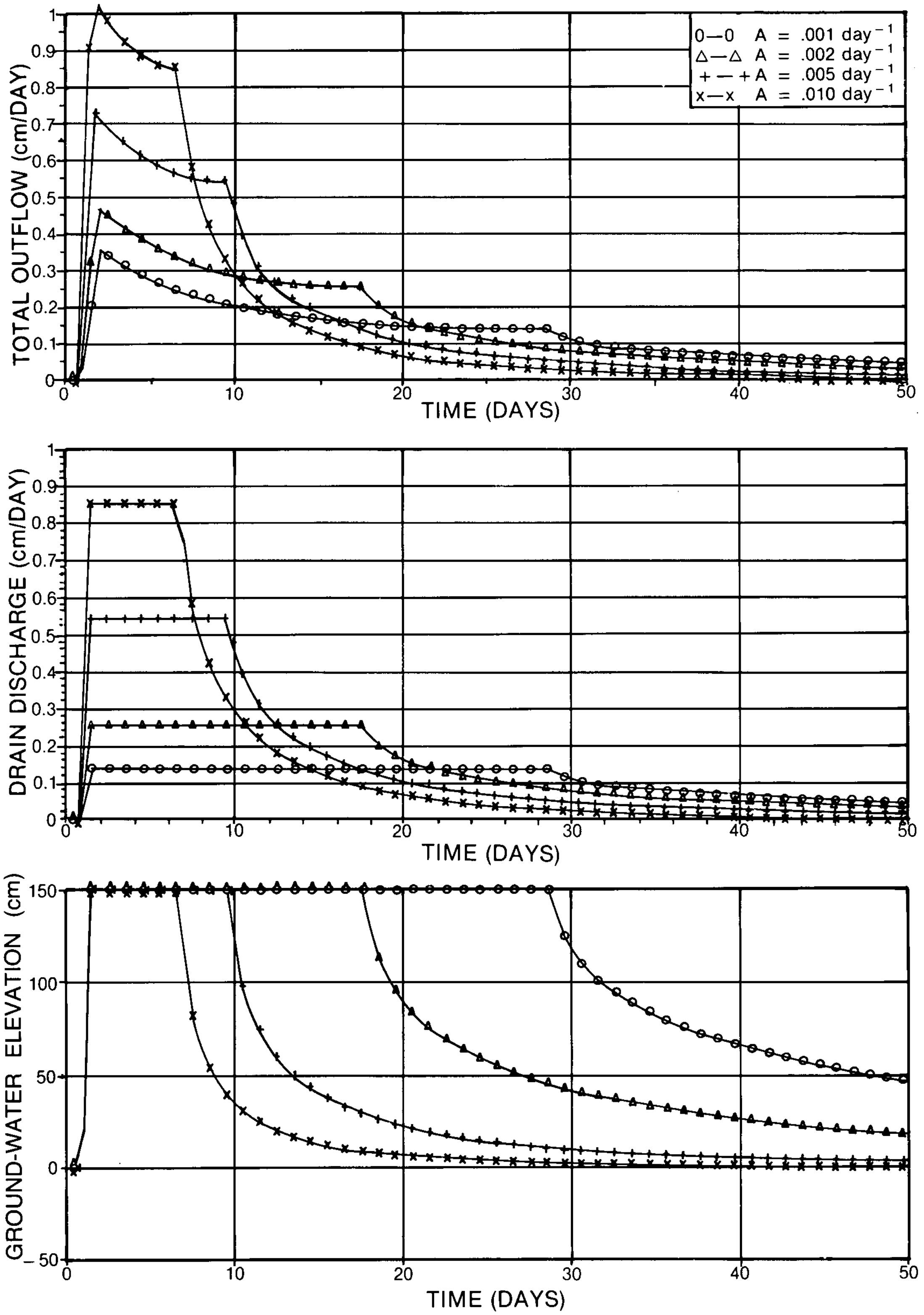

Figure 25. A high-intensity short-duration event: clay loam. $K_o = 2$ cm day^{-1}; $\alpha = 0.02$ cm^{-1}; D = 150 cm; $A_b = 0.01$ cm^{-1} day^{-1}; $P_{max} = 0.4$ cm.

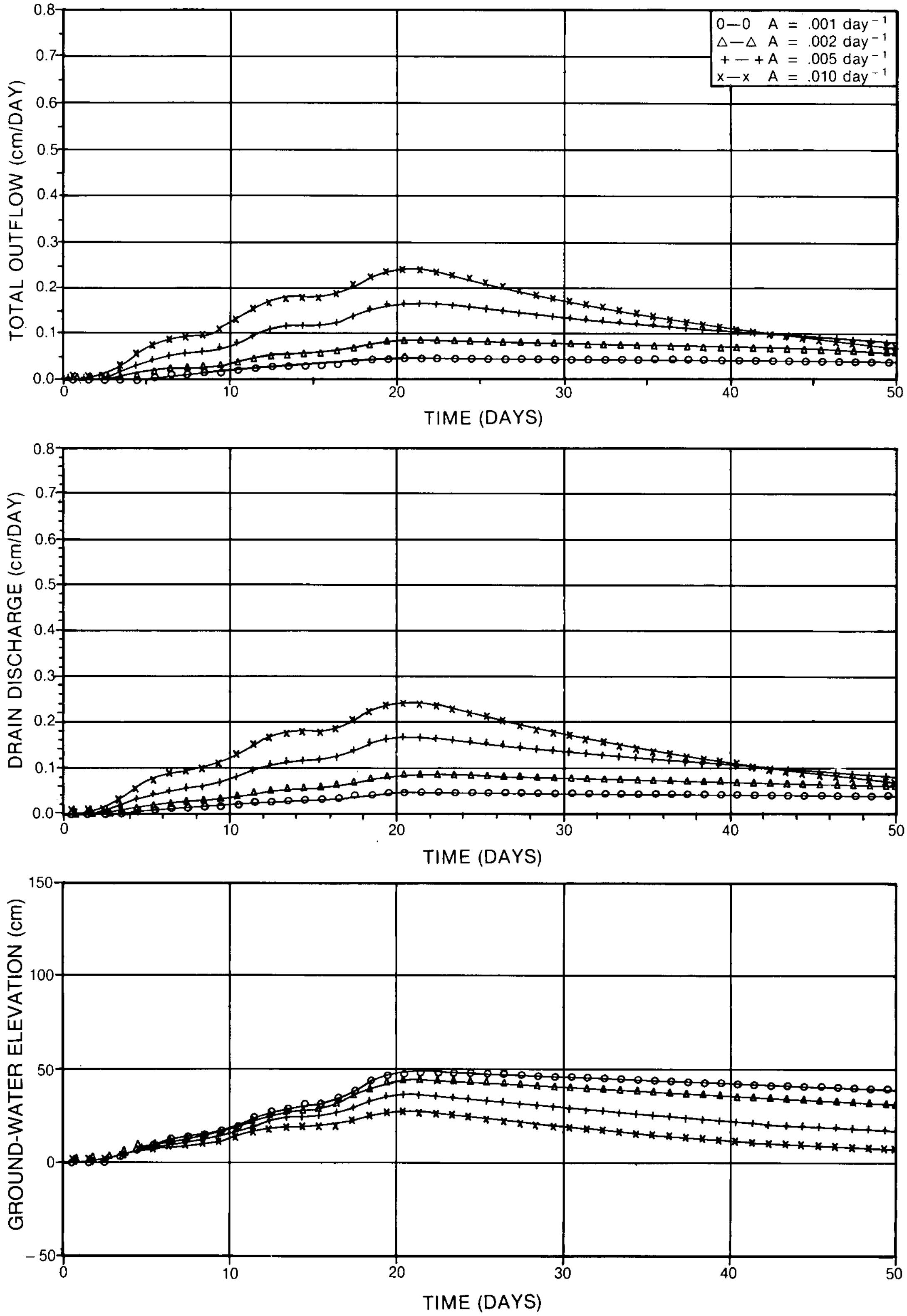

Figure 26. Three heavy one-day storms, one week apart: sand. K_0 = 2 cm day^{-1}; α = 0.02 cm^{-1}; D = 150 cm; A_b = 0.2 cm^{-1} day^{-1}; P_{max} = 0.4 cm.

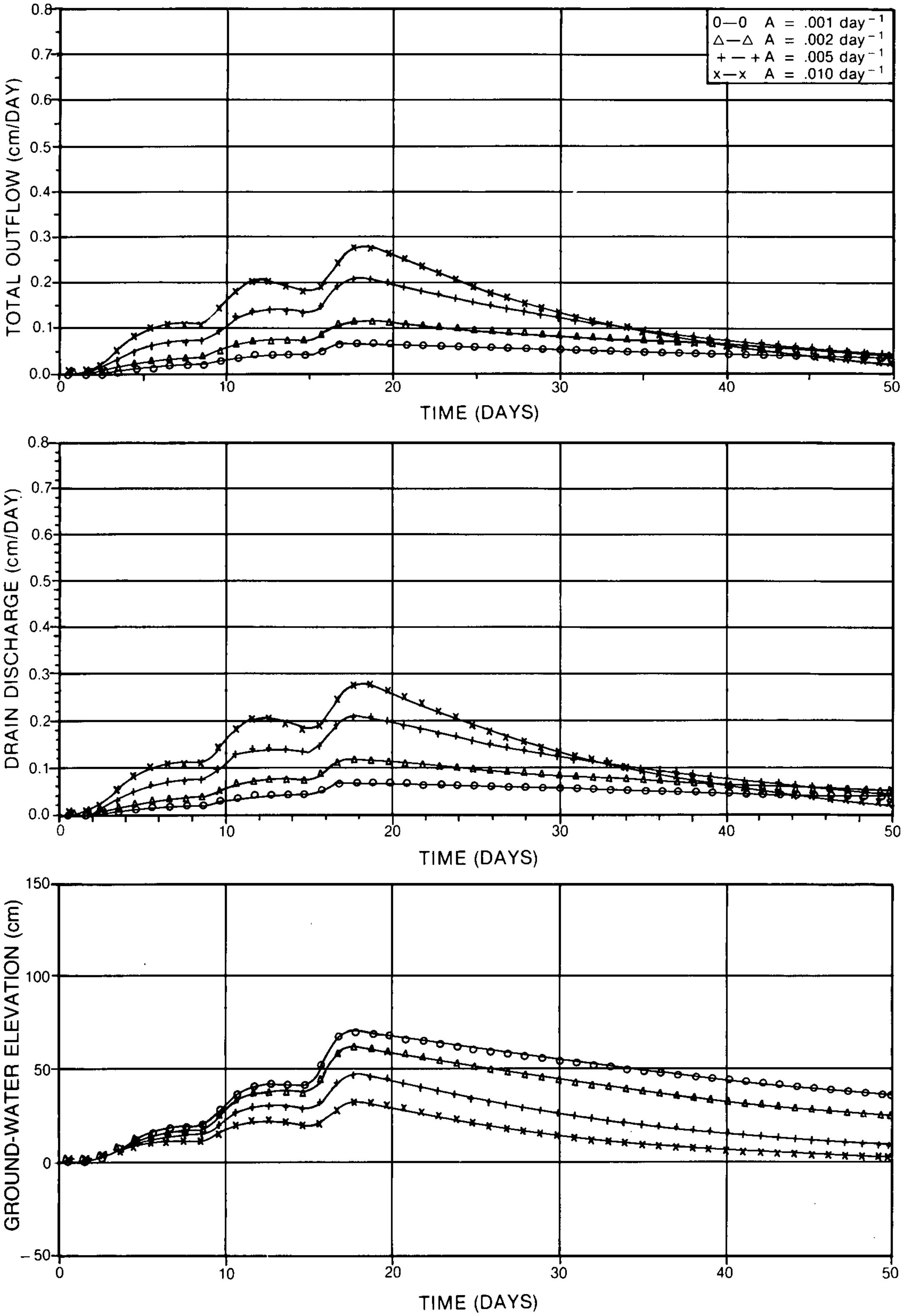

Figure 27. Three heavy one-day storms, one week apart: sandy loam. $K_0 = 2$ cm day^{-1}; $\alpha = 0.02$ cm^{-1}; D = 150 cm; $A_b = 0.2$ cm^{-1} day^{-1}; $P_{max} = 0.4$ cm.

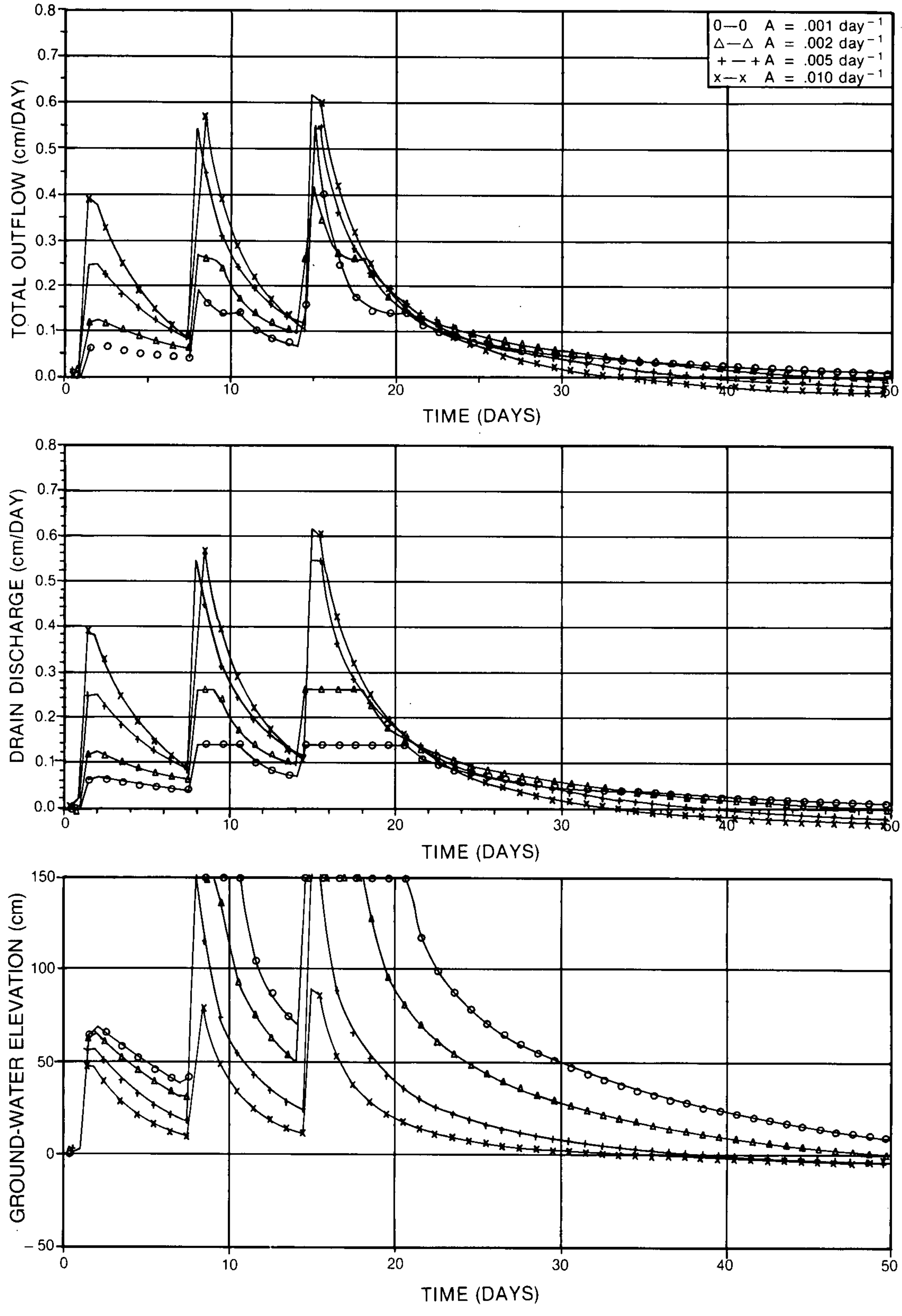

Figure 28. Three heavy one-day storms, one week apart: clay. K_0 = 2 cm day^{-1}; α = 0.02 cm^{-1}; D = 150 cm; A_b = 0.2 cm^{-1} day^{-1}; P_{max} = 0.4 cm.

Appendix A
Fortran Code

```
      PROGRAM FLO(OUTPUT,TAPE1,TAPE6)
C           SIMULATION OF INFILTRATION,GROUNDWATER AND SURFACE WATER
C
C                       DISCHARGE FROM DRAINED FIELDS
C
C                                A.VANDENBERG
C
C          THIS SIMULATION IS AN ADAPTATION OF PROGRAM FLOW ORIGINALLY
C     DEVELOPED BY G.P.WIND AND DESCRIBED IN J.OF.HYDROLOGY,24(1975)1-20.
C     THE PRESENT MODEL ADDS A ROUTINE FOR SIMULATION OF SURFACE RUNOFF,
C     FOR INPUT OF A STEADY FLUX FROM WHICH THE INITIAL MOISTURE DISTRI-
C     BUTION IS CALCULATED,A FAST ITERATIVE (NEWTON) ROUTINE FOR THE CAL-
C     CULATION OF HEIGHT OF GROUNDWATER TABLE,AND PROVIDES THE OPTION OF
C     WRITING A NUMBER OF VARIABLES-GROUNDWATER DISCHARGE,SURFACE DISCHAR
C     GE,TOTAL DISCHARGE - TO DISK,IN A FORMAT SUITABLE FOR PLOTTING.
C
C       DESCRIPTION OF INPUT VARIABLES.
C
C     VARIABLES ARE LISTED IN THE ORDER THEY HAVE TO APPEAR IN THE INPUT.
C      INPUT IS IN FREE FORMAT,EXCEPT FOR THE FIRST TWO CARDS,WHICH MAY
C      CONTAIN 70 CHARACTERS EACH,WHICH WILL BE PRINTED AS A 2-LINE
C      TITLE ON OUTPUT,COPIED ONTO FILE6 AND PRINTED AS A TITLE ON A
C      PLOT CREATED FROM THIS FILE.
C
C     NUMSIM     =NUMBER OF SIMULATIONS.IF NUMSIM GT. 1 THEN NUMSIM OF THE
C                 FOLLOWING DATASETS MUST BE INPUT.
C     M          =NUMBER OF SOIL LAYERS
C     DZ         =THICKNESS OF ALL SOIL LAYERS (CM)
C     ALF        =COEFFICIENT ALPHA IN THE EQ. FOR UNSAT.COND(1/CM)
C     A          =COEFFICIENT IN HOOGHOUDTS EQUATION (1/DAY)
C     AKO        =SATURATED CONDUCTIVITY (CM/DAY)
C     AB         =COEFFICIENT IN SURFACE RUNOFF EQ:QS=AB*(POOL-PMAX)**2
C                 (1/(CM.DAY))
C     PMAX       =POOL DEPTH ABOVE WHICH SURFACE DISCHARGE BEGINS (CM)
C     DPRINT     =TIME INTERVAL AT WHICH RESULTS ARE TO BE PRINTED AND/OR
C                 WRITTEN TO DISK (DAYS)
C     DELT       =PREFERRED LENGHT OF TIME STEP (DAYS),HOWEVER IF CALCULA-
C                 TED MAXIMUM LENGHT OF TIMESTEP IS LT. THEN DELT IT WILL
C                 BE REPLACED BY THE CALCULATED VALUE.
C     TIME       =TIME AT BEGINNING OF SIMULATION,USUALLY ZERO (DAYS)
C     NT         =NUMBER OF ENTRIES IN THE TABLE OF THE PSI-THETA FUNCTION
C     POOL       =INITIAL HEIGHT OF WATER POOLED ON THE SURFACE (CM).
C     DITCH      =INITIAL HEIGHT OF WATER IN THE DITCH (CM)
C     IOPT(1)    =OPTION SELECTOR NO. 1:
C                    =0,THEN M VALUES OF THE INITIAL MOISTURE ARE EXPECTED
C                    =1 ,ONLY A VALUE OF QD, THE STEADY GROUNDWATER DISCHAR
C                        GE WILL BE READ,AND THE INITIAL MOISTURE
C                        DISTRIBUTION CALCULATED.
C                    =2,M VALUES OF PSI WILL BE READ,AND INITIAL MOISTURE
C                        DISTRIBUTION CALCULATED
C     IOPT(2)    =OPTION SELECTOR NO. 2
C                    =0,EXTENDED OUTPUT FORMAT WITH COMPLETE MOISTURE
C                        PROFILE IS PRINTED EACH DPRINT DAYS
C                    =1  OUTPUT IS WITHOUT MOISTURE PROFILE,
C                        BUT ALL INTERNAL FLOWS ARE LISTED
C                    =2  OUTPUT LIMITED TO TIME ,THE STORAGES.PRECIP,POOL,
C                        DITCH,TOTAL SOIL MOISTURE ABOVE DRAINS,AND THE
```

```
C                     RATES.INFILTRATION,SURFACE DISCHARGE,GROUNDWATER
C                     DISCHARGE,TOTAL DISCHARGE,Q(M-1),AND THE HEIGHT OF
C                     THE WATERTABLE.ONE LINE OF PRINT EACH TIME.
C    IOPT(3)   =OPTION SELECTOR NO.3 :
C                =0  NO TAPE WITH PLOT DATA WILL BE WRITTEN
C                =1  PLOTTING COORDINATES WILL BE WRITTEN TO TAPE6.
C    THEY ARE THE VALUES OF:TIME,ACCUMULATED WATER IN DITCH,DEPTH OF
C    WATER ON THE SURFACE(POOL),INFILTRATION RATE,WATER TABLE ELEVATION,
C    GROUNDWATER DISCHARGE RATE,SURFACE RUNOFF RATE AND TOTAL RUNOFF
C    RATE.
C    TT(I),PP(I),I=1,NT .NT PAIRS OF VALUES OF MOISTURE AND PRESSURE,
C                        DEFINING THE PSI-THETA FUNCTION (CHARACTERISTIC
C                        CURVE)FOR THE SOIL IN QUESTION .NOTE THAT
C                        PRESSURE VALUES MUST HAVE A NEGATIVE SIGN AND
C                        MUST INCLUDE A VALUE OF MOISTURE FOR PSI=0.
C                        TT IS IN (CM/CM) AND PP IN CM.
C    THET(I),I=1,M  =ONLY TO BE ENTERED IF IOPT(1)=0 :M VALUES OF
C                    INITIAL MOISTURE CONTENT (CM/CM)
C    PSI(I),I=1,M   =ONLY TO BE ENTERED IF IOPT(1)=2  :M VALUES OF
C               INITIAL PRESSURES (NEGATIVE OR O,IN CM)
C    QD        = ONLY TO BE ENTERED IF IOPT(1)=1 :ONE VALUE OF INITIAL
C               EQUILIBRIUM GROUNDWATER DISCHARGE ,ALWAYS POSITIVE
C               (CM/DAYS)
C    NPER      =NUMBER OF DISTINCT PERIODS FOR WHICH A CONSTANT RAINFALL
C               RATE IS GIVEN
C    RAINTO(I),RATE(I),I=1,NPER . NPER PAIRS OF VALUES OF
C                RAINTO =TIME AT WHICH PERIOD ENDS (DAYS),NOT THE
C                THE INTERVAL TIME
C                RATE   =AVERAGE RATE OF RAIN OVER THE PERIOD (CM/DAY)
C
C           NOTE.ALL OF THE ABOVE DATA,EXCEPT NUMSIM,MUST BE REPEATED
C                NUMSIM TIMES.
*********************************************************************
C     STORAGE BLOCKS
C
      COMMON TT(100),PP(100),NT
      DIMENSION THET(50),AK(50),PSI(50),IOPT(3) ,RAINTO(100),RATE(100)
     1 ,Q(100)
**********************************************************************
C     OUTPUT FORMATS
C
  100 FORMAT(/*     MOISTURE AND CONDUCTIVITY PROFILE*/
     113X,*THETA(CM/CM)*,8X,*K(CM/DAY)*/(5X,E20.6,5X,F12.6))
  101 FORMAT(*0  QD=*,F12.3,5X,*ZG=*,F12.3/)
  102 FORMAT(*0 MAXIMUM TIMESTEP=*,F15.5)
  103 FORMAT(*1*,4X,*TIME*,4X,*PRECIP*,6X,*POOL*,5X,*DITCH*,2X,
     1*MOISTURE  INFILTR.*,4X,*RUNOFF*,2X,
     2*GW DISCH TOT DISCH    Q(M-1)  GW TABLE*)
  104 FORMAT(6F10.4)
  105 FORMAT(8A10)
  106 FORMAT(1X,8A10)
  200 FORMAT(* STORAGES*,4F10.5/* INFILT AND RUNOFF*,2F10.5/* INTERNAL F
     1LOWS*,(10F8.4)/)
  300 FORMAT(*0  M*,8X,*DZ*,5X,*ALPHA*,9X,*A*,8X,*KO*,8X,*AB*,6X,*PMAX*,
     14X,*DPRINT*,6X,*DELT*,6X,*TIME NT POOL DITCH*/I4,9F10.3,I3,2F5.1/)
  400 FORMAT(* OPTIONS *,3I3//10X,*CHARACTERISTIC*//* PRESSURE(CM) MOIS(
     1CM/CM)*/)
```

```
  500 FORMAT(1X,2E12.4)
  600 FORMAT(/I5,1X,*RAIN PERIODS*//*  PERIOD  ENDS AT(DAYS)   RATE(CM/D
     1AY)*/)
  700 FORMAT(3X,I5,2F15.4)
  800 FORMAT(*OTIME,STEP,GW DISCH.,WATER TABLE,TOT DISCH *,5E15.6/)
  900 FORMAT(F8.2,3X,2F10.4,3X,F10.4,4X,F11.2,2X,2F10.4,F14.4)
 1000 FORMAT(1X,F8.1,E10.3,F10.3,E10.3,F10.2,5F10.3,E10.3)
 1100 FORMAT(1X,*QD TOO LARGE,RESET TO MAX. VALUE*,E12.4,*CM/DAY*)
C
*****************************************************************
C       READ DATA AND ECHO DATA TO PRINTED OUTPUT
C
      READ(1,105)(PSI(I),I=1,16)
      WRITE(6,105)(PSI(I),I=1,16)
      PRINT 106,(PSI(I),I=1,16)
      READ(1,*)NUMSIM
      DO 1 K=1,NUMSIM
      READ(1,*)M,DZ,ALF,A,AKO,AB,PMAX,DPRINT,DELT,TIME,NT,POOL,DITCH
      PRINT 300,M,DZ,ALF,A,AKO,AB,PMAX,DPRINT,DELT,TIME,NT,POOL,DITCH
      READ(1,*)(IOPT(I),I=1,3)
      READ(1,*)(TT(I),PP(I),I=1,NT)
      PRINT 400,(IOPT(I),I=1,3)
      PRINT 500,(PP(I),TT(I),I=1,NT)
*****************************************************************
C     INITIAL CALCULATIONS
C
      AA=EXP(ALF*DZ)
      M1=M-1
      AAB=SQRT(AA)
      DPRINT=DPRINT*.9999
      DEPTH=(M-1.)*DZ
      RNGE=TT(NT)-TT(1)
      DO 42 I=1,NT
   42 PP(I)=AKO*EXP(ALF*PP(I))
C
C     PP-VALUES OF TABLE WILL NOW HOLD CONDUCTIVITY VALUES
C
      IF(IOPT(1).EQ.1)GOTO2
      IF(IOPT(1).EQ.2)GOTO3
      READ(1,*)(THET(I),I=1,M)
      DO 4 I=1,M
    4 CALL TABLE(THET(I), AK(I),1)
      GOTO 5
    3 READ(1,*)(PSI(I),I=1,M)
      DO 6 I=1,M
      AK(I)=AKO*EXP(ALF*PSI(I))
    6 CALL TABLE(THET(I), AK(I),2)
      GOTO 5
*****************************************************************
C       CALCULATE K AND THETA FOR ALL LAYERS FOR EQUILIBRIUM FLOW QD
C
    2 READ(1,*)QD
*****************************************************
*
*                        IF
*  QD IS TOO HIGH IT WILL BE RECALCULATED;THE NEW VALUE
*  WILL BE THE MAXIMUM RATE AND WILL BE PRINTED ON THE
```

```
*   OUTOUT FILE.
*
*************************************************************
      QDMAX=A*DEPTH
      QDMAX=QDMAX*AKO/(QDMAX+AKO)
      IF(QD.LE.QDMAX)GOTO 77
      QD=QDMAX
      ZG=DEPTH
      NSAT=M
      PRINT 1100,QD
      GOTO 78
   77 ZG=QD*AKO/(A*(AKO-QD))
      NSAT=ZG/DZ +1.000001
      PART=ZG-NSAT*DZ
      AP=EXP(-ALF*PART)
      AK(NSAT+1)=(QD*(AP-1.)+AKO)/AP
      IF(NSAT.LT.1)GOTO 81
   78 DO 7 I=1,NSAT
      THET(I)=TT(NT)
    7 AK(I)=AKO
   81 IB=NSAT+2
      IF(IB.GT.M)GOTO10
      DO 8 I=IB,M
    8 AK(I)=(QD*(AA-1.)+AK(I-1))/AA
      IB=NSAT+1
      DO 9 I=IB,M
    9 CALL TABLE(THET(I), AK(I),2)
      GOTO 10
************************************************************************
C       COUNT NUMBER OF SATURATED LAYERS AND STORE IN NSAT
C
    5 NSAT=0
      DO 13 I=1,M
      IF(THET(I).LT.TT(NT))GOTO 14
      NSAT=NSAT+1
   13 CONTINUE
C
C       CALCULATE WATERTABLE ELEVATION WITH SUBROUTINE NEWT
C
   14 ZG=NSAT*DZ
      CALL NEWT(AK(NSAT+1),AKO,DZ,A,ALF,ZG,NSAT)
C
C       CALCULATE NUMBER OF SAT. LAYERS,NSAT,AND QD
C
      NSAT=ZG/DZ+1.000000
      THET(NSAT)=TT(NT)
      AK(NSAT)=AKO
      QD=A*ZG*AKO/(AKO+A*ZG)
      PART=ZG-NSAT*DZ
C
C       PRINT INITIAL VALUES OF THETA AND K IN PROFILE,QD,ZG AND
C       RAINFALL DATA
C
   10 PRINT 100,(THET(M+1-I),AK(M+1-I),I=1,M)
      PRINT  101,QD,ZG
      READ(1,*)NPER
      READ(1,*)(RAINTO(I),RATE(I),I=1,NPER)
```

```
      PRINT 600,NPER
      PRINT 700,(I,RAINTO(I),RATE(I),I=1,NPER)
      IF(IOPT(3).EQ.1)WRITE(6,104)AKO,ALF,DEPTH,AB,A,DZ
************************************************************************
C
C       CALCULATE MAXIMUM ALLOWABLE TIMESTEP DT
C
      DT=1.E12
      DO 11 I=2,NT
      DU=(TT(I)-TT(I-1))/(PP(I)-PP(I-1))
      IF(DU.LT.DT)DT=DU
   11 CONTINUE
      DT=.95*DZ*DT*(AA-1.)/(AA+1.)
      IF(DT.GT.DELT)DT=DELT
      PRINT  102,DT
      PRNT=0.
      PRECIP=0.
      IF(IOPT(2).GE.2)PRINT 103
      DO 16 IP=1,NPER
      IPTEST=0
*************       *****************      *****************      ********
C
C       INCREMENT TIME AND START NEW ITERATION
C
*************       *****************      *****************      ********
   31 TIME=TIME+DT
      DTA=DT
C
C       TEST FOR END OF RAIN PERIOD AND ADJUST TIMESTEP IF NECESSARY
C
      IF(TIME.LT.RAINTO(IP))GOTO 17
      DTA=RAINTO(IP)+DTA-TIME
      TIME=RAINTO(IP)
      IPTEST=1
   17 PRNT=PRNT+DTA
      NSA=NSAT+1
      IF(NSAT.GT.0)Q(NSAT)=-QD
      IF(NSA.GE.M)GOTO 27
      DO 18 I=NSA,M1
   18 Q(I)=(AK(I)-AK(I+1)*AA)/(AA-1.)
      IF(NSA.GT.1) GOTO 34
      NSA=2
      THET(1)=THET(1)-(QD+Q(1))*DTA/DZ
   34 DO 21 I=NSA,M1
   21 THET(I)=(Q(I-1)-Q(I))*DTA/DZ+THET(I)
      NSA=NSAT+1
      DROS=0.
      IF(THET(NSA).LE.TT(NT))GOTO 27
      DROS=THET(NSA)-TT(NT)
   27 THET(M)=THET(M)+Q(M1)*DTA/DZ
      PREVAP=RATE(IP)*DTA
      IF(PREVAP.GE.0.)GOTO 35
      IF(POOL+PREVAP.GE.0.)GOTO 35
      PRECIP=PRECIP+POOL
      EVAP=PREVAP+POOL
      EVAP=EVAP*(THET(M)-TT(1))/RNGE
      POOL=0.
```

```
      EMAX=(TT(1)-THET(M))*DZ
      IF(EVAP.LT.EMAX)EVAP=EMAX
      PRECIP=PRECIP-EVAP
      THET(M)=THET(M)+EVAP/DZ
      DISCHA=0.
      RINF=EVAP
      GOTO 30
   35 POOL=POOL+PREVAP
      PRECIP=PRECIP-PREVAP
************************************************************************
C       AMAXI=MAXIMUM INFILTRATION VOLUME TOP LAYER CAN ABSORB
C
      AMAXI=(TT(NT)*.9999-THET(M))*DZ
C
C       RINF=TOTAL VOLUME INFILTRATING DURING TIMESTEP
C
      RINF=(AKO*AAB-AK(M))/(AAB-1.)*DTA
      DIF=POOL-PMAX
      DISCHA=0.
C
C       BALANCING DISCHA(=SURFACE RUNOFF) AND RINF
*************     *****************     *****************      ********
      IF(DIF.LE.0.)GOTO 23
      DISCHA=AB*DIF*DIF*DTA
      IF(DISCHA.GT.DIF)DISCHA=DIF
   23 IF(RINF.GT.AMAXI)RINF=AMAXI
      TOT=RINF+DISCHA
      IF(TOT.LE.POOL)GOTO 24
      RINF=RINF*POOL/TOT
      DISCHA=DISCHA*POOL/TOT
   24 THET(M)=THET(M)+RINF/DZ
      POOL=POOL-RINF-DISCHA
      IF(NSA.LT.M)GOTO 30
      DROS=0.
      IF(THET(M).LT.TT(NT))GOTO 30
      DROS=THET(M)-TT(NT)
   30 DITCH=DITCH+DISCHA +QD*DTA+DROS*DZ
      DO 25 I=NSA,M
   25 CALL TABLE(THET(I),AK(I), 1)
      IF(DROS.LE.0.)GOTO 29
      NSA=NSA+1
      NSAT=NSAT+1
   29 CALL NEWT(AK(NSA),AKO,DZ,A,ALF,ZG,NSAT)
      NSAT=ZG/DZ+1.000001
      PART=ZG-NSAT*DZ
      QD=A*ZG*AKO/(AKO+A*ZG)
C
C       SUM=TOTAL SOIL MOISTUTE
C
      SUM=NSAT*TT(NT)*DZ
      N2=NSAT+1
      DO 26 I=N2,M
   26 SUM=SUM+THET(I)*DZ
      IF(PRNT.LT.DPRINT)GOTO 28
      PRNT=0.
      TOT=  QD+DISCHA/DTA
      RINF=RINF/DTA
```

```
      DISCHA=DISCHA/DTA
      IF(IOPT(2).LT.2)GOTO 32
      PRINT 1000,TIME,PRECIP,POOL,DITCH,SUM,RINF,DISCHA,QD,TOT,Q(M1),ZG
      GOTO 33
   32 PRINT 800,TIME,DTA,QD,ZG,TOT
      PRINT 200,PRECIP,POOL,DITCH,SUM,RINF,DISCHA,(Q(I),I=1,M1)
      IF(IOPT(2).EQ.1)GOTO 33
      PRINT 100,(THET(M+1-I),AK(M+1-I),I=1,M)
   33 IF(IOPT(3).EQ.0)GOTO 28
      WRITE(6,900)TIME,DITCH,POOL,RINF,ZG,QD,DISCHA,TOT
   28 IF(IPTEST.EQ.1)GOTO 16
      GOTO 31
   16 CONTINUE
      P=0.
      IF(IOPT(3).EQ.1)WRITE(6,900)P
    1 CONTINUE
      STOP
      END
```

```
      SUBROUTINE TABLE(T,P,IS)
      COMMON TT(100),PP(100),NT
      IF(IS.EQ.2)GOTO 1
      IF(T.LE.TT(1))GOTO 2
      IF(T.GE.TT(NT))GOTO3
      DO 4 I=2,NT
      IF(T.LT.TT(I))GOTO 5
    4 CONTINUE
    5 FAC=(T-TT(I-1))/(TT(I)-TT(I-1))
      P=FAC*(PP(I)-PP(I-1))+PP(I-1)
      RETURN
    2 P=PP(1)
      RETURN
    3 P=PP(NT)
      T=TT(NT)
      RETURN
    1 IF(P.LE.PP(1))GOTO 12
      IF(P.GE.PP(NT))GOTO 3
      DO 14 K=2,NT
      I=K
      IF(P.LT.PP(I))GOTO 15
   14 CONTINUE
   15 FAC=(P-PP(I-1))/(PP(I)-PP(I-1))
      T=FAC*(TT(I)-TT(I-1))+TT(I-1)
      RETURN
   12 T=TT(1)
      RETURN
      END
```

```
      SUBROUTINE NEWT(AKN,AKO,DZ,A,ALF,ZG,NSAT)
      IF(AKN.LT.AKO-1.E-12 )GOTO 4
      ZG=DZ*NSAT
      RETURN
    4 FAC=AKO/(A*(AKO-AKN))
      AA=FAC*AKN-DZ*NSAT
      BB=FAC*AKO
      IC=0
      Y=ZG-NSAT*DZ
    1 EX=EXP(ALF*Y    )*BB
      IC=IC+1
      Z=Y-(Y-AA+EX)/(1.+EX*ALF)
      IF(IC.GT.20)GOTO 2
      IF(ABS(Y-Z).LT..01)GOTO3
      Y=Z
      GOTO 1
    2 ZG=DZ*NSAT+Z
      PRINT 100,ZG
      RETURN
  100 FORMAT(3X,*NO CONVERGENCE*,E12.4)
    3 ZG=DZ*NSAT+Z
      RETURN
      END
```

EXAMPLE OF DATA FILE

```
FIGURE 18:EFFECT OF CONDUCTIVITY:SANDY LOAM$
KO=.1,.5,2,10 (A)=.02;D=150;A=.006;AB=.01;PMAX=.4
4 16 10 .02 .006 .1 .01 .4 .5 .05 0 19 0 0 1 2 1
.28 -295 .29 -265 .3 -237 .31 -210 .32 -186 .33 -163 .34 -138
.35 -118 .36 -102 .37 -88 .38 -77 .39 -68 .4 -60 .41 -52 .42 -43
.43 -33 .44 -19 .445 -10 .45 0
0 2 15 .6 50 0
  16 10 .02 .006 .5 .01 .4 .5 .05 0 19 0 0 1 2 1
.28 -295 .29 -265 .3 -237 .31 -210 .32 -186 .33 -163 .34 -138
.35 -118 .36 -102 .37 -88 .38 -77 .39 -68 .4 -60 .41 -52 .42 -43
.43 -33 .44 -19 .445 -10 .45 0
0 2 15 .6 50 0
  16 10 .02 .006 2  .01 .4 .5 .05 0 19 0 0 1 0 1
.28 -295 .29 -265 .3 -237 .31 -210 .32 -186 .33 -163 .34 -138
.35 -118 .36 -102 .37 -88 .38 -77 .39 -68 .4 -60 .41 -52 .42 -43
.43 -33 .44 -19 .445 -10 .45 0
0 2 15 .6 50 0
  16 10 .02 .006 10 .01 .4 .5 .05 0 19 0 0 1 0 1
.28 -295 .29 -265 .3 -237 .31 -210 .32 -186 .33 -163 .34 -138
.35 -118 .36 -102 .37 -88 .38 -77 .39 -68 .4 -60 .41 -52 .42 -43
.43 -33 .44 -19 .445 -10 .45 0
0 2 15 .6 50 0
```

Appendix B

Cyber Control Language for Running the Model and Plotting Results

APPENDIX B

CYBER CONTROL LANGUAGE FOR RUNNING THE MODEL AND PLOTTING RESULTS

The following control language statements will result in the calculation of drain discharge, total discharge and ground-water table elevation and the plotting of these results as in Figure 6, and Figures 8 to 28. For the plotting, use is made of the DISSPLA-routines and a special program written by J. Giovannitti, a complete description of which will be made available as an NHRI internal publication.

```
    IC9XX,CM130000,T500,P2.
    ACCOUNT,24072.
(1) ATTACH, SOILBI, ID=VDB.
(2) ATTACH, TAPE1, CLAY,ID=VDB.
(3) REQUEST,TAPE6,*PF.
(4) SOILBI.
    CATALOG,TAPE6,TEMP,ID=VDB.
    RETURN,TAPE6.
(5) ATTACH,TAPE5,TEMP,ID=VDB.
(6) ATTACH,LGO,PLOTBI,ID=VDB.
(7) ATTACH,TAPE6,ID=JGG.
(8) BEGIN,DISSPLA,,CAL1051,NAME=VANDENBERG/562 BOOTH ST.
```

1. Attach the binary code of Program FLO.

2. Attach the file with data for running FLO.

3. TAPE6 will hold the results used as data for plotting.

4. Run program FLO.

5. Attach the file with output from the run of FLO, catalogued as TEMP, with the local file name TAPE5.

6. Attach the binary code of the plot program.

7. Attach TAPE6, which contains one line of parameters for the plot routine.

8. Generate the plot.

Canada