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A lack of reliable criteria for designing tile drainage systems in the Willamette Valley has lead to tile drainage installations in a given soil series being based on general observations of previous drain performance in the series. Relatively few quantitative measurements, which would aid in designing economical installations, have been made on existing tile systems in the Valley.

An experimental tile installation with tile spacings of 30, 60, and 90 feet was made in what was considered to be a modal soil of the Amity Soil Series. Records of rainfall, tile flow, water table position, and water table profiles were obtained during the winter and spring for three years.

Mathematical models programmed for a digital computer were constructed from the field data to simulate water table movement for combinations of 90, 120, and 150 foot tile spacings; unrestricted,

1.0, and 0.5 inch per day main line capacities; surface storage; and a grassed or bare soil surface.

Rainfall in the Willamette Valley is quite variable in amount and distribution from year to year, hence 16 years of hourly rainfall and monthly evaporation were used with the simulator programs to generate 16 years of monthly summaries of water table depths for March, April, and May. The data from the simulator programs were then analyzed to obtain estimates of probable water table depths for the several drainage installations simulated. Estimates were also obtained for the effects of surface cover, surface storage, restricting main line capacity, and changing tile spacing.

A STUDY OF SIMULATED WATER TABLE FLUCTUATIONS IN A TILE DRAINED AMITY SOIL

by

PAUL ARTHUR TAYLOR, JR.

A THESIS

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DEFINITIONS

"Capillary Fringe - The subsurface zone immediately above a water-table and within the zone of aeration in which the moisture content is in excess of the field capacity," (Farrall, 1965).

"Drain - An artificial or natural channel which receives and carries off the gravitational water of a drainage area. The artificial drain is either an open ditch or an underground conduit, is designed to carry off excess or unwanted water from a land area. Ordinarily the drain does not carry sewage and is therefore distinguished from a sewer. To remove water from the surface of land or to remove excess water from the soil by ditching, tiling or other procedures" (Farrall, 1965).

Drainable Porosity or "Specific Yield - The amount of water which a rock or earth will yield after being saturated and allowed to drain under the conditions specified for determining specific retension. It is expressed as percent of volume" (Farrall, 1965).

Drainage Coefficient or "Drainage Modulus - 1. The run-off of surplus surface and ground water from an area expressed in inches of depth per 24 hours. Also called drainage coefficient. 2. In design, the flow capacity to be provided in inches of depth to be removed in 24 hours" (Farrall, 1965).

Drainage Requirement - A standard ". . . based on (1) the maximum duration and frequency of surface ponding, (2) the maximum height of the water table, or (3) the minimum rate at which the water table must be lowered. Often termed the degree or intensity of drainage" (U. S. Department of Agriculture, 1961).

"Drainage System - 1. An artificial network of furrows, ditches, tile drains or combinations of these that provides drainage for land" (Farrall, 1965).

"Evapo-transpiration - Combined loss of water from soils by evaporation and plant transpiration" (Farrall, 1965).

"Relaxation Method - A trial-and-error determination of the value of the hydraulic head at the intersection points of a grid placed on the flow region (a steady state solution)" (Farrall, 1965).

"Steady State - The condition which exists when the transmission of a substance past a fixed point is constant with the passage of time" (Farrall, 1965).

"Tile Drainage - Drainage of low depressional areas and/or flat heavy wet soil areas by means of a series of tile laid in a continuous line at a specified depth and grade below the ground surface so that free water entering the tile line at the joints or thru perforations can flow to an outlet by gravity" (Farrall, 1965).

"Water Table - The upper boundary of the zone of saturation except where it is bounded by an impervious stratum. A surface where the hydrostatic pressure, as determined by the water level in open wells that barely penetrate the zone of saturation" (Farrall, 1965).

A STUDY OF SIMULATED WATER TABLE FLUCTUATIONS IN A TILE DRAINED AMITY SOIL

INTRODUCTION

Over a half million acres of poorly drained soils in the Willamette Valley, when provided with adequate drainage during the wet months and irrigation in the dry summers, may produce larger yields from existing crops and, in some instances, raise more valuable crops than they are now. Today less than 50 percent of the poorly drained soils have a functioning drainage system (Montgomery, 1963). A lack of reliable criteria for tile drainage design in the Willamette Valley has lead to tile installations in a given soil series being based on general observations of previous drain performances in the given series. Such installations generally result in a working system if one notes that any amount of drainage is considered better than no drainage.

In the Willamette Valley, relatively few quantitative drainage measurements have been made on existing tile systems. The current practice of designing for a half inch drainage coefficient on most sites was derived mainly by observing the performance of tile drain installations for many years (Powers, 1931). Relying on the highly variable results of past experience with tile drains in a soil similar to the one needing drainage, depths and spacings have been selected to meet the half inch drainage requirement.

Frequently, systems installed with depths and spacings determined on this basis could satisfy a larger drainage requirement if the main line capacity had been designed for a flow greater than 0. 5 inch per day. This would indicate that a wider, hence less costly, spacing could have been used so that the main line capacity would not be restricting drainage to 0. 5 inch per day, but rather the rate at which gravitational water moves through the soil into the laterals would be the limiting factor. On the other hand, the spacings selected by past experience are sometimes too wide, and the system does not satisfy the drainage requirement. These installations may be improved by placing tile lines between the existing laterals (Floyd, 1958). However, at this narrower spacing, the laterals may again be capable of providing better drainage than the main line capacity will allow, and an "unmatched" system has been installed at a greater cost than if a suitable depth and spacing could have been selected initially.

Since the aim of drainage is to realize maximum benefit per unit cost from the system (Powers and King, 1950), it would be of value to have more reliable information to use with past results in designing an economical drainage system. Such information as the crops to be grown and their individual tolerances to excess moisture conditions need to be considered. Also information is needed to relate the performance of tile drains with selected geometries, to the physical characteristics of the soil; rainfall intensity, duration, and distribution; and evapotranspiration. Incorporating this information in a design would make it possible for a drainage engineer to more consistently derive the maximum benefit from a drainage installation.

The current study- neglecting the area of crop tolerances - has attempted to relate the probable performance of several tile drain geometries in a typical soil of the Amity Series, to the soil surface topography, surface cover, rainfall, and evapotranspiration. It is hoped that the results of this investigation and related studies presently in progress, will provide a more reliable method of designing future tile drainage systems in the Willamette Valley and similar regions.

REVIEW OF LITERATURE

Numerous investigations have been made to develop equations relating the water table height above a tile drain to drainage system geometry and specific soil properties. Steady-state and transient drainage theories have arisen from mathematical investigations based on assumptions of horizontal flow toward the tile drains, radial flow toward the tile, a combination of horizontal and radial flow, or by use of the more exact potential theory. Also, electrical analog studies, laboratory models, and field records have lead to drainage theories. Much of the tile drainage work prior to 1956 was summarized by Jan van Schilfgaarde (1956), and the discussion below is based on his report. For the investigations cited below, only those which have been reviewed by the author are listed in the bibliography.

Steady-State Investigations

Steady-state investigation, based on the assumption of horizontal flow toward the drain with a velocity proportional to the slope of the free water surface, but independent of depth, originated with Dupuit in 1863. This assumption lead to the equation of an ellipse for the water table profile above parallel drains. Rothe (1924), Kozeny (1932), Hooghoudt (1937), Aronovici and Donnan (1946), and Gustafsson (1946), have subsequently used the Dupuit assumption of horizontal flow in analyzing drainage problems.

Using the method of images with the assumption of radial flow toward the tile drains, Hooghoudt (1940), Gustafsson (1946), and Kirkham (1940), (1945), (1949), (1941), (1948), (1951), have investigated specific drainage problems. Vedernikov (1939) was the first to combine the horizontal flow assumptions at some distance from a tile drain with radial flow assumptions near the drain. Hooghoudt (1940) used the combined assumptions in analyzing the case of an impermeable layer at a finite distance below the tile. Van Deemter (1949), (1950) developed a hodographic solution based on these assumptions.

The relaxation technique, which is used in solving problems based on potential theory, was employed by Van Deemter (1949), (1950) for a steady-state drainage situation with a curved free water surface, while Luthin and Gaskell (1950) used the method for a soil saturated to the surface.

Non-Steady State Investigations

Following Dupuit's approach, investigation of transient drainage phenomena results in a differential equation analogous to the differential equation describing heat flow. Forchheimer (1930) was the first to consider this approach, then Kano (1940) and Visser (1953) each used a modified form of the ellipse equation - a solution to this differential equation for steady-state conditions - for transient drainage problems. Glover as reported by Dumm (1954), based his solution on horizontal flow to tile drains placed over an impermeable layer. Other solutions describing the falling water table were developed by Spöttle (1911) and Walker (1952) using modified radial flow assumptions.

Kirkham and Gaskell (1951) applied the method of relaxation and followed the water table drawdown by solving a series of steady-state solutions at several times during a recession. Isherwood (1959) and Taylor and Luthin (1963) considered separate drainage problems following an approach similar to Kirkham and Gaskell, however, they used a digital computer to iterate for their solutions. Childs (1947) also treated the water table recession as a series of steady-state solutions, but used an electrical analog. An electrical resistance network was used by Brutsaert, Taylor, and Luthin (1961) to describe a transient drainage situation. Their model was made more realistic by incorporating an "apparent drainable porosity" which varied linearly with depth, instead of remaining constant, and by accounting for the capillary fringe that exists above a water table.

Van Schilfgaarde (1963) published an analysis similar to that of Glover, based on the Dupuit assumptions. He used a variable, instead of a constant thickness for the water bearing stratum, and by introducing Hooghoudt's equivalent depth, corrected for convergence of flow when the tile drain is not placed on an impermeable layer.

One can see that there have been many studies made which attempt to relate soil characteristics to the expected performance of tile drains placed in a soil. Some of the theories resulting from these investigations would definitely be more laborious than others to use in designing a tile drainage system. All present results, perhaps with the exception of analyses made with potential theory, are only approximations to most field situations. Such simplifications as a constant drainable porosity, isotropic, homogeneous soils, a constant hydraulic conductivity, and instantaneous draining of the pore space during a water table drawdown, have rendered them approximations. Some investigations have considered anisotropic soils with a variable drainable porosity, but even these improvements only reduce the degree of approximation.

It is encouraging to note that such investigators as Talsma and Haskew (1959), Maasland, and others, in checking field or model data with a theory, have found reasonable agreement whenever the underlying assumptions of the particular theory are met. Nevertheless, if one did succeed in estimating the soil properties for a particular site and subsequently were able to select an appropriate theory, he would still need to arrive at tile depth and spacings based on some minimum allowable drainage requirement.

In regions where precipitation is generally of long duration with occasional intense rains of short duration, it would be feasible to design for a steady-state situation which would allow the water table to exceed a given depth only after a short intense rainfall. However, in regions such as the Middle Willamette Valley where rainfall is variable in amount and distribution from year to year, a realistic design must relate the water table position with the rainfall patterns obtained from several years of records.

Investigations of Soil Moisture Recharge in Drainage

Maasland (1959) has made a contribution toward this method of approaching tile drainage design. Non-steady state drainage theory, following the Dupuit assumptions, was incorporated with the effect of rainfall recharge by stating all results in the form of infinite series which applied to any number of successive recharges. This process did not become extremely cumbersome because the series generally converged rapidly and only the first few terms were necessary.

The Bureau of Reclamation Engineers have applied transient drainage theory to subsurface drainage problems caused by irrigation. The Bureau's approach used an equation, based on a fourth degree parabola for the initial water table shape, to describe the water table recession with time. Then the water table rise produced from irrigation was calculated by dividing the amount of moisture percolating to the water table by an estimate of the drainable porosity. The amount of rise added to the water table height prior to the irrigation gave a new starting point from which the drainage equation could again be used to determine a new water table position just before the next irrigation. Repetition of this process aided in predicting the water table depth throughout the year. The present study, involving soil moisture recharge by rainfall in the Willamette Valley, has used the same general technique in simulating a record of the water table depth.

Another method of incorporating the effect of moisture recharge in tile drainage design was proposed by Ede (1960). Selecting an inadequately drained area similar to the site to be drained, he maintained continuous records of water table depth and rainfall. The records made it possible to calculate an inflow, outflow water balance, to obtain an estimate relating midpoint water table height above the tile drains to tile flow, and to arrive at a constant value for the "effective drainable porosity". Ede noted that for shallow drains the "effective drainable porosity" was essentially the same value for a rising or falling water table, hence it was used in determining the height of water table rise after rainfall.

Long-term records of rainfall were examined to estimate the mean rainfall and probable departures from the mean at various times of the year. The relation between midpoint water table height and tile flow was used with the mean rainfall estimate to calculate the steady-state water table height above the tile lines for an assumed spacing. Then excess rainfall, with some magnitude greater than the mean, and a given probability of occurring, was divided by the "effective drainable porosity" to obtain the height of water table rise above steady-state conditions. Summing this rise, the height maintained by the mean rainfall, and the desired minimum water table depth below the ground, gave a tile depth that would be necessary for the assumed spacing and rainfall situation. The desired combination of depth and spacing could finally be selected by several trial calculations with depth, spacing combinations.

In 1965 van Schilfgaarde developed a procedure using daily precipitation records, that inherently took into account the undetermined probability distribution for a region's daily rainfall, in predicting the water table depths in a tile drained field. A differential form of the steady-state equation presented by Toksöz and Kirkham in 1961 was modified by a shape factor, $0.8 < C < 1.0$, which compensated for the change in shape of the water table during drawdown. Instead of integrating to find a solution, a forcing function was imposed to represent the water table rise. A Laplace transform of this equation followed by the inverse transform, lead to an exponentially decaying function describing the water table height as a function of time after an instantaneous rise caused by rainfall.

An interval of continuous precipitation was subdivided into n equal time increments with each increment assumed to have a constant precipitation rate. A summation of the water table response for each increment of precipitation as it occurred in time, gave the total response for the whole precipitation period. As the time increments became infinitesimally small in the limit, the summation led to an integral having a solution, provided the precipitation rate was constant during the time interval of integration.

To use the solution, van Schilfgaarde selected a time period of one day and assumed the precipitation was uniformly distributed during the day. Also evapotranspiration and soil moisture storage calculations reduced the amount of precipitation when appropriate. The solutions for each day were summed to arrive at a water table depth after each day. Applying this technique on a digital computer with records of daily rainfall, van Schilfgaarde developed graphs predicting the frequency of water table heights for several drainage intensities and for selected recurrence intervals.

OBJECTIVES

There have been some investigations related to tile drainage of Willamette Valley soils; (Powers, 1931, 1950), (Floyd, 1958), and (Evans, 1961), however they have been either of a qualitative nature or, at the other extreme, related to a very specific problem. It is not known how well existing drainage theories describe the water table movement in response to tile drains installed in the Valley's layered, anisotropic soils. Even if this information were available, extensive soil investigations would likely be made only at experimental sites to arrive at quantitative estimates of the soil parameters used in drainage equations. Manpower and time limitations would probably necessitate that most future subsurface drainage installations in the Valley be made on the basis of soil series. The soil series at each new site would be determined first, then tile depth and spacing would be selected according to results obtained from intensive subsurface drainage investigations made on experimental sites for the given soil series.

Because of the lack of knowledge about the applicability of existing theories to Willamette Valley soils and the fact that soil series classification will probably continue to be the main factor influencing the choice of drain depth and spacing, it seemed most feasible to establish experimental plots to collect drainage data for the more important soil series. The Amity series, which is the most frequently drained soil in the Willamette Valley, was selected for the present study.

The experimental plots were established with two general objectives in mind. The first objective was to collect sufficient field data to derive empirical equations describing the water table fluctuations resulting from rainfall, evapotranspiration, and the effect of the tile drains.

The second objective was to use the empirical equations in a computer program to model the water table fluctuations on the site. Then the program was to be used with records of precipitation and evaporation, to simulate several seasons of water table fluctuations so that the following considerations could be made in an effort to develop more reliable procedures for designing a drainage system.

1. The probabilities that the mean water table would be above various depths during a given spring month were to be predicted.
2. The probabilities that the mean water table would spend any number of consecutive days above selected depths, were to be estimated during given spring months.
3. Investigate the effect a change in tile spacing would have on 1 and 2 above.
4. Investigate the effect on 1 and 2, of restricting the main line capacity.

PROCEDURE

Establish a Field Site for Data Collection

In 1963 an experimental site was selected in a field near Philomath, Oregon, which had been mapped as being in the Amity soil series. A soil scientist at Oregon State University delineated a 3.5 acre area in the field, as being modal for the Amity series. The site had a cover of perennial ryegrass for at least one year prior to 1963 and remained in ryegrass for the duration of the experiment. (See the appendix for a soil morphologist's description of the site.)

During the late summer of 1963, four inch clay tile laterals were placed in the soil approximately three feet deep at 30, 60, and 90 foot spacings. Four inch unperforated Bermico pipe was installed for the main lines to eliminate any effect a perforated main line would have on the water table fluctuation. As shown in Figure 1, each spacing had two replications, however only general comparisons were made between the replications, and the records from the west 90 foot and west 60 foot plots were used in constructing the model. The tile placed at a 30 foot spacing drained the plots too rapidly to be of practical value, hence this spacing was not included in the analysis.

It was found during the study that the east 60 foot plot responded quite differently from the west 60 foot plot due to slight fragipan characteristics about two feet below the soil surface on the east plot.

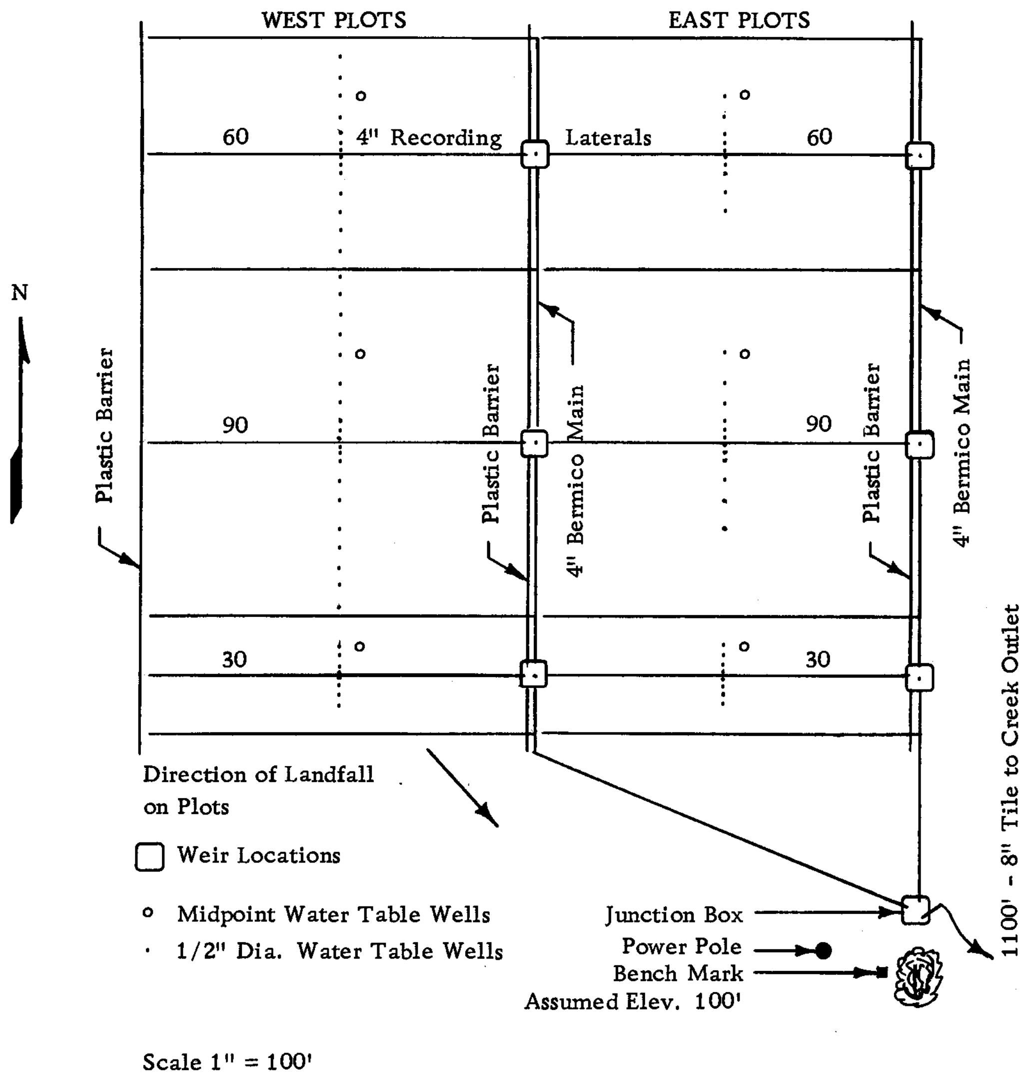

Figure 1. Plan view of field drainage experiment near Philomath, Oregon.

More detailed investigation at the site indicated that the east 60 foot plot was the only one with fragipan characteristics. The fragipan occurs frequently in Amity soils toward the northern end of the Valley, while in the southern portion of the Valley, it is generally absent in this series. Only Amity soils which do not have the fragipan have been considered in this report, however an Oregon Agricultural Experiment Station Bulletin is to be written, which will discuss more extensively the drainage results one might expect from tile drains placed in Amity soils having a fragipan.

An attempt was made to isolate the drained plots from the undrained portion of the field by digging trenches approximately four feet deep along the east and west boundaries which were then filled with a mixture of bentonite clay and soil excavated from the trenches. At this depth, the impermeable mixture of bentonite and soil placed in the trenches extended a few inches into the C horizon which was believed to have a very low hydraulic conductivity relative to the upper horizons. Subsequent hydraulic conductivity measurements made in the spring of 1965 by Bennett[1] verified this assumption.

The soil and bentonite did not form an exceptionally good mixture

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[1] Bennett, Douglas, former graduate research assistant at Oregon State University. Unpublished hydraulic conductivity measurements made in auger holes on the experimental plots near Philomath, Oregon. Corvallis, Oregon, Department of Agricultural Engineering, 1965.

since the bentonite was not finely powdered, but consisted of many particles nearly one inch in diameter. Because of this it was later feared that the barrier might not be working well, and in the fall of 1965 barriers of black plastic were placed about 40 inches deep along the east and west boundaries.

Maintain Continuous Tile Flow Records

Weirs ranging in maximum capacity from six gallons per minute to 62 gallons per minute were constructed to measure tile effluent from the recording laterals for 30, 60, and 90 foot spacings. The smaller weirs were used initially, but later it was found that peak flows of about 48 cubic feet per foot of tile per day could be expected for ponded conditions. Hence the larger capacity weirs were used in collecting the flow data for the 1965-66 season.

Each weir was calibrated by using a point gage to measure the head, and scales to weigh the volume of water discharged in a given time period. With the stage measurements, calculated flow rate data, and a stepwise regression program, an IBM 1410 computer calculated "best fit" equations relating stage to the flow rate. In most cases, sufficient accuracy was obtained by determining three equations for each weir, each equation being specifically used to calculate flows for a particular range of stages.

The calibrated weirs were placed in the field and, with the exception of two Casella type recorders used in the 1963-64 and 1964-65 wet seasons, a Stevens chart recorder with eight inch diameter float was installed with each weir to maintain a continuous record of the weir stage resulting from tile flow. Figure 2 shows one such field installation used in maintaining the flow records.

Record Midpoint Water Table Fluctuations

To measure the midpoint water table positions, six inch diameter auger holes three and one half feet deep, were placed at the midpoint position to the north - uphill at an approximate slope of 0.5 percent - of the recording lateral for each spacing. A Stevens chart recorder with a five inch diameter float was positioned over each auger hole so that vertical movement of the float in the auger hole would operate the recorder, maintaining a continuous record of midpoint water table elevation as established from surveyed reference elevations.

Record Water Table Profiles

To establish the water table profile at various times during a drawdown period, an electrical probe was used to take periodic measurements of the water table position in 0.5 inch (I. D.) slotted pipes placed in 0.75 inch diameter holes three feet deep; spaced across the plots perpendicular to the laterals. Reference elevations were established in a survey to permit calculating the water table elevation

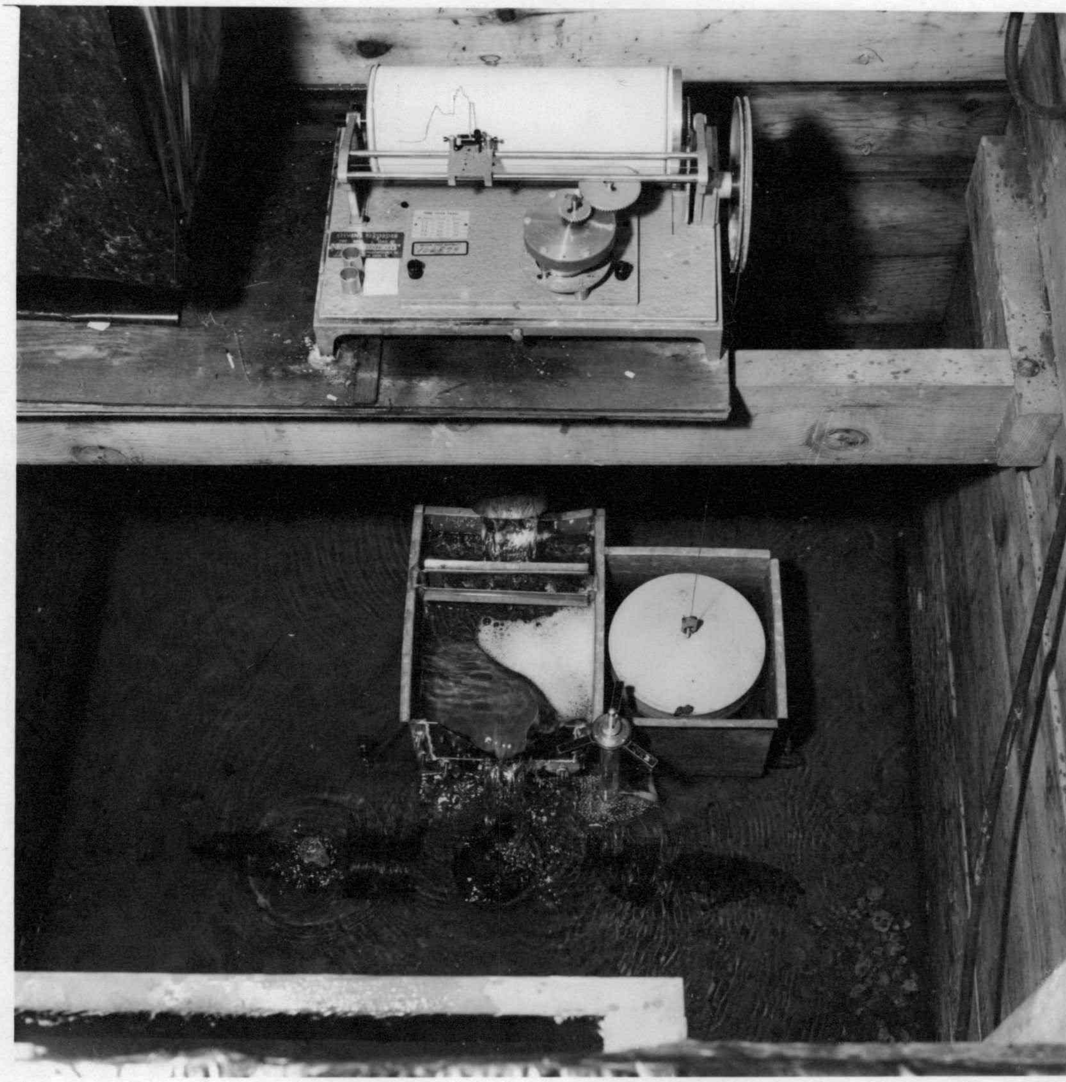


Figure 2. A typical field installation used to obtain records of tile flow.

in each well.

Record Precipitation

A weighing-type recording rain gage was installed at the experimental site to obtain continuous precipitation records for future use in testing the accuracy of the model, calculating a water balance, and making estimates of any deep percolation losses.

Data Collection

During the winter and spring months of 1963-64, 1964-65, and 1965-66, rainfall data, stage data for the weirs, records of midpoint water table position, and records used to establish water table profiles, were collected. Due to equipment failures or exceptionally heavy rainfall at times, some of the weirs and recorders were inoperative during the 1963-64 and 1964-65 seasons, resulting in records of only moderately high tile flows and water table positions. Fortunately heavy rains in December 1965 and January 1966 produced records of nearly ponded conditions for the 60 and 90 foot spacings. The data were checked for errors then selected segments of the records were used in developing a mathematical model for the west 90 foot plot.

Reduction of Data to Relations Needed in the Mathematical Model

Relation of Mean Water Table Versus Midpoint Water Table

Water table heights measured in the 0.5 inch wells spaced across the plots to establish water table profiles between the tile laterals at several times during rain-free periods of water table recession, were checked and placed on punch cards. A Fortran program was written for an IBM 1620 computer to plot the water table heights recorded in the 0.5 inch wells during a drawdown period. Each water table profile, in the series of profiles established for a given tile spacing during a recession, was obtained by connecting a series of the water table heights which had been measured at nearly the same time during the recession.

It was found that mud oozing into some wells gave readings that were too high. An attempt was made to locate these wells so they could be cleaned, however it was not always possible to find a muddy well until the readings were plotted. Therefore in a few instances when sketching the successive water table profiles, if the heights plotted for an observation well appeared consistently high relative to values for other wells, it was assumed that mud had moved into the well causing erroneous probe readings, and its points were neglected in sketching the water table profiles.

After sketching the profiles, a planimeter was used to determine the area bounded by the water table, the recording lateral centerline, and the midpoints to each side of the recording lateral. Dividing this area by the tile spacing gave a mean water table height. A graph of mean water table height versus the midpoint water table height was constructed using this procedure for several profiles at different positions above the lateral. Figure 3 shows the graph of mean water table height versus midpoint water table height established for the 90 foot tile spacing. The point representing surface ponding, an upper limit, was selected by plotting the mean ground surface elevation determined by a planimeter, with the midpoint ground surface elevation at the midpoint water table recorder.

The relationship developed between the mean and midpoint water table heights for a 90 foot spacing was checked by applying the above procedure to records for the west 60 foot plot. The graphs had similar characteristics, hence the relationship developed was assumed to be correct.

Determining Mean Water Table Height as a Function of Time

A computer program was written which used the mean water table versus midpoint water table relation in converting the midpoint water table records to mean water table heights as a function of time. Referring to precipitation records, periods of no rainfall were selected. Neglecting the hysteresis effects encountered with a fluctuating

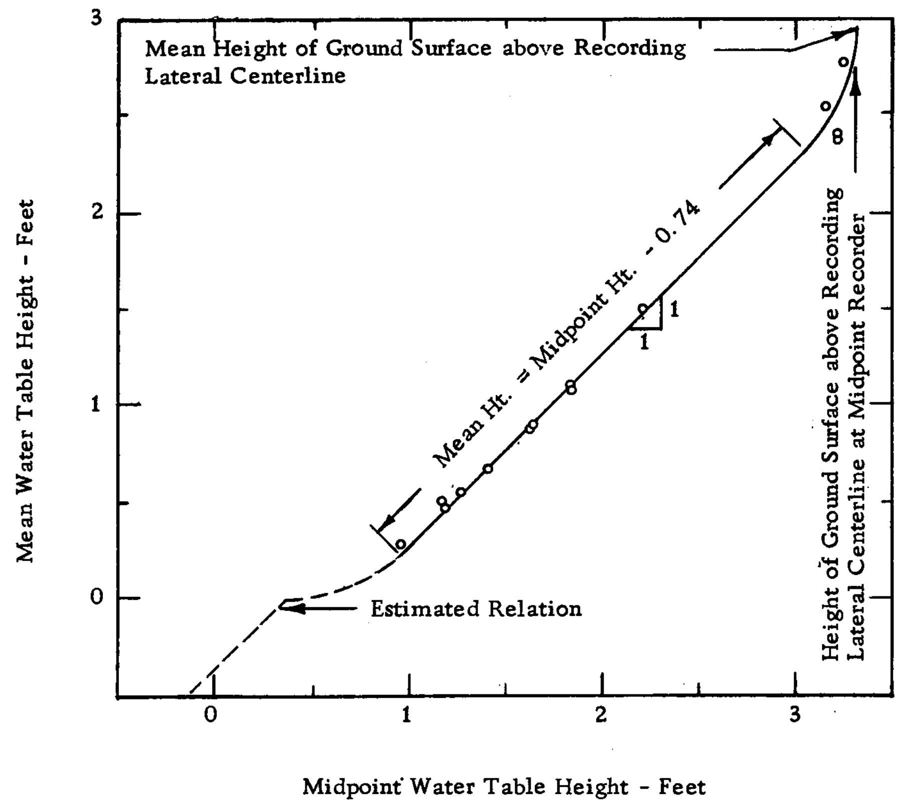


Figure 3. Mean water table height above recording lateral centerline plotted as a function of midpoint water table height above recording lateral centerline for west 90 foot plot at experimental site.

water table, and following the method of piecing together sections of stream flow recession from several storms, as outlined on page 154 in Linsley, Kohler, and Paulhus (1958), a recession curve was constructed for the mean water table height, starting from ponded conditions between tile lines spaced 90 feet apart in an Amity soil. Figure 4 illustrates the data points and the resulting drawdown curve.

Semi-logarithmic and logarithmic plots were made in an unsuccessful attempt to calculate an empirical equation for the recession curve. Since the plotting techniques were unfruitful, points on the constructed recession curve were run through a stepwise regression program on an IBM 1410 computer to obtain an expression for the mean water table height as a function of the time during a rain-free drawdown period starting from ponded conditions.

A general relation of the form

$$MWT = A + Be^{-t} + Ce^{-t^{1/2}} + De^{-t^{1/3}} + Ee^{-t^{1/4}} + Fe^{-t^{1/5}}$$

was assumed where,

MWT = mean water table height in feet above the recording lateral's centerline.

A, B, C, D, E, and F are constants.

t = time in hours after the start of a water table drawdown following ponded conditions.

e = 2.718

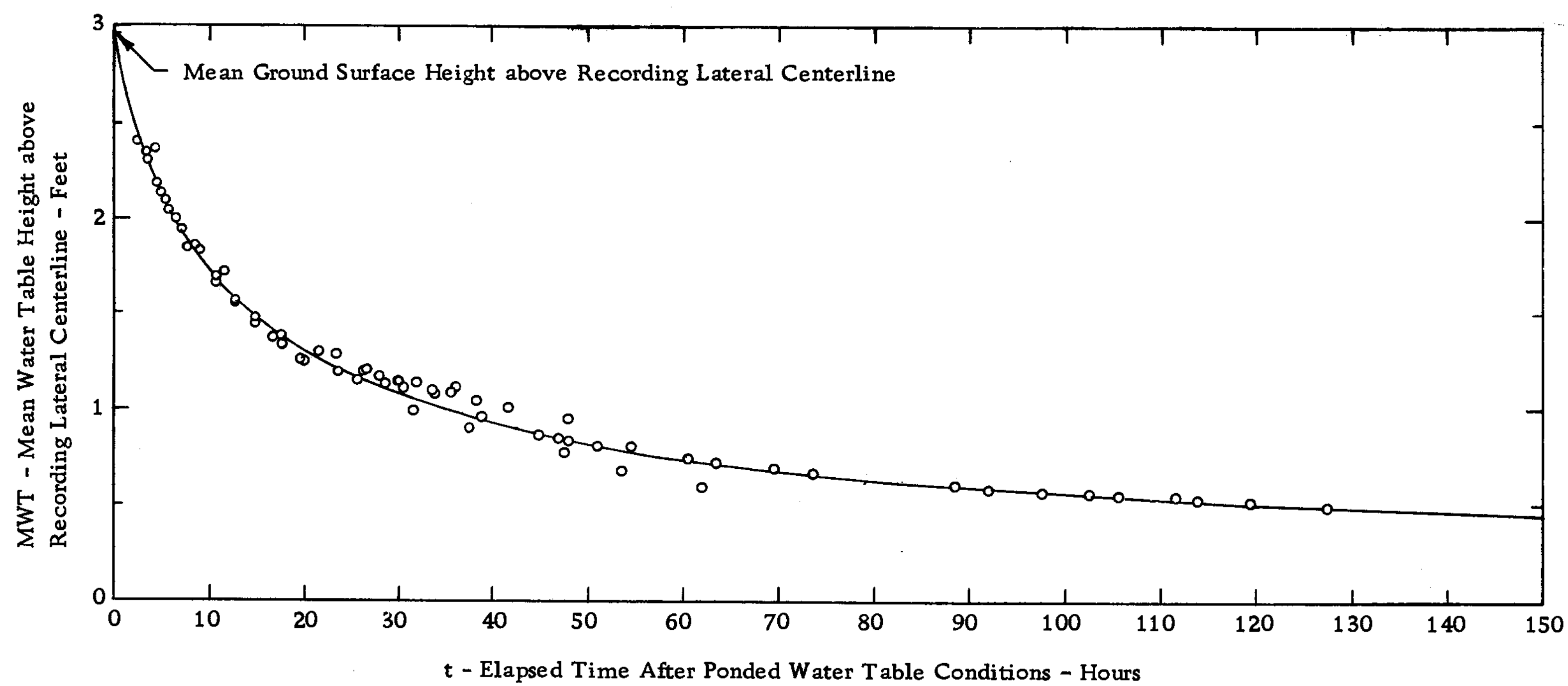


Figure 4. Constructed mean water table recession curve for west 90 foot plot.

The computer then calculated the following equation.

$$MWT = 0.027 - 0.483e^{-t} - 2.398e^{-t^{1/2}} + 8.284e^{-t^{1/4}} + 1.874e^{-t^{1/5}}$$

Due to the range of input data used in arriving at this equation and the form of the equation, it was found necessary to use this equation only for values of t in the range 1.5 hours $\leq t \leq$ 82.4 hours. For 0 hours $\leq t <$ 1.5 hours, the mean water table recession curve was sufficiently straight on a semi-logarithmic plot to permit using the exponential equation

$$MWT = 2.95e^{-0.09t}$$

The constant 2.95 represents the mean ground surface height above the recording lateral centerline on the 90 foot plot. Hence when $t = 0$, MWT = 2.95, and ponded conditions prevail on the ground surface.

For 82.4 hours $< t \leq$ 120 hours, the slope of the drawdown curve was essentially constant at -0.00315 feet per hour. For $t > 120$ hours, the mean water table was in a region near or below tile level. In this region the rate of recession was similar to that on undrained Amity soils, and a rate of recession equal to -0.0018 feet per hour was estimated from the constructed recession curve and values obtained from measurements made on untiled sites by Boersma and Collins (1965).

The stepwise regression approach did not succeed in calculating the inverse function - time as a function of the mean water table height - hence the curve was divided into six regions, each region being represented by an exponential or linear equation which closely approximated the constructed recession curve in this region.

Converting Weir Stage Data to Tile Flow

Another computer program employing equations developed earlier by regression analysis of weir calibration data, was written to convert the weir stage data taken from recorder charts to tile flows. From the computer output, tile flows during the periods of no rainfall previously selected in constructing the mean water table recession curve, were plotted in the same relative time positions as the mean water table heights to construct a curve representing the decline in tile flow following ponded conditions. Due to the high hydraulic conductivity of this soil, there was essentially no apparent time lag between the maximum water table height recorded and the maximum recorded tile flow.

Calculating Effective Drainable Porosity

In a field, the drainable porosity for a given volume of soil is a function of its location relative to the water table and time, since the soil moisture tension increases in the upper soil regions as the water table recedes, causing the soil above the water table to become more thoroughly drained. The volume of water removed from a tile drained field for an incremental drop in the water table is the total volume of water obtained by partial drainage of the soil volume between the two successive water table positions and the volume of water obtained from any continued draining of the soil above the water table.

To simplify calculations it is generally assumed that a given volume of soil is drained instantaneously as the water table passes below it. To obtain valid estimates of water table movement using this assumption, one must use drainable porosity values which are determined from the total volume of water removed from the soil profile for an incremental drop in the water table. In some instances, such as during very slow water table recessions, the volume of water draining from the soil region above the water table is very small. Therefore, the actual volume of water removed, hence drainable porosity, between two water table positions becomes essentially a function of the water table position. For these conditions estimates of drainable porosity made with soil samples subjected to 60 centimeters tension in a laboratory could probably be used as valid estimates of drainable porosity.

However when the water table recedes quite rapidly as it did above tile level on the plots at Philomath, the volume of water draining from the soil region above the water table becomes appreciable. Hence for the mathematical model to represent the actual field situation, it was necessary to use effective drainable porosity values with the assumption of instantaneous draining of the pore spaces, instead of the drainable porosity values determined from soil samples. The effective drainable porosities were calculated by a short computer program using values from the constructed mean water table and tile flow recession curves. In a given time interval, the mean water table dropped to a new position and the volume of soil "drained" was calculated by multiplying the change in mean water table height by the tile spacing and length of the laterals. Multiplying the average flow rate during this period by the time interval, gave the total volume of water drained from the soil. Dividing this volume of water by the volume of soil "drained", produced a value for the effective drainable porosity in the soil region between the two mean water table positions. Table I shows the effective drainable porosity values calculated by repetition of this process. To aid accuracy, smaller time increments were used in the regions of rapid change with larger time increments when the curves became more linear.

The relations shown below were developed for use in calculating effective drainable porosity values in the model.

$0.76 \leq MWT$	$f = 0.058$
$0.67 \leq MWT < 0.76$	$f = 0.973 - 1.206\ MWT$
$0.00 \leq MWT < 0.67$	$f = 0.014 + 0.2255\ MWT$
$MWT \leq 0.00$	$f = 0.014$

As shown in Table I, the average drainable porosity calculated

TABLE I. EFFECTIVE DRAINABLE POROSITY VALUES CALCULATED FROM TILE FLOW AND MEAN WATER TABLE RECESSION CURVES CONSTRUCTED FOR THE 90 FOOT TILE SPACING.

Mean Water Table Height - MWT Feet	Calculated Effective Drainable Porosity - f Percent	Calculations
2.81	6.643	
2.63	6.038	
2.54	6.392	
2.46	5.640	
2.38	5.081	
2.31	6.203	
2.24	4.898	
2.18	5.275	
2.12	4.890	
2.06	5.474	
2.01	5.115	
1.97	5.977	
1.93	5.592	Average of
1.89	5.225	porosity values
1.85	6.521	calculated for
1.82	4.592	mean water table
1.78	5.752	heights greater
1.74	5.280	than 0.76 feet is
1.68	4.779	
1.62	5.254	$\bar{f} = \frac{202.889}{36} = 5.636$
1.57	4.839	
1.53	5.626	
1.49	5.275	
1.45	4.979	
1.40	6.157	
1.34	5.637	
1.28	5.228	
1.22	5.855	
1.18	6.816	
1.14	8.407	
1.11	5.848	
1.05	6.047	
0.99	6.120	
0.93	5.347	
0.87	4.827	
0.81	5.258	
0.76	6.194	
0.71	8.923	
0.68	16.844	
0.66	16.109	
0.64	15.374	
0.62	14.505	

for heights greater than 0.76 feet above the recording lateral was 0.056. After testing the model with this average value, a value of 0.058 was selected to see if slight adjustment of the effective drainable porosity would make the model describe actual water table fluctuations better. The adjustment seemed to make a small improvement, hence the value 0.058 was used.

Values in the table also show that effective porosity values increased to about 0.17 at a height of 0.67 feet above the recording lateral. Then a decrease in the porosity values seemed to be occurring. This increase in porosity between 0.67 and 0.76 feet was likely due to the decreasing rate of water table recession which allowed water draining more slowly from the upper soil regions to become a more significant part of the tile flow. Then as the water table continued to slowly fall below 0.67 feet, the flow from the upper soil region began to decrease as it became more thoroughly drained, producing a corresponding decrease in the calculated effective drainable porosities. It was assumed that the porosity values continued to decrease linearly until the value estimated for depths equal to or greater than tile depth, was reached.

The effective porosity below tile level was approximated by the value 0.014; estimated from measurements of drainable pore space, at 60 centimeters tension and depths below about 36 inches, on several Amity soil sites in the Valley.

Selecting Precipitation Data

Even for the widest tile spacing of 90 feet, the water table fluctuations were quite rapid. The rapid water table movement made it necessary to use hourly rainfall data in producing an accurate representation of the water table positions recorded each day. Since the weather bureau station at the airport in Salem, Oregon, was the nearest weather station with several years of consistent hourly precipitation records, their data were selected for use in simulating 16 years of drainage records. Also, the Salem records were selected because local meteorologists indicated that there was high correlation between Salem and Corvallis precipitation, hence the Amity soils needing drainage would likely have rainfall similar to that recorded at Salem. Aided by the local U. S. Weather Bureau staff, records of hourly rainfall from July 1948 to December 1964 at the Salem station were obtained on punch cards from the National Weather Records Center in Asheville, North Carolina. Only the months March, April, and May were used because it was believed they represented the time of year when subsurface drainage would be of most value in the Willamette Valley.

Estimating Evapotranspiration

Because the Salem Airport Weather Bureau Station does not maintain evaporation records, records of evaporation maintained on the Hyslop Agronomy Farm near Oregon State University were used. Records of evaporation at the Farm were available for the months of April and May during most of the years for which rainfall data had been obtained. The mean monthly evaporation was used for the few months that evaporation data were not available. Evaporation records were not maintained for the month of March because evaporation is generally very low during that time of the year. Therefore evaporation was considered to be zero for March.

It is known that evapotranspiration follows a daily cycle to reach a maximum value during the daylight hours and a minimum at night. However as an estimate for the hourly evapotranspiration on the plots, the monthly records of pan evaporation were multiplied by a coefficient and distributed uniformly during the hours of the month.

Based on comparisons made by Pruitt and Angus (1961), between evapotranspiration in a ryegrass field and evaporation from a U. S. Weather Bureau Class A evaporation pan, a coefficient of 0.65 was selected for the spring months. Their investigations indicated a coefficient ranging from 0.75 to 0.80 when the pan was in a vegetated area. When the pan was located in an area with no surface cover they noted that pan evaporation increased nearly 30 percent. A pan placed in a partially vegetated area had an evaporation rate somewhat less than the pan in an open area, but greater than the pan surrounded by vegetation. Since the evaporation pan at the Hyslop Agronomy Farm was located in an area similar to the partially vegetated area in the study by Pruitt and Angus, their coefficients were reduced to an approximate value of 0.65.

Building Models to Simulate Water Table Fluctuations

Initially a computer program was written to develop a satisfactory model of the west 90 foot plot, then the program was modified to form a series of similar programs or models simulating the effects of restricting the main line capacity, changing tile spacing, changing from a vegetated to a bare soil surface, and changing the amount of surface storage to represent good and poor surface drainage.

Each mathematical model was designed to simulate fluctuation of the mean water table resulting from drainage by subsurface drains, recharge of soil moisture by precipitation, evapotranspiration, and surface storage of rainfall during high water table conditions. The relations developed previously for mean water table height as a function of time, time as a function of the mean water table height, effective drainable porosity as a function of water table position, and evapotranspiration as a function of monthly pan evaporation, form the basic structure of each model.

The programs were written to calculate a new mean water table height at the end of a time interval ranging from one to four hours.

The mean water table height was first calculated at the end of each interval as if there were no precipitation. Then following a procedure similar to that used by the Bureau of Reclamation (Dumm, 1964), the rainfall was reduced by evapotranspiration to obtain an effective rainfall. Dividing the effective rainfall by a calculated effective drainable porosity for the water table position, gave the mean water table rise. Repeating this process at one to four hour time intervals simulated the mean water table fluctuation in response to drainage, evapotranspiration, and precipitation. The water table position was located in one of six depth categories at the end of each time interval so that a monthly summary could be printed giving the percent of time and the maximum number of consecutive days that the mean water table was less than selected depths below the ground surface.

Testing the Model

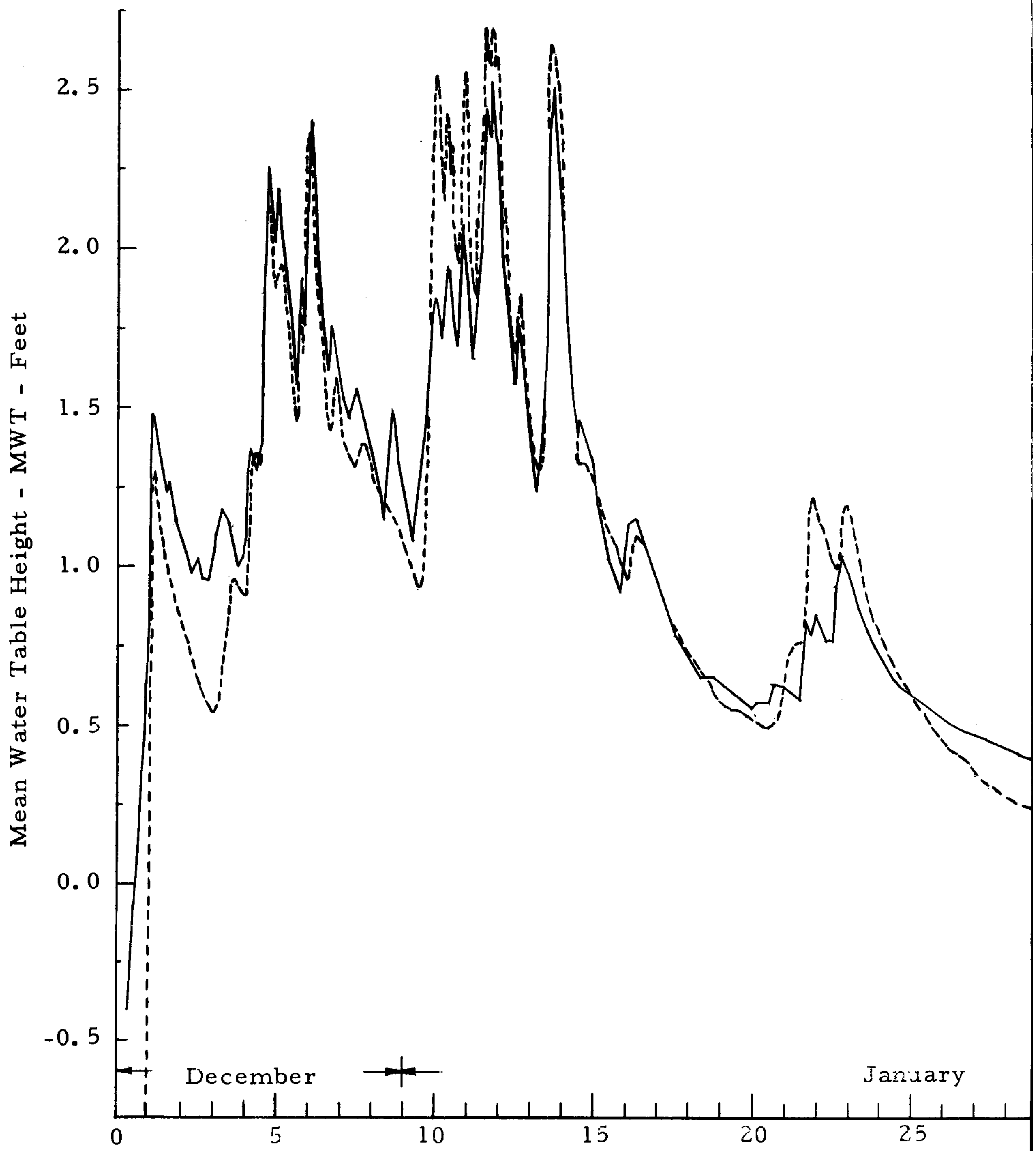
Before developing the entire series of computer programs mentioned above, the program written for the west 90 foot plot was tested with records, from December 23, 1965 to March 20, 1966, of midpoint water table heights which had been converted to mean water table heights by the mean versus midpoint relation. Records of the hourly precipitation collected on the plots were placed on punch cards and read into the simulator program, which was modified for this test to print out the simulated mean water table height at the end of each time interval.

Figure 5 shows the mean water table fluctuation on the west 90 foot plot compared to the simulated mean water table fluctuation during this period of record. The model appeared to predict the fluctuations very well, however the test is limited in that the test period was short and during the time when evapotranspiration was negligible. When all of the records for the 1965-66 season have been collected, it is planned to test the model for the entire season to see how accurate it is during the spring months when there is evapotranspiration.

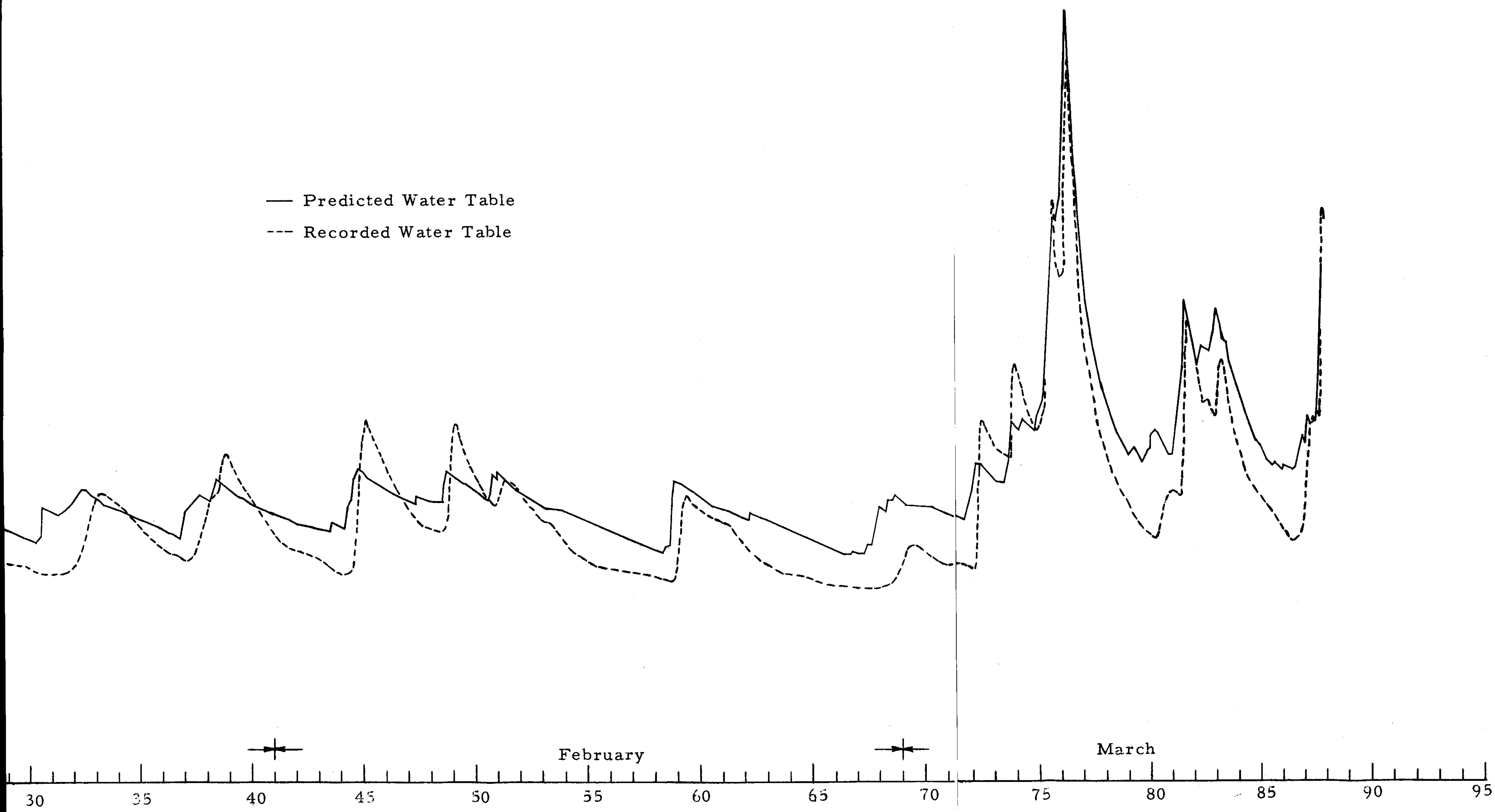
Simulating a Limited Main Line Capacity

Maximum gravity flow in a conduit is reached when the depth of flow is 94 percent of the conduit's diameter. For flow depths greater than this, the quantity of flow decreases. To again obtain a flow equal to the maximum gravity flow a pressure gradient has to be developed in the conduit. Calculations by Lembke (1960) have shown for a conduit flowing full, that a 15 percent increase in the slope of the hydraulic grade line for gravity flow would produce a quantity of flow in the full conduit equal to its maximum gravity flow.

Gravity flow prevailed in the recording lateral when the maximum flow of 48 cubic feet per foot of tile per day for the 90 foot tile spacing was measured. This flow represented the maximum rate at



Mean Water Table Height - MWT - Feet
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
December
January
0
5
10
15
20
25



and predicted mean water table heights for the west 90 foot experimental plot.

which water could be removed from the soil at this site with tile drains spaced 90 feet apart and about three feet deep. The peak flow represented a water removal rate of 6. 5 inches per day. To simulate a limited main line capacity resulting in a peak water removal rate such as 0. 5 inch per day, the model was modified to let the mean water table drop at a constant rate representing water removal of 0. 5 inch per day. The restricted rate of fall continued until a mean water table height was reached for which the mean water table height on the constructed recession curve corresponded to a recorded tile flow of 0. 5 inch per day. Then as the water table receeded below this position gravity flow was assumed to develop and the recession curve was again used as in the original model.

Figure 6 illustrates that the process consisted essentially of replacing the upper portion of the constructed recession curve, where the rate of water table drawdown corresponded to a tile flow greater than that for a particular rate of drainage, by a line representing a constant rate of drawdown equal to that determined for the given rate of drainage.

The above procedure was not entirely correct in that it neglected the decrease in flow rate that occurs when the depth of flow exceeds 94 percent of the conduit diameter and the slope of the hydraulic grade line is less than 1. 15 times the conduit slope. Also it ignored the increase in flow rate which actually occurs when a high water

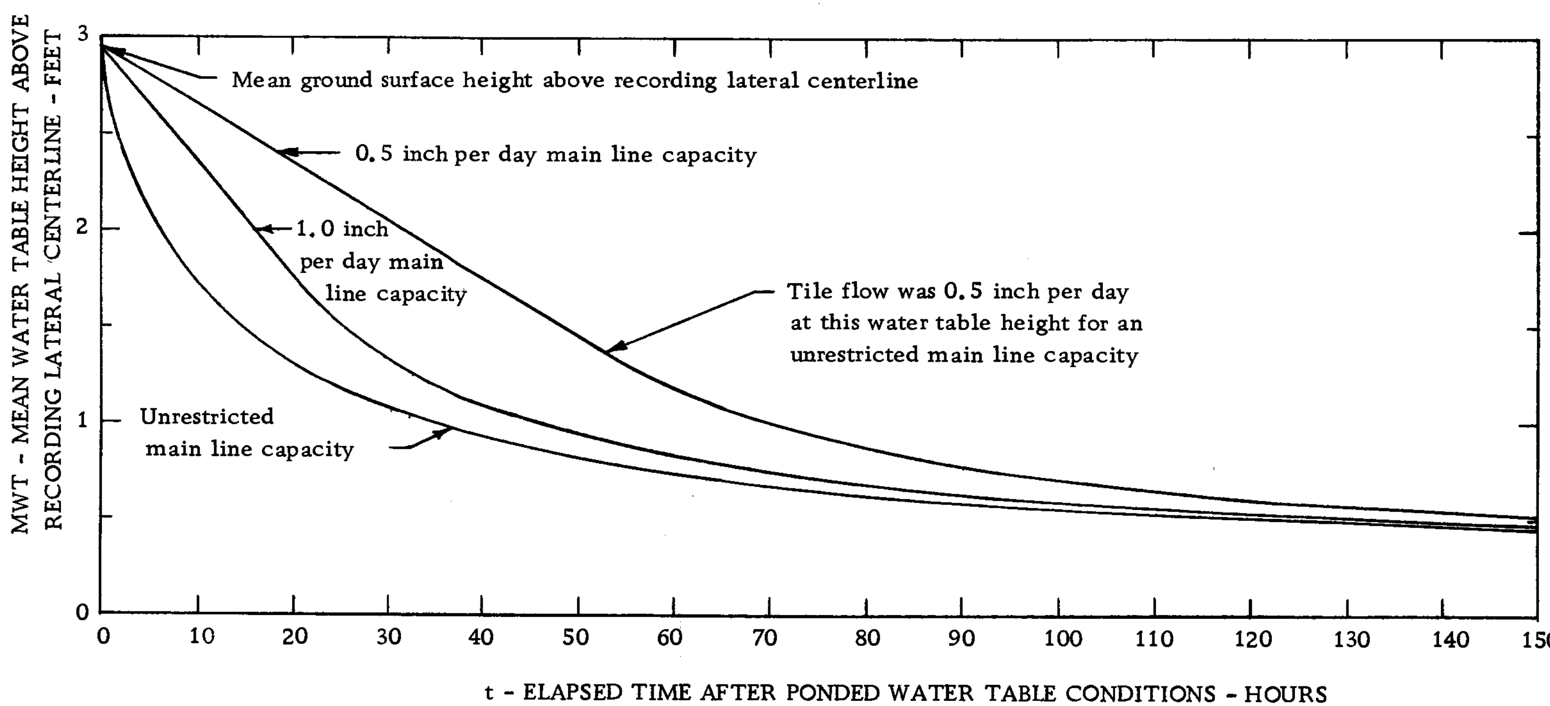


Figure 6. Mean water table recession curves used by the computer programs to simulate 0.5 inch per day, 1.0 inch per day, and unrestricted main line capacities for a 90 foot tile spacing.

table increases the slope of the hydraulic grade line above 115 percent of the conduit slope. Instead of the constant water removal rate such as 0.5 inch per day used in the program for mean water table positions above a limiting mean water table height, the physical system would remove water at a rate slightly greater than 0.5 inch per day for a water table near the soil surface. The water removal rate would then decrease to 0.5 inch per day at the limiting water table height.

Using Manning's equation and the area, A, of a conduit flowing full, one can calculate the change in quantity of flow resulting from an increase in the slope of the hydraulic grade line.

$Q = kS^{1/2}$ where

Q = the quantity of flow

k = conveyance factor (constant for a conduit flowing full)

S = slope of the hydraulic grade line

Now assume that $Q_1 = kS_1^{1/2}$, $Q_2 = kS_2^{1/2}$, and $S_1 = z/x$ while $S_2 = (z + 1.25)/x$. Consider z/x as the slope of the hydraulic grade line that produces a flow of 0.5 inch per day in the restricting main line and 1.25 feet as the maximum amount the head on the restricting main line can increase before the water table reaches the soil surface causing surface runoff.

Assuming $z = 2$ feet for a typical field installation, one can show that $Q_2 = 1.27Q_1$. This indicates that using a constant water removal rate above a given mean water table height when simulating limited main line capacities results in some error in the predicted water table fluctuations.

However based on the records of unrestricted tile flow on the 90 foot plot, a 1.25 foot change in water table height from ponded water conditions resulted in the quantity of flow Q_2 being equal to over 7.2 times Q_1. Since the change in flow rate for these conditions was much larger than that calculated when main line capacity was limiting, it was assumed the approach used to simulate limited main line capacities would give reasonable estimates of water table fluctuations for comparison with fluctuations under gravity flow conditions. In addition, the errors involved in neglecting the change in tile flow caused by a change in slope of the hydraulic grade line tend to cancel each other.

Simulating Tile Spacings

Van Schilfgaarde (1965) has developed an approximate transient state drainage equation of the following form.

$$t = \frac{fS^2}{9Kd} \log_e \frac{m_o (2d + m)}{m (2d + m_o)} \qquad \text{where,}$$

t = time

f = drainable porosity

S = tile spacing (length)

K = hydraulic conductivity (length/time)

d = equivalent depth of impervious layer below drain axes (length)

$\log_e$ = natural logarithm

m = midpoint water table height above the drain axes (length)

m_o = initial value of m (length)

If one assumes that the values f, K, and m_o are nearly equal for different tile spacings having the same water table height and that the equivalent depth - a function of tile spacing - is essentially constant for the spacings considered, the following expression results.

$$t_{S_1} \doteq t_{S_2} \left(\frac{S_1}{S_2}\right)^2 ,$$

which indicates that the time required for the water table to reach a given height for one tile spacing is approximately equal to the product of the time required to reach the same height on another spacing and the ratio of the spacings squared.

A recession curve for the 60 foot tile spacing was constructed in the same manner as described previously for the 90 foot tile spacing, and calculations were made to test the feasibility of using this relation to calculate the drawdown for a 60 foot tile spacing from the drawdown for a 90 foot tile spacing. A comparison of the values in Table II shows that the relation is reasonably accurate when used to

TABLE II. MEAN WATER TABLE RECESSION FOR THE 90 AND 60 FOOT TILE SPACINGS AND RECESSION FOR 60 FOOT TILE SPACING CALCULATED FROM RECESSION FOR 90 FOOT TILE SPACING.

Mean Water Table Height-MWT Feet	Time on Recession Curve for 90 foot Tile Spacings-t_{90} Hours	Time on Recession Curve for 60 foot Tile Spacing-t_{60} Hours	Calculated Time on Recession Curve for 60 Foot Tile Spacing $t = t_{90}(\frac{60}{90})^2$ Hours	Water Table Height on Recession Curve for 60 Foot Tile Spacing at Calculated Time-t Feet
2.95	0.0	0.0	0.0	2.95
2.90	0.18	0.04	0.08	2.88
2.80	0.50	0.18	0.22	2.76
2.70	0.90	0.34	0.40	2.67
2.60	1.40	0.55	0.62	2.57
2.50	2.00	0.80	0.89	2.47
2.40	2.60	1.10	1.16	2.38
2.30	3.30	1.40	1.47	2.28
2.20	4.20	1.78	1.87	2.17
2.10	5.08	2.19	2.26	2.08
2.00	6.00	2.61	2.67	1.99
1.90	7.15	3.12	3.18	1.89
1.80	8.50	3.73	3.78	1.79
1.70	10.10	4.40	4.49	1.70
1.60	12.00	5.30	5.33	1.59
1.50	14.30	6.35	6.36	1.50
1.40	17.00	7.72	7.56	1.41
1.30	20.30	9.35	9.02	1.32
1.20	24.00	11.30	10.67	1.23
1.10	29.50	13.30	13.11	1.11
1.00	35.30	15.70	15.69	0.99
0.90	42.00	18.80	18.67	0.91
0.80	49.00	24.90	21.78	0.84
0.70	59.80	35.90	26.58	0.78
0.60	89.00	47.00	39.56	0.67
0.50	122.50	57.30	54.44	0.53

calculate the water table heights on a 60 foot spacing from the time values and heights on a 90 foot spacing. Based on these results, the approximate time relation was used in modifying the original program to simulate 60, 120, and 150 foot tile spacings.

Simulating Vegetated and Bare Soil Surfaces

When precipitation occurred it was reduced by the estimated evapotranspiration or evaporation to represent the effects of a vegetated or bare soil surface respectively.

During rain-free periods on a vegetated surface evapotranspiration increased the rate of water table decline to a depth of 1.5 feet. It was assumed that plants would not be removing moisture from the soil at depths greater than 1.5 feet and that evaporation by capillary movement of soil moisture was negligible so that when the water table passed below 1.5 feet, the hourly evapotranspiration no longer speeded the water table recession. Instead, the evapotranspiration began building a soil moisture deficit such that rainfall would have to overcome any accumulated deficit before it could percolate through the soil to raise the water table. Therefore during periods when a soil moisture deficit existed, the mean water table was allowed to receed along the constructed water table recession curve without being affected by rainfall or evapotranspiration.

For a bare soil surface, evaporation was considered to occur only in the upper six inches of the soil. At depths greater than six inches the capillary movement of moisture toward the surface was considered to be negligible. The computer programs simulated this situation by allowing evaporation to increase the rate of mean water table decline only if the mean water table depth was less than six inches. After the water table passed below the six inch depth, it was estimated that continued drying of the upper soil region would produce a soil moisture deficit of 0. 25 inch before evaporation became negligible. As with the grass cover, precipitation had to overcome any soil moisture deficit before it could cause the mean water table to rise again.

Simulating Surface Storage

Surface storage effects were introduced by allowing the mean water table to rise some maximum height above the mean ground surface before surface runoff was considered to be draining away the excess precipitation. A surface storage of 0. 2 inch was used in all of the simulator programs except in the two programs simulating a 150 foot tile spacing having a bare soil surface and 0. 5 inch main line capacity. For these two programs, one used a surface storage of 0. 2 inch while the other program used a storage of 0. 75 inch to permit a comparison of the effects good and poor surface drainage would have on a tile drainage system. The programs were written to treat this storage above the mean ground surface as inches of water so that a record of any surface runoff could be maintained.

Following the procedures outlined above, various combinations of main line capacities, tile spacings, surface covers, and amounts of surface storage were simulated by the computer programs to predict the results one might expect for each combination as well as to gain an insight into the results that might be obtained with other combinations.

Analysis of Computer Results

A preliminary examination was made of the 48 monthly summaries (16 summaries for each month) printed for March, April, and May by each simulator program. Based on the observed results and the comparisons that were to be made, portions of the output for each month were analyzed. A sample summary for March 1963 is shown in Figure 7.

Sixteen years of hourly rainfall data resulted in 16 values for the percent of time and 16 values for the maximum number of consecutive days in each month that the mean water table depth below the mean ground surface would be less than one of the six depth levels established in the simulator programs for locating the water table position. Due to time limitations only the more important depths for a particular month were investigated. The 1 and 2 foot depths were

Month 3 Year 1963

.5 D. C., 150 ft spacing, grass cover, 0.2 in surface storage

A = 744.00

Percent of time and maximum number of consecutive days mean water table less than given depth in feet

Percent	Consecutive Days	Depth
9.140	2.833	0.50
9.543	2.958	0.75
10.753	3.042	1.00
14.113	4.375	1.50
24.731	4.667	2.00
100.000	31.000	2.50

Total surface runoff = 1.622 inches

Peak runoff = 0.159 inches/hour

Figure 7. Sample summary of water table position in March 1963.

considered in March while the 2 and 2.5 foot depths were investigated in the drier months April and May.

Analysis of the simulated data was based on procedures generally outlined by many investigators for frequency analysis of hydrologic data. Chow (1964) has presented a detailed discussion pertaining to the methods most frequently used for analysis of hydrologic data. Chow (1954) has also shown that the modified log-normal probability distribution has the widest application in statistical analysis of hydrologic data. The modified log-normal distribution includes as special cases, the normal, log-normal, and certain extreme-value distributions, hence it was selected to represent the frequency distributions for the simulated monthly water table summaries.

A graphical procedure presented by McGuinness and Brakensiek (1964) for working with the modified log-normal distribution was used. In a given month the 16 values for the percent of time or the maximum number of consecutive days the mean water table was less than a depth such as 2 feet, were ranked from the largest to the smallest value. The mean of the set of 16 values was calculated by dividing their total by 16. In some instances only three values were non-zero, however the total of these three values was still divided by 16 to obtain a mean.

To aid in plotting, each ranked value was divided by the mean and the resulting value plotted on log-normal probability graph paper.

The plotting positions along the probability axis were computed from the ratio m/(n + 1) where m is the order number of the ranked data point (m = 1 for the largest data point) and n is the number of data points. This ratio, which was developed by Gumbel and Chow, does not depend upon the shape of the frequency distribution for the data (McGuinness and Brakensiek, 1964).

Table III is a representation of the 16 ranked values for the maximum number of consecutive days that the mean water table was less than two feet deep in March for a 90 foot tile spacing. Figure 8 shows the probability curve obtained when values from the table are plotted on a log-normal probability graph paper.

With the limited number of data points available, some plots appeared to represent straight lines indicating that they might follow a log-normal distribution. Other plots had definite curvature or skewedness such that one would believe the data could be represented by a modified form of the log-normal distribution. Generally the approximating curves drawn through the data points plotted on log-normal probability graph paper exhibited gradual curvature so that the curves could be extended with a reasonable degree of certainty to obtain an estimate of values that would probably be equaled or exceeded on the average once every 20 years.

To make further comparisons, values were taken directly from the curve drawn through the data points on each graph, instead of

TABLE III. SAMPLE TABLE USED TO OBTAIN VALUES FOR PLOTTING ON LOG-NORMAL PROBABILITY PLOTS.

Month 3

Spacing 90 feet   Drainage Coefficient 0. 5 inches

bare surface cover   0. 2 inch surface storage

VALUE = Number of consecutive days mean water table less than 2. 00 feet deep.

Year	Value x	Rank No. m	Ranked Value x	$x/\bar{x}$	Plotting Position F_n
1949	0. 04	1	11. 17	3. 68	5. 9
1950	3. 08	2	6. 25	2. 06	11. 8
1951	2. 33	3	5. 92	1. 95	17. 6
1952	0. 00	4	4. 50	1. 48	23. 5
1953	2. 67	5	3. 67	1. 21	29. 4
1954	2. 88	6	3. 08	1. 01	35. 3
1955	1. 42	7	2. 88	0. 95	41. 2
1956	2. 83	8	2. 83	0. 93	47. 1
1957	11. 17	9	2. 67	0. 88	52. 9
1958	0. 00	10	2. 33	0. 77	58. 8
1959	1. 79	11	1. 79	0. 59	64. 7
1960	4. 50	12	1. 42	0. 47	70. 6
1961	6. 25	13	. 08	0. 03	76. 5
1962	5. 92	14	. 04	0. 01	82. 4
1963	3. 67	15			88. 2
1964	0. 08	16			94. 1

Total of Ranked Values 48. 63

$\bar{x}$ = Total/16 = 48. 63 /16 = 3. 039

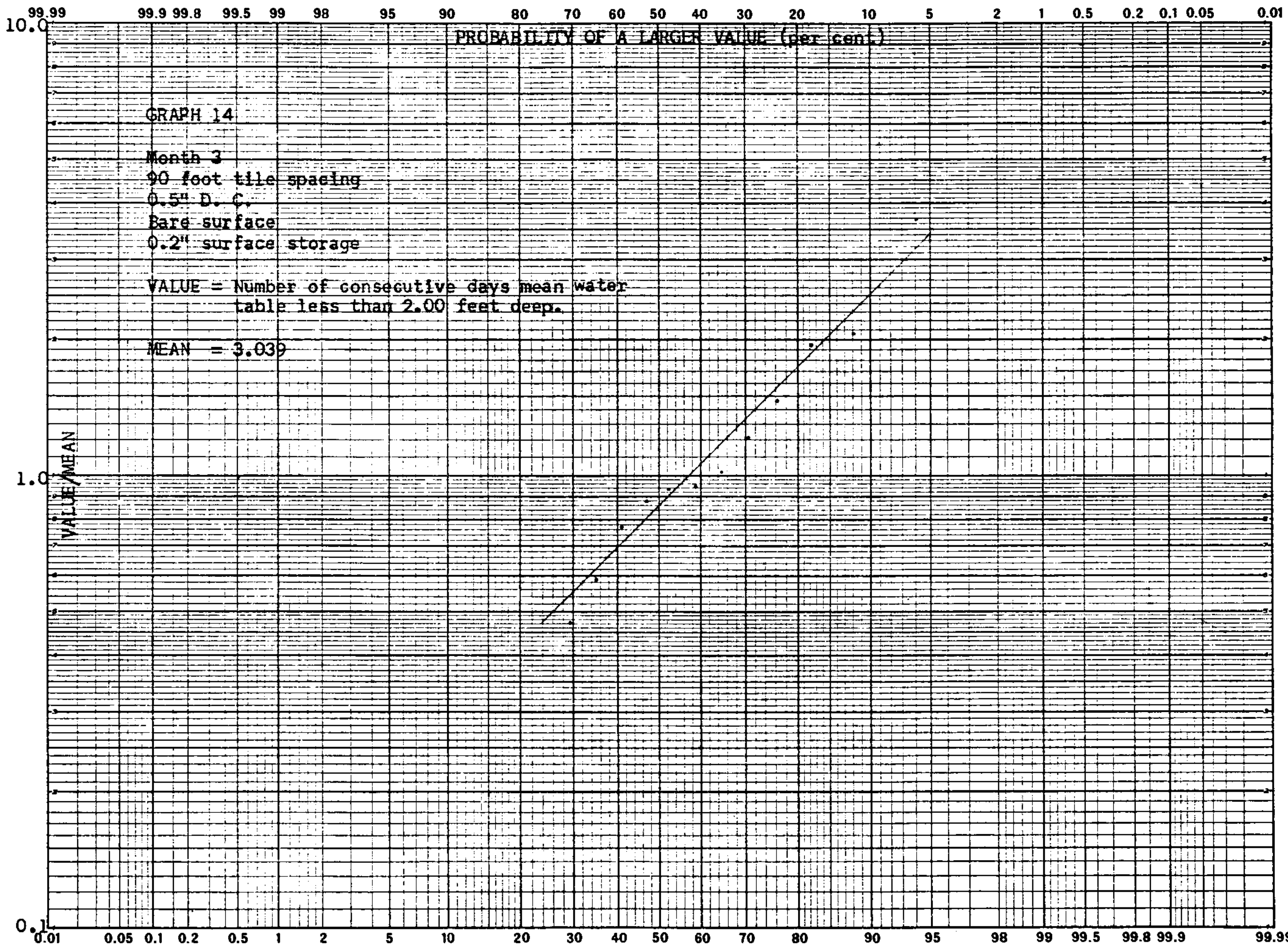


Figure 8. Sample log-normal probability graph obtained using the values in Table III.

using mathematical equations calculated for each curve to obtain values for making comparisons. In using either procedure it was assumed that the curve drawn through the data points on each graph approximated the unknown frequency distribution of water table fluctuation for a given drainage system. Points on the curve were selected at the 5, 10, 20, 50, and 75 percent positions for the probability of observing a value greater than some magnitude. Since the plotted values represented the original values divided by their mean, the points selected were multiplied by their mean to obtain the final values used for making comparisons among the drainage systems. The final values were placed in tables similar to Table IV, page 55.

DISCUSSION OF RESULTS

The reliability of conclusions based on the values presented in Tables IV-X depend upon how well the simulated data and the probability curves drawn through the data points represent the actual frequency distribution of water table positions for a given drainage system. Although the data was simulated, it does provide information needed in making general statements pertaining to selected drainage installations in an Amity soil.

After the simulator programs had been run on the IBM 7094 computer, it was realized water table recession rates less than the minimum value determined for water table recession below tile level were being calculated and used by the programs simulating 120 and 150 foot tile spacings. The recession rates calculated for the 120 foot spacing were less than the minimum value of 0.0018 feet per hour whenever the water table was more than about 2.35 feet deep. With a 150 foot spacing the calculated recession was less than 0.0018 feet per hour whenever the water table was more than 2.25 feet deep.

It was not possible to rerun all the simulator programs, hence a maximum bound on the error was determined by rerunning a corrected program for the 150 foot tile spacing with 0.5 inch per day main line capacity, bare soil surface, and 0.2 inch surface storage.

The error had accumulated to produce its maximum influence on the summaries for May. Making a comparison between the summaries for the corrected and uncorrected programs, it was found the corrected program reduced the amount of time the water table was less than 2.5 feet deep in May, by about 50 percent. The amount of reduction became progressively less to about 20 percent in April at the 2.5 foot depth and 4 percent in March at the depth of 2.0 feet. Also due to the form of the error, it would be less for the simulated 120 foot tile spacings. Therefore when interpreting comparisons made with the tabulated values for 120 and 150 foot tile spacings, it must be remembered that these spacings would actually provide better drainage than indicated by the tabulated values. Despite the error, the results aid in making general conclusions related to tile drainage installations in an Amity soil.

The values in Table IV show that restricting the main line capacity increased the amount of time for which the mean water table was less than one foot deep in March. The amount of increase became smaller as the probability that a value would be equaled or exceeded increased. A combination of two factors explain the latter result.

First, for values with low probability of being equaled or exceeded, the rainfall rate would be more intense than for values with a higher probability of occurrence. The intense rainfall would exceed a restricted drainage rate more of the time than would a rainfall

TABLE IV. PROBABLE MEAN WATER TABLE DURATIONS DETERMINED FROM LOG-NORMAL PROBABILITY PLOTS OF WATER TABLE DATA SIMULATED FOR MARCH.

Tile Spacing Feet	Main Line Capacity Inches/day[a]	Surface Cover	Surface Storage Inches	Value[b]	Probability of a Larger Value 0.05 / Average Return Period-Years 20	0.10 / 10	0.20 / 5	0.50 / 2	0.75 / 1.33
90	0.5	Bare	0.2	# <1.0	6.71	4.14	1.14		
	1.0			# <1.0	2.77	1.57	(0.80)		
	UR			# <1.0	0.93	0.42	(0.16)		
	0.5			% < 2.0	52.47	37.58	25.24	11.63	6.24
	1.0			% < 2.0	41.19	30.96	21.47	10.86	(6.24)
	UR			% < 2.0	39.56	29.86	21.15	10.70	(5.97)
	0.5			# <2.0	10.39	7.66	5.32	2.61	(1.47)
	1.0			# <2.0	7.64	5.89	4.24	2.33	(1.43)
	UR			# <2.0	7.64	5.91	4.29	2.35	(1.44)
120	0.5	Bare	0.2	# <1.0	6.44	4.59	2.40	(0.18)	
	1.0			# <1.0	2.72	1.78	0.80	(0.04)	
	UR			# <1.0	2.37	1.52	0.65	(0.06)	
	0.5			% <2.0	90.53	54.96	49.09	24.84	15.08
	1.0			% <2.0	85.78	52.87	45.00	21.80	14.43
	UR			% <2.0	85.78	52.87	45.00	21.80	14.43
	0.5			# <2.0	16.19	12.62	9.33	5.24	3.28
	1.0			# <2.0	15.42	12.06	8.95	5.04	3.17
	UR			# <2.0	14.57	11.55	8.69	4.98	3.19
150	0.5	Bare	0.2	# <1.0	7.17	4.67	2.71	0.92	(0.34)
	1.0			# <1.0	4.55	2.96	1.77	0.66	(0.30)
	UR			# <1.0	3.97	2.66	1.63	0.63	(0.30)
	0.5			% <2.0	98.82	89.09	76.29	50.18	33.28
	1.0			% <2.0	96.45	84.96	72.46	50.22	33.98
	UR			% <2.0	96.45	84.96	72.46	50.22	33.98
	0.5			# <2.0	28.77	22.31	16.47	8.99	5.55
	1.0			# <2.0	27.05	21.11	15.58	8.65	5.38
	UR			# <2.0	27.05	21.11	15.58	8.65	5.38

[a] UR = Unrestricted

[b] # <1.0 - Maximum number of consecutive days mean water table was less than one foot deep.

% < 2.0 - Percent of time the mean water table was less than two feet deep.

( ) - Numbers enclosed in parentheses may be inaccurate due to the lack of sufficient data points for this and greater probabilities of occurrence.

of less intensity. Secondly, in Figure 6 it may be seen from the water table recession curves used for simulating main line capacities, that the rate of water table recession for any two main line capacities would not be linearly related. This non-linear relation, combined with the effect of rainfall intensity, would result in the increased amount of time for which the water table was less than one foot deep becoming smaller as the probability of occurrence increased.

Restricting the main line capacity did increase the amount of time the water table was less than two feet deep during March, however the relative increase was much less than that observed for depths less than one foot. Hence the effects of restricting main line capacity are more pronounced for high water table conditions.

With the possible exception of water table depths less than one foot on a 90 foot tile spacing, the data indicates that the unrestricted main line capacities of 6.5 inches per day for a 90 foot tile spacing, 4.8 inches per day for a 120 foot tile spacing, and 3.9 inches per day for a 150 foot tile spacing, did not produce appreciably better drainage than a rate of 1.0 inch per day. Designing the main line for a maximum capacity near 1.0 inch per day would seem to be indicated.

As shown by the values in Table V, the water table was usually low enough during April and May that restriction of the main line capacity, even to the smallest value of 0.5 inch per day, had very

TABLE V. PROBABLE MEAN WATER TABLE DURATIONS DETERMINED FROM LOG-NORMAL PROBABILITY PLOTS OF WATER TABLE DATA SIMULATED FOR APRIL AND MAY.

Month	Tile Spacing Feet	Main Line Capacity inches/day[a]	Surface Cover	Surface Storage inches	Value[b]	Probability of a Larger Value 0.05 / Average Return Period-Years 20	0.10 / 10	0.20 / 5	0.50 / 2	0.75 / 1.33
April	120	0.5	Bare	0.2	%<2.0	39.93	31.96	19.92	3.89	
April	120	UR	Bare	0.2	%<2.0	32.84	26.78	17.60	3.56	
May	120	0.5	Bare	0.2	%<2.0	27.95	9.09	2.44		
April	150	0.5	Bare	0.2	%<2.0	60.37	52.13	37.08	10.76	
April	150	UR	Bare	0.2	%<2.0	57.48	51.47	37.76	10.36	
May	150	0.5	Bare	0.2	%<2.0	26.90	20.37	12.03	(0.67)	

[a]UR - Unrestricted

[b]%<2.0 - Percent of time the mean water table was less than two feet deep.

little effect on the amount of time for which the mean water table was less than two feet deep for both the 120 and 150 foot tile spacings. The amount of time that the mean water table was less than 2.5 feet deep during April and May was nearly identical for all main line capacities simulated (unrestricted, 1.0 and 0.5 inch per day) with 120 and 150 foot tile spacings. For April and May, the simulated results at all depth levels with a 90 foot tile spacing were identical, except one year when the results were nearly identical, for the three main line capacities used.

Therefore the values in Table VI, although calculated for a 0.5 inch main line capacity, are essentially equal to the values for 1.0 inch and unrestricted main line capacities. Since the effects of main line restriction are negligible, the values in Table VI relate the effect of tile spacing on water table fluctuations in April and May. The table also shows that the mean water table has a strong tendency to remain between 2 and 2.5 feet deep during this period if one remembers that values determined for the 120 and 150 foot tile spacings are high.

Table VII shows that the amount of time the mean water table was less than one foot deep in the wetter month March, was greater for a 90 foot tile spacing with 0.5 inch main line capacity than for a 120 or 150 foot tile spacing with unrestricted or 1.0 inch main line capacity. However Table VIII indicates that for water table depths

TABLE VI. PROBABLE MEAN WATER TABLE DURATIONS DETERMINED FROM LOG-NORMAL PROBABILITY PLOTS OF WATER TABLE DATA SIMULATED FOR APRIL AND MAY.

Month	Tile Spacing Feet	Main Line Capacity inches/day[a]	Surface Cover	Surface Storage inches	Value[b]	Probability of a Larger Value 0.05 / Average Return Period-Years 20	0.10 / 10	0.20 / 5	0.50 / 2	0.75 / 1.33
April	90	0.5	Bare	0.2	% < 2.0	20.13	9.67	4.00		
	120				% < 2.0	39.93	31.96	19.92	3.89	
	150				% < 2.0	59.53	51.29	36.99	10.09	
April	90	0.5	Bare	0.2	% < 2.5	70.58	57.82	43.07	13.86	
	120				% < 2.5	100.00	95.04	76.28	34.26	12.64
	150				% < 2.5	100.00	100.00	100.00	57.18	35.10
May	90	0.5	Bare	0.2	% < 2.0	(12.83)	(3.74)	(0.88)		
	120				% < 2.0	(27.95)	(9.09)	(2.44)		
	150				% < 2.0	26.90	20.37	12.03	(0.67)	
May	90	0.5	Bare	0.2	% < 2.5	29.25	24.21	19.18		
	120				% < 2.5	46.67	44.79	40.74	18.98	
	150				% < 2.5	97.85	83.31	68.77	43.21	(7.66)

[a]Even though the values were calculated for spacings with 0.5 inch main line capacity, results in Table V show that they would be essentially the same during April and May for 1 inch and unrestricted (UR) main line capacities.

[b]% < 2.0 - Percent of time mean water table was less than two feet deep.

TABLE VII. PROBABLE MEAN WATER TABLE DURATIONS DETERMINED FROM LOG-NORMAL PROBABILITY PLOTS OF SIMULATED WATER TABLE DATA FOR MARCH.

Tile Spacing Feet	Main Line Capacity inches/day[a]	Surface Cover	Surface Storage inches	Value[b]	Probability of a Larger Value 0.05 / Average Return Period-Years 20	0.10 / 10	0.20 / 5	0.50 / 2	0.75 / 1.33
90	0.5	Bare	0.2	# < 1.0	6.71	4.14	1.14		
120	1.0	Bare	0.2	# < 1.0	2.72	1.78	0.80	(0.04)	
120	UR	Bare	0.2	# < 1.0	2.37	1.52	0.65	(0.06)	
150	1.0	Bare	0.2	# < 1.0	4.55	2.96	1.77	0.66	(0.30)
150	UR	Bare	0.2	# < 1.0	3.97	2.66	1.63	0.63	(0.30)

[a] UR = Unrestricted

[b] # < 1.0 - Maximum number of consecutive days mean water table was less than one foot deep.

TABLE VIII. PROBABLE MEAN WATER TABLE DURATIONS DETERMINED FROM LOG-NORMAL PROBABILITY PLOTS OF SIMULATED WATER TABLE DATA FOR MARCH.

Tile Spacing Feet	Main Line Capacity inches/day[a]	Surface Cover	Surface Storage inches	Value[b]	Probability of a Larger Value 0.05 / Average Return Period-Years 20	0.10 / 10	0.20 / 5	0.50 / 2	0.75 / 1.33
90	0.5	Bare	0.2	# < 2.0	10.39	7.66	5.32	2.61	(1.47)
120	1.0	Bare	0.2	# < 2.0	15.42	12.06	8.95	5.04	3.17
120	UR	Bare	0.2	# < 2.0	14.57	11.55	8.69	4.98	3.19
150	1.0	Bare	0.2	# < 2.0	27.05	21.11	15.58	8.65	5.38
150	UR	Bare	0.2	# < 2.0	27.05	21.11	15.58	8.65	5.38
90	0.5	Bare	0.2	%< 2.0	52.47	37.58	25.24	11.63	6.24
120	1.0	Bare	0.2	%< 2.0	85.78	52.87	45.00	21.80	14.43
120	UR	Bare	0.2	%< 2.0	85.78	52.87	45.00	21.80	14.43
150	1.0	Bare	0.2	%< 2.0	96.45	84.96	72.46	50.22	33.98
150	UR	Bare	0.2	%< 2.0	96.45	84.96	72.46	50.22	33.98

[a]UR = Unrestricted.

[b]# < 2.0 - Maximum number of consecutive days mean water table was less than two feet deep.

less than two feet in March, a 90 foot tile spacing with 0.5 inch main line capacity could provide somewhat better drainage than a 120 foot tile spacing with an unrestricted or 1.0 inch main line capacity. It also indicates that the 90 foot tile spacing would be better than a 150 foot tile spacing.

Returning to Table VI for results during April and May, one finds that the 90 foot tile spacing provides the best drainage since the simulated main line capacities were not the factors limiting water table recession. Instead the tile spacings produced the differences in mean water table positions. Nevertheless one notes that in April and May the mean water table would probably not be less than two feet deep a great percent of the time for the 90, 120, and 150 foot tile spacings.

Based on economic considerations and the simulated results tabulated in Tables VI, VII, and VIII, one might recommend a 120 foot tile spacing with a main line capacity near 1.0 inch per day for many tile drain installations in a modal Amity soil. Tile systems with a 1.0 inch main line capacity and laterals spaced 120 feet apart would be less costly to install than systems with a 0.5 inch main line capacity and 90 foot lateral spacings. A system with the 120 foot spacing would provide better drainage during high water table conditions than a 90 foot tile spacing with 0.5 inch main line capacity. Furthermore, the amount of time the <u>mean</u> water table would be less than two feet deep for a 90 foot tile spacing with restricted capacity would probably be only slightly less than for a 120 foot spacing with 1.0 inch main line capacity.

The values in Table IX indicate that a grass surface cover, as compared to a bare soil surface, produced a slight reduction in the amount of time during April and May that the mean water table was less than the given depths. For an undrained Amity site the effect of a grass surface cover would probably be more pronounced. Since evaporation during March was considered negligible in the simulator programs, the results for a grass surface cover and bare soil surface were identical for this month.

Table X shows for the 150 foot tile spacing with 0.5 inch main line capacity, changing the surface storage from 0.2 inch to 0.75 inch produced some increase in the amount of time the mean water table was less than one foot deep. A smaller increase was noted for the amount of time the mean water table was less than two feet deep. The increased surface storage had its greatest effect, as would be expected, for low probabilities of occurrence where rainfall intensities were likely to be high. Values are indicated only for March since this was the only month with sufficient rainfall to produce ponding on the soil surface.

TABLE IX. PROBABLE MEAN WATER TABLE DURATIONS FOR GRASS AND BARE SOIL SURFACE WITH 150 FOOT TILE SPACING AND 0.5 INCH MAIN LINE CAPACITY, DETERMINED FROM LOG-NORMAL PROBABILITY PLOTS OF SIMULATED DATA FOR APRIL AND MAY.

Month	Surface Cover	Surface Storage inches	Value	Probability of a Larger Value 0.05 / Average Return Period-Years 20	0.10 / 10	0.20 / 5	0.50 / 2	0.75 / 1.33
April	Bare	0.2	% <2.0	59.53	51.29	36.99	10.09	
	Grass	0.2	% <2.0	59.51	51.21	34.61	8.30	
May	Bare	0.2	% <2.0	26.90	20.37	12.03	(0.67)	
	Grass	0.2	% <2.0	(23.26)[a]	(16.43)[a]	(10.81)[a]		
May	Bare	0.2	% <2.5	97.85	83.31	68.77	43.21	(7.66)
	Grass	0.2	% <2.5	84.75	72.04	49.15	8.37	

[a]All but three of the simulated data points at this depth were zero for the grass cover while all but seven were zero for the bare soil surface.

TABLE X. PROBABLE MEAN WATER TABLE DURATIONS IN MARCH, RESULTING FROM SIMULATED 0.2 AND 0.75 INCH SURFACE STORAGES FOR A BARE SOIL SURFACE WITH 150 FOOT TILE SPACING AND 0.5 INCH MAIN LINE CAPACITY.

Surface Storage inches	Value	Probability of a Larger Value 0.05 / Average Return Period-Years 20	0.10 / 10	0.20 / 5	0.50 / 2	0.75 / 1.33
0.2	# < 1.0	7.17	4.67	2.71	0.92	(0.34)
0.75	# < 1.0	9.56	5.58	2.93	0.86[a]	0.31[a]
0.2	# < 2.0	28.77	22.31	16.47	8.99	5.55
0.75	# < 2.0	29.57	22.65	16.46[a]	8.86[a]	5.40[a]

[a]The physical impossibility of these values being less than the values for a 0.2 inch surface storage indicates the error probably introduced in sketching the curves on the log-normal probability graphs.

SUMMARY AND CONCLUSIONS

In 1963 an experimental tile drainage installation was made in what was considered to be a modal soil of the Amity series. Records of rainfall, water table fluctuations, and tile flow were maintained for tile drains approximately three feet deep at 30, 60, and 90 foot spacings. The records were used to develop empirical relations which formed the basic structure of digital computer programs simulating water table fluctuations for 90, 120, and 150 foot tile spacings; 0.5, 1.0 inch per day and unrestricted main line capacities; 0.2 and 0.75 inch allowable ponding on the surface; and a grass or bare soil surface.

After determining that results from the simulator program compared favorably with a short period of field water table records for the 90 foot tile spacing, 16 years of hourly rainfall data from Salem, Oregon, were used with the programs to obtain monthly summaries of mean water table fluctuations in March, April, and May for 16 years.

The following conclusions were obtained from observations made at the experimental plots and 16 years of simulated water table data.

1. Tile spacings of 30 and 60 feet would be too narrow for a modal Amity soil. Laterals at these spacings provide very good drainage, however they would not be economically

feasible for most situations.

2. A 120 foot tile spacing with 1.0 inch per day main line capacity would satisfy nearly the same drainage requirements as a 90 foot tile spacing with 0.5 inch per day main line capacity. Based on results from the simulator programs, and the fact that tile spaced 120 feet apart would be less costly to install than tile spaced 90 feet apart, a tile spacing of 120 feet might be recommended for many tile drainage installations in a modal Amity soil.

3. Restricting the main line capacity had the greatest effect on the amount of time for which the water table was in the upper soil regions. The effect diminished progressively as the water table receeded to greater depths.

4. A very slight reduction in the amount of time the water table was less than given depths below the ground surface would probably be realized for a grass surface cover compared with a bare soil surface over a tiled area.

5. A surface storage of 0.75 inch ("poor surface drainage") made some increase in the amount of time the water table remained in the upper soil regions as compared to a surface storage of 0.2 inch ("good surface drainage"). The magnitude of the increase was greatest for values having larger average return periods.

6. The conclusions drawn from the study are limited by how well the simulated data represents the actual data one would have recorded at the experimental site from 1949 to 1964. Also the general applicability of the results to Amity soils depends upon the degree by which the experimental plots represent Amity soils in the Willamette Valley.
7. The study indicates a need to install in a modal Amity soil for testing purposes, a tile system with 1.0 inch main line capacity and laterals spaced 120 feet apart.
8. Finally results calculated with analytical solutions need to be compared with the field data to see if any one theory will adequately describe changes in water table position in an Amity soil.

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APPENDIX

DESCRIPTION OF SOIL AT SITE[2]

Amity Silt Loam-Philomath Drainage Plots

Ap	0-7"	Very dark grayish brown (10 YR 3/2) silt loam; moderate medium and coarse granular structure; friable, slightly sticky and slightly plastic; abundant grass roots; abrupt smooth boundary.
A12	7-12"	Dark brown (10 YR 3/3) silt loam; moderate fine subangular blocky structure; friable, slightly sticky and slightly plastic; few faint fine browner and grayer mottles; few fine Fe-Mn concretions; many fine and medium, and few coarse pores; abundant grass roots; gradual wavy boundary.
B1 or A2	12-20"	Dark grayish brown (10 YR 4/2) silt loam; moderate medium subangular blocky structure; friable, sticky and plastic; many distinct medium yellowish brown (10 YR 5/4), and common faint medium grayer mottles; common fine Fe-Mn concretions; many fine and medium, and common coarse pores; common roots; gradual smooth boundary.
B21t	20-32"	Grayish brown (10 YR 5/2) light silty clay loam; weak medium prismatic breaking to strong medium subangular blocky structure; friable, sticky and plastic; many distinct medium yellowish brown (10 YR 5/6) and faint grayer mottles; common fine and few large Fe-Mn concretions; many medium and coarse pores; thin patchy clay films on peds and in pores; common roots; gradual smooth boundary.
B22t	32-36"	Grayish brown (10 YR 5/2) light silty clay loam; moderate medium prismatic breaking to moderate medium subangular blocky structure; friable, sticky and plastic; some peds slightly brittle; abundant distinct medium yellowish brown (10 YR 5/6) and faint medium grayer mottles; common

[2] Description made by Dr. Gerald H. Simonson, Associate Professor of Soils, Oregon State University.

		fine and medium Fe-Mn concretions; Mn coatings on some ped surfaces; thin patchy clay films on peds and in pores; common medium pores; few roots; clear wavy boundary.
B23t	36-44"	Grayish brown (10 YR 5/2) light silty clay loam; moderate medium prismatic breaking to moderate medium subangular blocky structure; friable, sticky and plastic; many large distinct strong brown (7.5 YR 5/4) and gray (2.5 Y 6/1) mottles; medium patchy clay films on peds and in pores; common medium pores; few Fe-Mn concretions; few roots; gradual smooth boundary.
B3t	44-54"	Brown (10 YR 5/3) silty clay loam; weak coarse prismatic breaking to weak coarse subangular blocky structure; common medium distinct browner and grayer mottles; few fine Fe-Mn concretions; common fine and few medium pores; few clay films in pores; few roots; diffuse smooth boundary.
C	54-66+"	Brown (10 YR 5/3) silty clay loam; nearly massive; slightly firm, sticky and plastic; common fine distinct strong brown and few coarse gray mottles; common fine and medium pores.

General Comments on Soil at Philomath Drainage Plots

The soils at the plot site are relatively uniform over most of the area and are fairly representative of the Amity soil series.

The Al horizon may average a bit thinner than for much of the Amity in the Valley. The horizon below the Al is mottled but is browner than the A2 horizon typical of the Amity series. The lack of mottles and concretions in the plow layer and the less distinct A2 horizon indicate that the soil at this site may be tending toward the high side of the somewhat poor drainage class.

The lower part of the profile is somewhat finer textured than is found in Amity soils nearer the Valley center. However, this seems to be the usual situation near the Valley margins in the southern part of the Willamette Valley.

Along the north side of the plots and extending in about as far as the first set of tile spacings, there seem to be slight variation in morphology, although still well within the range of the Amity series. In this part of the plots, a 4 to 5 inch layer beginning at about 30 or 32 inches depth has somewhat more manganese coatings and brittleness suggestive of slight fragipan characteristics. Also the substratum below 40 or 45 inches is more firm and seems to have a medium to heavy silty clay loam texture. These variations are not striking in appearance but would tend to have some affect on permeability of the soil in this part of the plots.