AN ABSTRACT OF THE THESIS OF

Harash V. Saluja for the degree of Master of Science

in Agricultural Engineering presented on October 13, 1977

Title: A MODEL FOR PREDICTING WATER TABLE FLUCTUATIONS IN LAYERED SOILS

Abstract approved: Redacted for privacy

Water tables in many soils of the Willamette Valley of Western Oregon are often near the surface. This is because they are underlain by a relatively impermeable layer at a shallow depth, and the rainfall during the winter months greatly exceeds the evapotranspiration. The high water tables combined with fine-textured soils cause the specific yield of the soils to be extremely sensitive to the exact position of the water table at any particular time.

Methods commonly used for predicting water-table fluctuations in response to rainfall assume that the specific yield is a constant for a particular soil. This assumption is not valid for many soils of the Willamette Valley. However, an estimation of water-table fluctuations is needed for the identification of drainage problems and for the design of drains. To obtain a more satisfactory method of predicting water-table fluctuations for such soils, models were constructed to extrapolate data from observation of water-table fluctuations for short periods of time.

Models were constructed for both naturally and artificially drained soils. When the models were constructed using data for an appropriate

period, i.e., when the hydraulic conditions of the soil profile were similar to those for which predictions were made, the models gave results in close agreement with observed water-table fluctuations.

The inputs required for the model are rainfall amounts as a function of time and the initial water-table position. The output is the water-table elevation as a function of time. The model also calculates an index, evaluating the quality of drainage in the field, by taking into account the elevation of the water table and the length of time that a water table remains closer than 30 centimeters to the soil surface.

A Model for Predicting Water Table
Fluctuations in Layered Soils

by

Harash V. Saluja

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Commencement June 1978

APPROVED:

Redacted for privacy

Professor of Agricultural Engineering in charge of major

Redacted for privacy

Head of Department of Agricultural Engineering

Redacted for privacy

Dean of Graduate School

Date thesis is presented October 13, 1977

Typed by Cindy Pratt for Harash V. Saluja

ACKNOWLEDGEMENTS

The author is grateful to the many individuals that have contributed to this study.

The author wishes special thanks to Dr. Arthur T. Corey and Dr. Royal H. Brooks, his advisors, for their guidance and academic advising, teaching, encouragement and friendliness. Thanks are also due to Dr. Robert B. Wensink, for help in running computer programs; to Professor Glen Page, for his description of the experimental site and collection of data; Mr. Pete Lyngstrand, for his fine draftmanship and Ms. Jane Owre for her assistance during completion of the thesis.

Finally, much thanks to all the members of my family for their patience and encouragement. The excellent typing of Mrs. Cindy Pratt is very much appreciated.

To

John W. Wolfe

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

Figure		Page

A MODEL FOR PREDICTING WATER TABLE FLUCTUATIONS IN LAYERED SOILS

I. REVIEW OF LITERATURE

Research workers throughout the world have tried different methods to quantitatively evaluate water-table changes. Most of the quantitative methods can be classified under the heading of steady water tables, falling water tables, and fluctuating water tables.

1.1 Steady Water Tables

A steady-state condition is said to exist in a soil-water system when its boundaries and the potential along these boundaries do not change with time. There are two directions of flow taking place in steady water tables. Vertical flow due to deep seepage, and horizontal flow towards flow channels. Colding, a Danish engineer, in 1872, was the first to present a mathematical solution describing the water-table profile in equilibrium with a constant, uniform infiltration rate. This equation is commonly called the ellipse, Hooghoult, or Donnan equation as it was developed by a number of researchers including the two whose name it bears. This equation is based upon the Dupuit approximations, namely, 1) That all streamlines in a system of gravity flow towards a shallow sink are horizontal, 2) That the velocity along these streamlines is proportional to the slope of the free surface, but independent of depth. The assumption was also made that no flow takes place above the water table. Hooghoult, among others, replaced the Dupuit Assumptions with the concept of radial flow towards the sink.

Investigators Rothe (1924), Kozeny (1932), Hooghoult (1937), Aronovici and Donnan (1946), Gustafson (1946) and Muskat (1946), have used the Dupuit-Forchheimer theory of horizontal flow to characterize steady-state water tables for the solution of drainage problems.

The radial-flow assumptions which take care of the non-horizontal flow situations occuring in the immediate vicinity of seepage faces of drains, have received considerable attention in the works of Hooghoult (1940), Gustafson (1946) and Kirkham (1940, 1941, 1945, 1948, 1949, and 1951).

An assumption of a combination of horizontal flow at some distance from a tile drain with radial flow near the drain was used by researchers Vedernikov (1939), and Hooghoult (1940), for investigating the steady-state water-table situation.

Another method of describing the position of a steady water table is by applying potential flow theory to the flow region below the water table. Laplace's equation (in terms of piezometric head) is solved numerically using a relaxation method. Van Demeter (1950) and Luthin and Gaskell (1950) have presented details of this method as it applies to steady-state water tables and have solved a number of example cases. Although the method does not require the Dupuit approximations, it is like the methods previously discussed in that no attempt is made to account for flow in the soil above the water table.

1.2 Falling Water Tables

If the conditions along the boundaries are a function of time, a non-steady state situation prevails. Unfortunately, a general solution is not available that evaluates a changing water table either by an exact or approximate method. Almost all attempts in solving non-steady state problems are based on the assumption of a constant specific yield representing the total fraction of the soil volume which is drained as the water tables move downward. It is assumed further that the soil pores empty instantaneously as the water table passes a given point in the profile. However, the assumption of a constant specific yield is in serious conflict with the actual situation. The value of the specific yield is, in fact, a function of the depth below the surface of the water table, being a sensitive function when the water table is high.

A large number of research workers throughout the world have considered falling water-table conditions in their work. Probably Forchheimer (1930), was the first to apply Dupuit's assumptions to non-steady state (transient conditions) by modifying the continuity equation. Kano (1940), derived a series of equations for the time required for a given drop in water table from a known height and for known placement of drains, given the porosity and hydraulic conductivity. Visser (1953) used a modified form of the ellipse equation to obtain a solution to the differential equation for the transient case. Dumm (1954), reported that R. D. Glover has derived an equation in the form of the heat flow equation which related the spacing of tile drains to the rate of drop of the water table at a given height above the drain. Solutions were obtained by assuming that the water table is initially flat and parallel to the soil surface. Subsequent solutions by R. D. Glover & Associates (U. S. Bureau of Reclamation) used other shapes for the water table. The Bureau (Luthin, 1973) has documented that the use of a fourth degree parabola to represent the initial position of the water table comes closer to the true situation.

Kemper (1954) compared the Glover's equation with the results of some electric analogue studies and concluded that if an empirical correction factor is introduced, the two analyses are in good agreement with each other. Ferris (1950) developed another solution to the rate of water-table drawdown in a homogenous, isotropic aquifer of infinite horizontal extent, bounded above and below by impermeable strata, with a single ditch drain. Walter (1952) proposed a solution for a predetermined rate of drawdown using a radial flow assumption. Kirkham and Gaskell (1951) extended the method of relaxation to falling water tables considering a series of successive steady states. Brutsaert, Taylor and Luthin (1961) used an electrical resistance network to describe a transient drainage situation. This method took into consideration an "apparent drainable porosity", which varied linearly with depth, instead of remaining constant, in this way accounting for the capillary fringe that exists above the water table.

Brooks (1961) analysed the unsteady situation for the case of horizontal flow towards drains. He showed that Glover's work was in fact the zero order term of his solution and thus a first approximation.

1.3 Fluctuating Water Tables

A steady-state water table occurs rarely if ever in nature, a fluctuating water table being much more common. Often, the significant factor determining the need for drainage is the length of time that the water table is above a critical level in the soil profile. Consequently, considerable research has been conducted to predict water-table fluctuations and in particular, to predict the probability that the water table will be above a critical elevation for a specified period of time.

Vaigneur and Johnson (1966) and Van Schilfguarde (1965) conducted research to predict the probability distribution of water-table heights given soil characteristics, precipitation and depth and spacing of drains. Sieben (1964), in the Netherlands, described the drainage condition in terms of a single SEW_{30} value having the unit of centimeters. SEW_{30} is defined as the sum of daily values by which the water table is higher than a level of 30 centimeters below the soil surface, midway between the drains. High SEW_{30} values indicate greater frequency and duration of water table levels above a 30 centimeter datum.

The U.S. Bureau of Reclamation (Luthin, 1973) has considered that a significant factor in respect to drainage needs is whether or not the range of water-table levels become reasonably constant over a period of time, i.e. from year to year. They have defined the term "dynamic equilibrium" to describe the condition when the amount of annual recharge is about equal to the annual discharge resulting in annual water-table fluctuations becoming reasonably constant from year to year. The Bureau's drainage design procedures have as an objective arriving at a drain spacing and depth such that a dynamic equilibrium is achieved with a specific range of water-table levels under specific soil, irrigation, crop, and climatic characteristics of the area.

In performing their calculations to achieve this objective, the Bureau uses an equation employing a soil parameter called "specific yield". The definition of specific yield given by Todd (1959) is the volume of water that an aquifer releases from or takes into storage per unit change in the component of head normal to the surface. In the Bureau's analysis, all the soil above the water table is assumed to be drained to the same moisture content.

Duke (1972) pointed out that the Bureau's assumption (in regard to a constant value of specific yield independent of the water-table elevation) is often misleading. Duke showed that specific yield is particularly sensitive to the water-table elevation for cases in which the water table is shallow and lies within fine-textured soils. It can be inferred from Duke's work that specific yields evaluated from decline of deep water tables are of little use for calculating the total volume of available water for shallow water tables. Thus, the method of analysis used by the Bureau for predicting water-table fluctuations would not be useful under conditions prevalent in the Willamette Valley where the soils tend to be fine-textured and the water tables shallow.

McWhorter and Duke (1976) have modified the Bureau's analysis to account for a variable specific yield and also for the flow in the capillary fringe above the water table. They developed an extension of Glover's equation (Dumm, 1954) to predict the fall of a water table (at the midpoint between drains) during a period of no recharge. However, the equation of McWhorter and Duke requires evaluation of the soil parameters obtainable from soil-water characteristic curves.

A number of attempts have been made for the specific purpose of predicting water-table fluctuations in soils of the Willamette Valley. Boersma (1965) in cooperation with the U.S. Army Corps of Engineers made continuous measurements of water-table elevations in the Willamette Valley with the objective of relating these to rainfall patterns. His analysis was based on the concept that changes in water-table elevations are brought about by water loss through deep seepage or water gain through rainfall. Boersma's equation employed a constant value of specific yield for particular soil layers, but the soils profile was divided into depth increments and seepage rates, drainable porosity and storage factors were determined for each depth increment. Boersma demonstrated that a simple model could predict water-table fluctuations using rainfall data and soil characteristics as inputs. Boersma, Simonson and Watts (1967, 1972) carried out another study of water-table fluctuations in soils of the Willamette Valley and devised a mathematical model which employed a variable specific yield determined from soil-water characteristic curves.

An empirical model for predicting water-table fluctuations was devised by Taylor (1963, 1966) for soils of the Amity series. His work had two objectives. The first was to collect sufficient field data to derive empirical equations describing water-table fluctuations as affected by rainfall, evapotranspiration, and tile drains. The second objective was to use the empirical equations as a mathematical model to simulate several seasons of water-table fluctuations and estimate, for a fixed spacing, the probabilities that the mean water table would be above various depths during a given spring month. Taylor used the model to develop a recession curve equation describing the mean water-table height as a function of time from ponded conditions when no rainfall takes place. The recession curve was divided into six segments and each segment was represented by an exponential or linear equation which closely approximated the constructed recession curve in that range. The input for Taylor's model included rainfall and evapotranspiration as functions of time and soil characteristics for each of the several layers in the soil profile. The position of the water table at any particular time was not considered in this model.

Nibler (1974) suggested that if a continuous record of water-table heights as a function of time could be predicted (or is available) a meaningful way of evaluating the condition of drainage is by determining the area of a curve of water-table elevation (above a prescribed datum) as a function of time. He defined a parameter IE_{30} given by the relation

$$IE_{30} \equiv \int_{t_1}^{t_2} H_{30}dt$$

where IE_{30} is called the "integrated excess water table" above a datum at a depth of 30 centimeters and H_{30} is the height of the water table above the 30 centimeter datum. The IE_{30} values reflect both the average height and the number of days above the datum. The datum of 30 centimeters below the soil surface was selected by Nibler because most water-table elevations during the winter months are above this elevation and because water tables more shallow than this probably have a substantial effect on plant growth.

In summary, the literature indicates that the traditional analytical procedures for predicting water-table fluctuations, which consider the specific yield to be independent of water-table depth, are not useful for the Willamette Valley. Any empirical model which does not use the position of the water table at a particular time as an essential input is also not likely to be reliable for the same reason. A reliable analytical procedure for predicting water-table fluctuations would necessarily require data for soil-water characteristic curves which are usually not available for the designers of drainage systems. Such data require specialized equipment and skills to obtain.

The practical use of analytical procedures for analyzing water-table responses awaits the development of simple field procedures for determining soil-water characteristic parameters. Consequently, an empirical model for predicting water-table fluctuations which does not require soil properties as explicit inputs, but which accounts for the position of the water table at any particular time, should be a significant contribution.

II. MECHANISM OF WATER-TABLE RESPONSE

A water table is defined as the locus of points where the gauge pressure of soil water is zero. The position of a water table in an unconfined aquifer, e.g., a soil, in most cases is continuously changing either upward or downward. When the rate of water entering the soil exceeds the rate at which water leaves the soil, the water table rises, and vice-versa.

The increment of rise or fall of the water table for a given increment of water entering or leaving the soil depends upon the soil-water characteristic curves for any soil layers above the water table. Soil-water characteristic curves are those relating soil-water content to soil-water pressure, an example being shown in Figure 1. The curves illustrated are subject to hysteresis, i.e. they are different for an increasing water content than for a decreasing water content. In fact, an infinite number of curves apply for any particular soil depending upon the water content (or the soil-water pressure) at the time a change in water content occurs. Hysterisis in soil-water characteristic curves has been discussed by many authors including Mualem (1973).

An important fact to note in regard to the relationship between soil-water content and soil-water pressure is that there is a range of negative pressures (relative to atmospheric pressure) over which a negligible change in water content occurs. At somewhat larger negative pressures the water content changes substantially and at still higher negative pressures, the water content appears to approach a minimum so that little additional change occurs with increasing negative pressures.

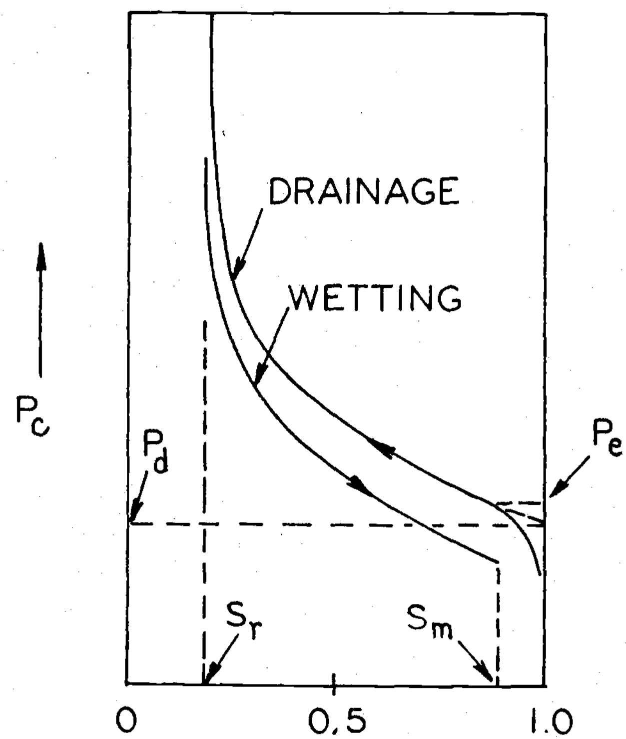


Figure 1. Capillary pressure as a function of saturation

For a soil profile in which the water above a water table is static, the negative pressure of the water is directly related to the elevation above the water table, i.e.

$$P_c = \gamma h \qquad (1)$$

in which P_c is the negative water pressure, called capillary or suction pressure, γ is the specific weight of the water and h is the elevation above the water table. Flow of water, either upward or downward, changes the relationship between P_c and h. Nevertheless, P_c is normally greater with increasing elevation above the water table unless the rate of downward flow exceeds the hydraulic conductivity of the soil.

When water tables are falling, i.e., h is increasing, it is possible to define a soil property called "specific yield" S_y by the relationship

$$Sy \equiv \frac{dV_d}{dD} \qquad (2)$$

in which V_d is the volume drained per unit surface area and D is the depth to the water table. An analogous definition for S_y applies to rising water tables, but the value of S_y is different because of hysteresis.

For a receding water table,

$$V_d = \phi \int_0^D (1-S)\,dh \qquad (3)$$

in which ϕ is the soil porosity and S is the saturation (or fraction of the pore space occupied by water) at any h at a particular time. An analogous expression holds for the volume of water added to a soil per unit of surface area when water tables rise due to water entering the soil faster than it leaves.

Water entering the soil may come from precipitation or irrigation (on the area under consideration) in which case the water moves more or less vertically downward from the surface. Water may also enter the soil by lateral flow from a source at some distance from the area under consideration or by upward flow from an underlying artesian aquifer. Water leaving the soil may move downward by deep percolation through underlying strata or laterally through the soil to open or closed channels, e.g., streams ditches or tile drains. Water may also move upward in response to evapotranspiration at the surface or within the root zone.

In most cases, a combination of vertical and lateral flow occurs, although in particular cases one or the other may predominate. The question of whether vertical or lateral flow predominates in a particular soil depends upon the conductivity of underlying soil, the slope of the soil surface, and the proximity of open or closed channels.

In the Willamette Valley water enters the soil primarily by rainfall which greatly exceeds evapotranspiration during the winter. A slowly permeable B horizon (hydraulic conductivity varying from nearly zero to 0.15 cm/hr) in combination with the high rainfall produces shallow water tables during the winter.

Where artificial drains are absent, the water table often reaches the surface and ponding or runoff sometimes occur. Some lateral flow also occurs within the soil above the B horizon, as well as deep percolation through the B horizon. In soils with artificial drains, lateral flow is greatly speeded up by the presence of perforated tubes positioned on a slight slope at more or less regular spacing and at a depth equal to or slightly greater than the depth to the B horizon.

If the drains are placed at sufficiently close spacings and at appropriate depths, the water table may not reach the surface. In any case, the major route whereby water leaves the soil is laterally toward the drains, and percolation through the B horizon is a negligible factor in the drainage of the soil.

Evidence for the latter conclusion has been found by R. H. Brooks (1974). Essentially all of the water entering the soils of the Amity and Dayton series (on hydraulically isolated plots) appeared as discharge from the drains. Drain discharge slightly exceeded the precipitation on some of the plots, indicating an artesian condition below the B horizon.

Water-table fluctuations (for cases in which lateral flow towards parallel drains is the predominant mechanism) have often been analyzed using a linearized version of the Dupuit-Forchheimer equation. The assumptions employed in this theory include the following:

(1) Flow is one-dimensional and horizontal toward the drains.

(2) The flow rate is proportional to the slope of the water table.

(3) The thickness of the flow section equals the mean elevation $\bar{D}$ of the water table above a relatively impermeable layer and is very thick compared to fluctuations in the elevation of the water table.

(4) The specific yield and the hydraulic conductivity of the soil within the flow section is independent of the depth of the water table assuming that the water table remains above the impermeable layer.

(5) The specific yield is independent of whether the water table moves upward or downward.

(6) The soil above the water table has zero conductivity and contains no drainable water.

(7) The water table is always below the root zone so that the specific yield is unaffected by the soil drying below field capacity.

Based on these assumptions, the flow equations becomes

$$V = -K\bar{D}\,\frac{\partial y}{\partial x} \qquad (4)$$

In which V is the volume of flow per unit time per unit length of drain in a direction perpendicular to the drain, K is the hydraulic conductivity of the soil, $\bar{D}$ is the average depth of the water table above the impermeable layer and y is the actual depth of the water table at the distance x from the drain. A material balance equation is given by

$$\frac{\partial V}{\partial X} = -S_y\,\frac{\partial y}{\partial t} \qquad (5)$$

Combining equations 4 and 5 gives

$$\alpha\,\frac{\partial}{\partial x}\left(\frac{\partial y}{\partial x}\right) = \frac{\partial y}{\partial t} \qquad (6)$$

where α is $K\bar{D}/S_y$ and is treated as a constant. Equation 6 is known as the Glover equation (1954) and has been used frequently by the U.S. Bureau of Reclamation.

Although the first two assumptions are probably satisfied to a sufficient degree by soils of the Willamette Valley catena with artificial drains, the other assumptions are not valid approximations in these soils. Unfortunately most of the research to arrive at improved equations for describing water-table fluctuations has been concerned with eliminating the first three assumptions and less research has been concerned with the others.

However, Kirkham (1951) conducted research relating to assumption 4 in so far as this assumption is invalidated by stratification of the soil within the flow region. Kirkham discussed the significance of varying hydraulic conductivities and thickness of the upper layer. McWhorter and Duke (1976) have presented a modification of Equation 6 which employs a variable of S_y and a variable value of K for the flow region above the water table.

An expression for S_y as a function of water-table depth was suggested by Duke (1972). The expression is valid for a case in which the water table moves in one direction only, such as downward. Duke's analysis is as follows:

$$V_d = \phi_e \int_0^D (1-S_e)\,dh \qquad (7)$$

in which ϕ_e is the "effective" or "drainable" porosity of the soil and S_e is the fraction of the drainable pore space occupied by water at any particular time. The drainable porosity is related to total porosity ϕ by the relation

$$\phi_e = \phi\ (S_m - S_r) \qquad (8)$$

in which S_m is the maximum fraction of the total pore space occupied by water in the field, some entrapped air being always present, and S_r is the minimum value of S corresponding to the water content at field capacity when practically all of the drainable water has been removed.

To simplify his analysis, Duke made the assumption that the water table falls very slowly so that the distribution of water pressure within the soil profile is as for a static case so that Equation (1) holds. He assumed further that the fraction S of the total pore space occupied by water remains equal to S_m over a range of elevations above the water table to an elevation of h_d. Duke also assumed that the value of S_e above h_d is given by the approximation of Brooks and Corey (1966). Substituting h for p_c and h_d for the "bubbling pressure head", the relation of Brooks and Corey becomes

$$S_e = \left(\frac{h_d}{h}\right)^{\lambda} \qquad (9)$$

for $h \geq h_d$, where λ is an empirical exponent related to the pore-size distribution of the soil. According to Brooks and Corey, λ is less than 2 for soils having a wide range of pore sizes (such as well-aggregated clays) and greater than 2 for soils with little structure. The values of both λ and h_d are different with rising water tables than with falling water tables.

Substituting Equation 9 into Equation 7, performing the indicated integration, and evaluating the derivative indicated by Equation 2 yields

$$S_y = \phi_e \left(1 - \left(\frac{h_d}{D}\right)^{\lambda} \right) \qquad (10)$$

for $D \geq h_d$. Equation 10 is revealing in that it shows that when h_d is close to the same value as D, especially when λ is small, S_y is much less than ϕ_e rather than being equal to ϕ_e as assumed in traditional analyses.

For cases in which D is large compared to h_d, especially if λ is large as for sandy soils, Equation 10 indicates that S_y is nearly equal to ϕ_e. The latter situation can be visualized by an examination of Figure 1. When the water table is at a substantial depth so that the upper part of the profile is at a large value of p_c, a further drop in the water table results in an equivalent depth of the profile being drained from the maximum to the minimum saturation.

In the Willamette Valley, however, the depth of the water tables is usually small during winter months. Values of λ also tend to be small because of the well-aggregated clay soils. For these reasons, the values of S_y are likely to be very sensitive to the value of D at any particular time and may vary from practically zero when $D \leq h_d$ to ϕ_e when $D >> h_d$.

For a rising water table encroaching into a root zone (at water contents less than field capacity) the value of S_y may be greater than ϕ_e. In the latter case, Duke's expression for S_y is not applicable. Furthermore, the values of both λ and h_d are affected by hysteresis so that the use of Equation 10 for fluctuating water tables may be impractical.

However, it is evident that water-table response in the Willamette Valley is affected by the position of the water table at any particular time. This is shown by the data plotted in Figure 2 indicating the response of the water table to rains. The data show that the water table rises following a rain, but the amount of rise depends upon the elevation of the water table at the time the rain occurred.

The procedure of McWhorter and Duke (1976) employed the Brooks-Corey relationship (1964) for conductivity as a function of negative pressure (assuming a static distribution of pressure) in the form

$$K_e = K_m \left(\frac{h_d}{h}\right)^{3\lambda+2} \qquad (11)$$

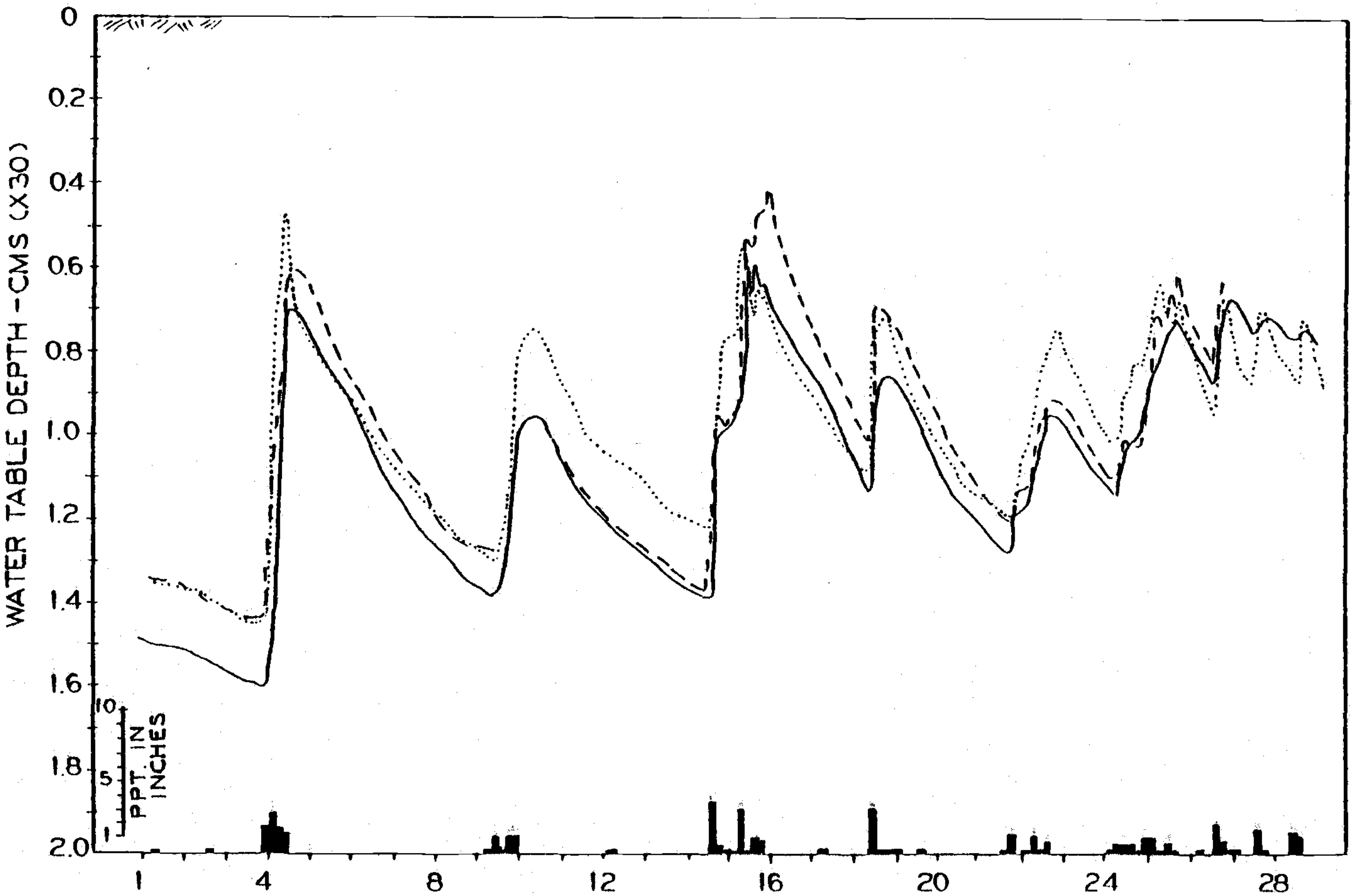


Figure 2. Curves of typical water table fluctuations in Willamette Catena soils

in which K_e is the actual or "effective" conductivity at any particular water content less than S_m and K_m is the conductivity when $h \leq h_d$. Using Equation 11 along with Equation 10, McWhorter and Duke modified Equation 6 to account for both flow and storage of water in the capillary region above the water table.

The procedure of McWhorter and Duke requires values of both λ and h_d as well as K_m for the particular soils under consideration. This implies that soil-moisture characteristic curves as well as conductivity values must be available. Since values of h_d and λ are likely to vary depending upon whether the water table is rising or falling, the use of the McWhorter-Duke equation for fluctuating water tables would be very difficult if not impossible. Moreover, it would not be valid for cases in which water tables move upward into soils at water contents below field capacity.

It is apparent from the mechanism of water-table fluctuations described above that an adequate analytical procedure for predicting the fluctuations is not now available. Furthermore, because of the extreme complexity of the soil-water system as it exists in the Willamette Valley soils, it is not likely that an adequate analytical procedure will be found. In order to be valid, an analytical procedure would have to use (as input) an infinite set of soil-water characteristic curves to include the effect of hysteresis.

For this reason, an analytical approach was not attempted in this thesis. The method employed was to construct a mathematical model using (as input) direct observations of water-table response to rainfall for particular fields. The observations are made over a relatively short period of time and the model is used to predict the fluctuations over any desired period for which rainfall records are available or for which a rainfall pattern can be assumed. The method of prediction takes into account both the initial position of the water table and whether the water table is rising or falling.

III. PROCEDURES AND RESULTS

After reviewing the existing models for predicting water-table fluctuations, it was decided to develop a new model using as input only such data as can be determined easily in the field, namely, the initial position of the water table and rainfall as a function of time. The rainfall amounts for successive 5-minute increments of time were used. Another objective was to make it possible to reconstruct water-table conditions which have occurred in the past and to predict those that might occur in the future so that the drainage needs of particular soils can be evaluated. The model might also be useful for drainage design, but this study did not include any work on finding drainage designs for the plots for which water-table data were available on naturally drained soils. This is suggested as an extension of this study by another investigator. The model could also be useful for retracing the water-table elevations if records were lost, with the help of a few days data for water-table elevations and rainfall amounts.

The equation describing water-table height as a function of time for different elevations in the soil profile during drawdown was used in a computer program to develop a model simulating the water-table elevations resulting from drainage either naturally, artificially or due to depletion of soil moisture by evapotranspiration. The equations using initial water-table position and rainfall amount to predict water-table positions for rising water tables were also incorporated in the model. The equations for rising water tables are different from those for the falling water table because of the hysteresis effect discussed in Chapter 3.

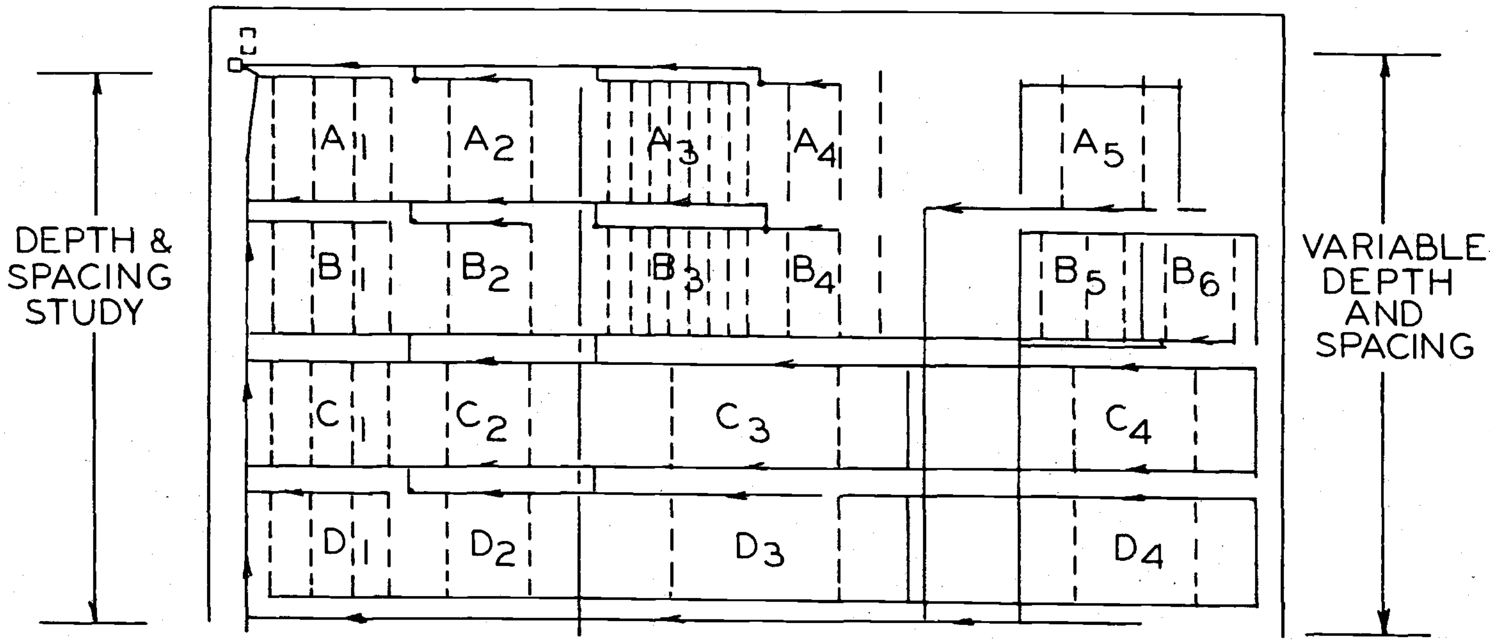
Water-table records for this study were taken from a large field drainage facility which was installed during the summer of 1969, located in the southern half of the Willamette Valley about 6.4 kilometers west of Lebanon, Oregon. This facility was located on a 7.3 hectare tract of typical Dayton soil for the purpose of studying drainage requirements and drainage design.

A system of drains of various designs was installed at various depths and spacings to study drainage performance on Willamette catena soils. Plastic drain tubing was installed at a uniform grade in plots A_1 to A_4 and B_1 to B_4. Clay tiles were similarly installed in the remainder of the plots with the help of a conventional wheel trenching machine. The spacing of drains in each plot has been selected such that the ratio of the spacing to the depth is equal to 10, 20, 30, and 40. The A and B rows have plastic drain lines installed at a depth of 0.46 meters. These plots also have vertical plastic barriers to hydraulically isolate plots from one another. The plot layout is shown in Figure 3.

Water-table data from Jackson Farm, for different plots, for the last seven years, were examined visually and as a result it was decided to analyse rising and falling branches of water-table fluctuations separately.

In these analyses a curve fitting method was used to extrapolate data from short period observations to obtain predictions for water-table fluctuations during other periods for which only rainfall data

DRAIN TILE LAYOUT FOR DRAINAGE FACILITY, JACKSON FARM.



Plot	Depth	Spacing	Drain diameter	Plot width
C_1	0.91	9.14	0.10	36.58
C_2	0.91	18.29	0.10	36.57

Figure 3. Arrangement and location of drains for depth and spacing study (dimensions in meters)

and initial water-table position have been measured.

3.1 Rising Curves

Individual rising branches of different curves were used for statistical analysis. From an examination of the data, empirical expressions were selected for the purpose of testing their ability to fit the data. Results, based on an excellent multiple correlation coefficient (R^2), indicated that a multiple linear regression involving two variables, namely initial water-table height (x) (datum 60 centimeters below soil surface) and rainfall amount (y), provides an appropriate representation of the rising branches. This equation fitted by a "least squares" procedure has the form:

$$z = a_0 + a_1x + a_2y$$

where z represents the final position of the water table and a_0, a_1, and a_2 are appropriate regression coefficients.

The output of the program included (1) input data, (2) means and variances, (3) simple correlation coefficients r_{xy}, r_{yz}, r_{zx}, (4) least square estimates, a_0, a_1 and a_2, (5) the square of the multiple correlation coefficient R^2 and (6) the maximum and minimum values of x, y and z.

3.2 Falling Curves

Based on the data available for recession curves, the "least square fit-exponential function" was found to represent the curves best, based on best coefficient of determination.

The equation

$$y = ae^{bx}$$

was linearized into the form

$$\ln y = \ln a + bx$$

$$\text{or } Y = A + bx$$

using a linear regression with

$$b = \frac{n\ \Sigma xY - (\Sigma x \Sigma y)}{n\Sigma x^2 - (\Sigma x)^2}$$

and

$$A = (\Sigma Y - b\Sigma x/n;\ a = e^A)$$

The correlation coefficient is given by

$$r = \frac{n\Sigma xY - (\Sigma x\Sigma Y)}{\sqrt{n\Sigma x^2 - (\Sigma x)^2 \quad n\Sigma Y^2 - (\Sigma Y)^2}}$$

$$r^2 = (r)^2 \text{ (Coefficient of determination)}$$

(1) Means, (2) Variances, (3) Coefficient b and a, (4) Correlation exponential linear, and (5) x maximum, y maximum, x minimum, y minimum, and range of x and y.

In this analysis, x is the time elapsed since the water table started falling from the initial position in the absence of rainfall. Recession equations depend on the position of the water table in the soil and type of soil, in the absence of rainfall. When water ponding occurred, the water table starts receding one hour after the rainfall was over. This factor was also incorporated in the computer program. Figures 4 and 5 indicate that the computer model predicted the water-table fluctuations reasonably well.

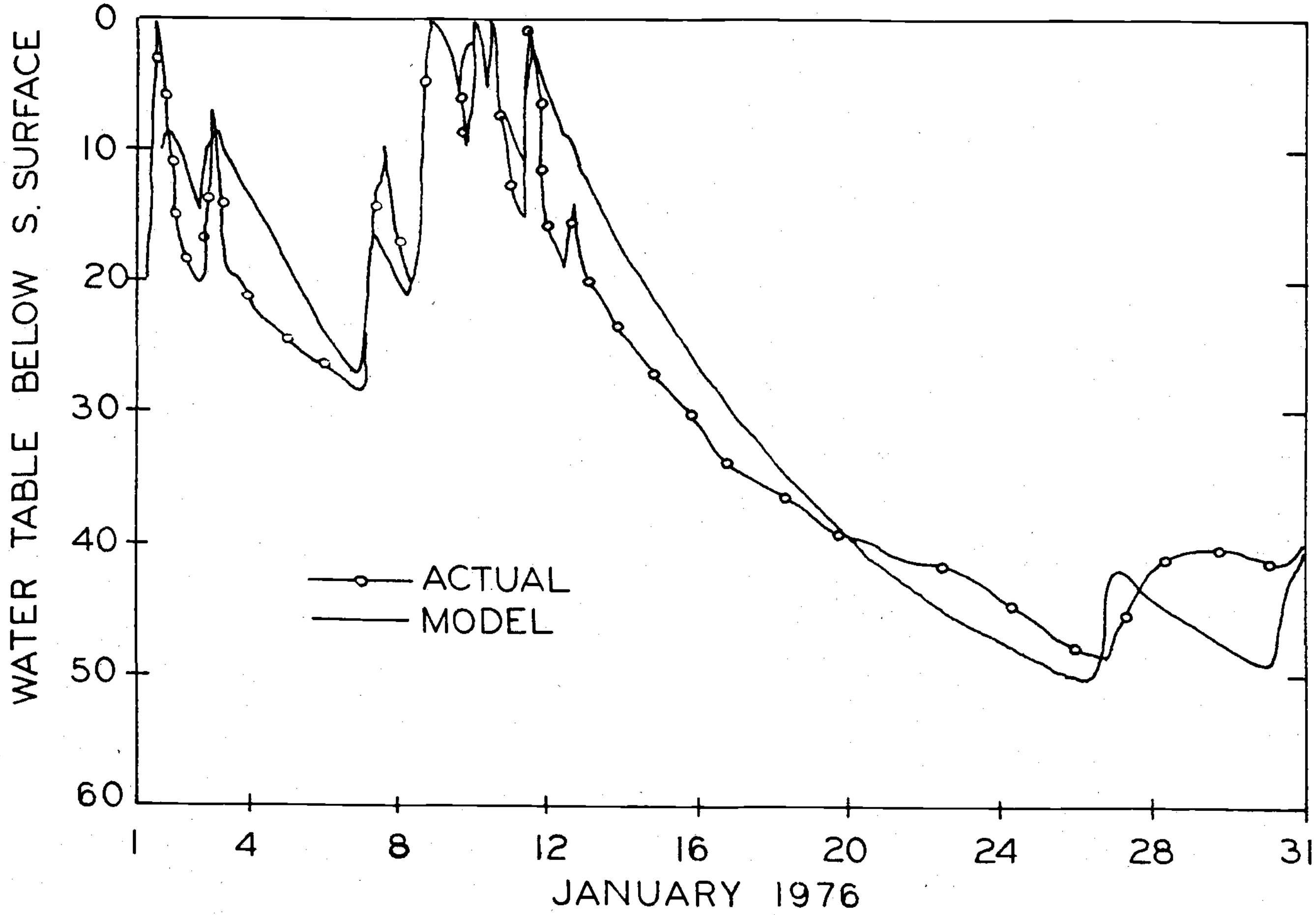


Figure 4. Actual and predicted water table fluctuations for the month of January, 1976

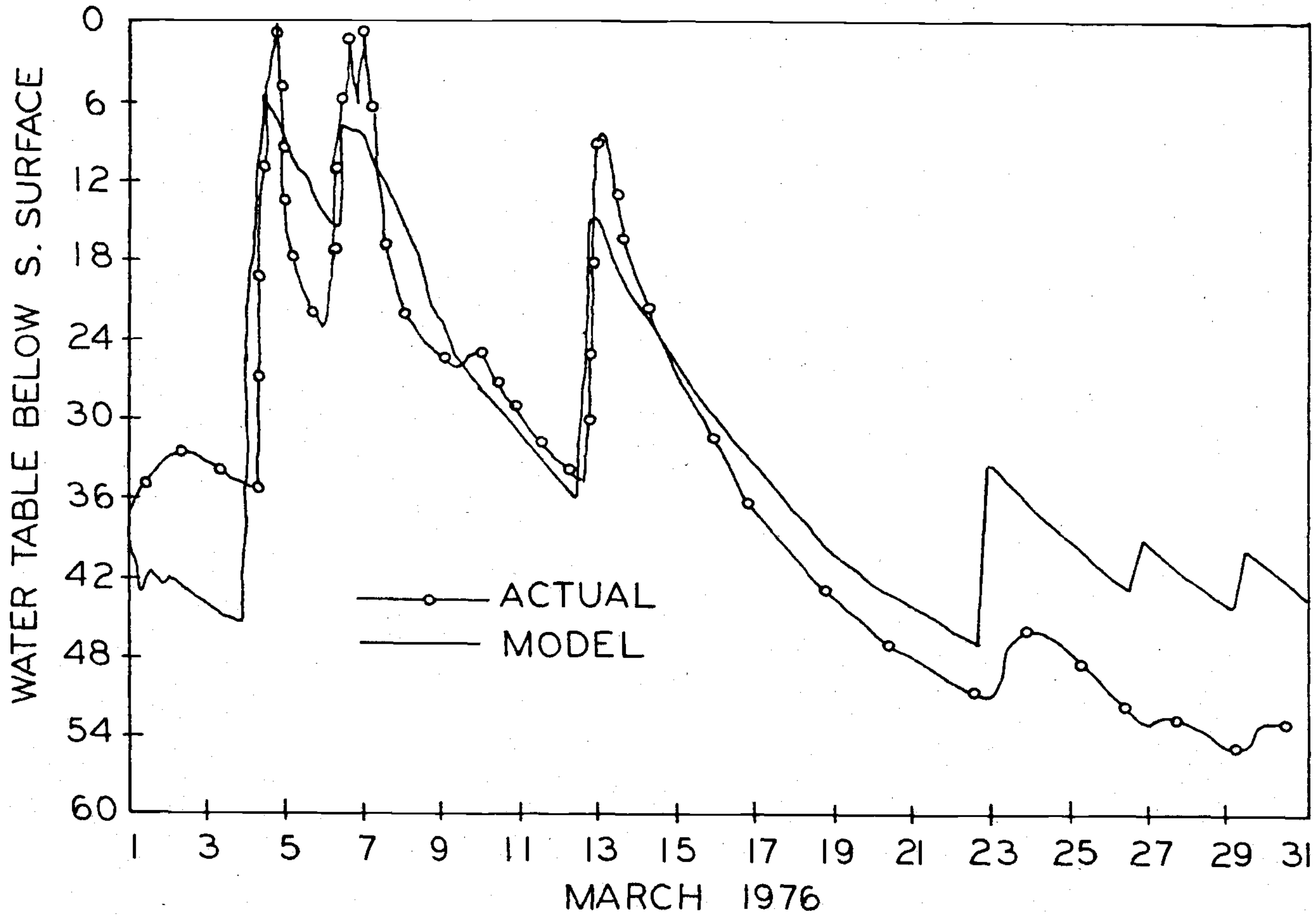


Figure 5. Actual and predicted water table fluctuations for the month of March, 1976

3.3 Collection of Data

After finding that the model results closely approximate the measured data, it was decided to consider plots C_1 and C_2 for this study. The plots dimensions and the diameters, depths and spacing of drains are shown in Figure 3.

Water tables were continuously recorded with a Stevens type F recorder model 68 from November 1976 to the first week of June 1977, at the mid-point between drains in an observation well 12.7 centimeters in diameter. The continuous water-table curves from the Stevens recorders were reduced in scale, and redrawn for the periods considered for constructing or testing the model with the help of a Hewlett-Packard calculator, digitizer, tape recorder, and x-y plotter. The 30-centimeter datum line was used to integrate the curve values with the help of a digitizer.

Rainfall was continuously recorded by a tipping-bucket rain gauge connected to an event recorder. The smallest rainfall considered in the analysis was 0.0254 centimeters (.01 inch). A standard precipitation gauge (22 centimeters) was also used in case the tipping bucket rain gauge stopped.

Fifteen days of data (8 February - 22 February 1977) was used to construct the computer model for C_1 and C_2 plots when these were being drained artificially. On March 10, 1977, the plots were plugged with the help of a water bladder to simulate naturally drained conditions as shown in Figure 6. (The bladder was lowered through the riser in the collector drain and was allowed to fill with water. The bladder

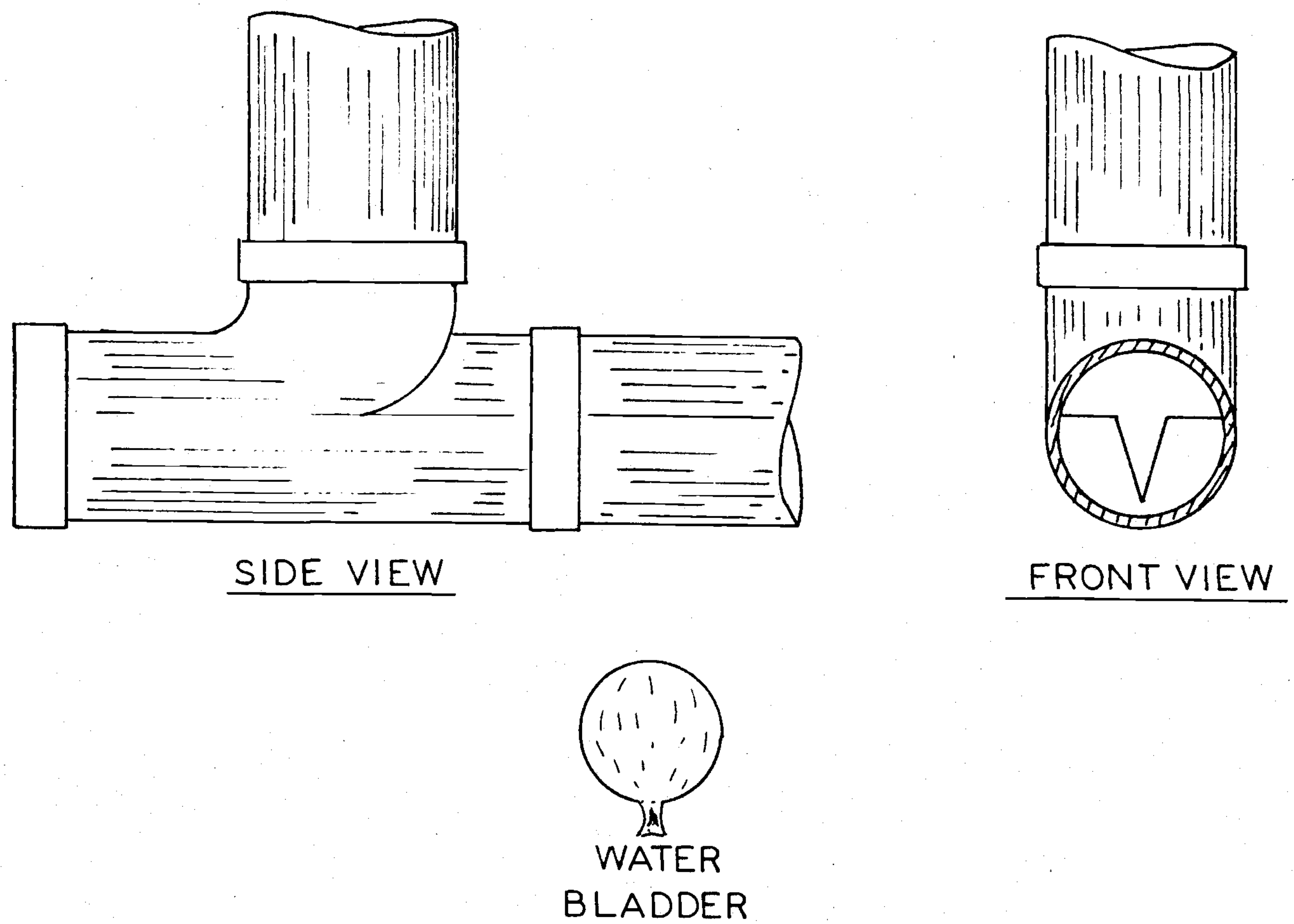


Figure 6. Scheme of treating the plots C_1 and C_2 under natural and artificial drainage

full of water plugged the collector drain so no water left the plot from drains and hence the plot could be treated as if it were under natural drainage conditions.) The data for the period from April 20 to May 26, 1977 were used to construct and test the model for plots under natural drainage conditions.

The approach used for construction of the model is shown in Appendix 1. The following assumptions were made in this study.

(1) The average water-table heights measured at the mid-point of a plot are representative of the water-table elevations in the plot as a whole.

(2) Water-table fluctuations are primarily affected by initial position of water table and rainfall pattern and the condition of drainage as measured by IE_{30} values.

(3) Response of the water table takes into consideration specific yield.

(4) All of the important variables have been taken into account. It did not account for initial wetness of the soil, type of crops, etc. which may affect the position of water-table elevation. It also does not take into consideration how long the water table had been at a particular point and the effect of evapotranspiration in reducing the water content below field capacity.

(5) A rising water table follows the multiple regression equation dependent upon the initial position of water table and rainfall amounts.

(6) A receding water table follows, the exponential equation dependent

upon the initial position of the water table and for the time a new event of rainfall does not occur.

(7) When ponding occurs, it takes one hour for the water table to start receding, after the rainfall stopped.

3.4 Development of Computer Model for Artificial-Drainage Conditions

The model was constructed from plots C_1 and C_2 for 1977 by using fifteen days of data in February under artificial drainage conditions. The analysis was run on the water-table records for the two plots, C_1 and C_2. A multiple regression analysis was made separately for each plot. The water table depth below the soil surface and the water table rise for a given rainfall event were incorporated into the computer program as given by the following equations, for plots C_1 and C_2:

For C_1,

WTHT(IT) = WTHT(IT-1) + (37.345-0.674*WTHT(IT-1)+ 18.317 * RAIN(IT)) (1)

For C_2,

WTHT(IT) = WTHT(IT-1)+(64.963-1.097*WTHT(IT-1)-37.675*RAIN(IT)), (2)

where WTHT(IT) is the final position of the water table at time (IT), and WTHT(IT-1) is the initial position of the water table before rainfall or additional rainfall took place in the 5-minute period.

These equations are different for the two plots since the soils have different characteristics and tile spacings for plots C_1 and C_2 are 9.14 meters and 18.29 meters, respectively.

The equations for the recession curves for the water table during times of no precipitation are given by the following equations for the plot C_1 and C_2.

The general expression for recession curves is

$$WTHT(IT) = WTHT(K) * A * e^{b(IT-K)} \qquad (3)$$

where WTHT(IT) is the final position of the water table, and WTHT(K) is the initial position of the water table after the rainfall event was over. For plot C_1, the values of A and b for various ranges of water-table depths below soil surface (datum being 60 centimeters below soil surface) are given below.

	Range of depth below soil surface	A	b
FOR	60 cm - 57 cm	1.075	-.003
PLOT	57 cm - 54 cm	1.026	-.003
C_1	54 cm - Datum	0.998	-.003
FOR	60 cm - 57 cm 57 cm - 54 cm	0.992 0.974	-.004 -.002
PLOT	54 cm - 51 cm 51 cm - 48 cm	1.001 0.992	-.003 -.004
C_2	48 cm - Datum	0.992	-.006

The above coefficients are the input functions for the model described earlier. In addition to the water-table position as a function of time, IE_{30} values were also calculated. The actual water table and the computed water-table depths as a function of time are shown in Figures 7 and 8. In Figure 9, accumulated IE_{30} values are shown plotted in Figure 8 for plot C_2. These data show that the IE_{30} values are within 5% of the actual IE_{30} values.

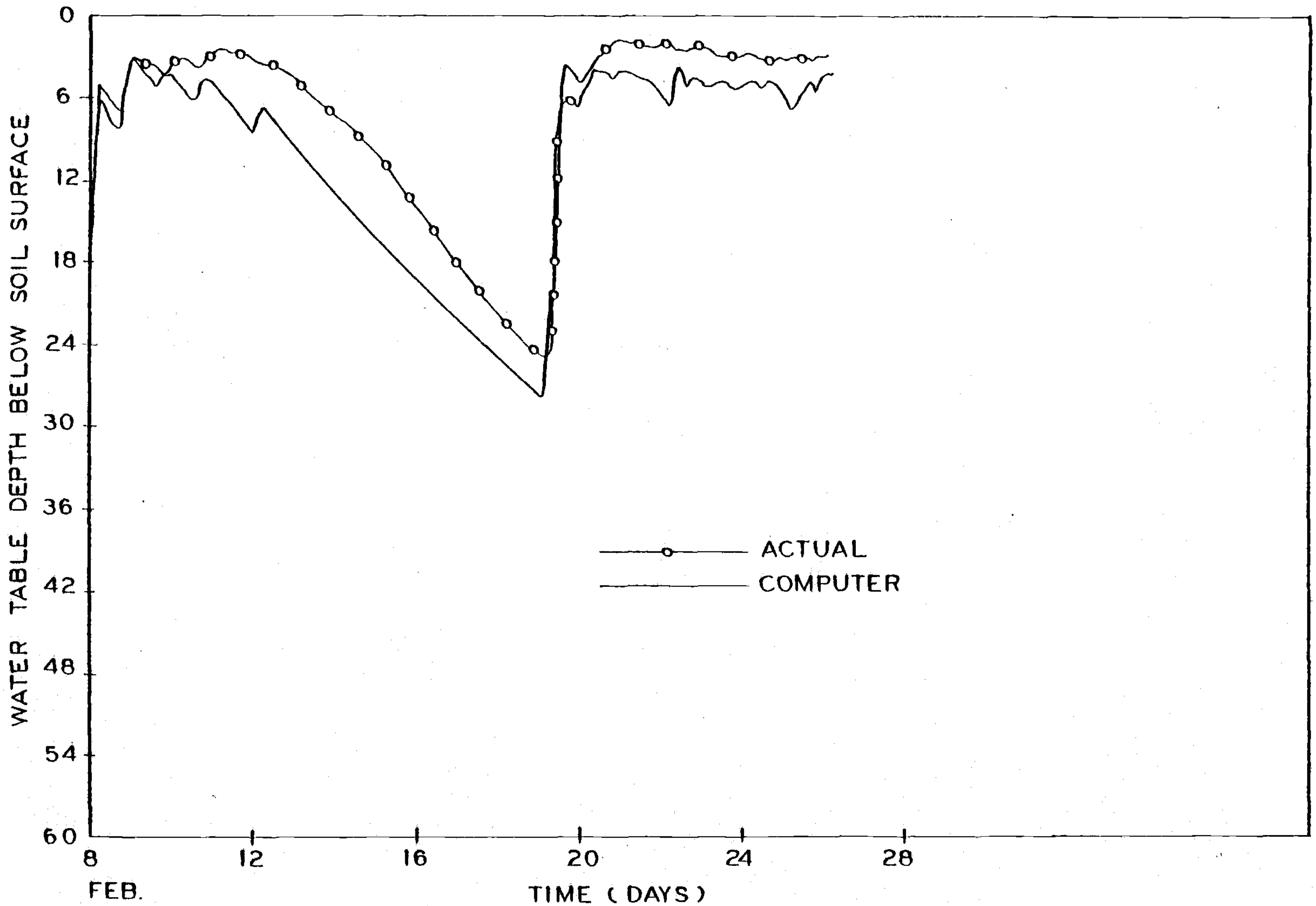


Figure 7. Actual water table and computed water table depths as a function of time for plot C_1 for artificially drained conditions

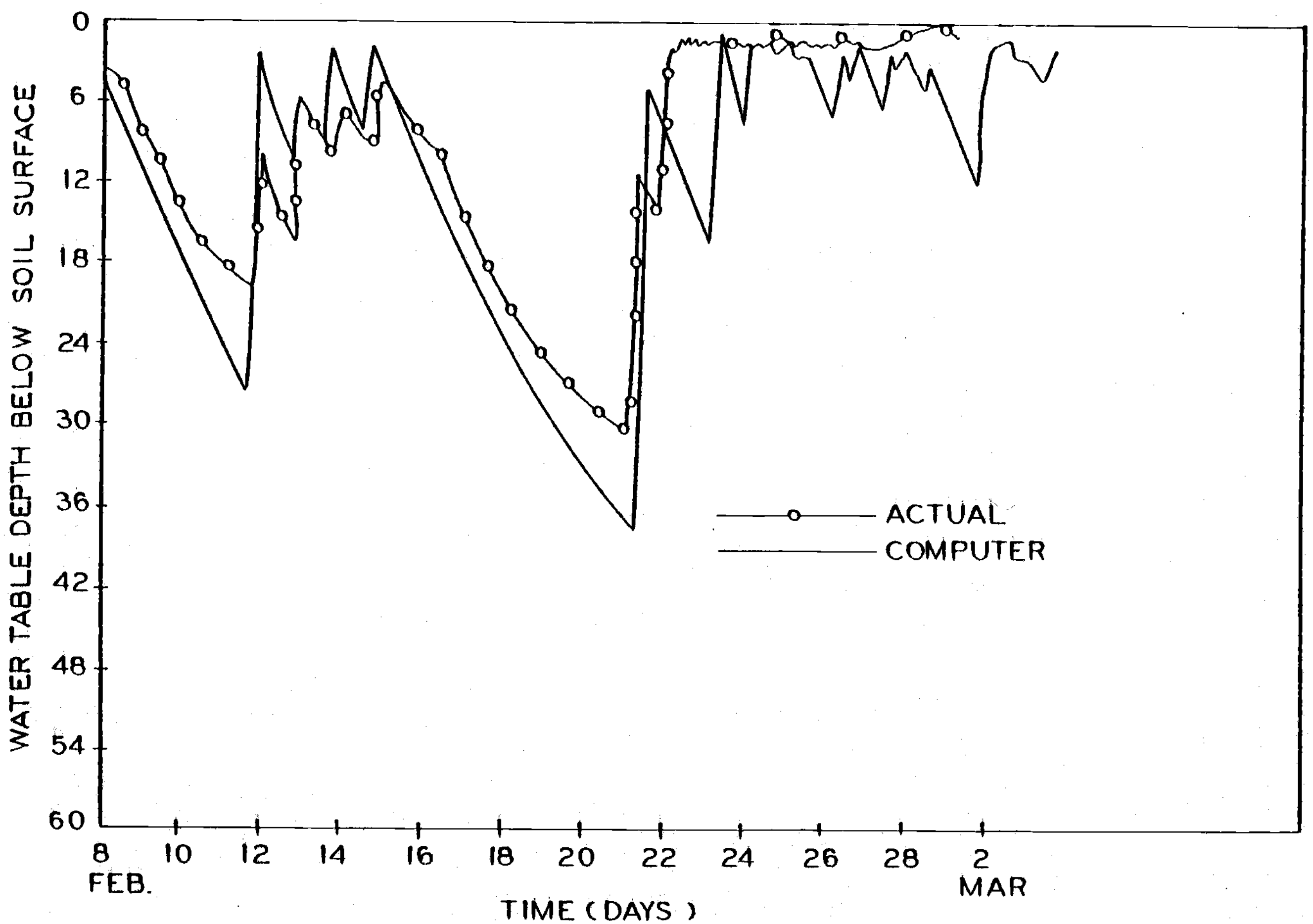


Figure 8. Actual water table and computed water table depths as a function of time for plot C_2, under artificially drained conditions

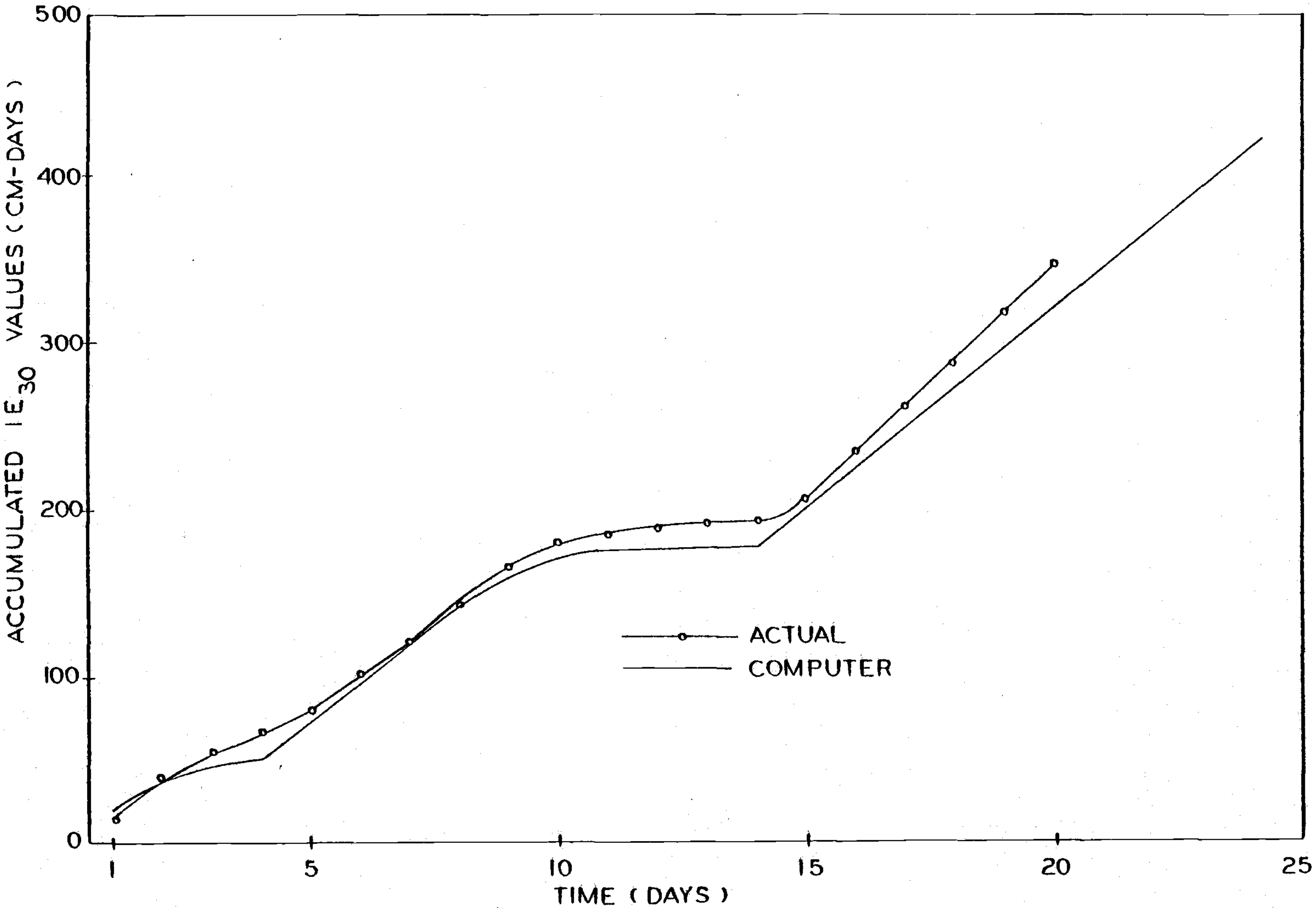


Figure 9. Accumulated IE_{30} values plotted against time for the time period of 20 days for plot C_2

Water table-time curves obtained from the experimental plots were compared with the water table-time curves computed from the model. The actual values for the drainage plots were compared with IE_{30} values computed from the drainage model.

3.5 Development of Computer Model Under Natural Drainage Conditions

For the natural drainage conditions, i.e., without artificial drains, water-table data for a 40-day period beginning March 10, 1977 were used to construct the model. The data were obtained from plots C_1 and C_2 by plugging the drains so that no flow took place from the soil to the clay tile drains. The plot behaved, therefore, as if it had no artificial drains. These data were analyzed and the resulting equations for the rising water table are:

For plot C_1,

WTHT(IT) = WTHT(IT-1)+(29.766 - 0.54*WTHT(IT-1)+15.642*RAIN(IT). (4)

For plot C_2,

WTHT(IT) = WTHT(IT-1)+(27.091-0.501*WTHT(IT-1)+15.726*RAIN(IT). (5)

Recession coefficients in the general equation are as follows:

	Range of depth below soil surface	A	b
PLOT C_1	60 cm - 58 cm	1.047	-.005
	58 cm - 54 cm	1.004	-.001
	54 cm - 39 cm	1.024	-.004
	39 cm - 24 cm	1.006	-.003
PLOT C_2	60 cm - 54 cm	1.031	-.006
	54 cm - 48 cm	0.998	-.005
	48 cm - 36 cm	0.974	-.003
	36 cm - 24 cm	0.998	-.003
	24 cm - Datum	0.980	-.003

Terminology used here is the same as used previously. The results of the model are compared with actual data shown in Figures 10 and 11. The accumulated IE_{30} values for the actual data are compared with those computed from the model in Figures 12 and 13. These IE_{30} values were within 7% of the actual experimental data.

3.6 Testing the Computer Model for Artificial Drained Plots

The model described above was tested for periods of time during 1977 in order to determine how well the model will perform under other rainfall conditions. Drainage data were obtained from plot C_1 and C_2 between April 20 and May 24, 1977. Rainfall data from the tipping bucket rain gauge were used as the only input to the drainage model for plots C_1 and C_2. Water-table depths as a function of time for plots C_1 and C_2 are shown in Figures 14 and 15. The output from the drainage model is also shown in these figures as indicated. In Figure 14, the drainage model does not adequately describe the water-table fluctuations in plot C_1. The actual water-table recession curves are much steeper than those predicted by the drainage model. The comparison of the drainage model with the data from plot C_2 is much more favorable. The reason for the discrepancy between the model and the experimental data shown in Figure 14 is not apparent. It is conceivable that the lack of agreement is because the model does not include evapotranspiration. However, any evapotranspiration occurring on plot C_1 would likewise occur on plot C_2 and would have a similar effect on both plots.

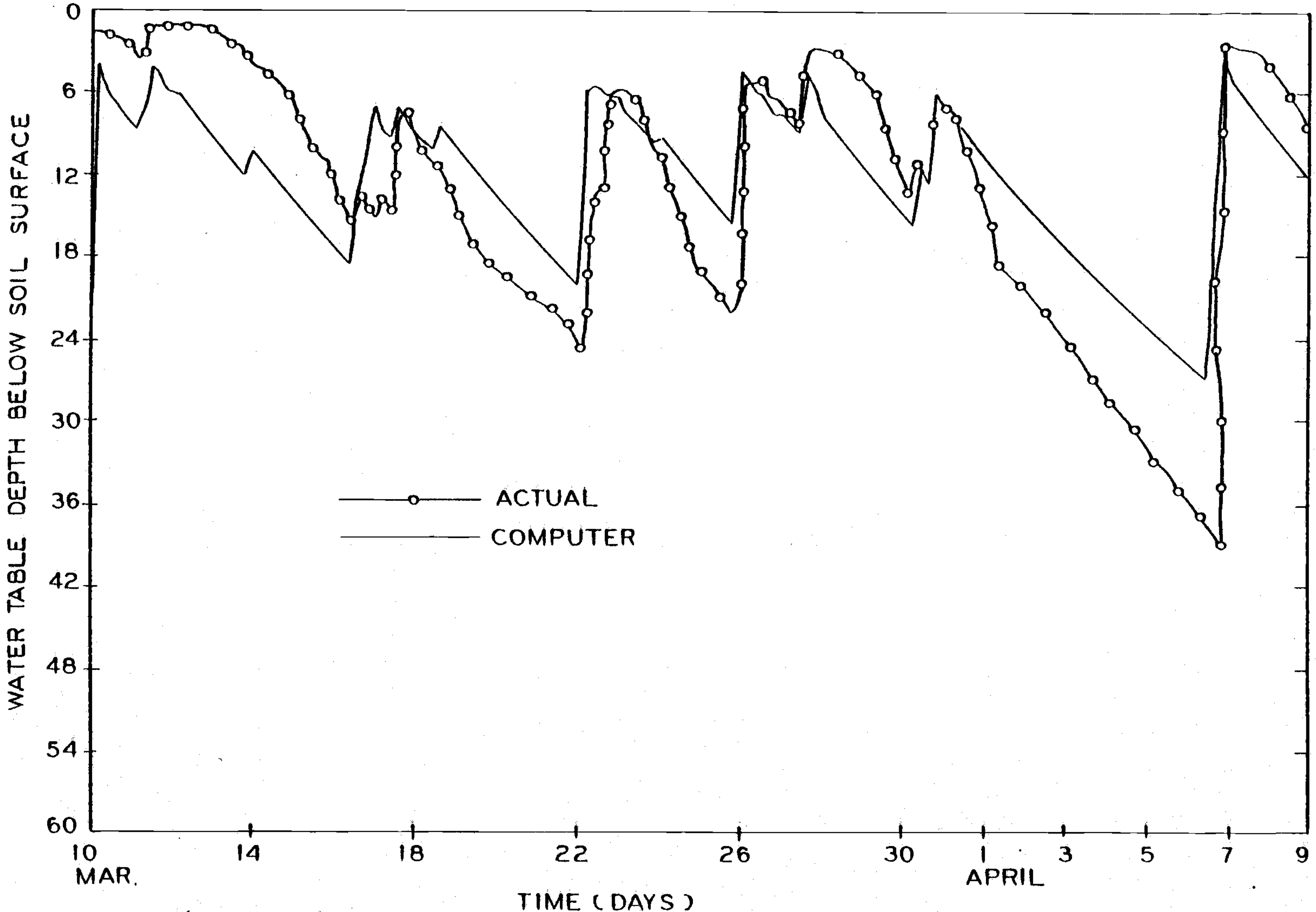


Figure 10. Actual water table and computed water table depths as a function of time for plot C_1, under naturally drained conditions

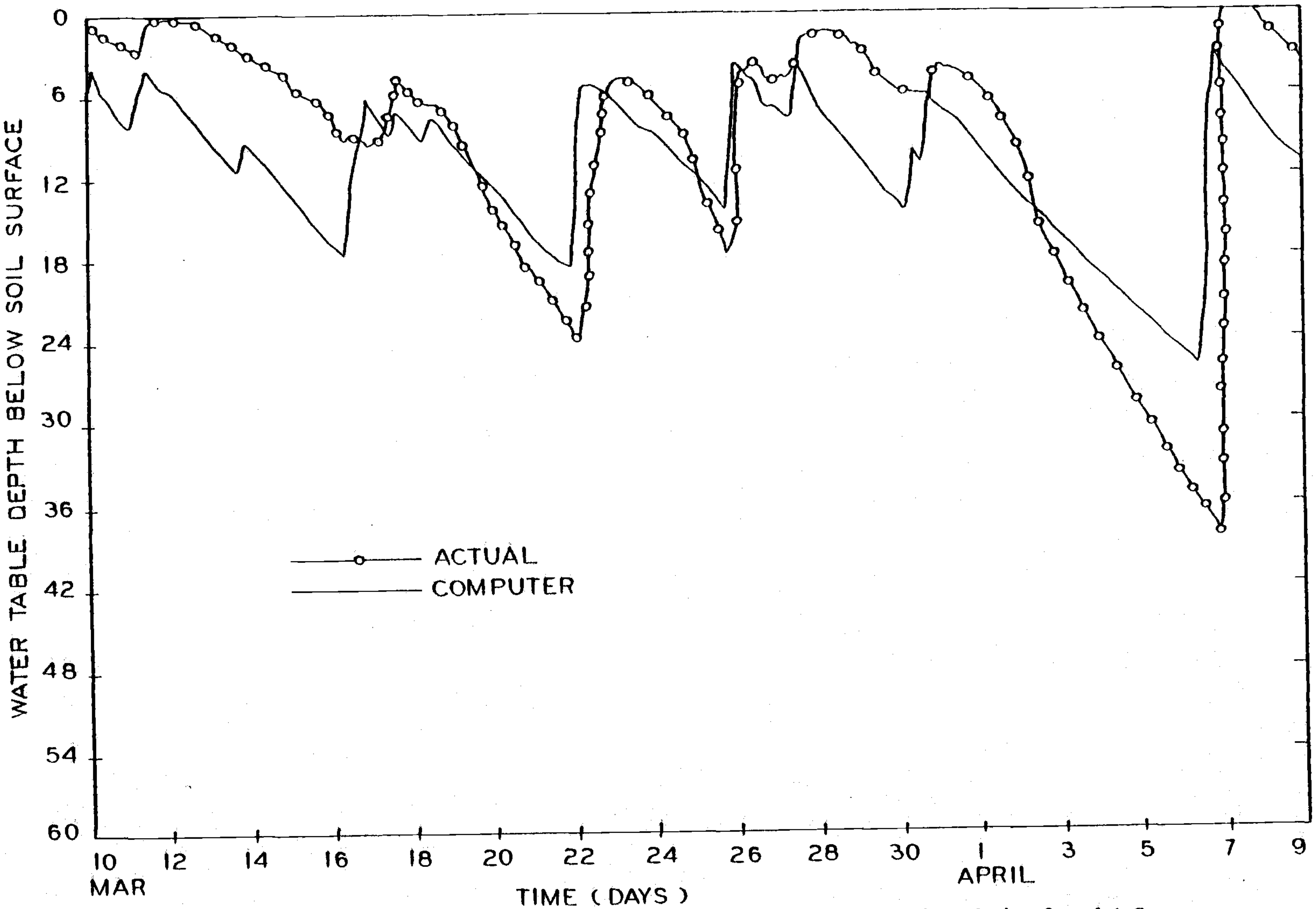


Figure 11. Actual water table and computed water table depths as a function of time for plot C_2, under naturally drained conditions

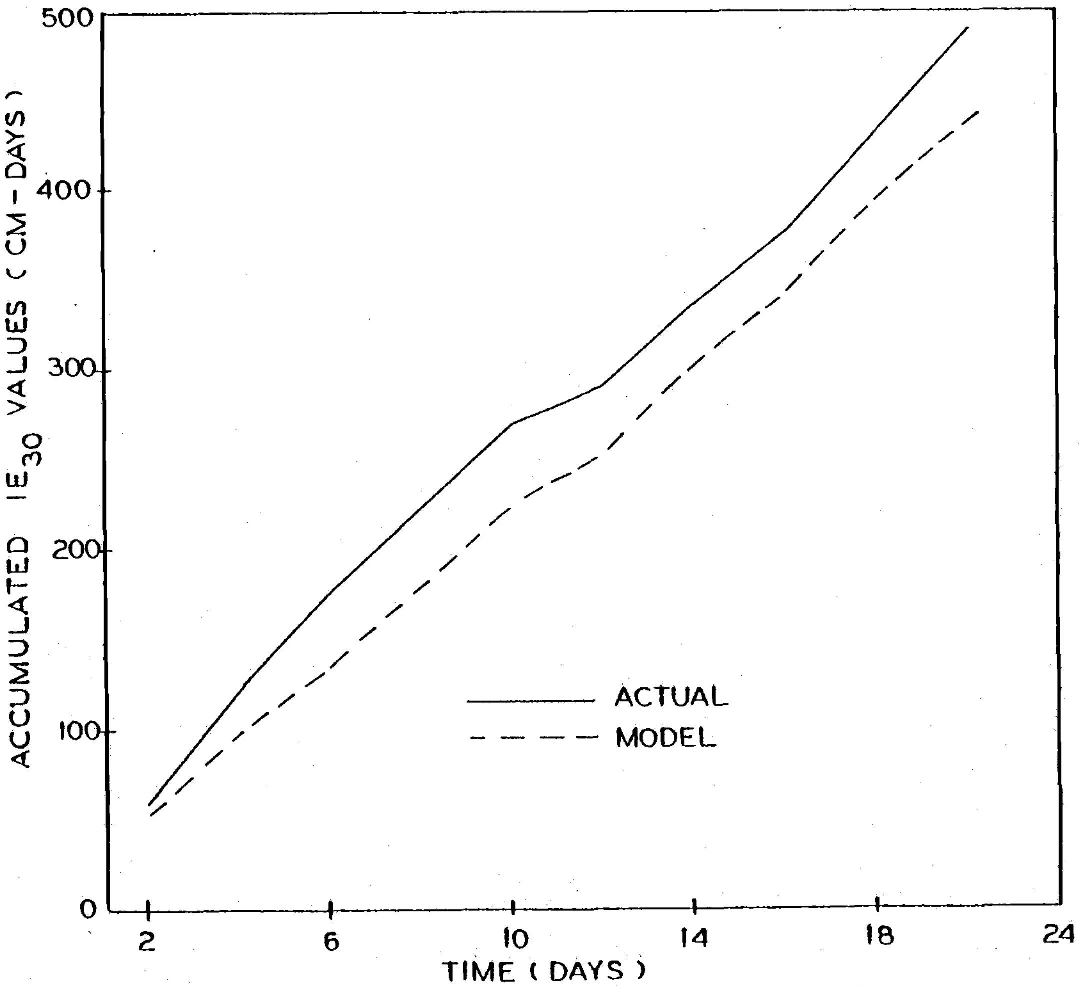


Figure 12. Accumulated IE_{30} values plotted against time for plot C_1

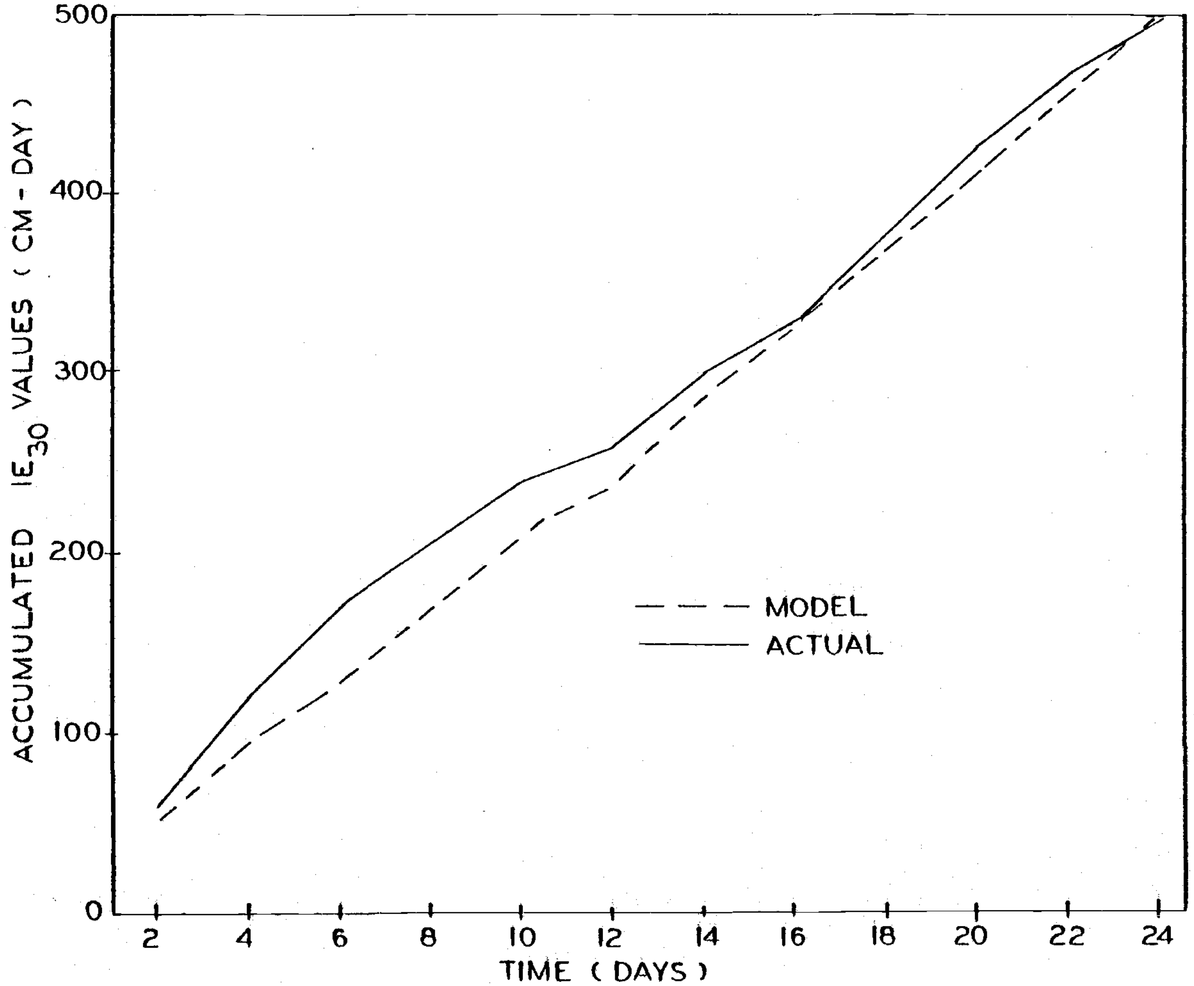


Figure 13. Accumulated IE_{30} values against time for plot C_2

3.7 Testing the Computer Model for Water-Table Fluctuations on Naturally Drained Plots

To test the model under the conditions of no artificial drainage, the drains in plots C_1 and C_2 were plugged as they were when the data were obtained for construction of the model. Only two weeks of data beginning May 24, 1977 were available for testing the model. Considerable difficulty occurred in obtaining the data for these plots during this time period. The water-stage recorder at various times did not operate properly. A limited amount of data for these two plots are shown in Figures 16 and 17, where actual water-table depths as a function of time are compared with results from the computer drainage model.

3.8 Prediction of Water-Table Fluctuations for 1970-71 with the Drainage Model for Artificially-Drained Plots

The drainage model, using the data for February 1977, was used to predict the water table for data that were taken six years earlier, 1970-71, to further test its validity. The results of this comparison are shown graphically in Figures 18,19,20 and 21. It shall be noted that there is a considerable difference between the performance of the drainage model and the actual water-table data. The actual IE_{30} values compared with IE_{30} values compiled from the model are shown in Figure 22. The IE_{30} values for the model differed from the experimental data by 300 cm-days, which is about 15% of the total IE_{30} values for the period considered. Researchers have noted over a period of

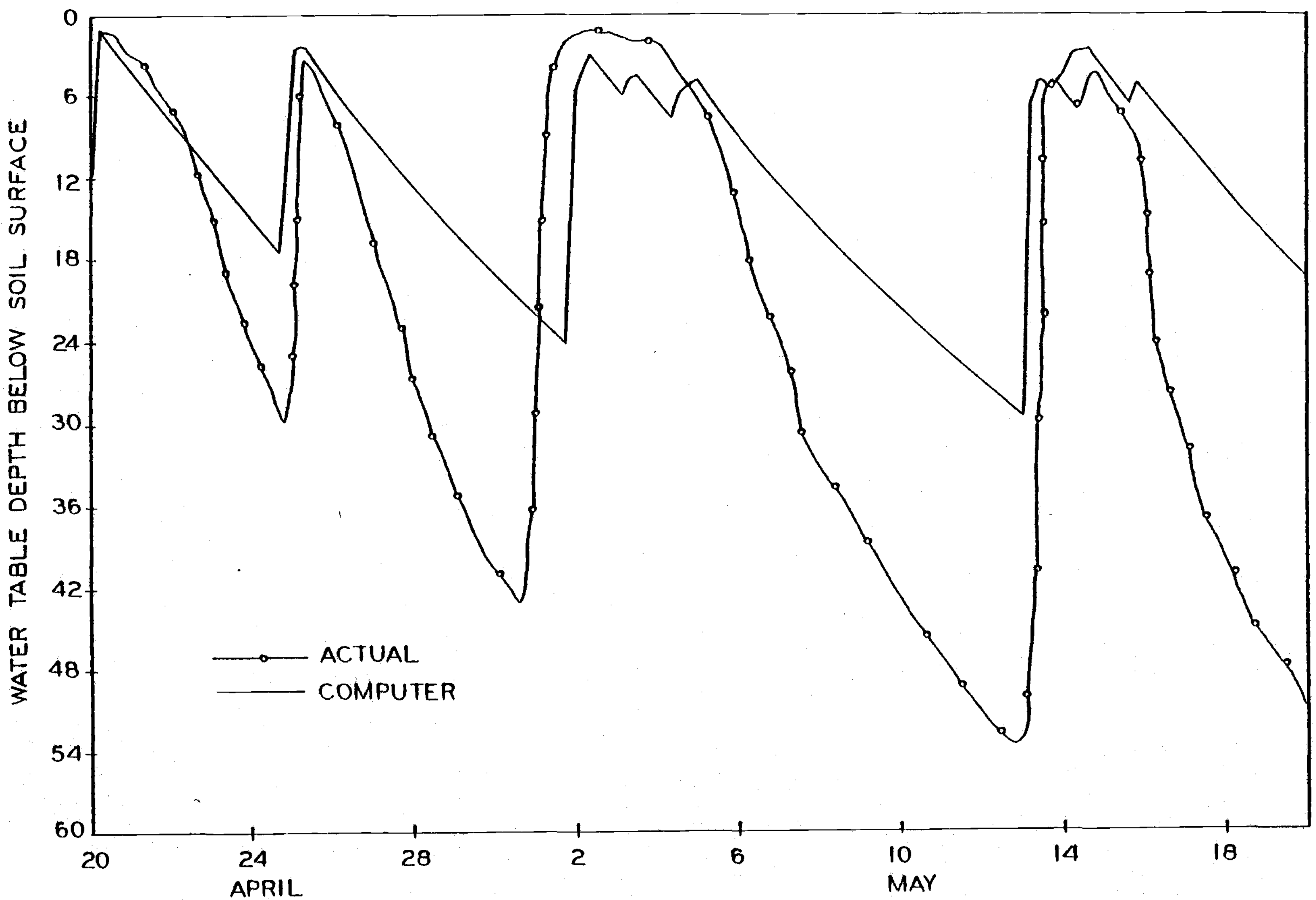


Figure 14. Actual water table and computed water table depths as a function of time for plot C_1 while testing for artificially drainage model.

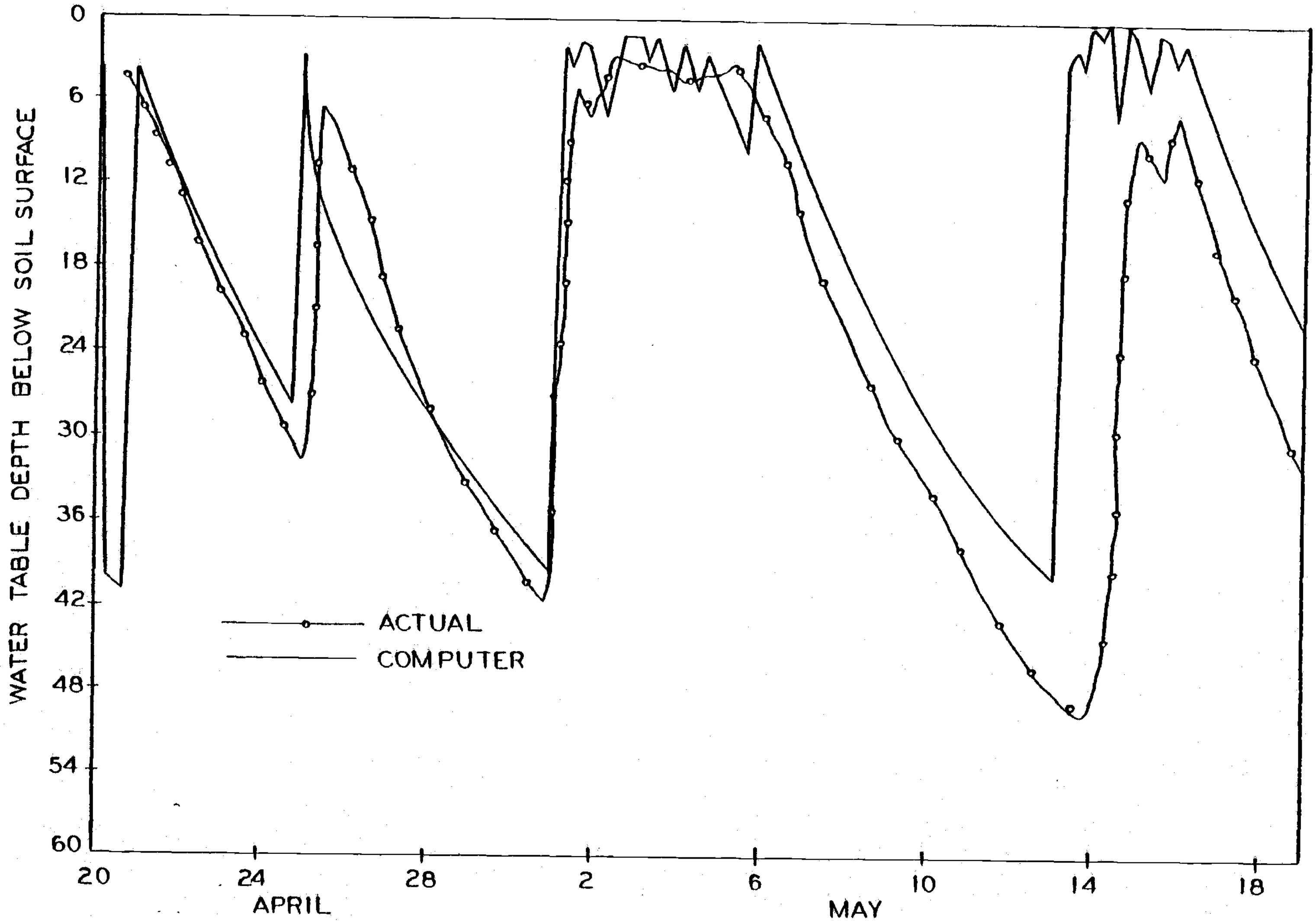


Figure 15. Actual water table and computed water table depths as a function of time for plot C_2 while testing for artificially drained model.

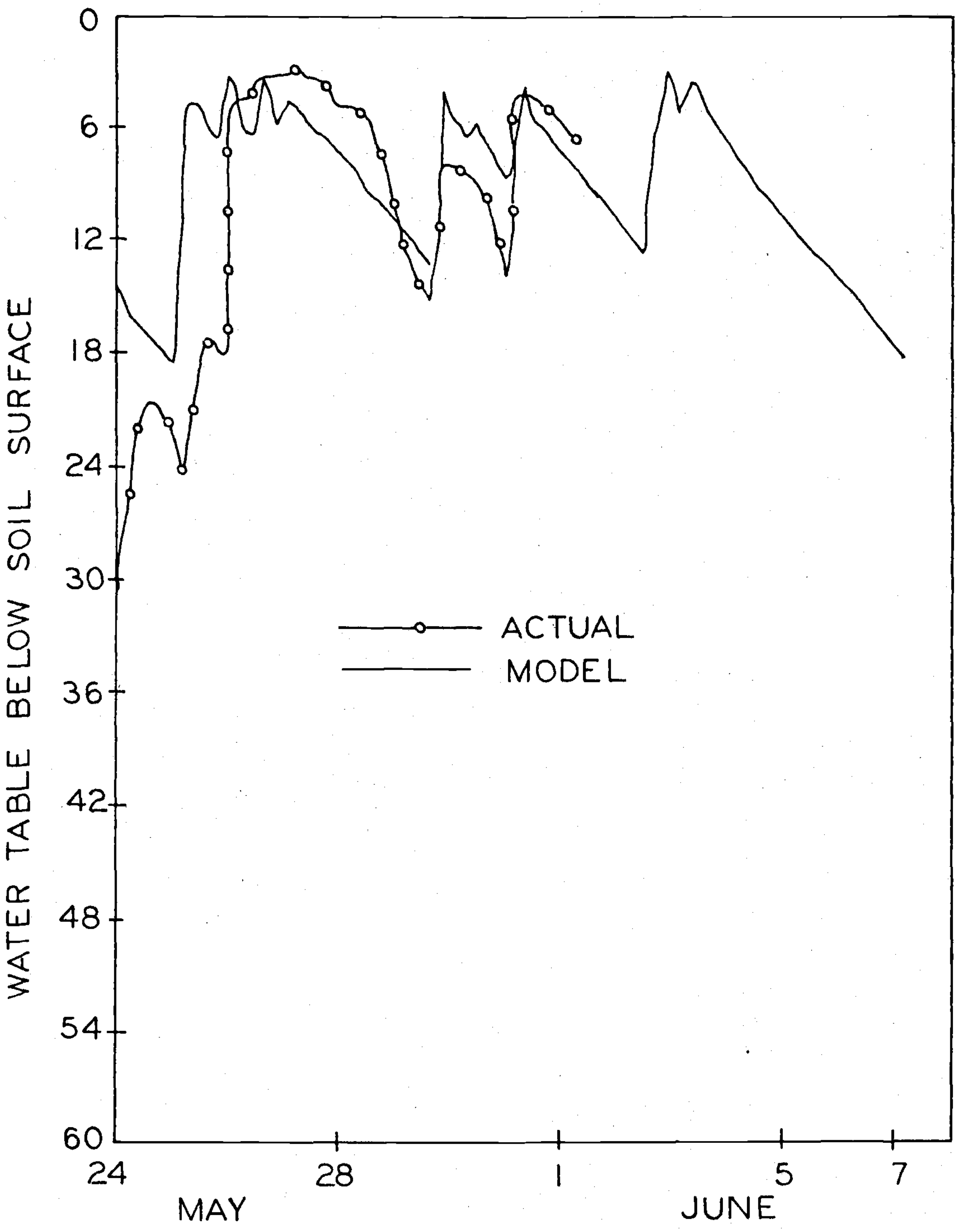


Figure 16. Actual water table and computed water table depths as a function of time for plot C_1 while testing for naturally drained conditions.

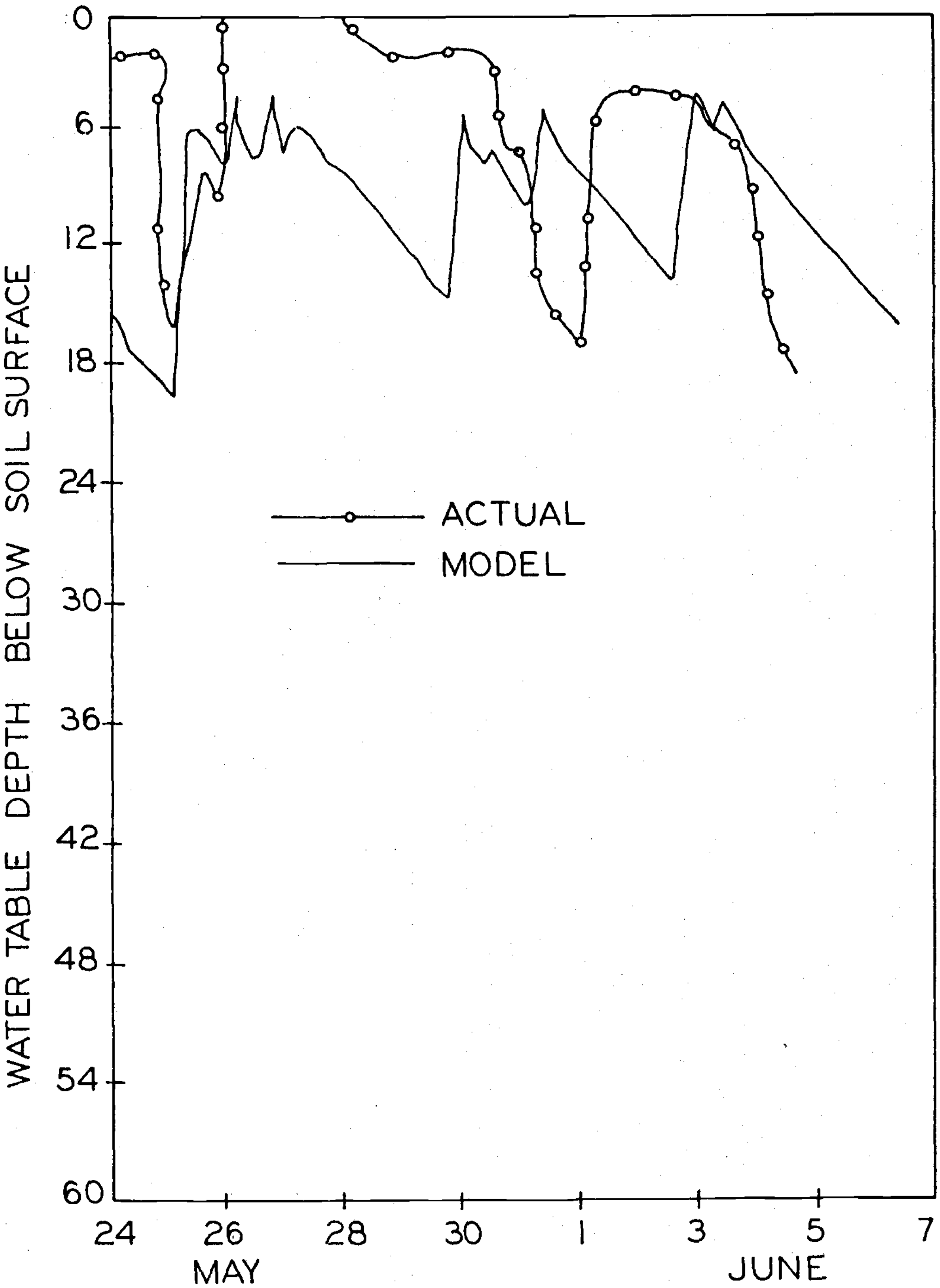


Figure 17. Actual water table and computed water table depths as a function of time for plot C_2 while testing for naturally drained conditions.

time that the irrigation well near the drainage plots flowed due to artesian conditions. Therefore, it was suspected that artesian conditions may have affected the construction of the model using data for 1977 with the result that the IE_{30} values were overestimated. Consequently, the drainage model was modified by using the actual drainage data for the month of February 1971, which have possibly included the artesian effects.

3.9 Prediction of Water-Table Fluctuations with the Drainage Model Constructed from the Data Obtained in February 1971

Data for twenty days during February 1971 for plot C_1 were utilized to construct a drainage model, using the method described earlier.

The rising water-table equations for this drainage model are:

WTHT(IT)=WTHT(IT-1)+34.885 - 0.652*WTHT(IT-1)+23.361*RAIN(IT). (7)

Receding water table constants for different equations are given below:

	Range below soil surface	A	b
FOR	at 60 cm depth	0.940	-.004
PLOT	60 cm - 54 cm	0.901	-.003
C_1	54 cm - Datum	0.974	-.004

Terminology in this case is the same as used before. The values of R^2 for the different equations were between 0.94 and 1.00. Using the data for these twenty days in February 1971, the model was operated for the period December 1970 through March 1971 for plot C_1.

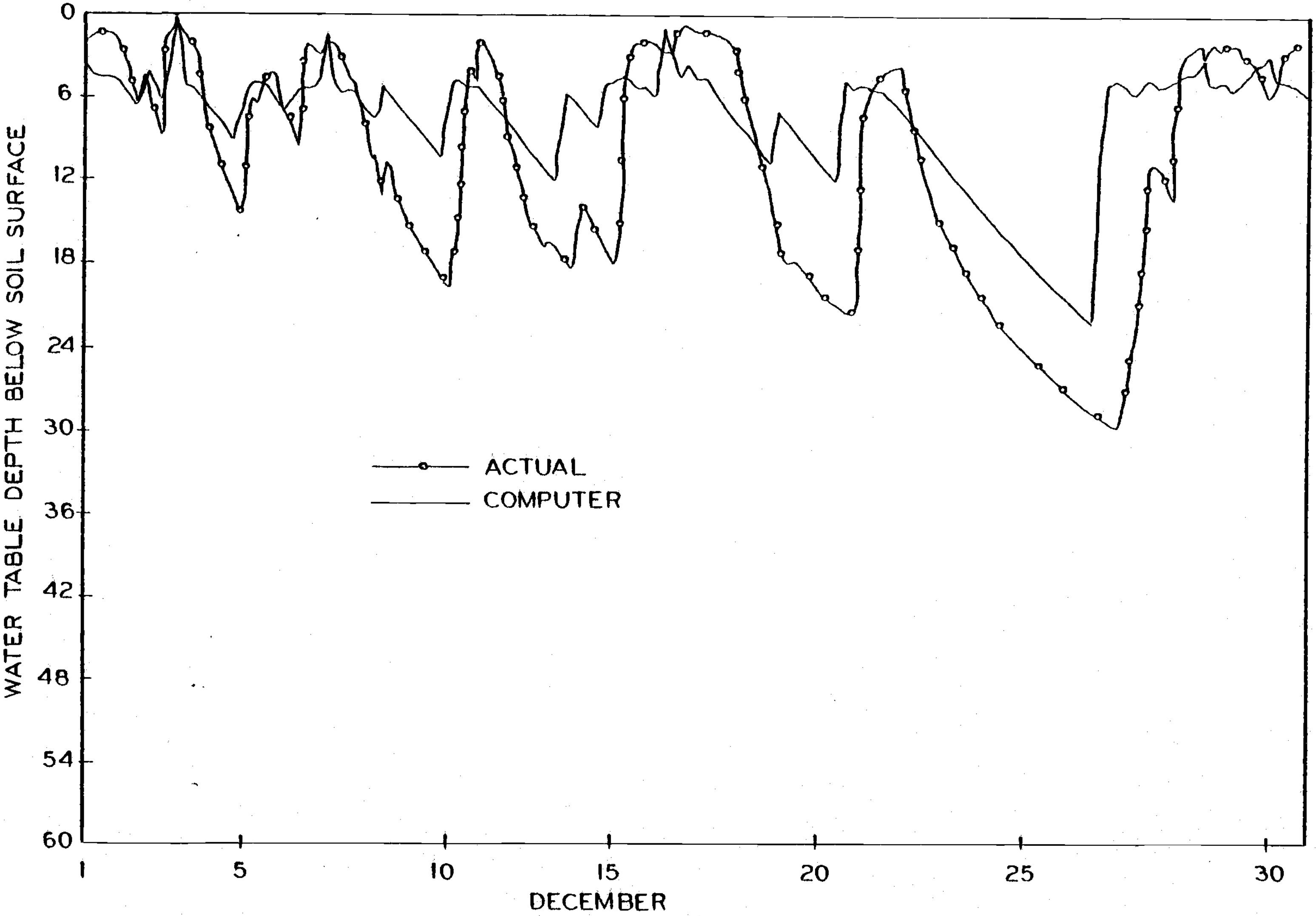


Figure 18. Actual water table and computed water table depths as a function of time for plot C_1 for the month of December 1970, under artificial drainage conditions.

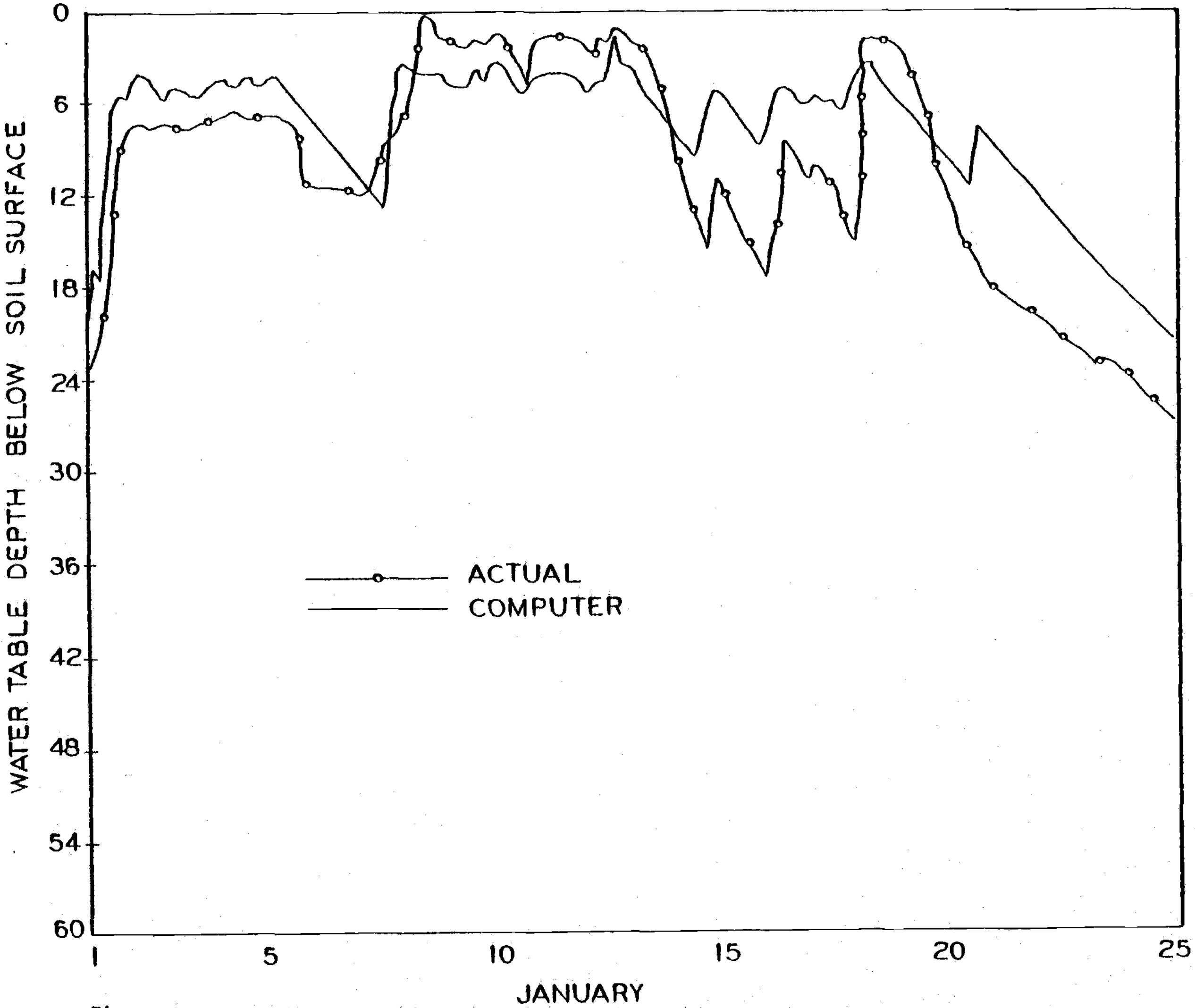


Figure 19. Actual water table and computed water table depths as a function of time for plot C_1 for the month of January 1971, under artificial drainage.

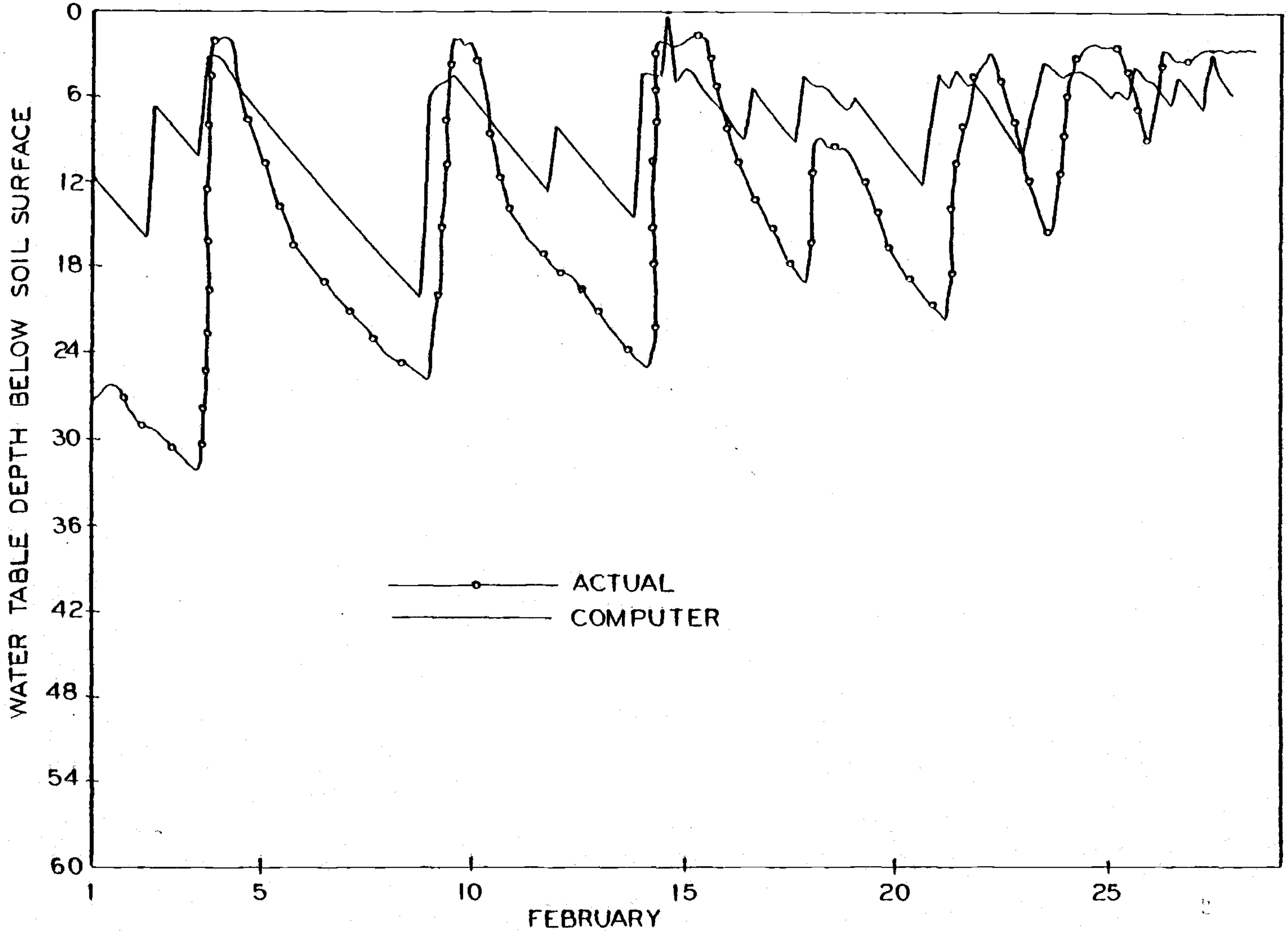


Figure 20. Actual water table and computed water table depths as a function of time for plot C_1 for the month of February 1971, under artificial drainage conditions.

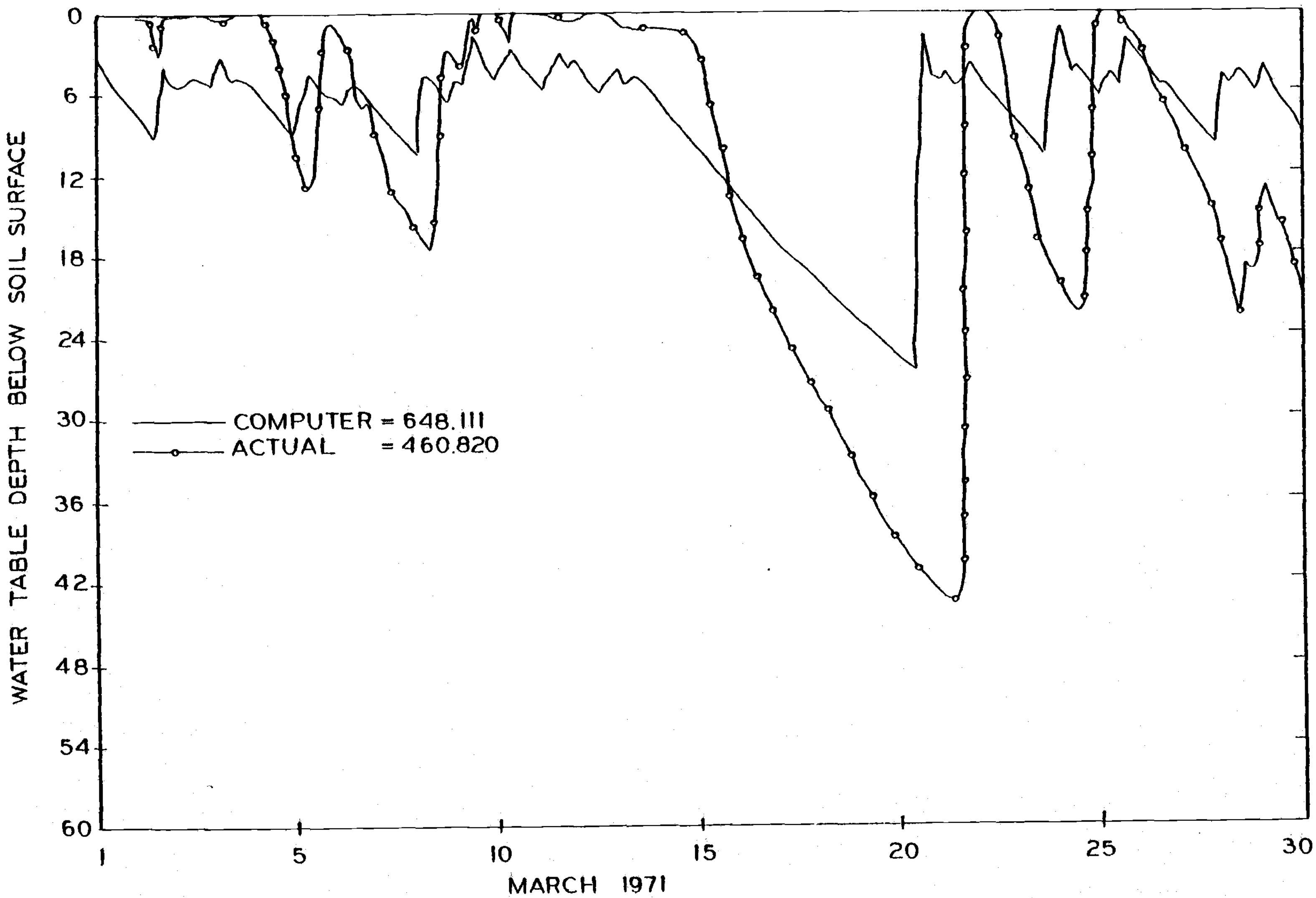


Figure 21. Actual water table and computed water table depths as a function of time for plot C_1 for the month of March 1971, under artificial drainage.

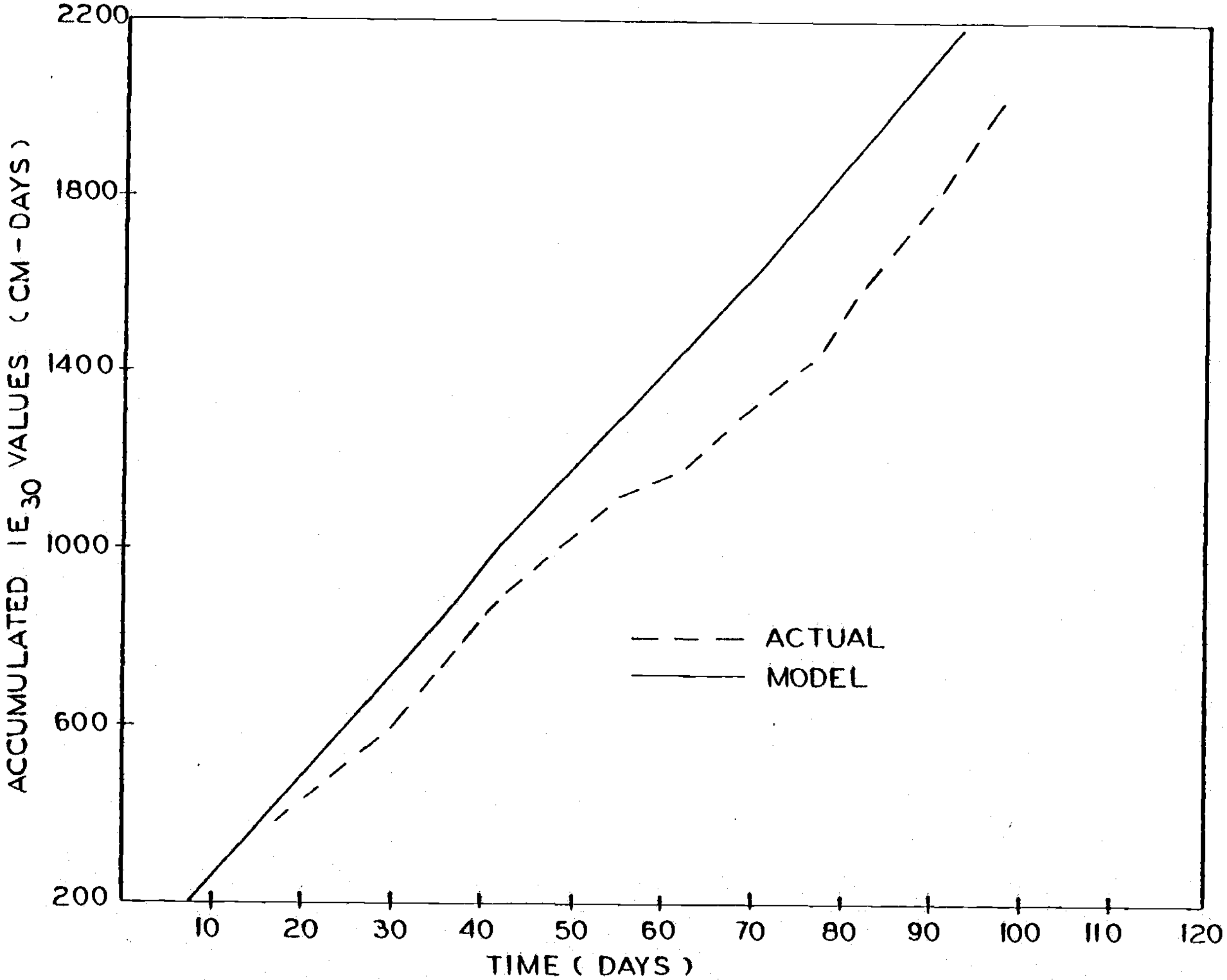


Figure 22. Accumulated actual IE_{30} values compared with IE_{30} values (using data for 1971) for the drainage model as a function of time.

The results are shown in Figures 23,24,25 and 26 respectively. Where water-table depths as a function of time as calculated by the model were compared with the actual measured experimental data. In Figure 27, the accumulated IE_{30} values for this period of time are compared with experimental data as well. A comparison of the data from plot C_1, for February 1971 and February 1977 are shown in Figure 28. The results of the model constructed for 1971 are compared with the actual experimental water-table data. These results are in relatively close agreement, but indicate that there are some differences in drainage conditions between these years. These differences may possibly be due in part to artesian conditions that may have existed in 1977 and not in 1971.

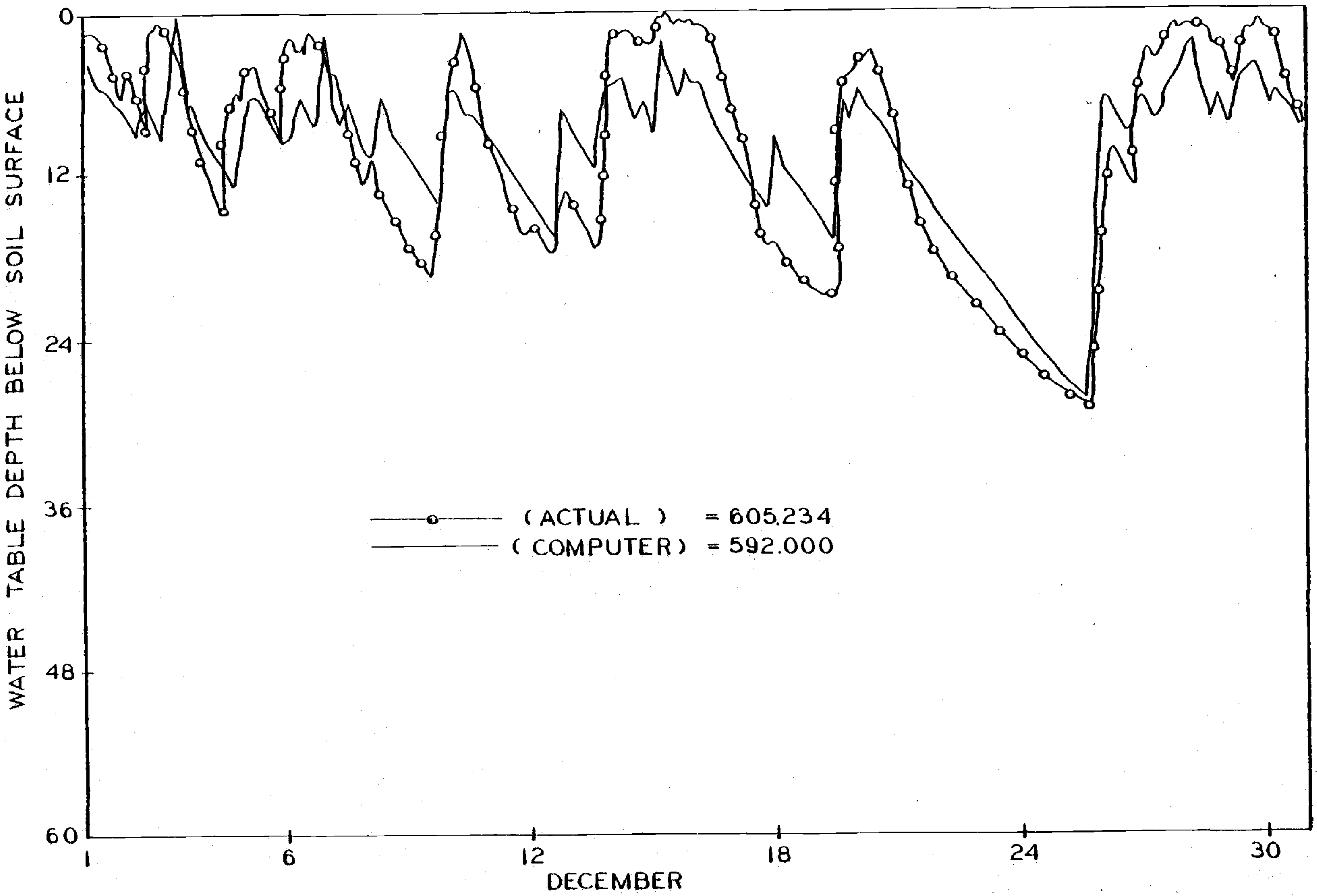


Figure 23. Actual water table and computed water table depths as a function of time with the help of drainage model (1971 data), for the month of December 1970, under artificially drained conditions.

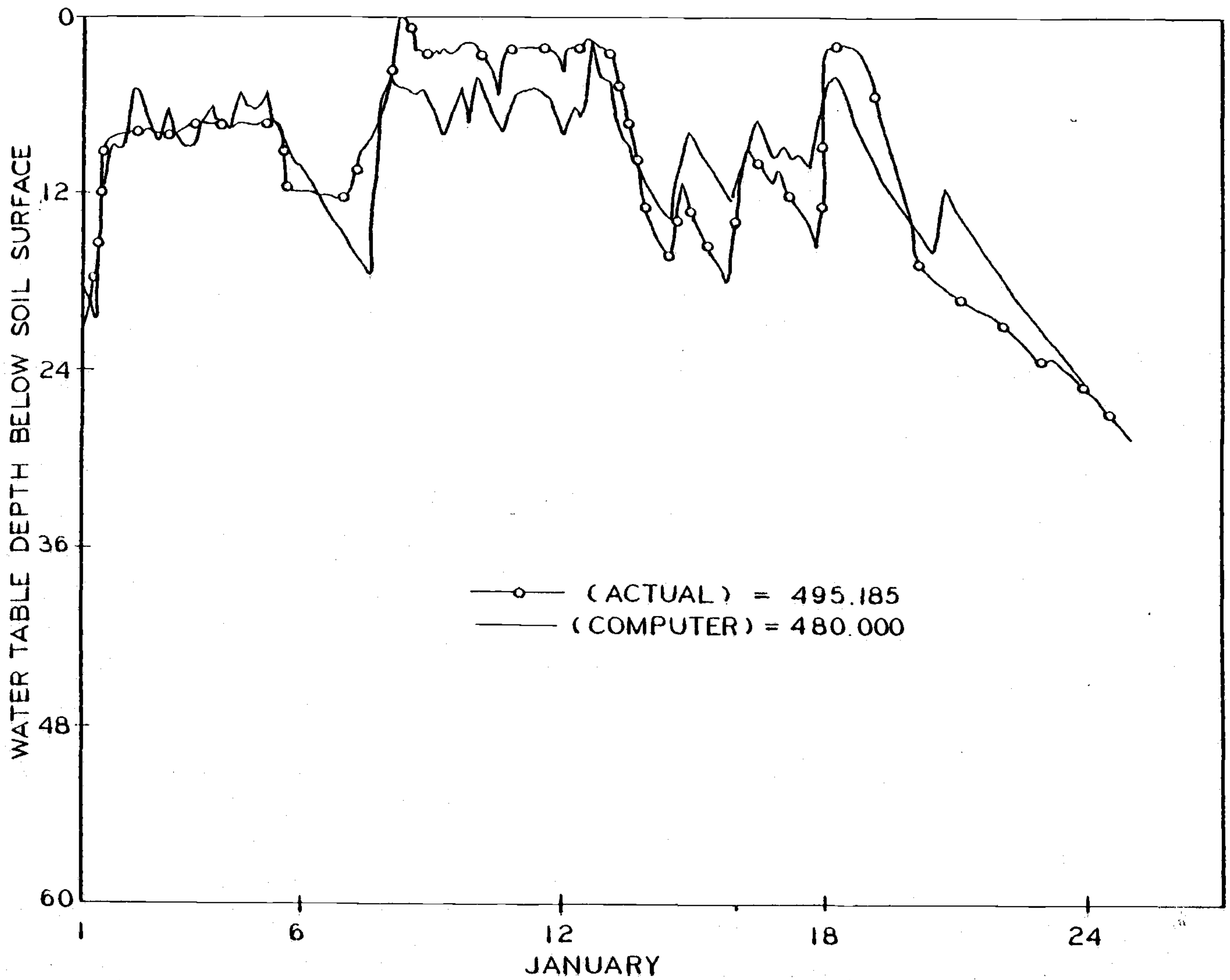


Figure 24. Actual water table and computed water table depths as a function of time with the help of drainage model (1971 data) for the month of January 1971, under artificially drained conditions.

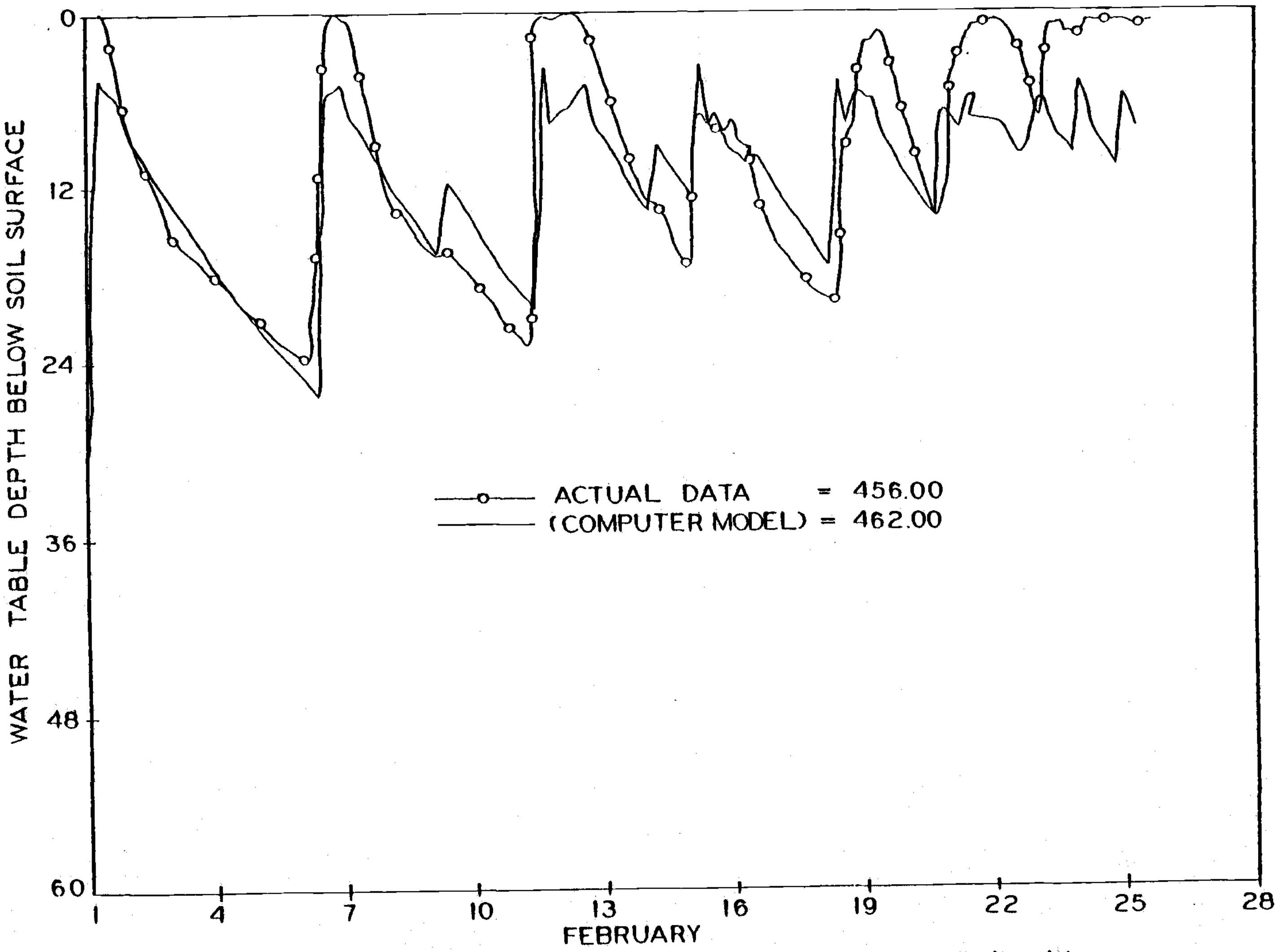


Figure 25. Actual water table and computed water table depths as a function of time with the help of drainage model (1971 data), for the month of February 1971, under artificially drained conditions.

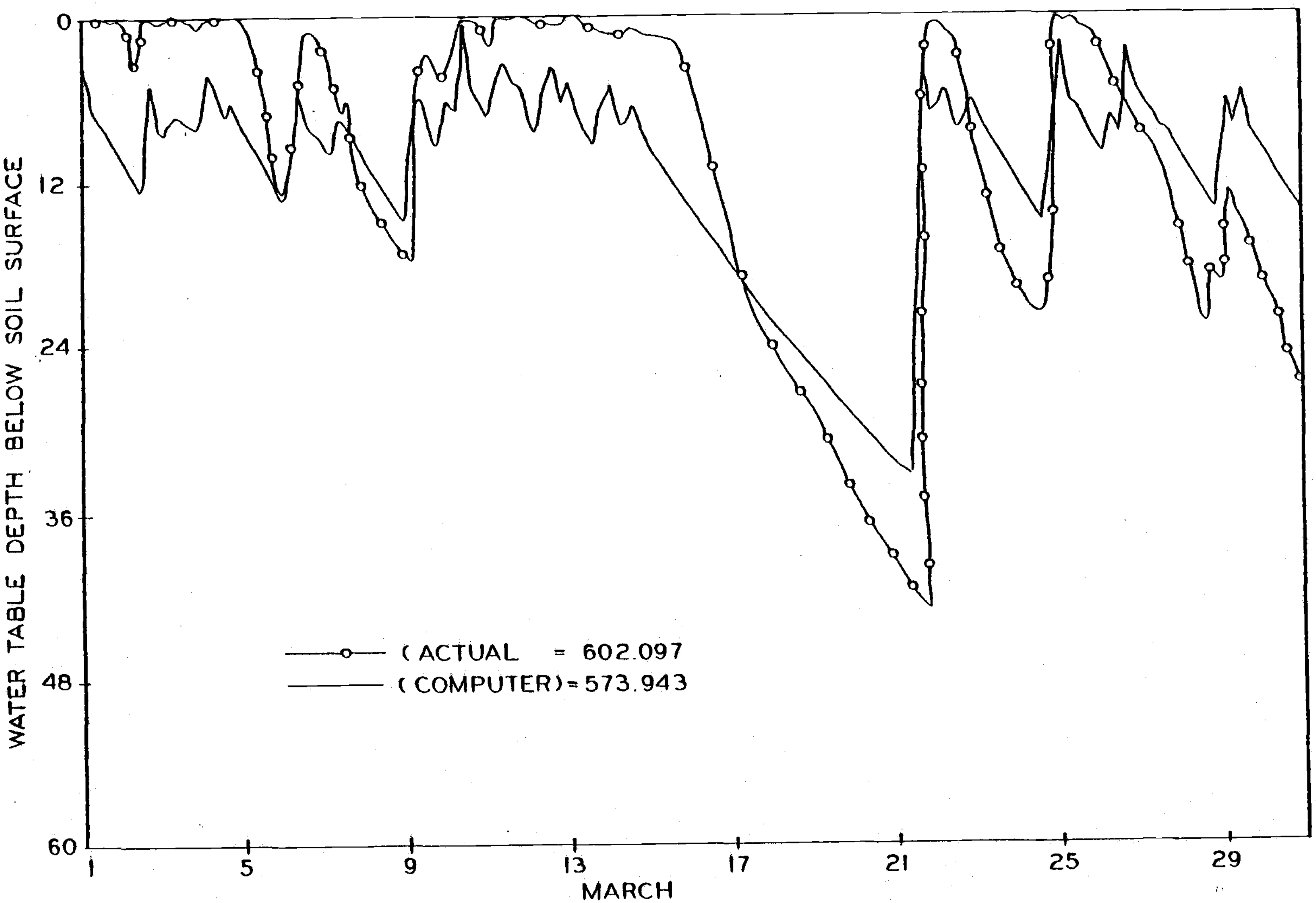


Figure 26. Actual water table and computed water table depths as a function of time with the help of drainage model (1971 data) for the month of March 1971, under artificially drained conditions.

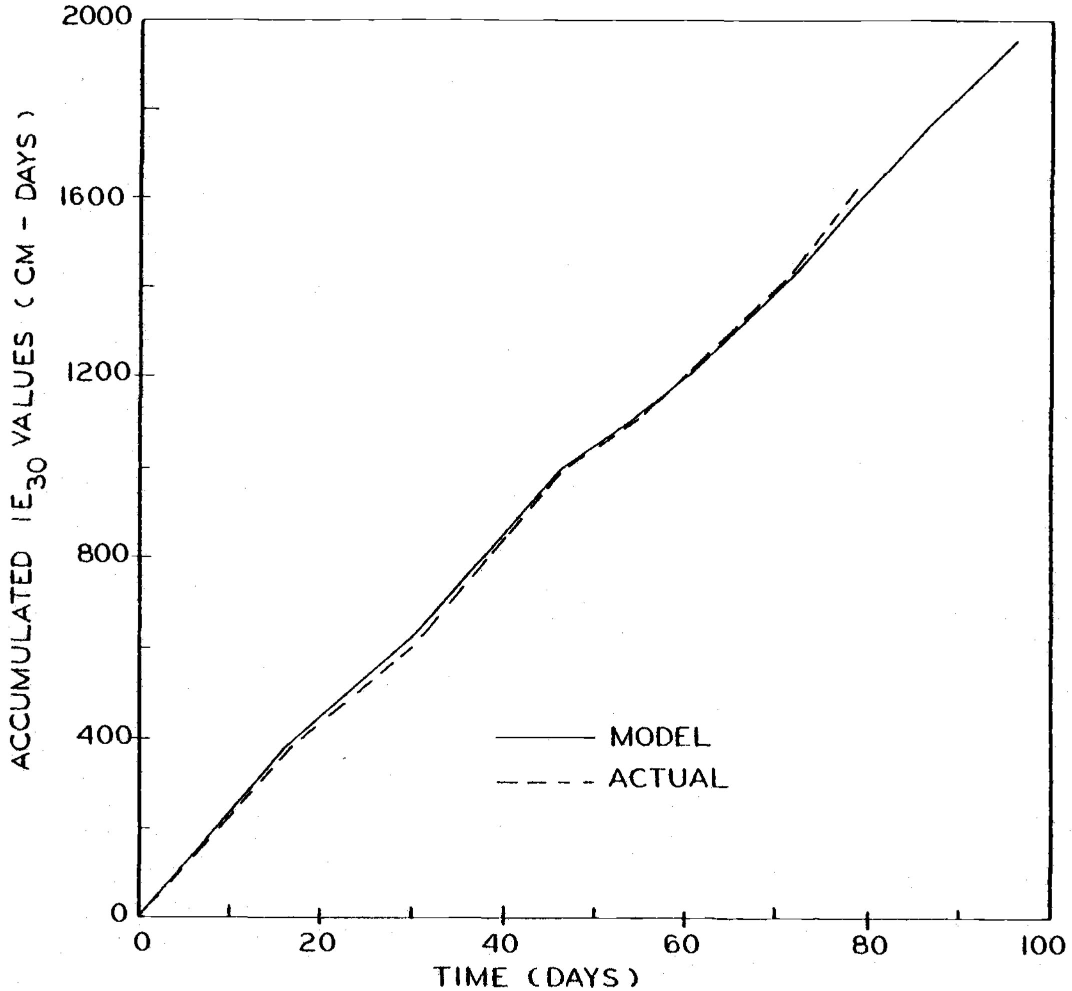


Figure 27. Accumulated actual IE_{30} values compared with IE_{30} values for the drainage model (using data for 1971), as a function of time.

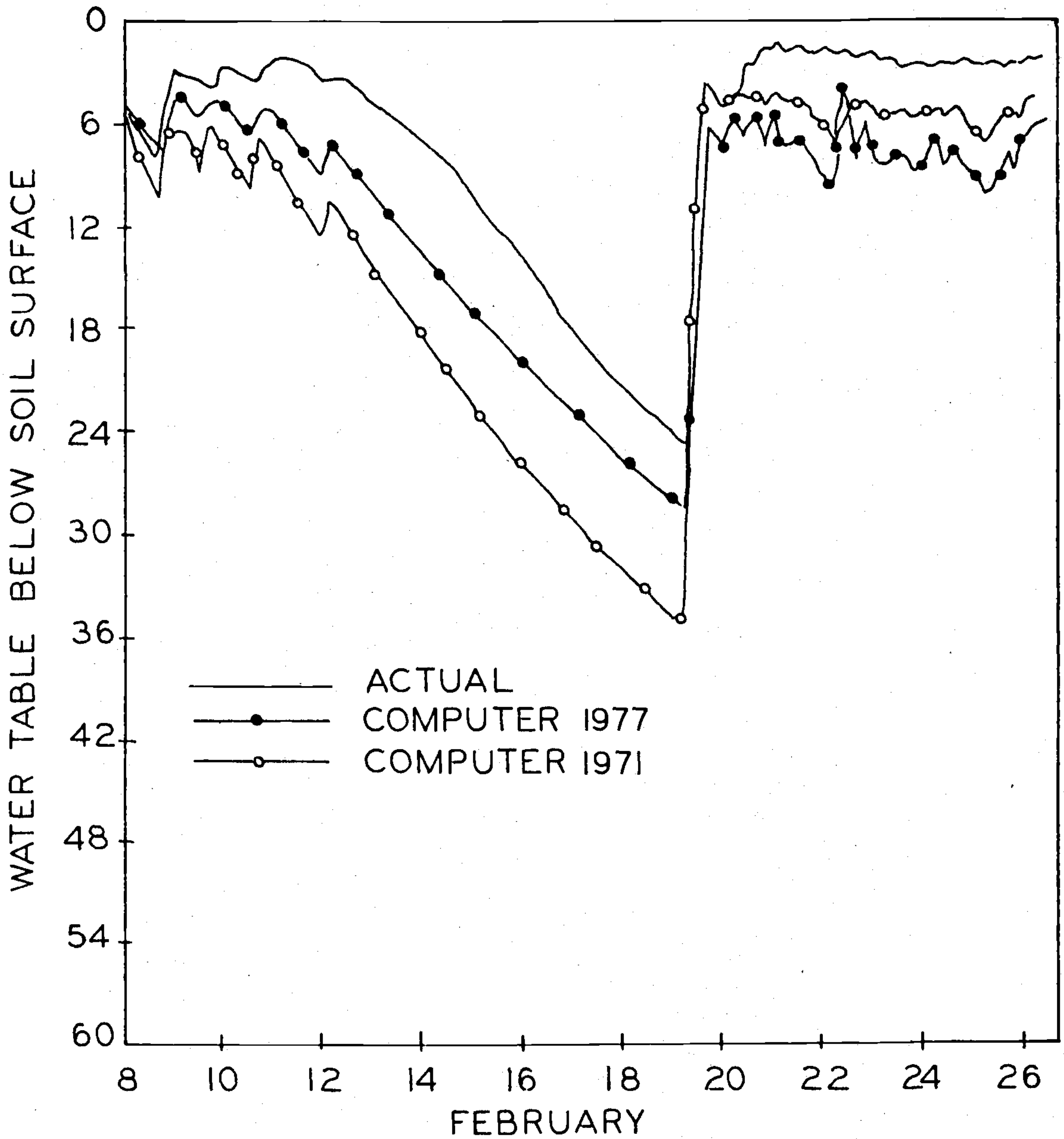


Figure 28. Comparison of computed water table depths by two drainage models (using data for 1971, data for 1977) with the actual experimental water table depth.

IV. SUMMARY & CONCLUSIONS

Winter water tables occur in Western Washington and Western Oregon due to excessive rainfall and subsurface stratigraphy. In as much as evapotranspiration is relatively small, it seems possible to predict water table elevations as a function of time with rainfall amounts and the initial water-table position as the only inputs. The prediction of water tables from a simple model would assist engineers and hydrologists in establishing the need for artificial drains in particular fields and in evaluating their performance.

This thesis presents a method, which takes into account the variation of specific yield for a particular soil for different positions of water table. The model is developed from water-table readings taken for short periods of time in undrained and drained soil profiles. It was tested using water-table data from a field drainage facility under controlled conditions.

The method of constructing the water-table model is to perform a multiple regression analysis of water-table position, rise of water-table due to a rainfall event and the amount of the rainfall. Multiple regression coefficients greater than 0.90 were found for these correlations. This regression analysis provided the input necessary to simulate the rising water-table curve. During periods of no precipitation, the water table generally falls according to some exponential function. The recession water-table curve was obtained using different exponential functions for various ranges of water-table depth below the soil surface. The IE_{30} (Integrated excess water table above the 30-centimeter datum) value was used for evaluating the performance of the plots. The IE_{30} values reflect both the average height and the number of days above the datum. The datum of 30 centimeters below the soil surface was selected, as most of the water-table elevations during the winter months are above this elevation.

Approximately 15 days of water-table data were needed to construct the model, which was subsequently used to predict the water-table fluctuations for the balance of the winter period using only rainfall and initial water-table position as input. The water-table model was compared with the actual graph of water-table fluctuations and it was found to produce satisfactory results. The results from the model were quantitatively compared with the field data by comparing the IE_{30} values for a specific period of time.

Because the model has the ability to reconstruct water-table elevations which have occured in the past, it is expected that the model should have the ability to predict water-table fluctuations for a hypothetical future rainfall pattern. The water-table fluctuations for 1970-71 were predicted by a model constructed from 1977 data. The predicted IE_{30} values were high when compared to IE_{30} values for actual data, apparently because of artesian conditions which developed on the plot after 1971.

Such a drainage model will provide a tool for assessing the drainage needs of certain soils. It may be possible to select an efficient and economical drainage design, if the water table in the soil profile can be predicted from a model using current water-table records of short duration.

BIBLIOGRAPHY

Behnke, Jerold J., W. C. Bianchi. Pressure distribution in layered sand columns during transient and steady-state flows. W. R. R. vol. 4, 1965, pp. 557-561.

Boersma, L. Water table fluctuation in the soil series of the Willamette catena. Transactions of American Society of Agricultural Engineers. 10(3):405-406, 410. 1967.

Boersma, L., G. H. Simonson, and D. G. Watts. Soil morphology and water table relations: I. Annual water table fluctuations. Proceedings of American Society of Soil Science. 36(4):644-653. 1972.

Boersma, L., G. H. Simonson, and D. G. Watts. Characterization of water tables in Oregon soils with reference to trafficability. Vol. I and II. Dept. of Soils, Oregon State University, Corvallis 1970. (Contract Report M-70-1 for the U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi).

Bonna, Ata K. Model study of drainage in shallow layers soils. M.S. thesis, Oregon State University. 1976.

Brooks, R. H., A. T. Corey. Hydraulic properties of porous media. Colorado State University, Hydrology Paper #3. March 1964.

Brooks, R. H., and A. T. Corey. Properties of porous media affecting fluid flow. J. Irrig. and Drainage Div., Proc. ASCE, IR2. 1966.

Brooks, R. H. and John C. Nibler. Water management by shallow drainage. National Water Resources Engineering Meeting, American Society of Civil Engineers. Washington, D.C. January 29 - February 2, 1973. 28 p.

Brutsaert, W., George S. Taylor, J. N. Luthin. Predicted and experimental water table draw down tile drainage. Hilgardia 31:389-418. 1961.

Colding, L.A. Om lovene for vandets be vaegelse i jorden. Danske Vidensk. Selsk. Skr. 5. Rackke Natur. v. og math. Afd. 9B:563-621 (Copenhagen) 1872.

Corey, A. T., R. H. Brooks. Drainage characteristics of soils. Soil Sci. Soc. of Amer. Proc. Vol. 39, #2. 1975. pp. 251-255.

Day, Paul R. and J. N. Luthin. Pressure distribution in layered soils during continuous water flow. Proceedings of Soil Science Society of America. Vol. 17 #2. 1953. pp. 87-91.

Duke, H. R. Capillary properties of soils - influence upon specific yield. Transactions, ASAE, Vol. 15, No. 4. 1972.

Duke, Harold. Drainage design based upon aeration. Ph.D. thesis, Colorado State University, Fort Collins, 1972, pp. 5-7.

Fausey, Norman R. and Randy D. Brehm. Shallow subsurface drainage. Proceedings of American Society of Agricultural Engineers, Davis, California, June 1975.

Floyd, Richard Thomas, Jr. Drainage studies on Dayton, Amity, and Willamette soils in the Willamette Valley, Oregon. Master's thesis, Oregon State University, Corvallis, 1958. 75 numb. leaves.

Hill, D. E. and J. Y. Parlange. Wetting front instability in layered soils. Proceedings of the Soil Science Society of America, 1972 Vol. 36. No. 5. pp. 697-702.

Kirkham, Don. Seepage into drain tubes in stratified soil. I - Drains in the surface stratum. Transactions American Geophysical Union, June 1951, Vol. 32, No. 3.

Linsley, R. K., M.A. Kohler, and J. L. H. Paulhus. Hydrology for Engineers. New York, McGraw Hill, 1975.

Luthin, J. N. The falling water table in tile drainage II. Proposed criteria for spacing tile drains. Transactions of American Society of Agricultural Engineers 2(1):41-47, 51, 1959.

Luthin, J. N. Drainage engineering. R. E. Kreiger Publishing Co. New York, 1973. 224 pages.

McWhorter, D. B. and Duke, J.R. Transient drawing with non-linearity and capillarity. ASCE, J. Irrigation Drain. Div., IR-2, Vol. 19, No. 2. 1976.

Nibler, John C. and Royal H. Brooks. Drainage: Numerically evaluated for humid regions. Proceedings of the American Society of Civil Engineers. Utah. August 13-15, 1975.

Nibler, John C. and Royal H. Brooks. Changing crop priorities and drainage requirements. Proceedings of the American Society of Civil Engineers. Spokane, Washington, September 1972.

Nibler, J. C. Quantitative evaluation of winter fluctuating water tables for drainage criteria in the Willamette Valley. M.Sc. Thesis. Oregon State University. 1974.

Powers, Wilbur Louis. Drainage and improvement of wet land. Corvallis, 1931. 19 p (Oregon Agricultural Experiment Station, Station Circular 102).

Powers, W. L. and Arthur Solomon King. Drainage practices for Oregon. Corvallis, 1950. 35 p. (Oregon Agricultural Experiment Station. Station Bulletin 492).

Sass, C. Joseph. Fortran IV - Programming and application. Holden-Day, Inc. San Francisco, 1974.

Sieben, W. H. Effect of drainage conditions of the soil on nitrogen supply and yield. Land Bou wkindig Tigdschrift. 76(20):784-802. 1964. (Abstract by Jon Van Schilufgaarde).

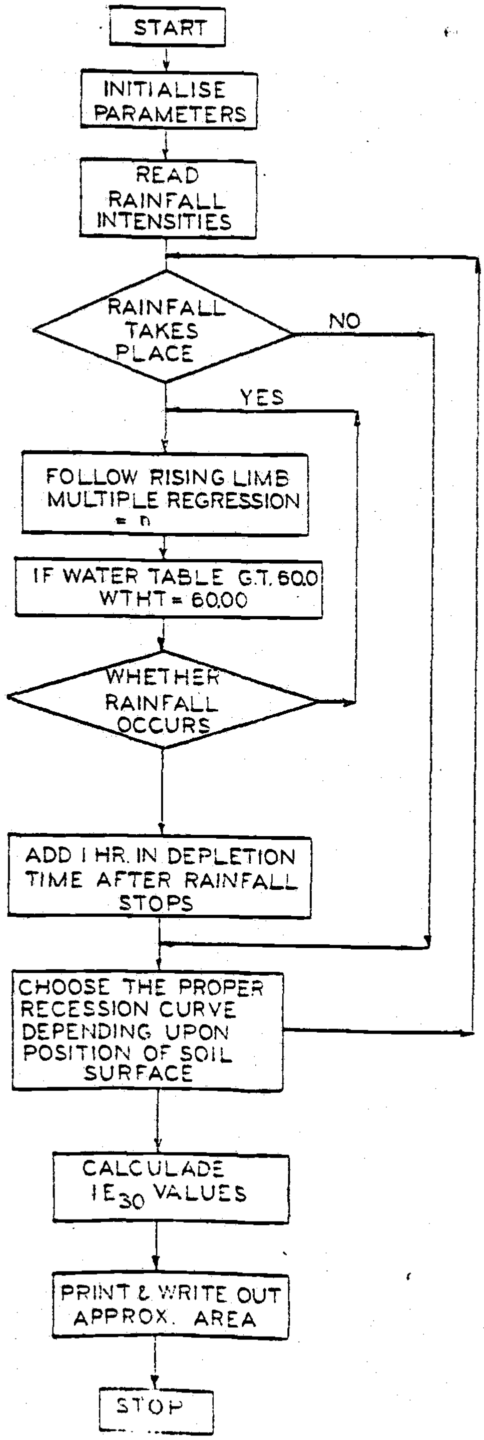
Steel, Robert G. D. and James H. Torrie. Principles and procedures of statistics. McGraw-Hill Book Co., New York, 1960.

Taylor, Paul Arthur. A study of simulated water table fluctuations in a tile drained Amity soil. Master's thesis. Oregon State University, Corvallis, 1966. 74 numb. leaves.

Van Schilfgaarde, J. Limitation of Dupuit-Forchheimer Theory in drainage. Transactions of the American Society of Agricultural Engineers, 1965, pp. 515-516, 519.

Watts, Darrell G. Results of a drainage investigation on a soil of the Woodburn series. Corvallis, 1963. 25 p (Agricultural Experiment Station, Special Report 162).

APPENDIX 1



FLOW CHART FOR CONSTRUCTION OF COMPUTER MODEL

APPENDIX 2

```
]LIST
      PROGRAM WTABLE
      DIMENSION RAIN(588),WTHT(588)
      READ(10,6001)(RAIN(I),I=2,588)
 6001 FORMAT(F10.2)
      WTHT(1)=43.67
      IWTHT=0
      DO 100 IT=2,588
      IF(IWTHT.EQ.0)GO TO 40
      IWTHT=0
   40 IF(RAIN(IT).EQ.0)GO TO 50
      IDOWN=0
      WTHT(IT)=WTHT(IT-1)+(73.41-1.22*WTHT(IT-1)-51.03*
     1RAIN(IT))
      IF(WTHT(IT).GT.60.)WTHT(IT)=60.0
      IF(RAIN(IT+1).EQ.0)GO TO 86
      WTHT(IT+1)=WTHT(IT)
      GOTO 100
   86 IWTHT=1
      GO TO 100
   50 IF(RAIN(IT-1).NE.0)GO TO 200
      IF(IDOWN.EQ.0)GO TO 60
      IF(IDOWN.EQ.2)GO TO 102
      IF(IDOWN.EQ.3)GO TO 103
      IF(IDOWN.EQ.4)GO TO 104
      IF(IDOWN.EQ.5)GO TO 105
  200 K=IT-1
   60 IF(WTHT(IT).LE.60.0.AND.WTHT(IT).GT.57.0)GO TO 102
      IF(WTHT(IT).LT.57.0.AND.WTHT(IT).GT.54)GO TO 103
      IF(WTHT(IT).LT.54.AND.WTHT(IT).GT.51.)GO TO 104
      IF(WTHT(IT).LT.51.0.AND.WTHT(IT).GT.48.)GO TO 105
      IF(WTHT(IT).LE.48.)WTHT(IT)=WTHT(K)*.992*EXP
     1(-.006*1.*(IT-K))
      GO TO 100
  102 WTHT(IT)=WTHT(K)*.992*EXP(-.004*1.*(IT-K))
      IDOWN=2
      GO TO 100
  103 WTHT(IT)=WTHT(K)*.974*EXP(-.002*1.*(IT-K))
      IDOWN=3
      GO TO 100
  104 WTHT(IT)=WTHT(K)*1.001*EXP(-.003*1.*(IT-K))
      IDOWN=4
      GO TO 100
  105 WTHT(IT)=WTHT(K)*.992*EXP(-.004*1.*(IT-K))
      IDOWN=5
  100 CONTINUE
      SUM=0.
      DO46 K=2,588
      IF(WTHT(K).LT.30.)GOTO 46
      SUM=SUM+(WTHT(K)+WTHT(K-1)-60.)*.5*(1./24.)
   46 CONTINUE
      WRITE(61,82) SUM
   82 FORMAT(3X,'APPROX. AREA = ',F10.3)
      WRITE(61,6101)((I,WTHT(I),RAIN(I)),I=2,588,5)
 6101 FORMAT(10X,I5,5X,2F10.2)
      STOP
      END
```