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by

Kovit Thuamsangiem

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Agricultural and Irrigation Engineering

Approved:

Major Professor

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1974

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Kovit Thuamsangiem

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ABSTRACT

A Field Evaluation of Combined

Mole-Tile Drain Systems in Heavy Soils

by

Kovit Thuamsangiem, Master of Science

Utah State University, 1974

Major Professor: Dr. Komain Unhanand
Department: Agricultural and Irrigation Engineering

An investigation was conducted to evaluate the field performance and to study the cost analysis of the combined mole-tile drain systems in heavy soils by comparison with a similar tile drain system. The field performance studies included the recession rates of water table in the system, the deterioration of mole drains in the combined systems during the period of two years. The economic analysis was made by comparing the cost of the combined systems with that of an equivalent tile drain system. The results of the experiments indicate that the combined systems were more effective than the tile drain system in lowering the water table. The difference in the effectiveness between the combined systems using the single and double mole drains was not distinctly apparent. There was no conclusive indication of the deterioration of the mole channels during the period of two years. Also, the construction cost of a combined system is always lower than that of an equivalent tile drain system.

(88 pages)

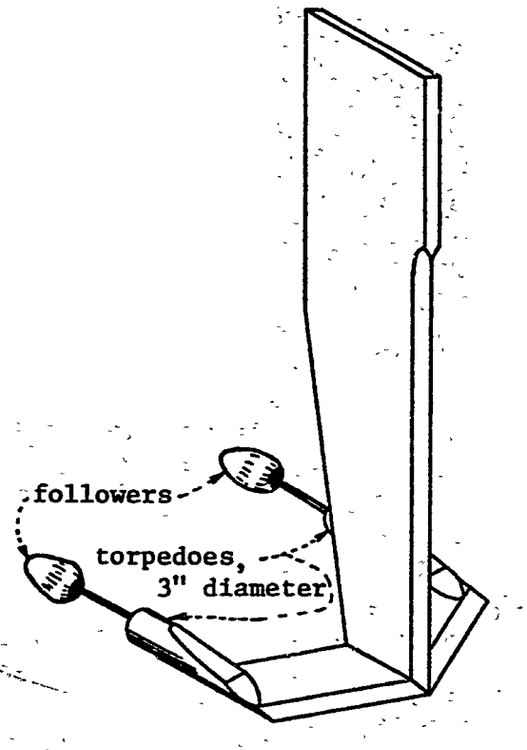
INTRODUCTION

A mole drain system provides shallow subsurface drainage and is most applicable to heavy soils. A mole drain is constructed by pulling a torpedo-shaped iron plug through the soil, at a depth of about 18 to 24 inches below the ground surface, to form a channel approximately the cross-sectional shape of the pulled object. The mole drain system may be installed easily at a relatively low construction cost. In addition, the construction of mole drain has a subsoiling effect which breaks up compacted layers and improves air circulation through the soil.

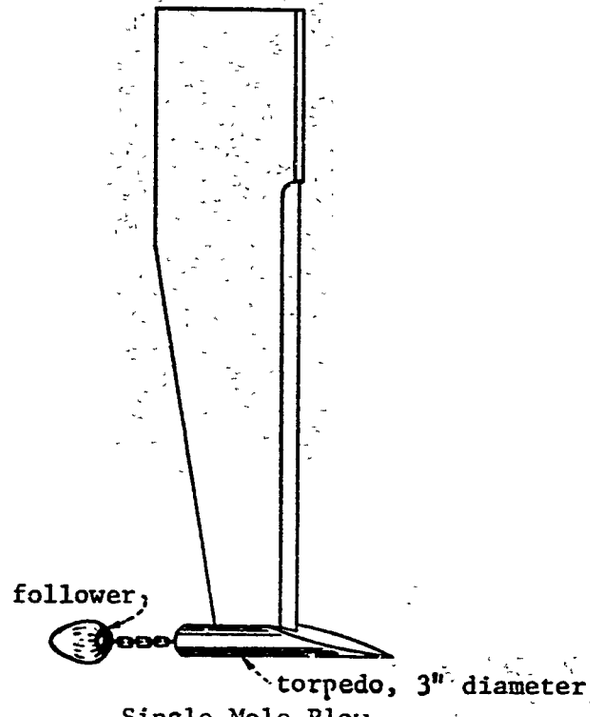
There are two types of mole drains, single and double. A single mole drain, commonly used in the mole drainage system, is constructed with a mole plow having one torpedo attached to a sharp-edged blade (see Figure 1). The moling process causes the soil in the vicinity of the drain to crack, and the vertical blade also leaves a slit which forms the main way for water to enter the drain (Piper, 1958; Theobold, 1963).

A double mole drain has been developed recently with an expectation of obtaining a more durable mole drain. The method of construction is the same as for a single mole drain with the exception that the plow pulls two torpedoes spaced 12 inches apart instead of one as for a single mole plow (Unhanand, 1972) (see Figure 1). Consequently, two channels are formed per pass instead of one.

Mole drains, if used alone, are normally drawn on a small slope from an open drain. Pipe outlets are always provided to prevent the exits of the mole channels from damage caused by the erosion of the flowing drainage water.



Double Mole Plow



Single Mole Plow

Figure 1. Single and double mole plows.

Importance of the Problem

The use of mole drains is limited to heavy soils in which the mole channels can retain the shape after being constructed. While being advantageous in having low cost and subsoiling effect, mole drains have a relatively short life. Because of the short life, mole drains must be redrawn as often as every two years. Although the installation cost of the mole channels is low, the work on outlets could be expensive and time consuming.

Tile drains, to be effective in heavy soils, require a close spacing due to the low hydraulic conductivity of the soils. Thus, even though tile drains have advantages of having a long life and requiring little maintenance, the high initial cost often offsets its economic feasibility.

A combined mole-tile drain system consists of mole drains, usually 5 to 12 feet apart, drawn across and at right angles to a widely spaced network of tile drains laid underneath at some suitable depth (see Figure 2). The tile drains are covered with a very permeable and durable material which allows water to flow directly from the mole channels into the tile drains.

In the combined system, the mole drains are intercepted and divided by tile drains into many short portions. Each portion discharges the drainage water directly through the gravel envelope into the tile drains (see Figure 3). With this arrangement, the length of each portion of the mole drains between the tile drains is relatively short. Therefore, if clogging occurs in the mole channel, the effect of clogging on the capacity to carry drainage water per unit length of the line will be much less than in the case where the same number of cloggings occur in a single, long mole line. In the combined system, new mole lines can

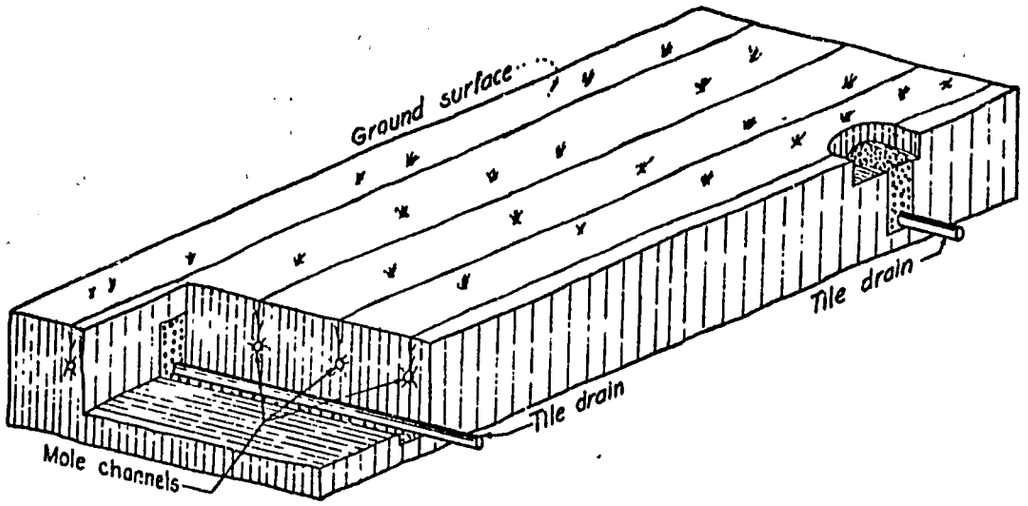


Figure 2. Combined mole tile drain system.

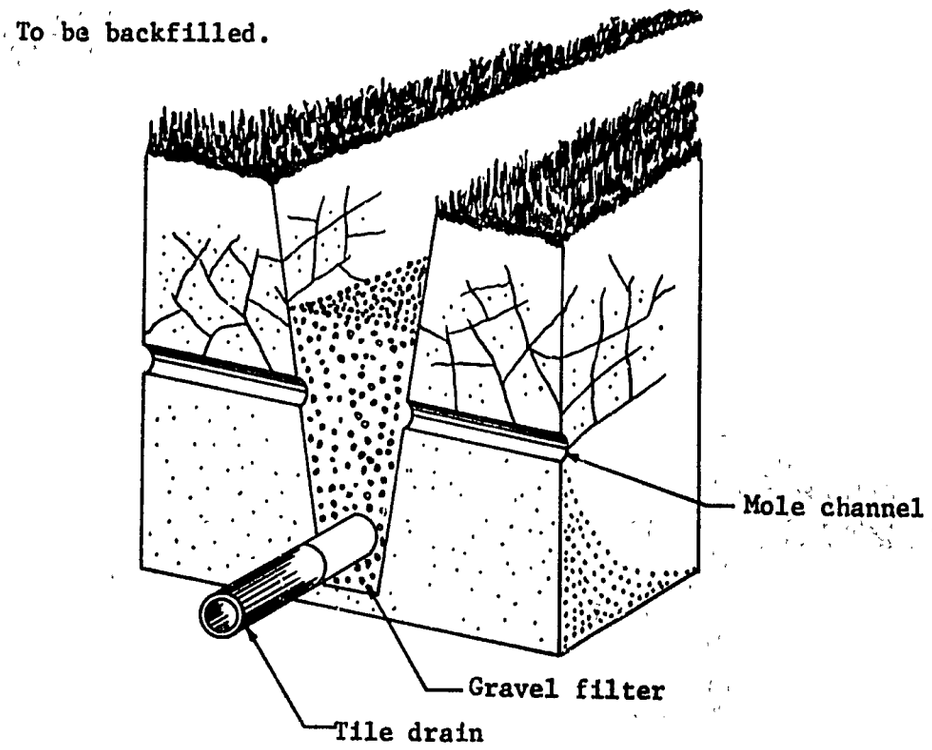


Figure 3. Typical arrangement of gravel envelope.

be redrawn rather easily and inexpensively, because the mole drains discharge water into the tile drain envelope instead of an open ditch, and no outlet construction is required.

Need of Study

The combined mole-tile drain system has been used with the expectation that it may be possible to obtain the advantages of each of the mole drains and tile drains with few of the disadvantages. Since no research or information on the performance and cost analysis of the combined system is available, such information is needed for the evaluation of the system.

Objectives

1. To compare the field performance of a tile drainage system with two combined mole-tile drain systems, one using double mole drains and the other using single mole drains.
2. To investigate the deterioration of the mole drains in the combined systems during the period of two years.
3. To make an economic study of feasibility.

REVIEW OF LITERATURE

History of Mole Drainage

According to Weaver (1964), there is evidence indicating that mole drains have been used in England since the beginning of the eighteenth century. During the early stages of development, the mole channel was constructed by placing a piece of pipe horizontally in a trench of a few feet deep and packing clay around it. When the clay dried, the pipe would be pulled out, leaving a hole later known as a "mole."

Klippart (1867) reported that the mole drain was introduced in the United States as early as 1859. According to Clayton and Jones (1941), mole drains of 12 feet spacing and 30 inches deep were installed between open ditches spaced from one-eighth to one-fourth mile apart in the Northern Everglades of Florida. Saveson (1946) reported that moling was practiced in heavy clay soils in Louisiana. He stated that the cane planted in mole-drained areas produced greater yields than that in the unmoled areas. The Soil Conservation Service (National Engineering Handbook, 1971) stated that mole draining was limited in the United States due partly to the lack of extensive farmland suited for mole drain construction, partly to the past high cost of adequate power equipment to install the drains, but largely due to the lack of understanding of their requirements and limitations which resulted in many past failures.

Mole systems can be connected in order to avoid a multiplicity of outlet constructions and reduce maintenance works. Hopewell (1953) reported that an experiment had been conducted to investigate some

methods of connecting minor mole drains to major mole drains at Massey Agricultural College Farm in New Zealand since 1939. Four methods of connection were used in his research named 30°-40° method, McLeod method, Cut-top method, and Spearing method, as shown in Figure 4. The minor and major mole drains were constructed by pulling a mole plow with a 3 inch plug. The depth of minor drains was about 18 to 19 inches while that of major drains depends on the method of construction. He concluded that the McLeod method has shown to be the most satisfactory for general use if properly carried out because the failure, due to silting of major drains, was comparatively small.

It is believed that one of the major factors causing rapid deterioration of the mole drain is the clogging of the mole channel by sediments deposited by water entering through the slit which is located directly above the mole channel (see Figure 5). To avoid such undesirable conditions, a double mole plow was developed such that, with the plow, the slit is located midway between mole channels (see Figure 5). Sukwiwat (1970) used a model to study and compare the durability of mole channels constructed in the laboratory with single and double mole plows at Utah State University. From the study, he concluded that the double mole channels were more durable than the single mole channels.

According to Unhanand (1972), several double mole plows have been designed, built, and tested at Utah State University in order to obtain the most desirable design which produces the well-formed mole channel and requires small power to pull the plow. The research on a field performance of double mole drains has been conducted at the University drainage farm since 1970, but no conclusive results have been reported.

A life of mole drains varies depending on the soil types, moisture condition at moling time, water table condition, etc. Many authorities

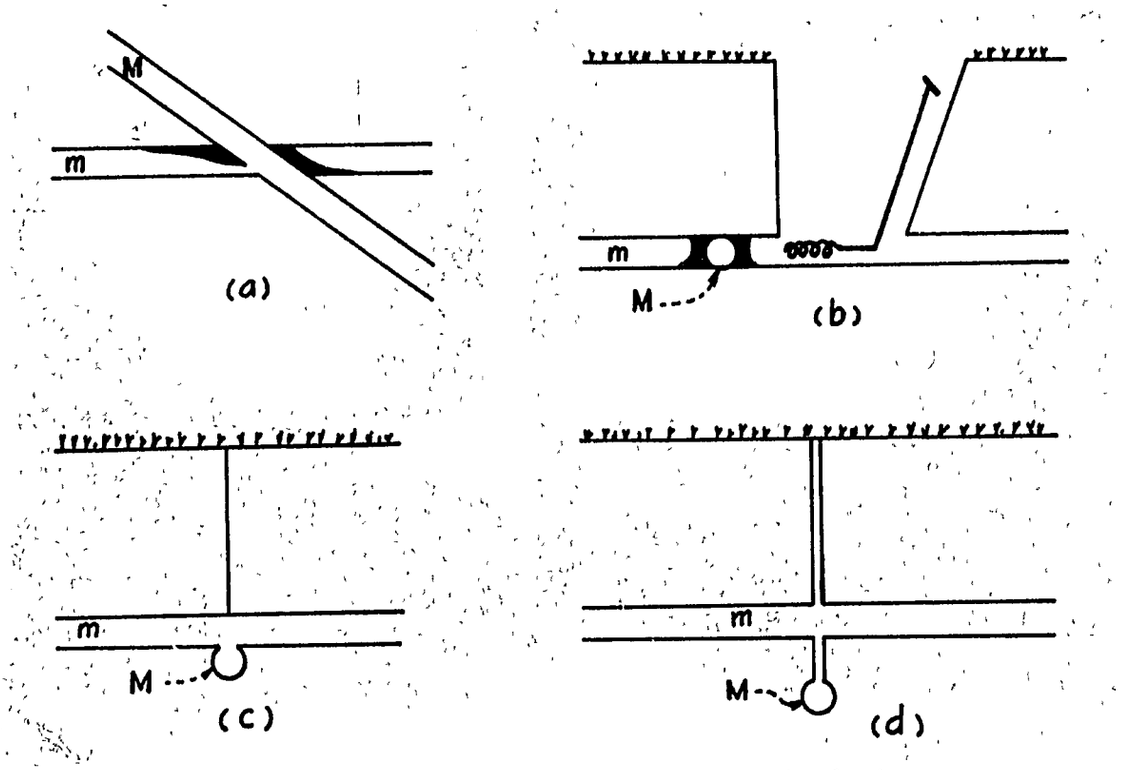
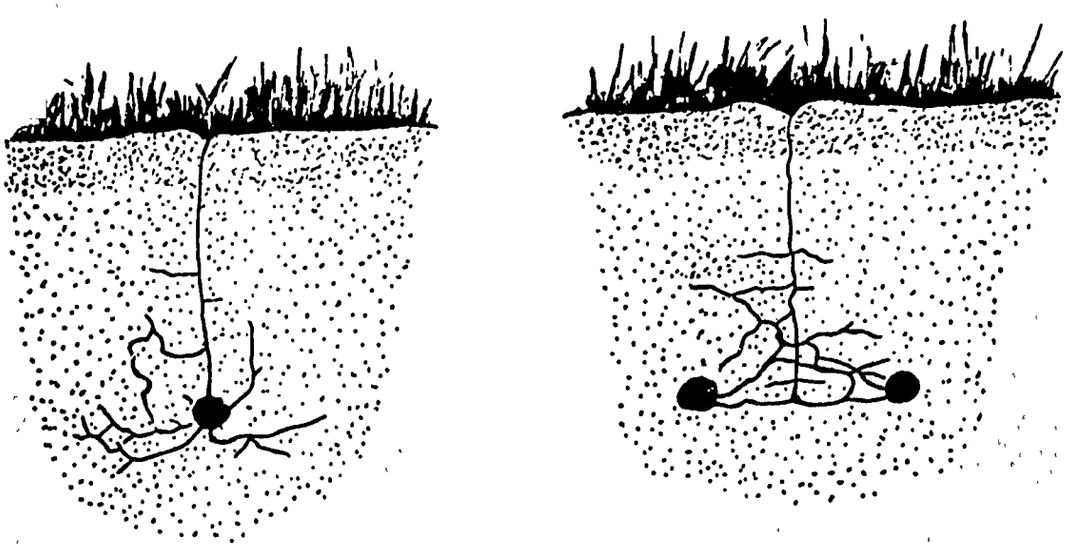


Figure 4. Methods of connecting minor and major mole drains.

(a) 30°-40° method, showing nature of blockage in minor (m) caused by passage of major (M)
(b) McLeod method
(c) Cut-top method
(d) Spearing method



(a) Single mole (b) Double mole

Figure 5. Cracks around mole channels.

(Hamblyn, 1950; Piper, 1958; Theobald, 1963) agree that the mole life ranges from 2 to 15 years with some mole drains found to be in serviceable condition after 25 years. Because of the short life of mole drains, the idea of the combined mole-tile drain system was developed.

Development of the Combined Mole-Tile Drain System

Duncan (1957) stated that the use of a combined mole-tile drain has been practiced in Okoia, New Zealand, in order to improve the drainage area where tile lines have been existing. The method of joining mole drains to the existing tile drains was done by using a drilling machine. At each junction where the mole drain intercepted a tile line, a small hole was drilled down from the ground surface through the top of the tile. By this procedure, the drainage water in the mole drains would be allowed to enter the tiles.

Piper (1958) recommended that where a combined system is being used the tile should always be laid deep enough to avoid the mole plow from striking them. The method of joining the mole to the tiles was done by thrusting a spear down from the ground surface to the side of the tile.

Depth and Spacing of Drains in the Combined System

Theobald (1963) stated that the distance between mole channels depends upon many factors but usually is from 6 to 15 feet, and the mole channel is about 20 inches deep. The depth of tile drain is about 30 inches with a maximum spacing of 328 feet in a normal condition, but this distance may have to be reduced to about 65 feet depending on the geographic and climatic conditions.

Plamenac, Pusic and Vlahinic (1971) reported that the combined system functioned satisfactorily on flat and heavy hydromorphic

soils along the Drava and Sava river valleys in Yugoslavia. The system consisted of mole drains which were drawn at a distance of 9 feet apart, 24 inches deep and collector drains laid in a ditch with filled gravel to a depth of 8 inches below the ground surface. They also stated that two alternative systems are being investigated in Posavina. The first system is composed of a tile drain with no filter at 100 and 160 feet spacing and 2.6 feet deep. On the other system, tile drains with gravel filter are located at a distance of 125 to 160 feet apart and at a depth of 2.6 feet. Mole drains in these systems were drawn at a spacing of 6.3 feet at a depth of 14 to 16.5 inches.

According to Trafford (1971), the use of a combined system has been practiced in almost all new mole drainage work in the United Kingdom. He reported that in the current use the system consists of mole drains drawn at 20 to 28 inches depth with 8 to 10 feet spacing, and tile drains were laid at a distance of 65 to 328 feet apart.

Cost of the Combined System

Baitch and Rieser (1971) stated that the cost of a combined system in the Federal Republic of Germany varies largely depending on soil conditions, morphology and type of arrangement. They reported that for one hectare (2.471 acres) the construction cost varies from 1,900 to 3,500 DM with the annual addition of 97 to 195 DM. The spacings of pipe collectors are from 30 to 80 meters, and mole drains are drawn at 2 meters spacing. The above estimation was made on the basis of the life of 30 years for tile drains and 10 years for mole drains, which means that mole drains have to be redrawn three times during the assumed life time of the tile drain. The tile drain trench is backfilled with 2.5 cubic

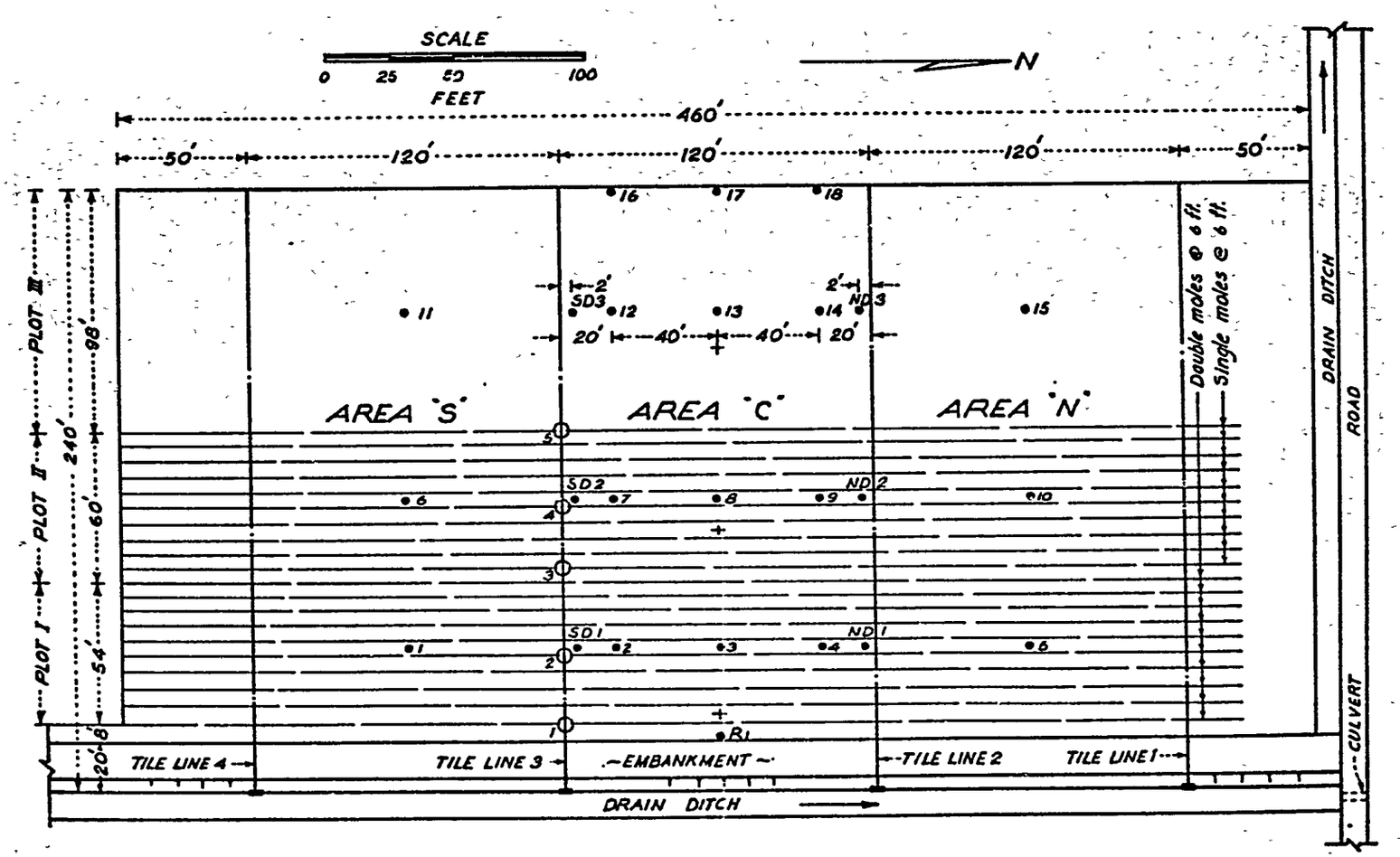
meters of filter material per meter. The interest rate is 5% and the redemption is 3.5%.

METHOD AND PROCEDURES

Description of Experimental Plots

The general layout of the experimental plots located at the Utah State University drainage farm, Logan, Utah, is presented in Figure 6 with details of all test installations. Soils in the area are classified as heavy, as reported by Perez (1969). The records of soil borings are shown in Appendix A. Before the test, the ground water table was observed to be at a depth of about 4 feet below the ground surface. The area was covered with weeds and alfalfa during the experiment. The water supply for building the water table for the experiment was from an artesian well and conveyed to the area in a pipe line. Water was applied by four sprinkler lines laid relatively close to one another to assure a reasonable application uniformity.

The experimental area, approximately 460 feet by 240 feet, was divided into three plots and constructed with four lines of tile drains spaced at 120 feet (Figure 6). The tile drains, located in the east-west direction and with the outlets at east ends, were numbered consecutively from north to south starting with No. 1. In Plot I, 10 lines of double mole drains were drawn above and orthogonal to tile drains in the north-south direction at the spacing of 6 feet. Plot II was constructed in the same way as Plot I except that single mole drains were used instead of double mole drains. Plot III was used as the control area, and no mole drain was constructed in the plot. Five manholes for measuring the discharges from drain outlets, numbered from 1 to 5, were located on Tile-line No. 3, as shown in Figure 6. A system of



LEGEND: ○ manhole
• observation well
+ piezometer location
▬ drain outlet

Figure 6. Layout of the experimental plots.

observation wells, of which the locations and designations are shown in Figure 6, were installed for measuring the elevations of the water table during the experiment. Three batteries of piezometers were built at the locations approximately 73 feet apart on the centerline between Tile-line No. 2 and No. 3 to observe the ground water movement. Each battery of piezometers consists of three 1/2 inch diameter pipes sunk one foot apart to the depths of 2, 4 and 6 feet from the ground surface.

Method of Construction

After the centerline of each line of the tile drains was located, the trench was excavated by a backhoe to the depth of 3.2 feet, and a 4-inch diameter perforated plastic pipe was laid horizontally in the trench on a gravel bed about 4 inches thick. No attempt was made to lay the tile drain on grade because the ground surface is practically horizontal throughout the area. The trench was then backfilled with a well graded gravel to about one foot below the ground surface. An aluminum pipe, 5 inch diameter and 8 feet long, was used as an outlet for each tile line to discharge the drainage water into an existing open drain.

After the completion of the tile drain construction, the area was sprinkled in order to create a soil moisture suitable for moling. The soil moisture within the moling depth in the area was checked with the aid of a soil auger, and the mole drains were pulled when the average moisture content of the soil was about 22 percent. The average depth was about 19 inches for the double mole drains and 20 inches for the single mole drains. All mole drains were pulled at a spacing of 6 feet.

Five manholes, 4 feet in diameter and 4 feet deep, were constructed along Tile-line No. 3 at the junctions of the mole drains and the tile

drain. Outlets were provided at the exits of all the drains in the manholes to enable the measurements of the flow rate in each drain line. The details of the manholes are given in Figure 7.

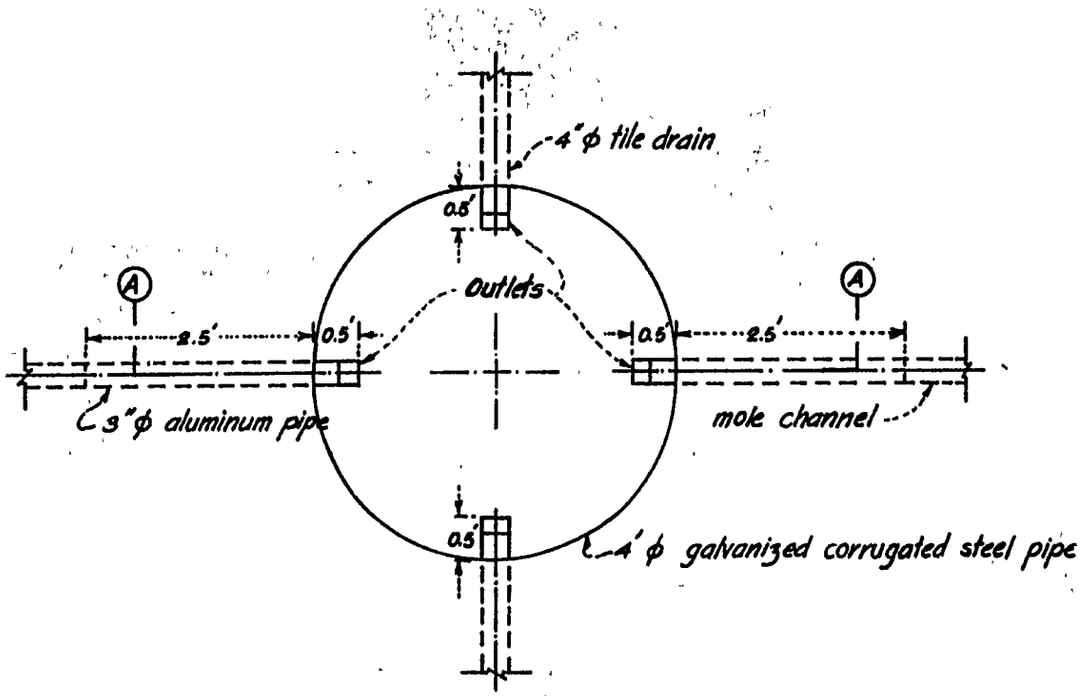
An observation well was built by augering a hole with about a 4 inch diameter to a depth of 6 feet, and a small quantity of gravel was placed at the bottom of the hole. Then a perforated aluminum pipe, 3 inches in diameter and 7 feet long, was centered in the hole, and gravel was placed in the space outside the pipe. The wells were numbered and covered with cans to prevent entry of foreign material.

The three batteries of piezometers (details have been mentioned earlier) were constructed by driving the precut length of 1/2-inch pipes to the required depth with a hammer while a marble was used to prevent the soil from entering the pipe. When the desired depth was reached, the marble was pushed down and the pipe was flushed so that a cavity was formed at the low end of the pipe.

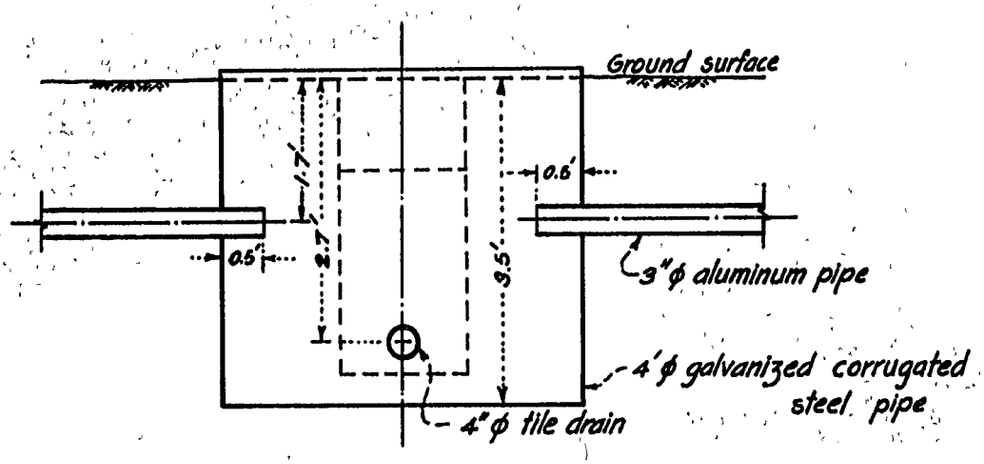
Experimental Procedures and Data Collection

The ground water table was built up by four sprinkler lines and by the seepage from open ditches along the east and west boundaries of the experimental area while all outlets were closed. When the water table was just below the ground surface and almost horizontal throughout the area, the sprinklers were shut off and the water table was allowed to adjust itself for 24 hours before the initial measurement of the water table elevations in the observation wells was taken.

Then all outlets were opened simultaneously allowing the area to drain. The discharge measurements were done at various time intervals by the direct method; i.e., noting the time required for the flow to fill a container of known volume.



PLAN



SECTION A-A

Figure 7. Details of a manhole.

Readings of water table elevations in the observation wells were taken at 3, 6 and 12 hours after the outlets were opened and thereafter at every 12 hours until the water level dropped to approximately the elevation of the mole drains. The water table elevation was measured to the nearest one-hundredth of a foot by using a graduated measuring tape. During the experiment, the water levels in the piezometers were measured daily.

Similar procedures just described were repeated in the test in 1973, except that the outlets were not closed during the water table build-up period. This is because it was believed that, by leaving the drain outlets open, the water in the drains was in motion and was thus capable of transporting sediments out of the drain instead of depositing and clogging the drains as in the case when the outlets were closed.

Hydraulic Conductivity Measurements

Tests to determine the field hydraulic conductivity of the soil in the experimental area were conducted using the single-auger-hole method. Several holes were tested in order to determine the average values of the hydraulic conductivity. The tests were made in three stages in each hole to find an impermeable layer. The first stage test was made with the depth of the hole 3 feet below the ground surface. In the second stage, the hole was deepened to the depth of 6 feet, and the water table in the hole was allowed to reach equilibrium before the test. The third stage test was conducted in the hole which was 9 feet deep. The hydraulic conductivity was calculated by using the formula developed by Maasland and Maskew (1957) for finding the hydraulic conductivity of the saturated soil below the water table:

$$K = C \cdot \frac{\Delta Y}{\Delta t}$$

in which

K = hydraulic conductivity, feet per day

C = a dimensionless variable from Ernst's chart

$\Delta Y = Y_1 - Y_2$ where Y_1 = distance from the normal water table to the water level at the beginning of the test and Y_2 = distance from the normal water table to the water level at the end of the test

Δt = increment of time in which water level changes from Y_1 to Y_2

RESULTS AND DISCUSSION

Results of the investigation and the pertaining discussion will be presented under three separate types of studies, the field performances of the systems, the deterioration of mole drains, and the economic study of the combined system.

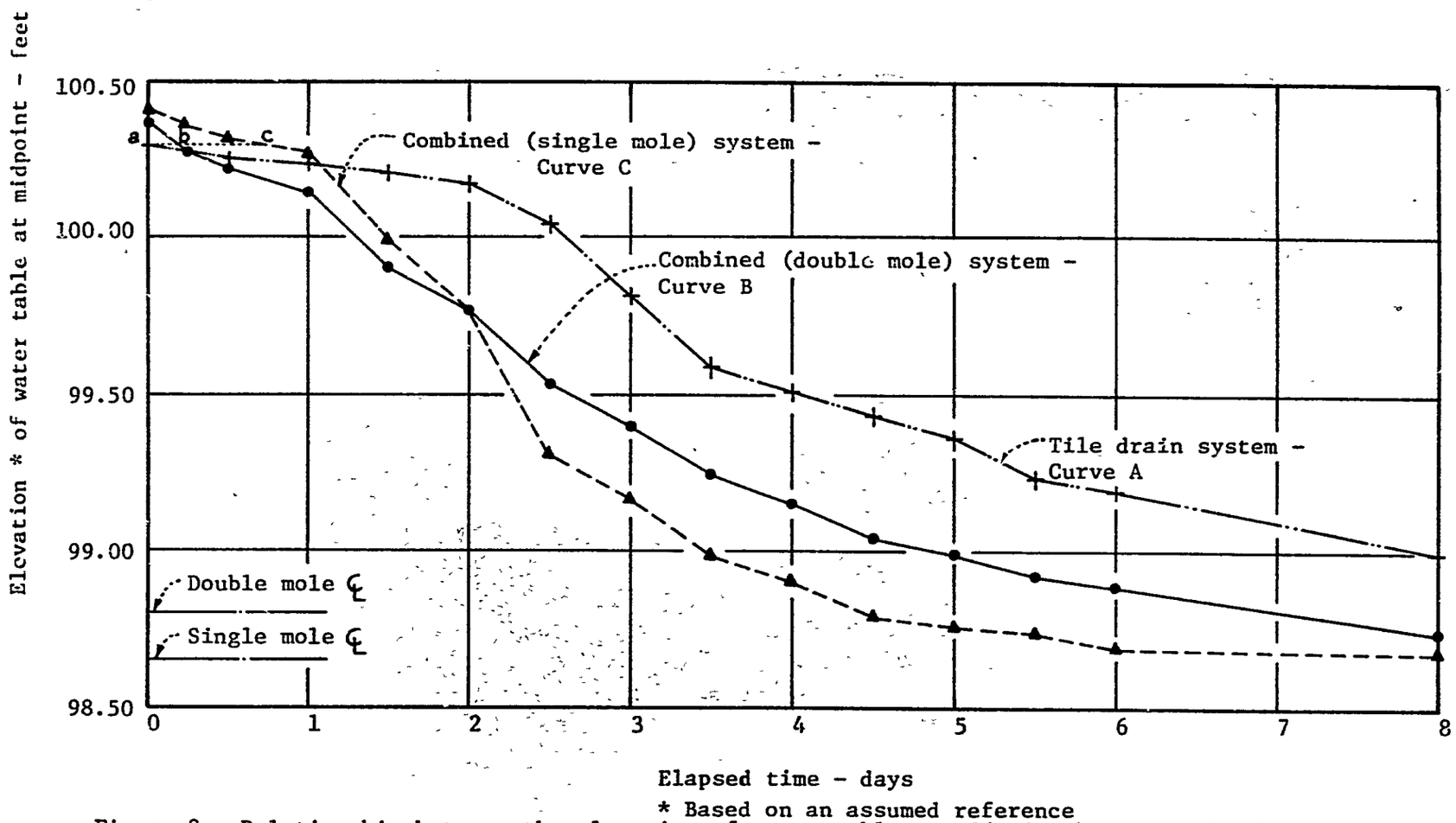
Field Performances of the Systems

A field performance of the combined system was investigated by studying the recession rate of the water table at midpoint, the accumulative drop of the water table at midpoint, the shapes of water-table profiles and the discharge rates in the tile lines. The performances of the combined systems were evaluated by comparison with the performance of the tile drain system, i.e., the check plot.

Recession rates at midpoints

An adequate drainage system should be able to remove excess water so that the water table at the midpoints between drains is kept sufficiently low to provide the best condition for root growth. Therefore, the information regarding the recession rates at midpoints is very important in the design of a drainage system.

Data obtained from the experiments in 1972 and 1973 are shown in Appendix B. The water-table elevations at midpoints of the three types of drainage systems were plotted against the corresponding elapsed times, as shown in Figures 8 and 9. The water-table elevations shown are the average values measured at the three midpoints between tile drains in areas N, C and S (see Figure 6).



* Based on an assumed reference

Figure 8. Relationship between the elevation of water table at midpoint between tile drains and the elapsed time after the drainage process began, 1972.

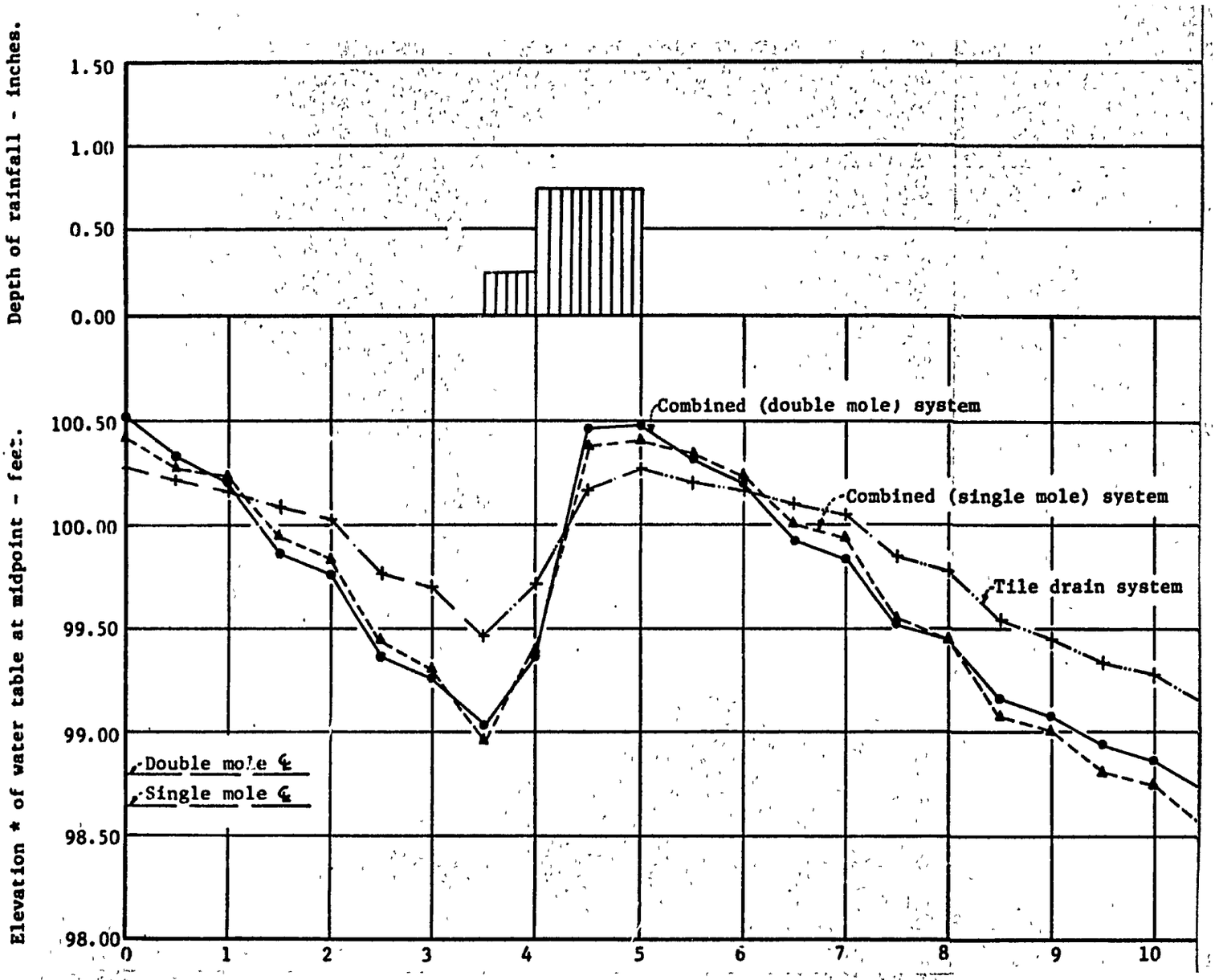
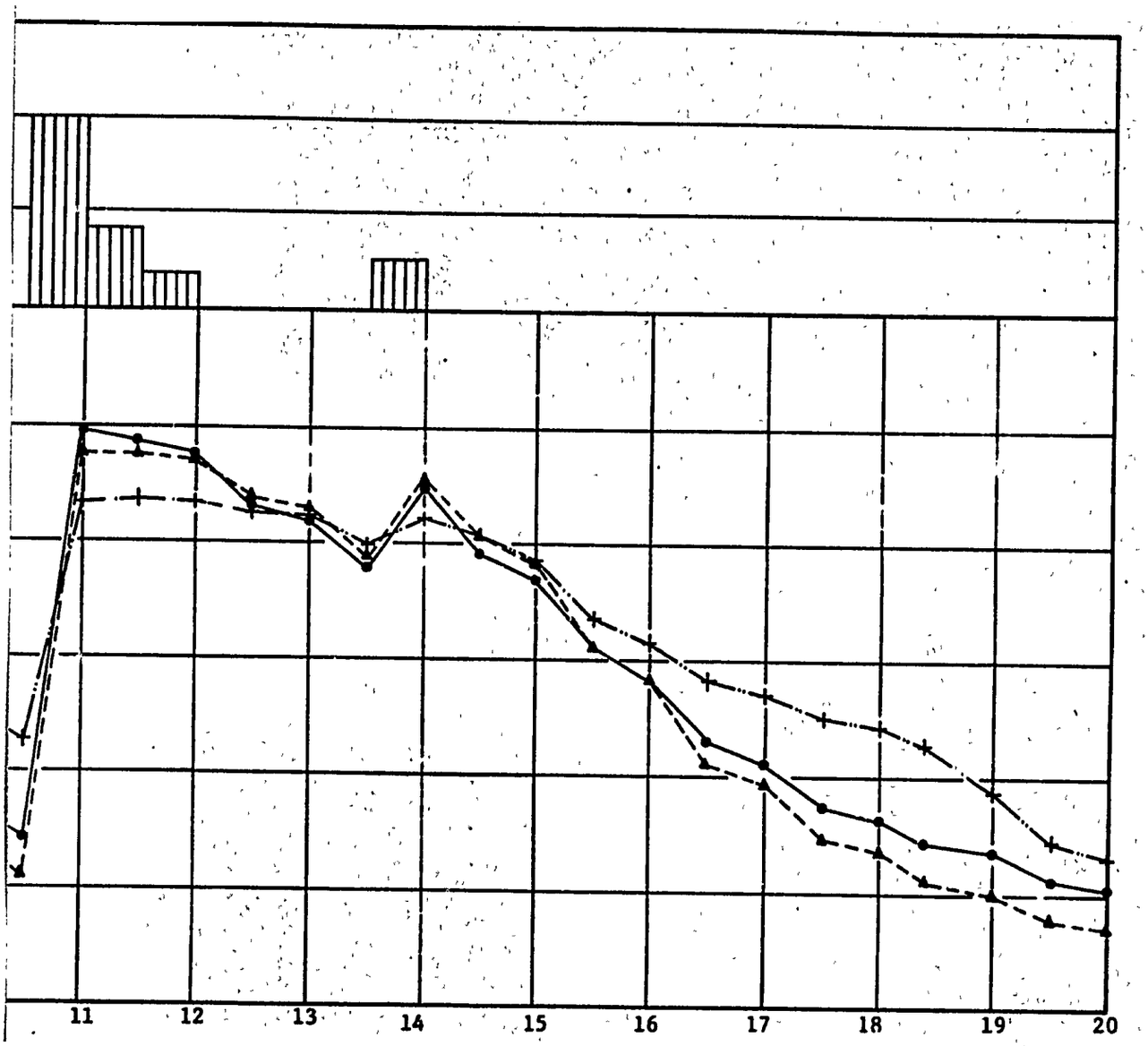


Figure 9. Relationship between the elevation of water table at midpoint between tile drains and the elapsed time after the drainage process began, 1973.



Elapsed time - days
* Based on an assumed reference

The curves in Figures 8 and 9 indicate that the water tables in the areas using the combined systems dropped faster than that in the tile drain area. The figures also show that the combined system employing single moles is slightly more effective than the combined (double mole) system in lowering the water table.

It should be noted that the initial water table for each curve in Figures 8 and 9 is not at the same elevation. In order to obtain a better comparison, a correction has been attempted to adjust the initial water table to be at the same elevation when the drainage process began. Referring to Figure 8, the correction procedure is as follows:

1. Draw a horizontal line from point a to intersect curves B and C at points b and c, respectively.

2. In Figure 10, curve A was drawn in the same manner as in Figure 8, curve B was drawn by taking the elapsed time at point b as zero, and curve C was drawn by using the zero elapsed time at point c. The discussion on the validity of the correction procedure will be made at the end of this section.

By the same correction procedure used in preparing Figure 10, Figure 11 was plotted to show the comparison of the water-table elevations obtained from the experiment in 1973. Since there are many cycles of water-table fluctuations resulting from the precipitations which occurred during the test, as shown in Figure 9, the longest period of no rainfall between the elapsed times of 5 and 10 days in Figure 9 was chosen to be corrected and drawn in Figure 11.

The results shown in Figures 10 and 11 indicate more clearly that the combined systems are more effective than the tile drain system in lowering the water table. For the combined systems themselves, the water

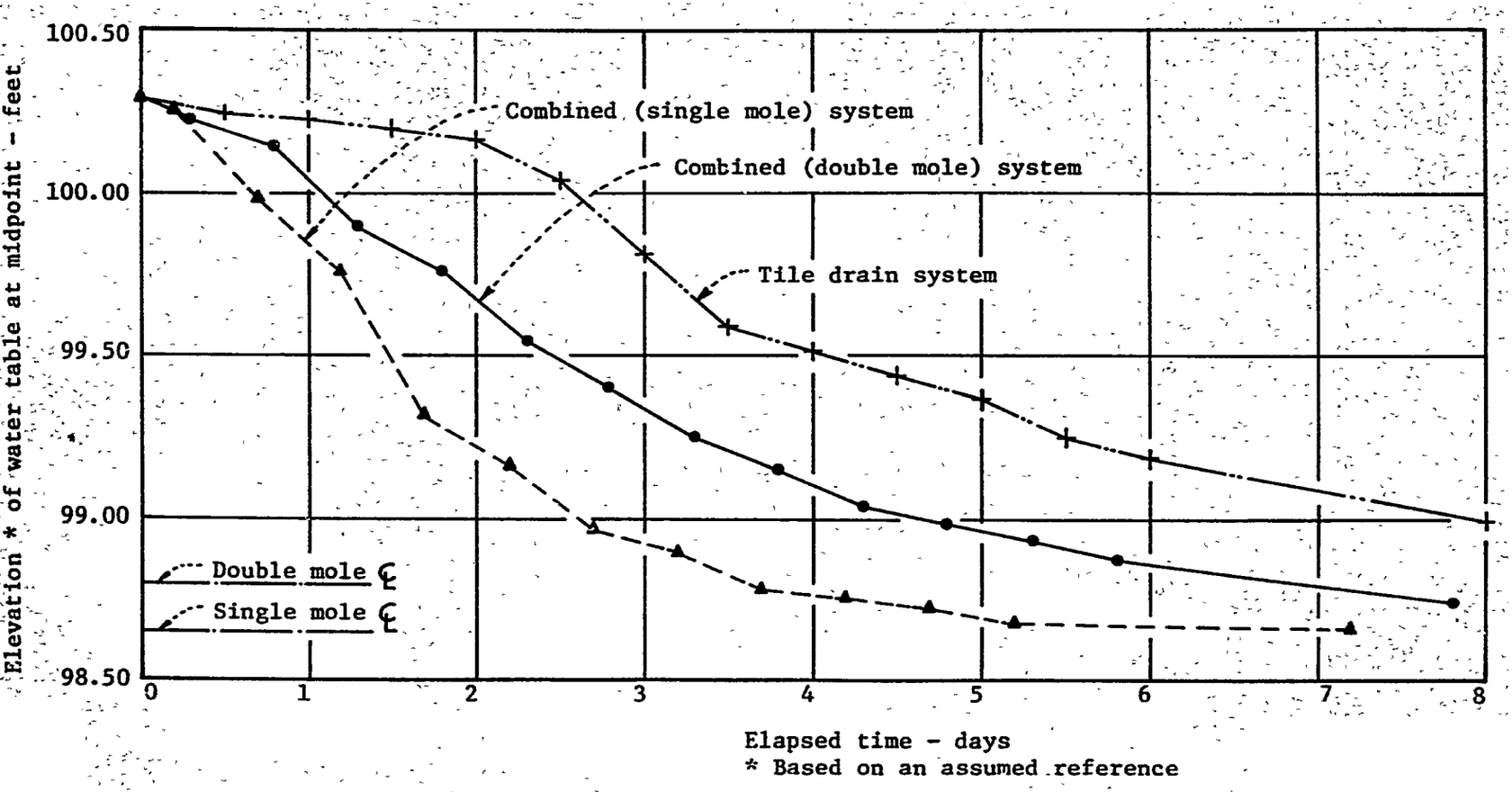


Figure 10. Relationship between the elevation of water table at midpoint between tile drains and the elapsed time after the drainage process began (corrected), 1972.

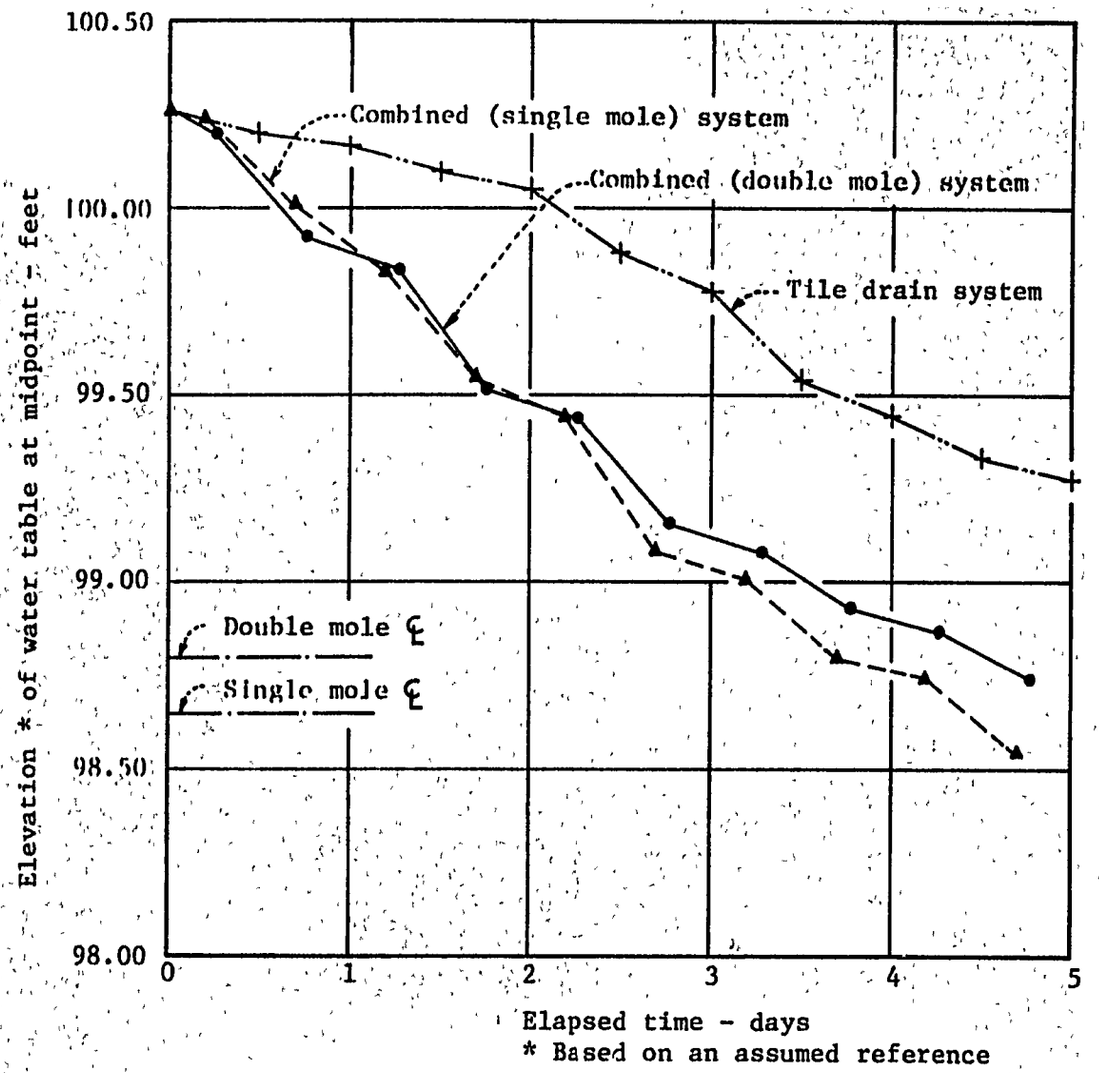


Figure 11. Relationship between the elevation of water table at midpoint between tile drains and the elapsed time after the drainage process began (corrected), 1973.

table drops faster in the single mole area than in the double mole area. This could be attributed to the fact that the single mole channels are lower than the double mole channels.

The performance of the three types of drainage systems for a long period during which rainfall occurred many times, as shown in Figure 9, is of special interest. Even without an attempt to correct for the effect of the initial water table, the curves indicate that the combined systems lowered the water table much more rapidly than the tile drain system. The curves also show that the water level in the tile drain area was always approximately 9 inches above the water level in the areas using the combined system during the three consecutive rainfalls which occurred at about a 4 to 6 day intervals. This characteristic of the performance indicates that in the humid area where soil is heavy and rainfall is frequent, the combined system can provide a better condition of root zone than a tile drain system alone.

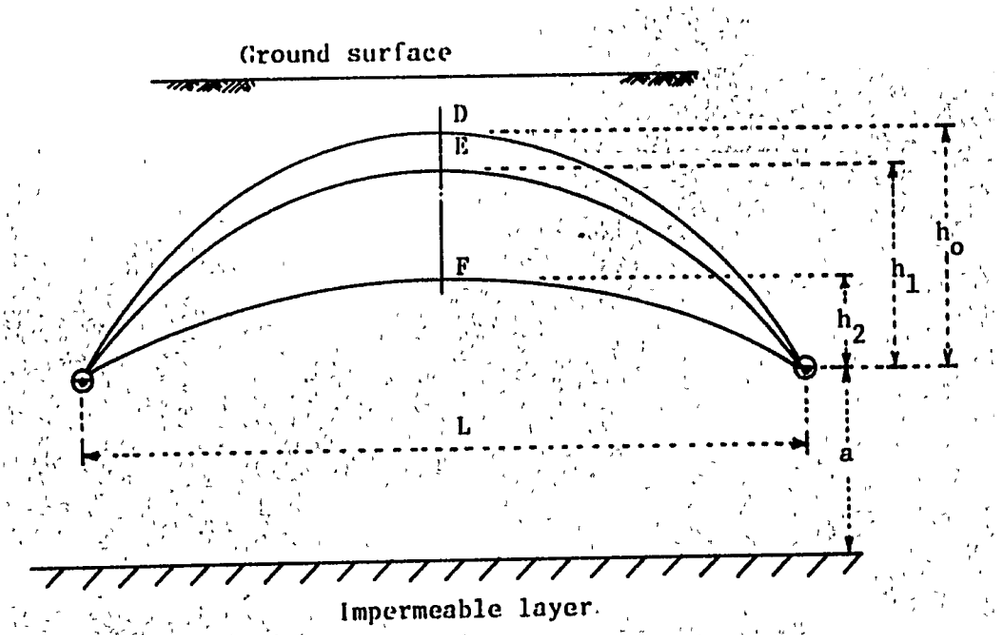
The following is the discussion on the validity of the method of correction used in preparing Figures 10 and 11.

In Figure 12, let D be the actual initial water-table elevation of the recession rate curve of a certain drainage system which shows the water-table elevation F at the elapsed time T_3.

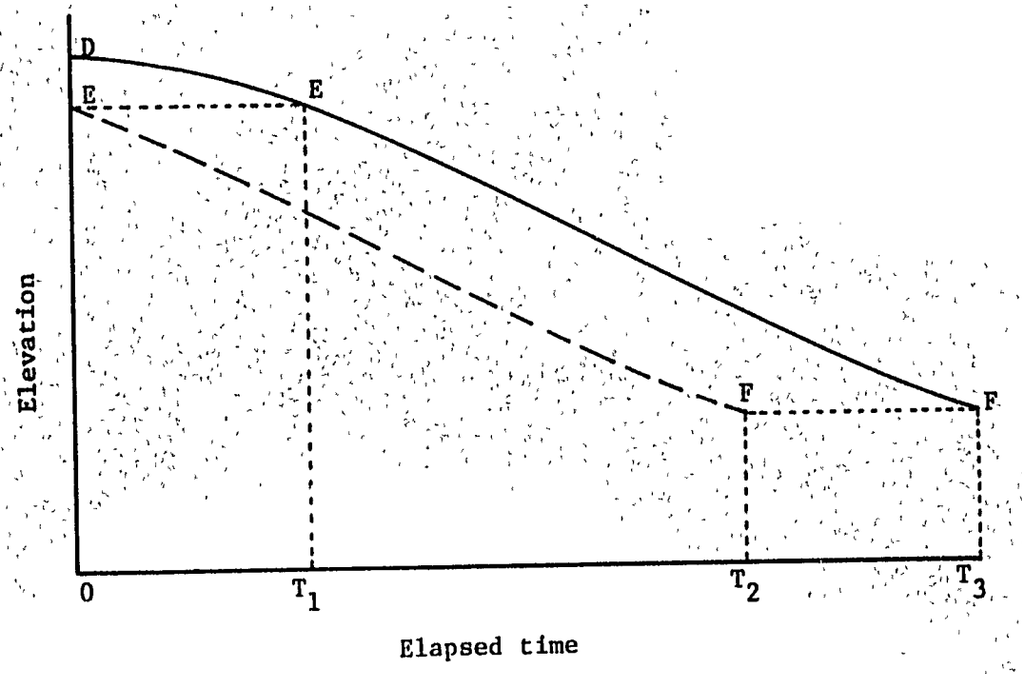
Now, it is desired to know if the initial water table elevation of the same system is at E, whether it will require the elapsed time of T_2 such that $T_2 = T_3 - T_1$ for the water table to drop to F, where T_1 is the time required for the initial water table D in the system to drop to E.

$$\text{If } T_2 = T_3 - T_1, \tag{1}$$

the method used in preparing Figures 11 and 12 is valid. The proof will be given below.



(a) Cross section of tile drains



(b) Recession rate of water table at midpoint between tile drains

Figure 12. Sketch showing some dimension parameters of tile drains.

Dylla's equation (1966) states:

$$T = \frac{L^2 f}{8ak} \cdot \ln \left[\frac{h_o\ (h_t + 2a)}{h_t\ (h_o + 2a)}\right] \qquad (2)$$

in which

T = time required for a water table to drop from h_o to h_t in days

L = spacing of tile drains in feet

a = depth of drains to impermeable layer in feet

k = hydraulic conductivity in feet per day

f = specific yield

h_o = initial height of water table midway between drains

h_t = height of water table above drains at time T

Substituting h_o and h_t in Equation (2) by h_o and h_1,

$$T_1 = \frac{L^2 f}{8ak} \cdot \ln \left[\frac{h_o\ (h_1 + 2a)}{h_1\ (h_o + 2a)}\right] \qquad (3)$$

Substituting h_o and h_t in Equation (2) by h_1 and h_2,

$$T_2 = \frac{L^2 f}{8ak} \cdot \ln \left[\frac{h_1\ (h_2 + 2a)}{h_2\ (h_1 + 2a)}\right] \qquad (4)$$

Substituting h_o and h_t in Equation (2) by h_o and h_2,

$$T_3 = \frac{L^2 f}{8ak} \cdot \ln \left[\frac{h_o\ (h_2 + 2a)}{h_2\ (h_o + 2a)}\right] \qquad (5)$$

Subtracting Equation (5) by Equation (3),

$$T_3 - T_1 = \frac{L^2 f}{8ak} \cdot \ln \left[\frac{h_o\ (h_2 + 2a)}{h_2\ (h_o + 2a)}\right] \left[\frac{h_1\ (h_o + 2a)}{h_o\ (h_1 + 2a)}\right]$$

or

$$T_3 - T_1 = \frac{L^2 f}{8ak} \cdot \ln \left[\frac{h_1 \ (h_2 + 2a)}{h_2 \ (h_1 + 2a)}\right] \qquad (6)$$

Since Equation (4) is equal to Equation (6), then $T_2 = T_3 - T_1$ (same as Equation (1)).

Hammad's equation (1962), given below, may be used in a similar way to prove:

$$T = \frac{Lf}{2\pi k} \cdot \ln \left(\frac{h_o}{h_t}\right) \cdot \ln \left(\frac{L^2}{\pi^2 ad}\right) \qquad (7)$$

in which

d = diameter of tile drain

Accumulative drop of water table at midpoints

The accumulative drop of water table as related to elapsed times is plotted in Figures 13 and 14. The accumulative drop for each type of drainage system is the average of the drops of water tables at midpoints in areas N, C and S (Figure 6). The data used in this analysis are given in Appendix B.

Figures 13 and 14 indicate that at any elapsed time the accumulative drop in the combined system is always greater than that in the tile drain system. It may appear that the combined system lowers the water table only slightly faster than the tile drain system, which seems to be of no practical advantage. For example, it takes about five to six days for the tile drain system to lower one foot of water table at midpoint, as compared to about three days by the combined systems. The ability of the combined systems just described may not be very significant for drainage of arid land, but it is quite useful and important for the humid areas where rainfall is frequent and the soil is heavy. Let us

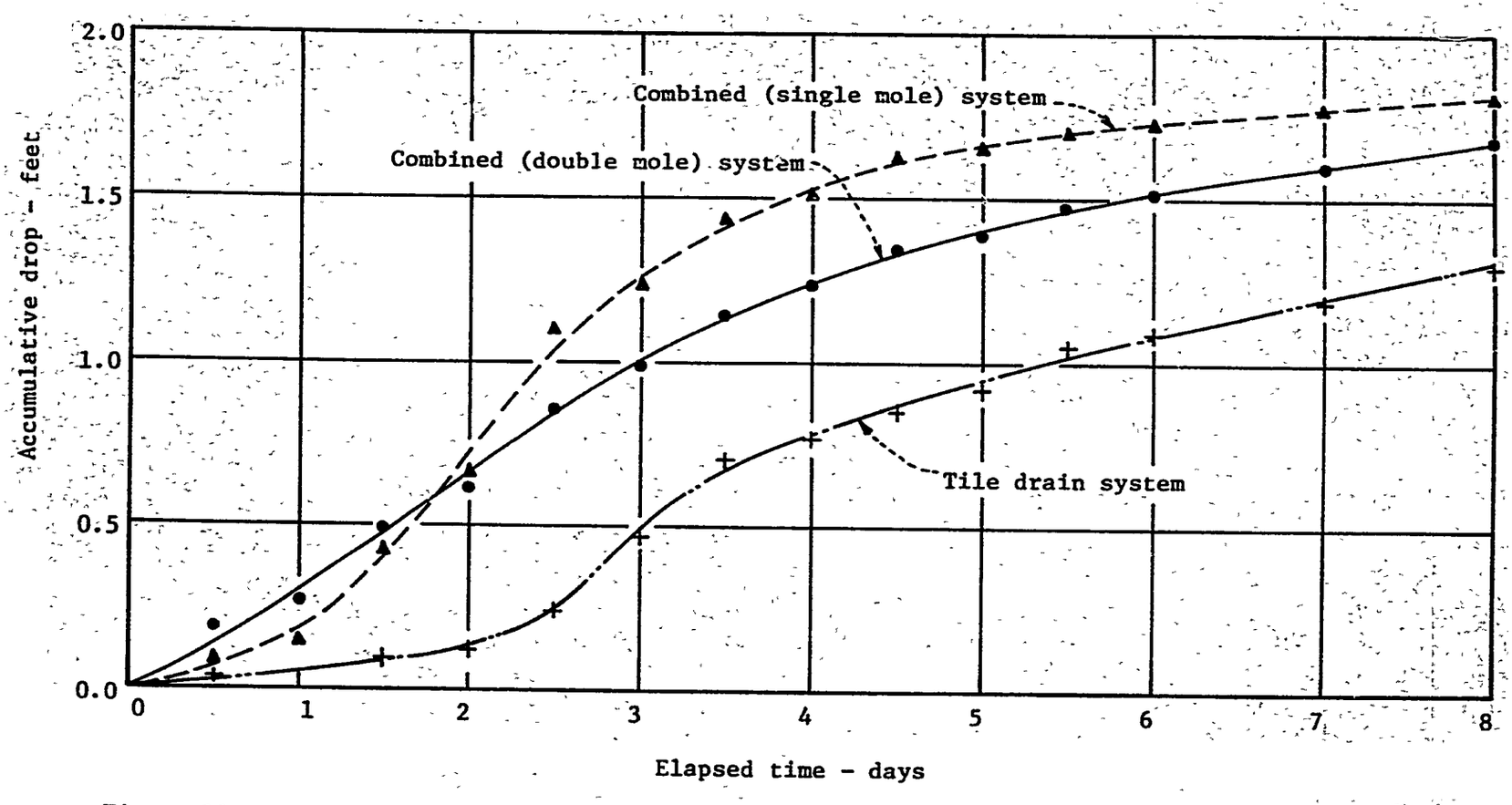


Figure 13. Accumulative drop of water table at midpoint for the three types of drainage method at various elapsed times after the drainage process began, 1972.

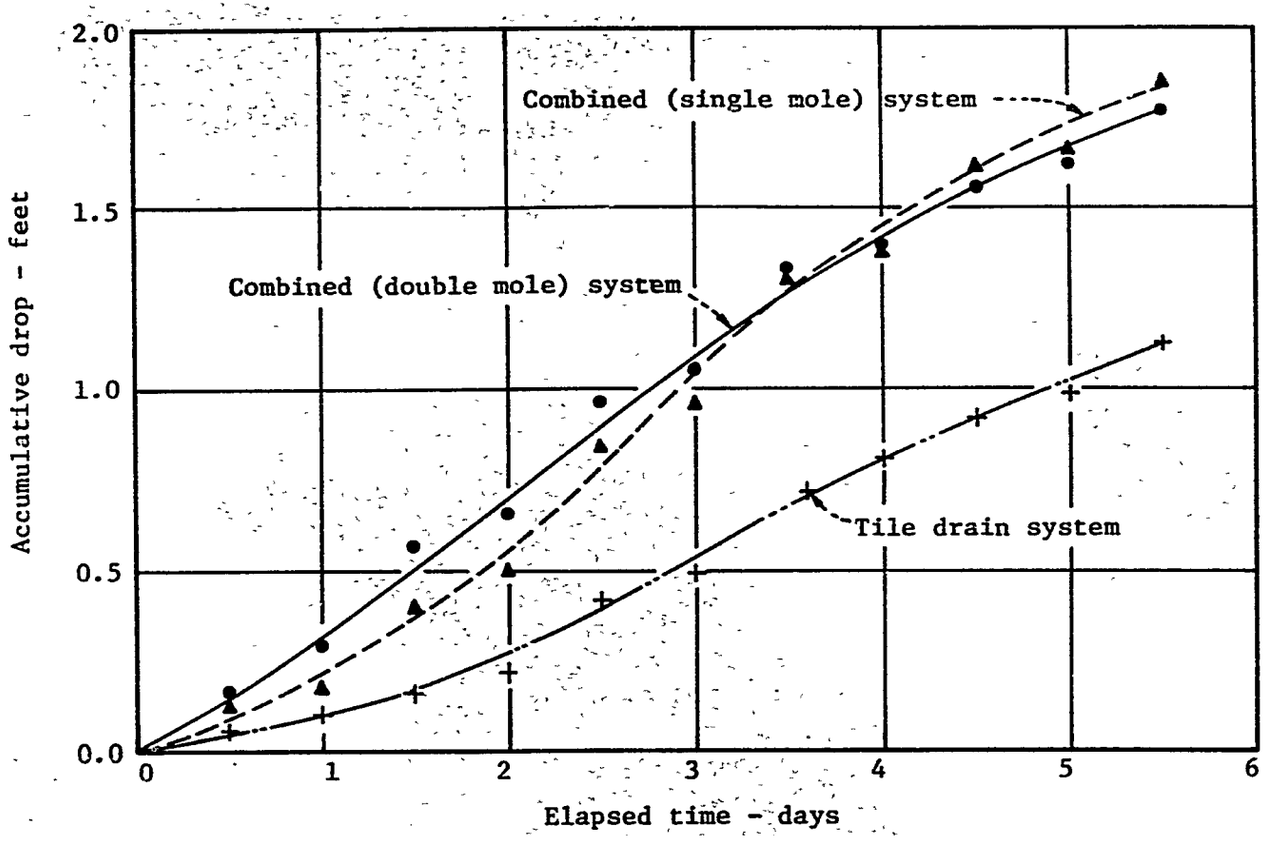


Figure 14. Accumulative drop of water table at midpoint for the three types of drainage method at various elapsed times after the drainage process began, 1973.

consider the frequency of rainfall for five days. The water table in the tile drain area will never drop more than one foot from the initial level, but it will drop more than one and one-half feet in the combined mole-tile area. This characteristic permits the drainage system of heavy soils in humid areas to employ widely spaced tile drains overlain with an inexpensive system of mole drains. More discussion on the economics of the combined system in comparison with the tile drain system will be presented later in the thesis.

Drawdown curves

The recession of the water table at midpoints presented earlier shows the characteristics of the water table at the midpoints between tile drains. In order to understand the characteristic of the water table at other locations in the experimental plot, drawdown curves plotted at various elapsed times are needed. These drawdown curves will also provide data for use in the future for verifying the theory of the combined mole-tile drain system.

Drawdown curves were obtained by plotting the water table elevations at various elapsed times after the drain outlets were opened. Since all theoretical analyses indicate that the drawdown curves are symmetrical about the centerline between tile drains, only one-half of the curves are shown in Figures 15 to 28. The elevation of the water table at any elapsed time at points located 2 feet (3 feet in 1973) and 20 feet from the tile drain is the average of the elevations at that point and its corresponding point on the opposite side of the centerline. The elevation of water table at centerline between the tile drains or midpoint is the average elevations measured at the centerlines in the areas N, C and S (see Figure 6).

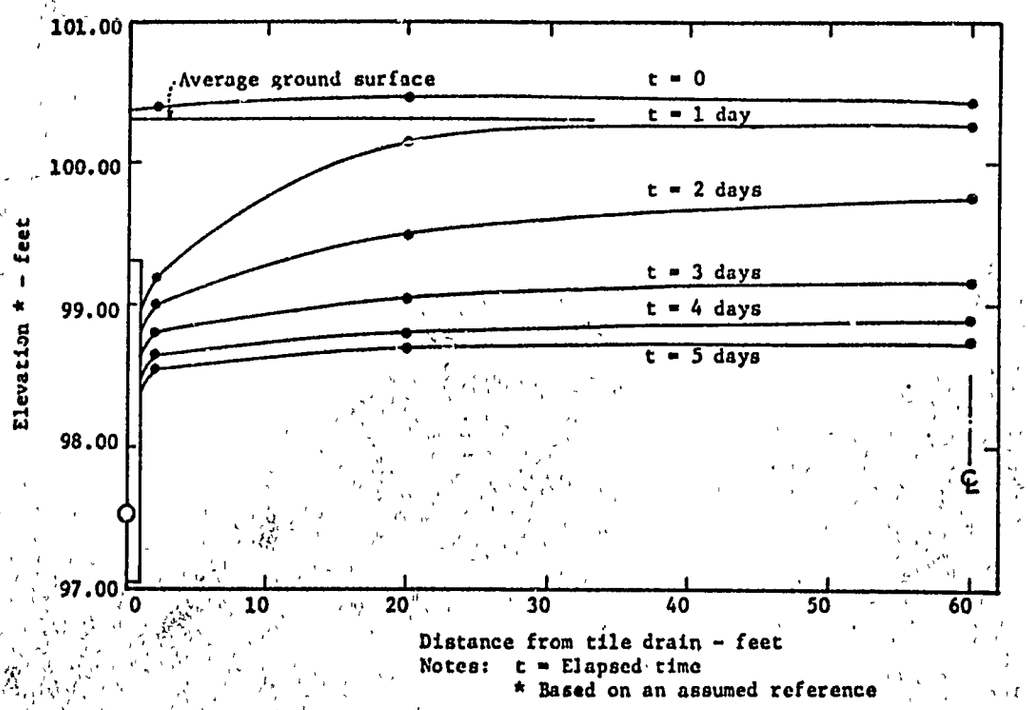


Figure 15. Drawdown curves at various elapsed times t for the area using combined (single mole) system, 1972.

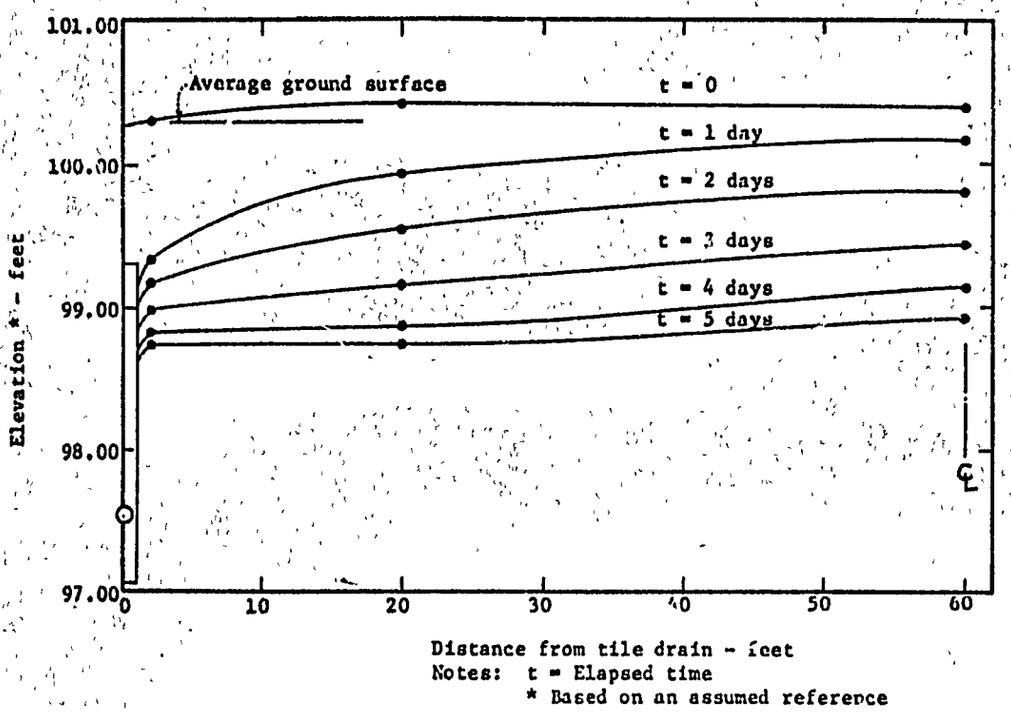


Figure 16. Drawdown curves at various elapsed times t for the area using combined (double mole) system, 1972.

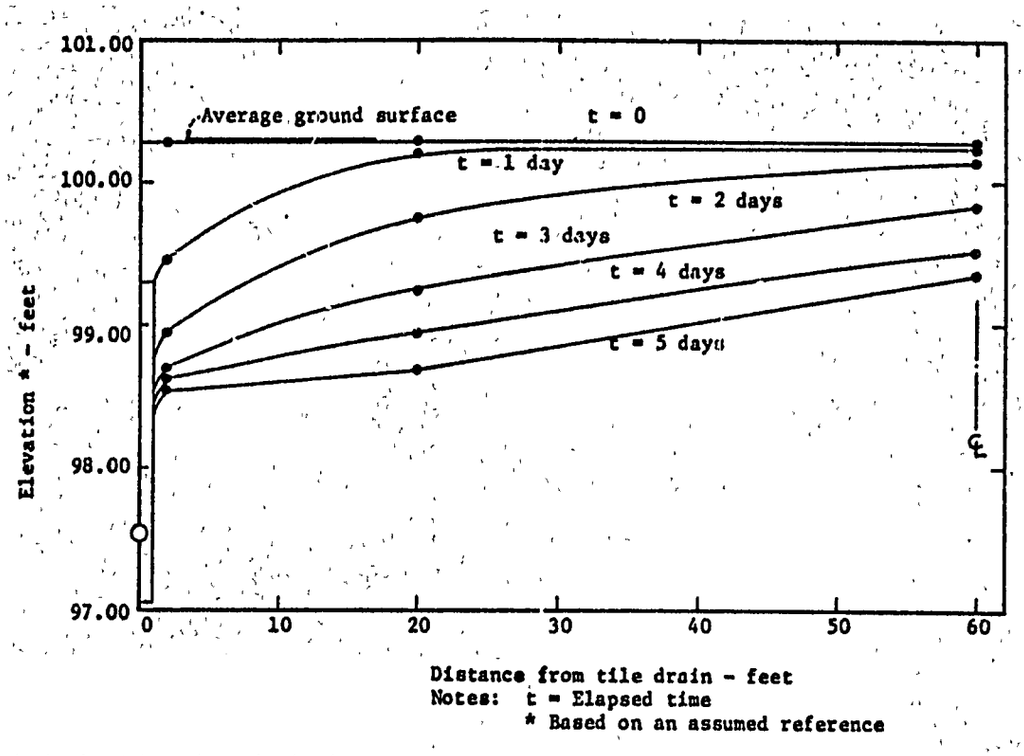


Figure 17. Drawdown curves at various elapsed times t for the area using tile drain, 1972.

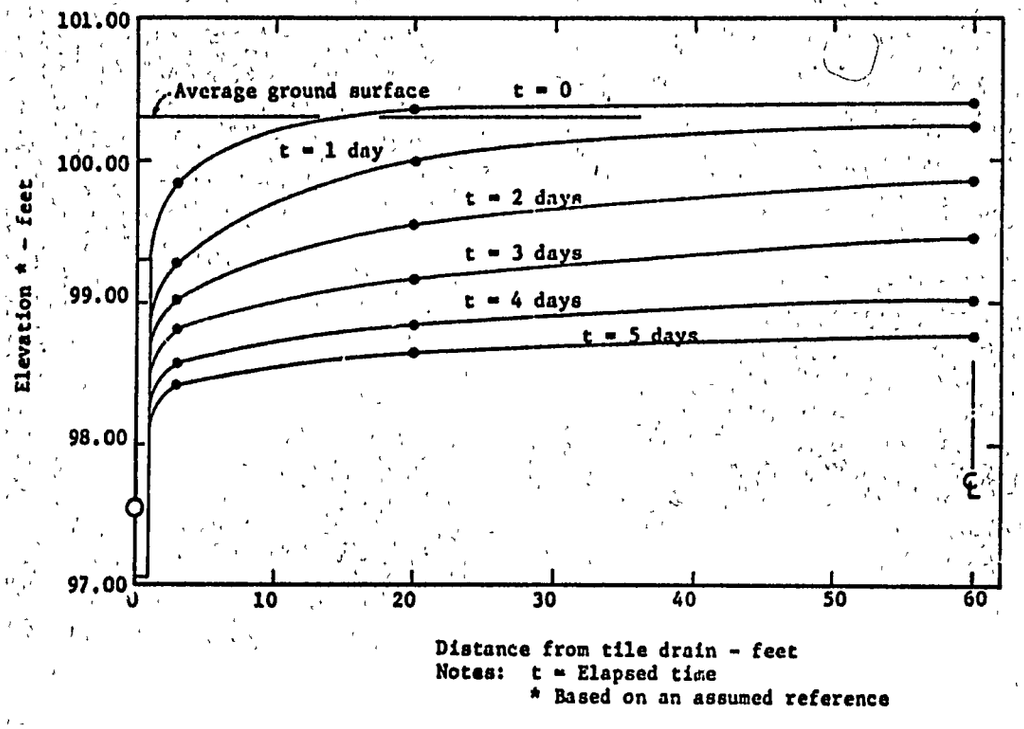


Figure 18. Drawdown curves at various elapsed times t for the area using combined (single mole) system, 1973.

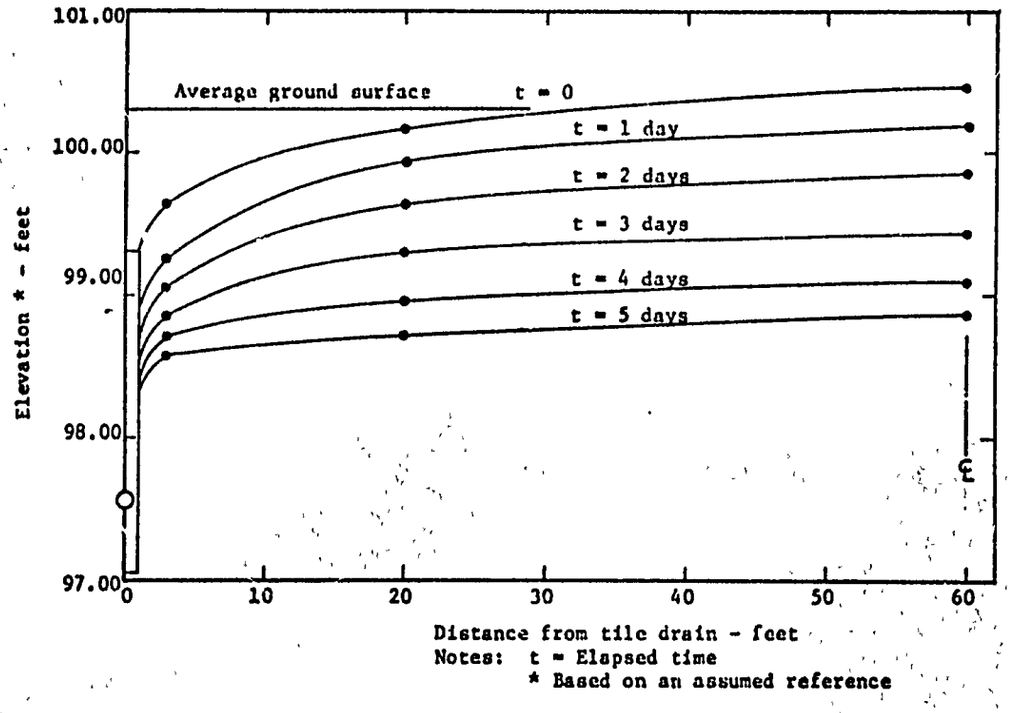


Figure 19. Drawdown curves at various elapsed times t for the area using combined (double mole) system, 1973.

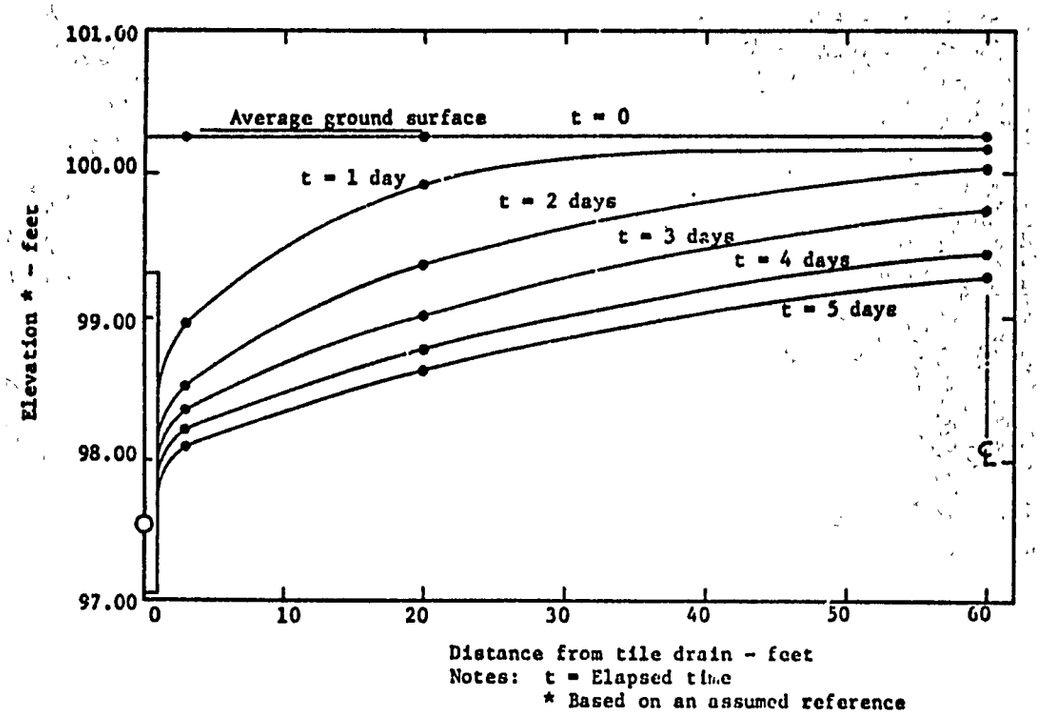


Figure 20. Drawdown curves at various elapsed times t for the area using tile drain, 1973.

Figures 15 to 17 show the drawdown curves obtained from the experiment in 1972 and Figures 18 to 20 show the drawdown curves from the experiment in 1973. The 1973 experiment was conducted for a period of three weeks, during which time there were three rainfalls. The drawdown curves in Figures 18 to 20 and 25 to 28 were drawn from the data taken during the longest period of no rainfall in the experiment in 1973, which is between the fifth to tenth day of the experiment.

It should be pointed out once again that the initial condition of the water table for the experiment in 1972 differed slightly from that of 1973. In the 1972 experiment, all drain outlets were closed while the water table in the area was built up with a sprinkler system and the seepage from ditches. When the water table was just below the ground surface, the sprinkler system was turned off. The water table was permitted to spread out more uniformly for 24 hours before the data on the initial water table were taken. As soon as the measurements were finished, all drain outlets were opened almost simultaneously. Water table elevations at various elapsed times were then measured. With the procedure just outlined, the initial water table was almost horizontal.

In the 1973 experiment, the initial water table was built up with the drain outlets open. The procedure used in 1972 was not applied in the 1973 experiment, because it was found that by closing the drain outlets the mole channels were submerged under stagnant water for a prolonged period of time, which caused part of the mole channels to collapse and block the flow passage. Building a water table with outlets open, even though the mole channels were submerged, water was flowing in the channels and, therefore, was able to move away sediments to provide a through passage. With this procedure, the initial water table was not

as horizontal as in the 1972 experiment, but curved slightly with the highest point at the centerline between tile drains, as shown in Figures 19 and 20. In the investigation of the comparative performance of the three types of drainage systems under study, no attempt will be made to correct the effect of the difference in the initial condition of the water table. This is not necessary because the study is based on the data from each year.

In order to compare the rate of drawdown of water tables in the entire drainage systems, the drawdown profiles at a selected elapsed time for the three drainage systems were drawn in the same figure (Figures 21 to 28). Again, because the initial water table of each system was not at the same elevation, the similar adjustment as used earlier in the study of the recession rate at midpoint was made. Figures 21, 22, 23 and 24, drawn with adjustments made, show drawdown profiles for the three types of drainage systems at the elapsed times of one, two, three and four days, respectively, for the 1972 experiment. Similar curves for the experiment in 1973 were drawn in Figures 25 to 28.

The drawdown curves shown in Figures 21 to 28 indicate that the combined (single mole) system is most effective in lowering water table in the whole area, and the combined (double mole) system is more effective than the tile drain system. In the four-day period, the water table in the area installed with the combined (single mole) system could be as much as one foot lower than the water table in the tile drained area. The curves also show that at the same elapsed time the water table in most of the combined systems is lower than that in the tile drain system, except in the regions approximately 10 to 15 feet of the tile drains where the water table in the tile drain system is lower than in the combined systems.

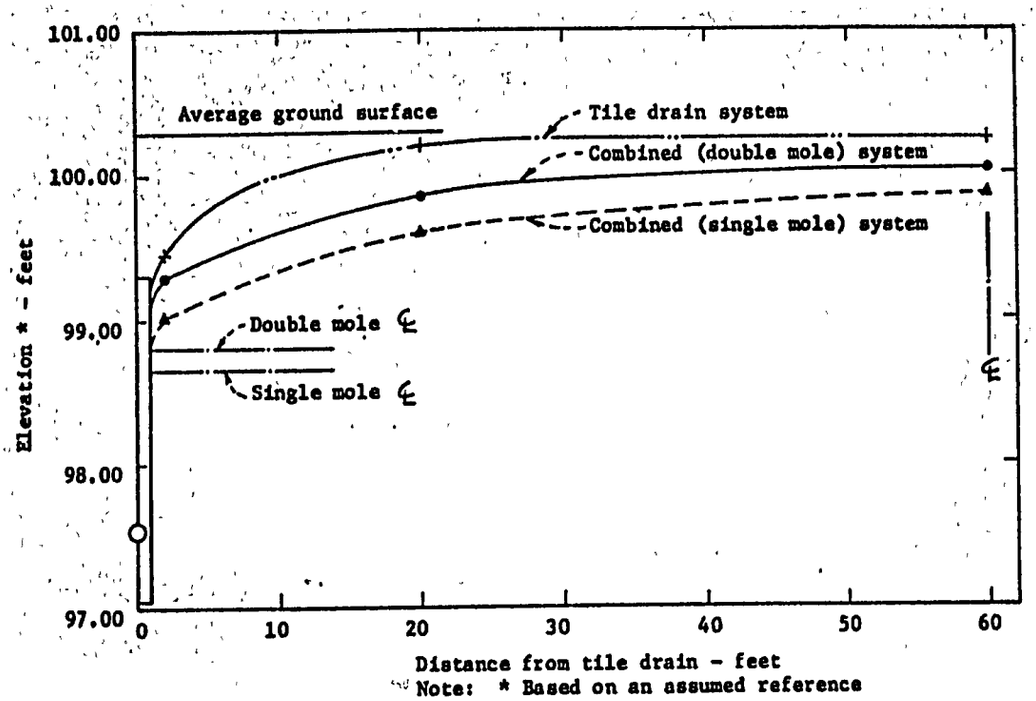


Figure 21. Comparison of the drawdown of the water table in areas using the tile drain system and the combined systems, one day after drainage process began, 1972.

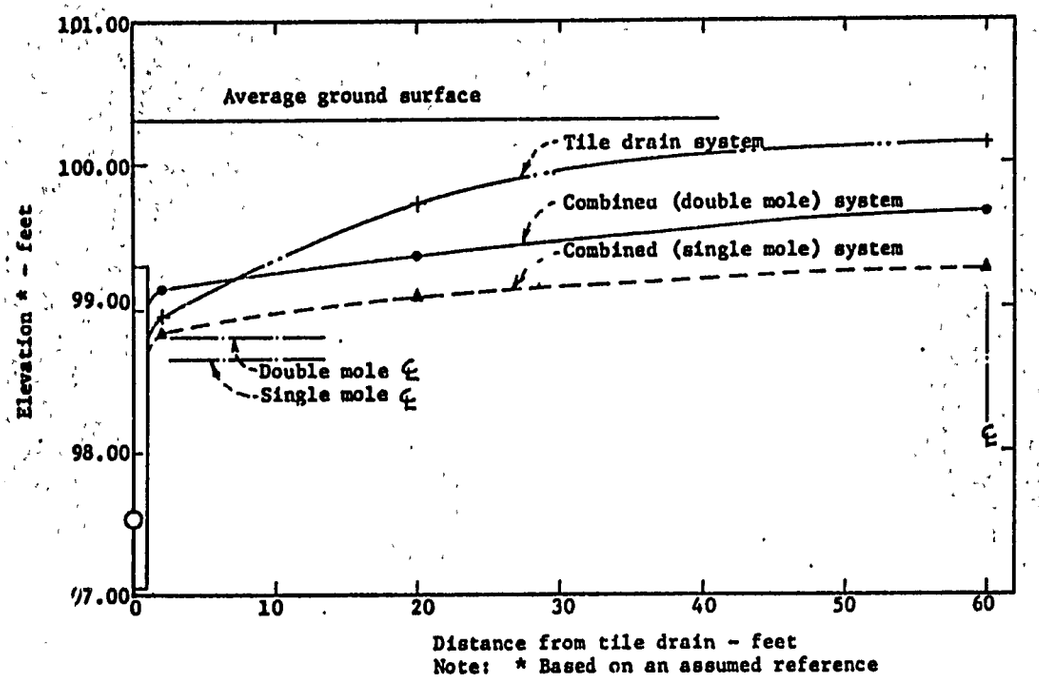


Figure 22. Comparison of the drawdown of the water table in the areas using the tile drain system and the combined systems, two days after drainage process began, 1972.

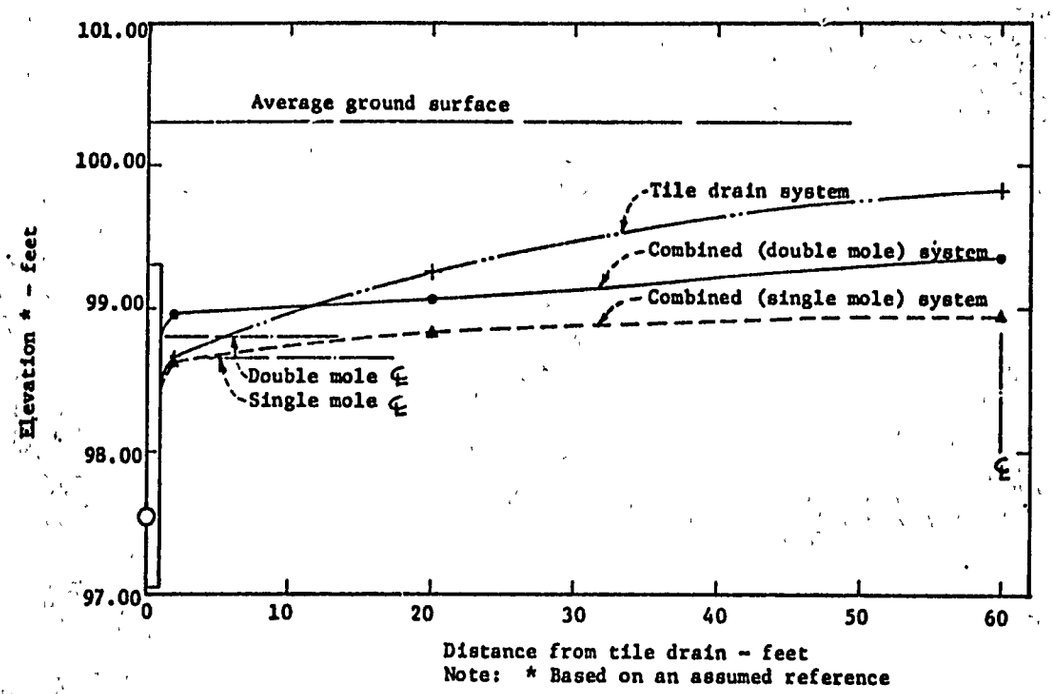


Figure 23. Comparison of the drawdown of the water table in the areas using the tile drain system and the combined systems, three days after drainage process began, 1972.

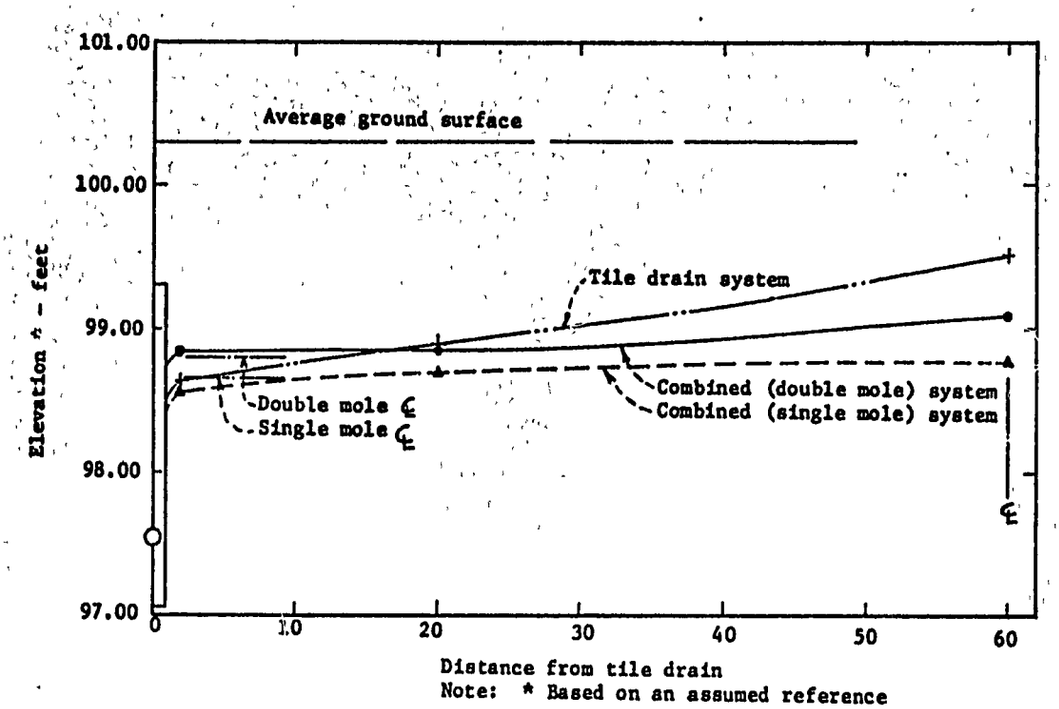


Figure 24. Comparison of the drawdown of the water table in the areas using the tile drain system and the combined systems, four days after drainage process began, 1972.

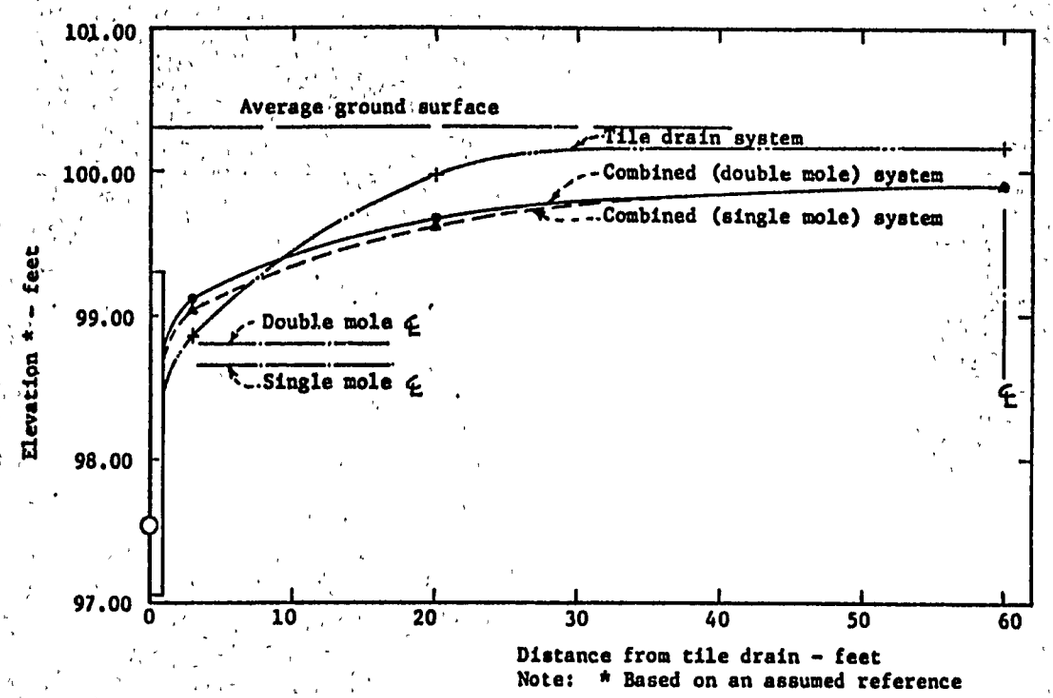


Figure 25. Comparison of the drawdown of the water table in the areas using the tile drain system and the combined systems, one day after drainage process began, 1973.

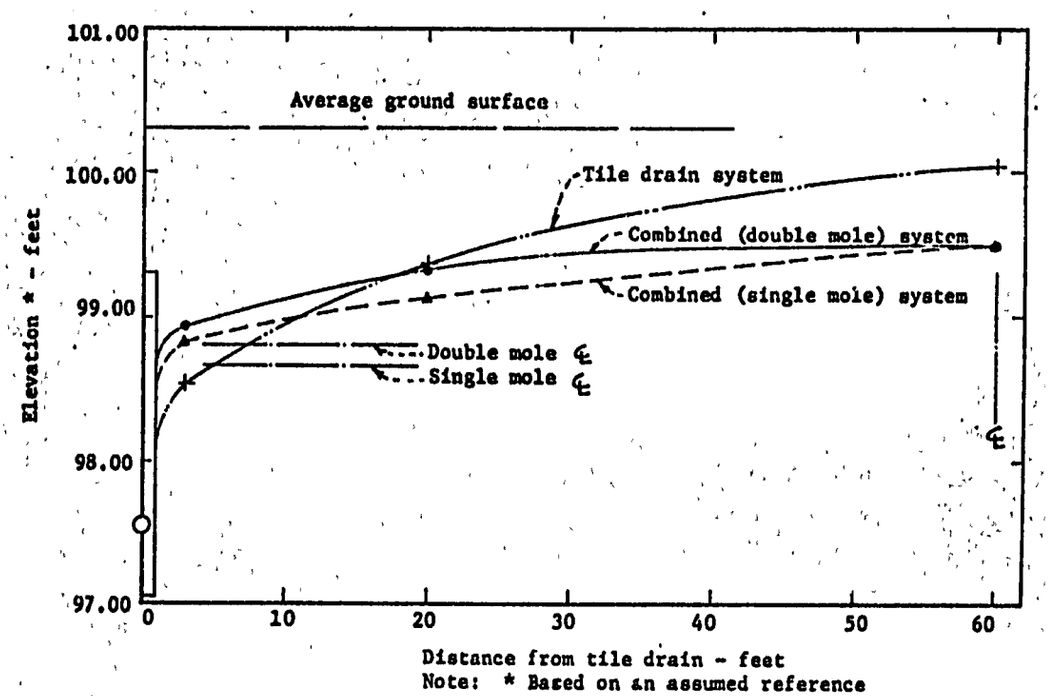


Figure 26. Comparison of the drawdown of the water table in the areas using the tile drain system and the combined systems, two days after drainage process began, 1973.

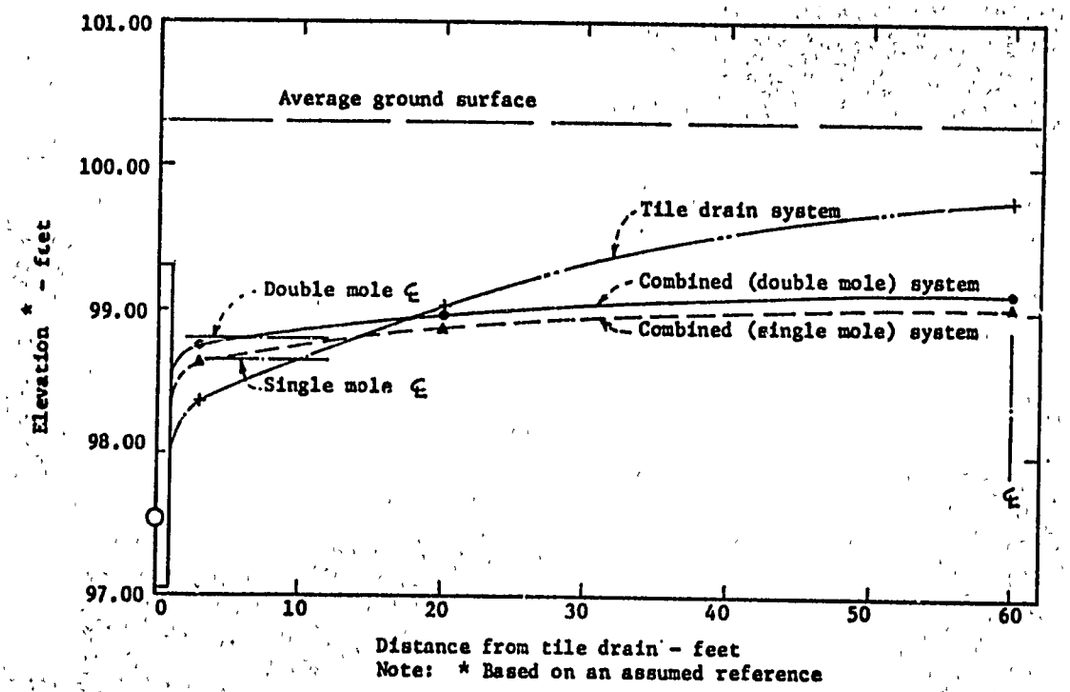


Figure 27. Comparison of the drawdown of the water table in the areas using the tile drain system and the combined systems, three days after drainage process began, 1973.

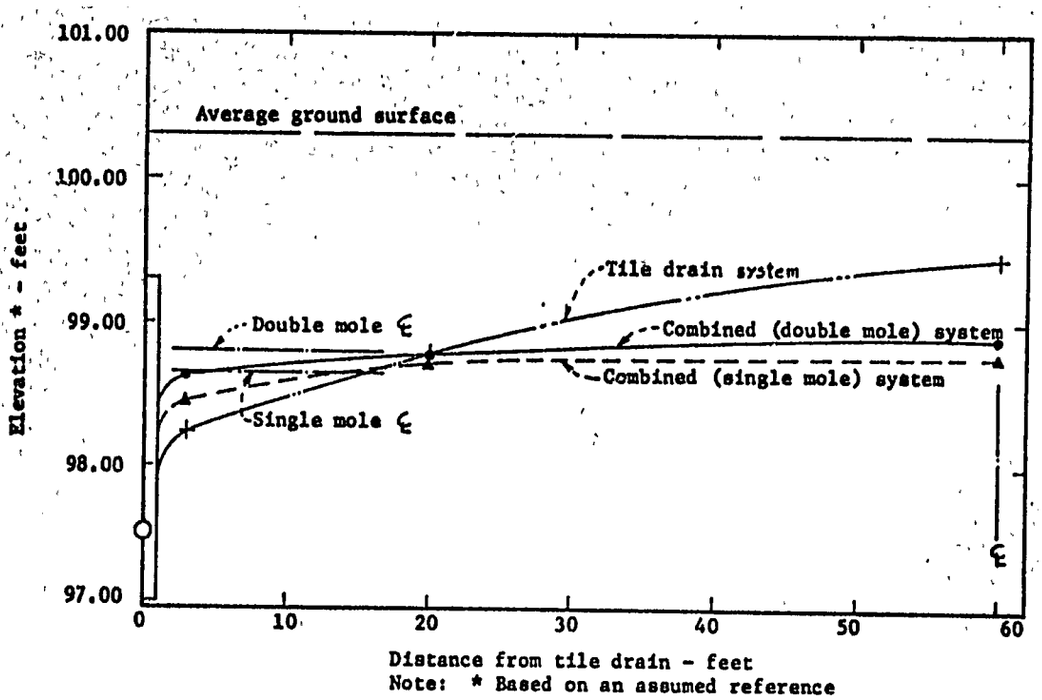


Figure 28. Comparison of the drawdown of the water table in the areas using the tile drain system and the combined systems, four days after drainage process began, 1973.

A very interesting characteristic of the combined mole-tile drain system is the flatness of the water table when compared to those of the tile drain system. A logical explanation of the characteristic may be that in the combined systems the water entered the mole drains, which are spaced more closely than the tile drains, and therefore, caused the water table in the location near the midpoint to drop faster than at the similar location in the tile drained area. The water is then carried along the mole channel, but most of the water seeps out before reaching the tile drain and probably attributes to the flatness of the water table in that vicinity.

Discharge rates

The discharge rates were measured at various time intervals at the outlet of the tile drain which carried the drainage water out from each area using a different type of drainage method. These measurements were made in manholes Nos. 1, 3 and 5 for the discharge rates from the combined (double mole) system, combined (single mole) system and tile drain system, respectively. The data of the measurements is shown in Table 1, and the results are plotted in Figure 29, which shows the discharge rate in cubic feet per day, per foot.

In Figure 29, the high rate of discharge at the beginning of the experiment which diminished rapidly could be attributed to the fact that a large quantity of water was accumulated in the trench before the drainage process was started. As soon as the outlets were opened, the water in the trench flowed quickly through the outlets. The figures also show the discharge rate for the combined (double mole) system to be less than that of the combined (single mole) and tile drain systems. The much smaller discharge rate from the combined (double mole) area than from

Table 1. Data of discharge rates measured during the experiment in 1972.

Date	Combined (Double Mole) Area		Combined (Single Mole) Area		Tile-Drain Area	
	Elapsed Time - Days	Discharge Rate cfd/ft.	Elapsed Time - Days	Discharge Rate cfd/ft.	Elapsed Time - Days	Discharge Rate cfd/ft.
Sept. 21	0.04	3.49	0.04	8.57	0.03	4.62
	0.19	2.12	0.09	4.96	0.10	1.93
	0.20	1.66	0.19	4.54	0.19	1.70
	0.36	0.83	0.36	3.92	0.36	1.44
Sept. 22	0.61	0.67	0.62	3.30	0.62	1.25
	0.99	0.86	0.98	2.60	0.98	1.20
	1.17	0.71	1.17	2.08	1.17	1.10
	1.36	0.35	1.36	1.41	1.37	0.96
Sept. 23	1.93	0.51	1.93	0.60	1.94	0.75
	2.38	0.13	2.38	0.44	2.38	0.26
Sept. 24	2.96	0.13	2.97	0.28	3.08	0.25
	3.36	0.08	3.35	0.20	3.35	0.16
Sept. 25	4.04	0.07	4.03	0.10	4.14	0.14
	4.32	0.06	4.31	0.09	4.29	0.12
Sept. 26	5.05	0.05	5.06	0.06	5.05	0.12

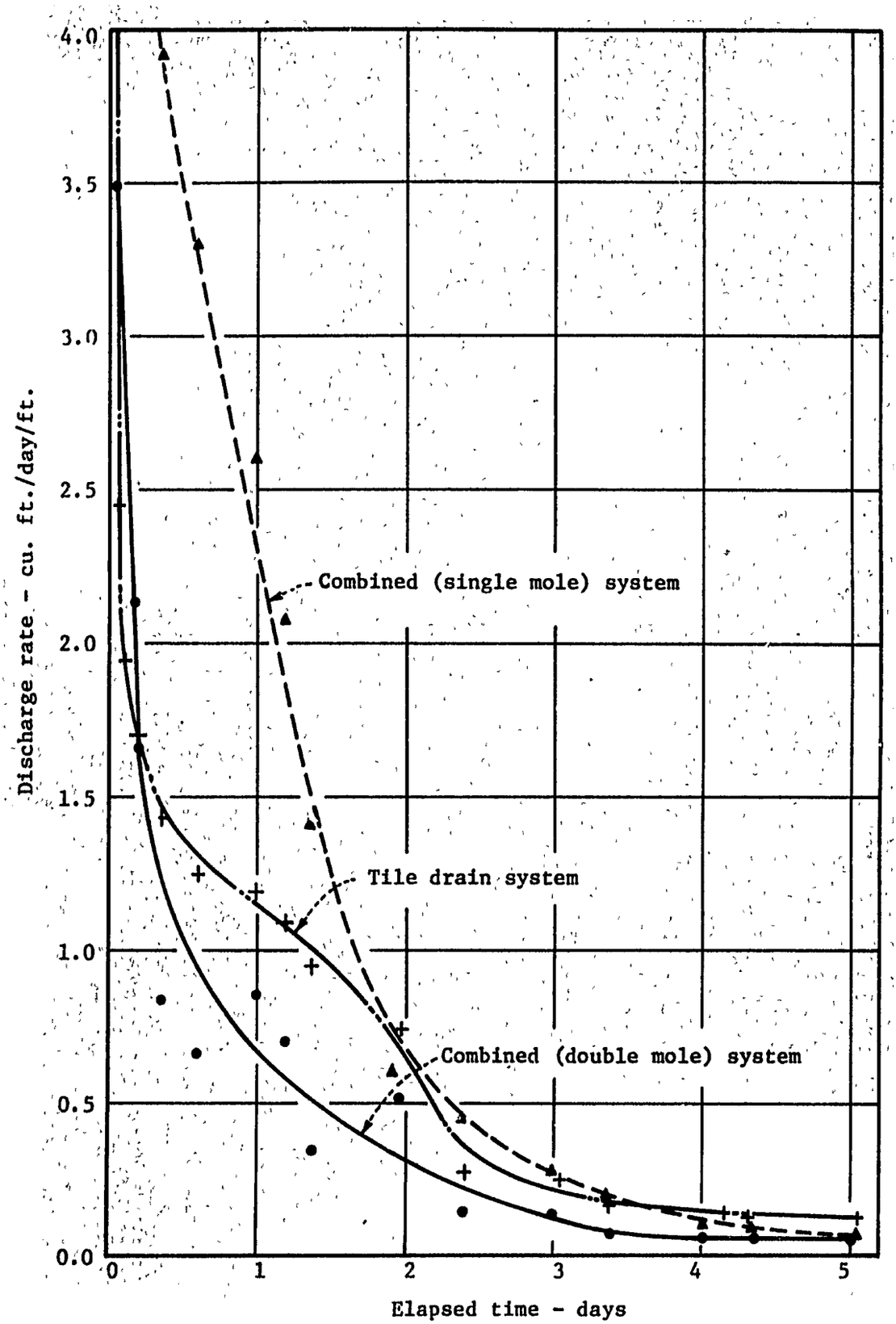


Figure 29. Discharge rates at various elapsed times after the drainage process began, 1972.

the combined (single mole) area was believed to be due to the effect of boundary condition in the combined (double mole) area. The east boundary of the combined (double mole) system is adjacent to an open drain ditch. When the drainage process started, the water table in the combined (double mole) system was much higher than the water level in the ditch, and a large amount of ground water in the double mole area could seep into the ditch, and thus reduce the amount of water which flowed into the mole and tile drains in the system.

Along the west boundary of the tile drain area, the reverse condition may exist. The water table along the west side of the tile-drain plot, as observed from observation wells, was higher than the water level inside the plot and, therefore, the ground water could flow from outside into the tile-drain area and increase the flow rate in the tile-drain area. For these reasons, the flow hydrograph presented should be regarded as containing some errors. For future experiments, an effective barrier along the boundaries of the experimental plot must be provided to avoid the undesirable boundary conditions which existed in this study.

Investigation of the Deterioration of Mole Drains

The investigation on the deterioration of mole drains is important for the evaluation of the combined system because the longevity of the mole channels is a major factor involved in the determination of the feasibility of the combined system.

The deterioration of mole drains during the period of two years may be investigated by comparing the performance of the combined system as found from the experiments in 1972 and 1973. Because the life of tile drain is quite long, as accepted by drainage authorities, the

deterioration of the tile drains in two years may be considered to be negligible. Therefore, any degradation in the performance during the two years could be taken as a result of the deterioration of the mole drains in the systems.

A direct comparison of the performances may lead to an error, because the initial conditions of the water table in the experiments in 1972 and 1973 were not identical. As mentioned earlier, the intial water table in the 1972 experiment was flat, while in the 1973 experiment the initial water table was slightly curved. In order to obtain a true comparison, the correction was attempted to adjust the initial water tables to be approximately in the same condition before comparing the performances of the systems.

Taking the correction for the combined (single mole) system as an example, the procedure is as follows:

1. The water table versus elapsed times for the 1972 and 1973 experiments were plotted, as shown in Figure 30.

2. By examining Figure 30, the drawdown curve at t = 3 hours, resembles most closely the drawdown curve at t = 0 of the 1973 experiment. A new curve showing the recession rate at midpoint for the 1972 experiment was drawn using the water table elevation at t = 3 hours as the initial water table elevation. The similar curve for the 1973 experiment was also drawn on the same figure (Figure 31).

3. The same correction method as described and applied under the heading "Recession Rates at Midpoints" was then applied in order to adjust the initial water table of the 1972 and 1973 experiments to the same elevation.

The recession rate curves at midpoint for the 1972 and 1973 experiments already corrected by the method just described are shown in Figure

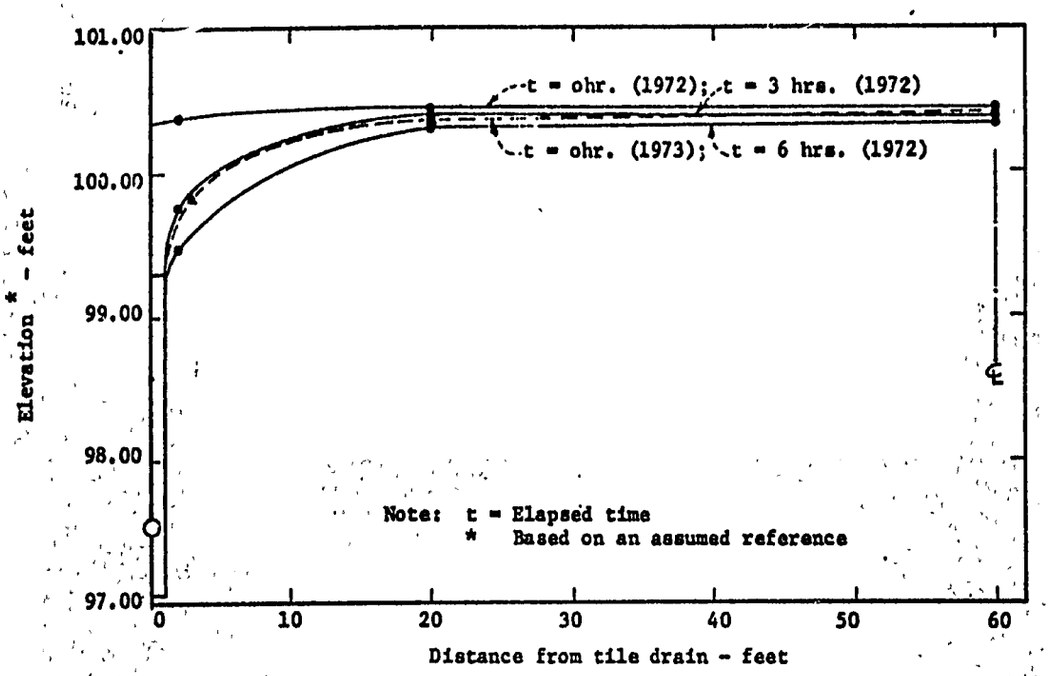


Figure 30. Examination of the resembled drawdown of the water table in the combined (single mole) area for the 1972 and 1973 experiments.

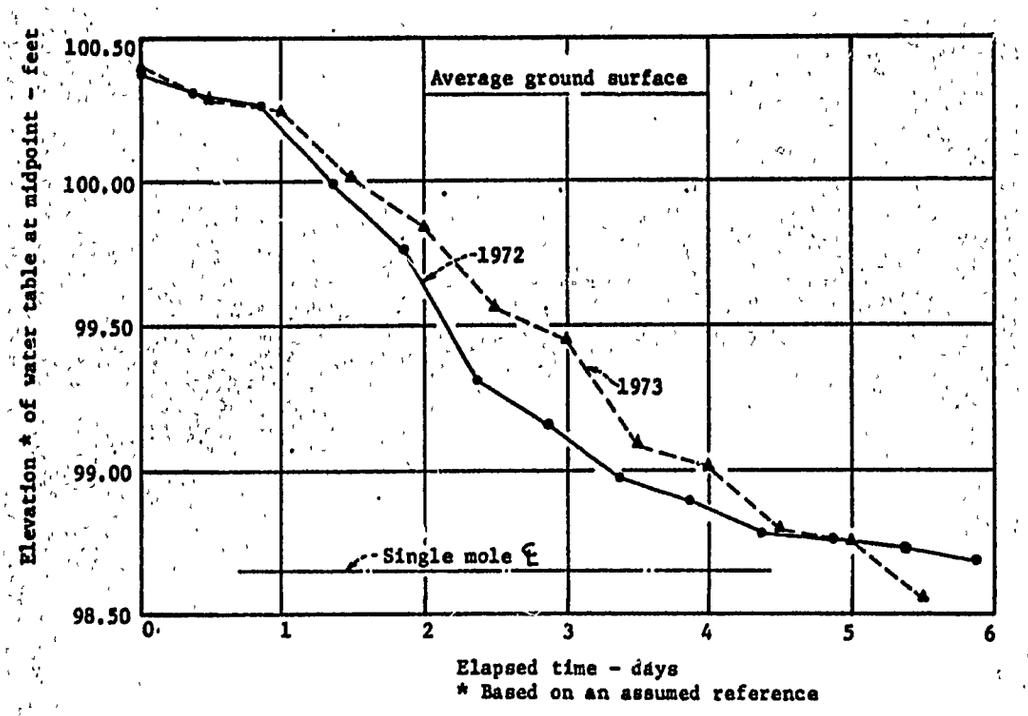


Figure 31. Recession rates of water table at midpoint in the combined (single mole) area for the 1972 and 1973 experiments after the initial conditions were adjusted.

32. Using the same method, Figure 33 was drawn for the combined (double mole) system.

In these experiments, in order to avoid the effect of the boundary conditions on the recession rates, the water table elevation along the boundaries of the experimental plots was observed. It was found that the boundary conditions in the 1972 experiment resembled closely with those of the 1973 experiment.

By comparing the recession rate curves of the combined systems shown in Figures 32 and 33, both combined systems appeared to perform equally efficient in the 1972 experiment as in the 1973 experiment. It may be concluded that the deterioration of the mole drains in the combined systems during the two-year period is not apparent in the result of the investigation just presented.

Economic Analysis

The evaluation of the combined system would not be complete without a cost analysis of the system. A most desirable drainage system should function effectively in removing water from the problem area, require minimum maintenance and be simple to construct and inexpensive.

The results of the experiments in 1972 and 1973 indicate that the combined systems functioned more effectively than the tile drain system. The operation and maintenance of both systems appear to be identical as far as the tile drain is concerned. The difference in the cost will depend on the life of the mole drains which is normally shorter than that of the tile drains and requires remoling at some intervals.

Because of the difference in the overall life of the two systems, a direct comparison of their initial costs will not represent the actual

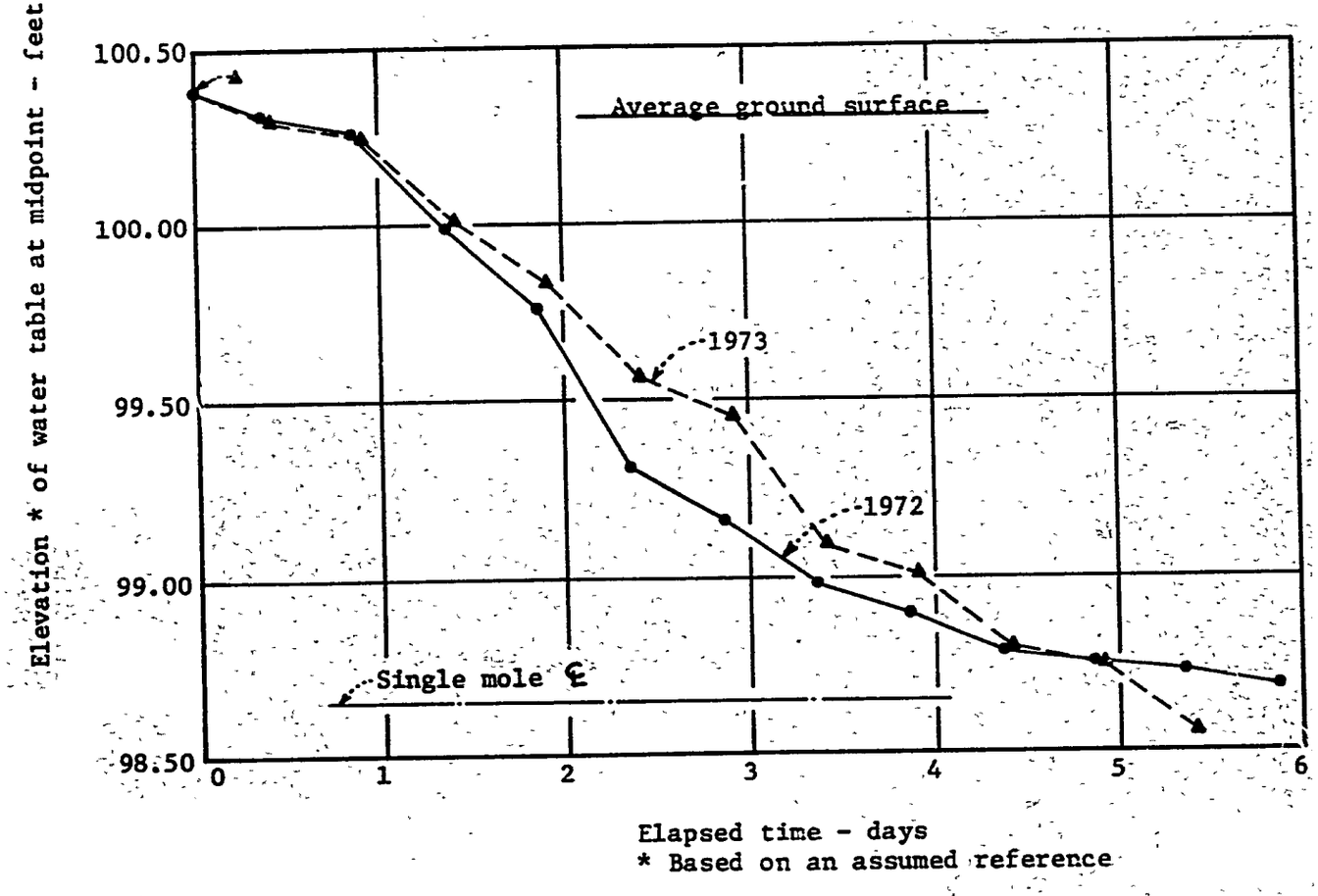


Figure 32. Comparison of the recession rates of water table at midpoint in the investigation on deterioration of single mole drains.

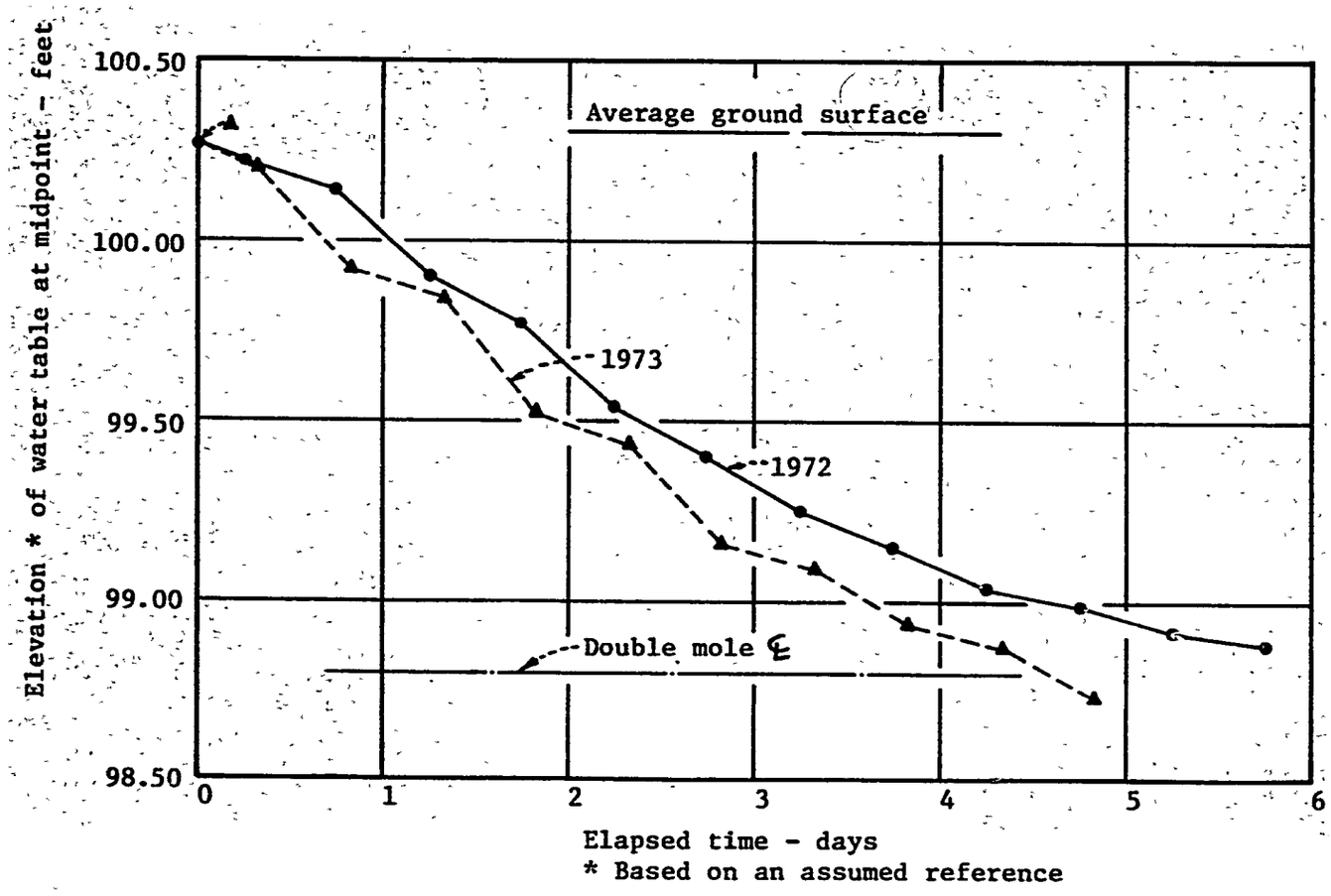


Figure 33. Comparison of the recession rates of water table at midpoint in the investigation on deterioration of double mole drains.

economic characteristic of the systems. Many methods of comparison are possible. In this study, the cost analysis will be made by comparing the annual costs of the systems.

In this section, the annual cost of the combined system, having the same construction details and performance as obtained in the experiments, presented in the early part of the thesis, will be computed. Then the spacing of a tile drain system which can function as effectively as the combined system will be determined. This tile drain system will be referred to as the equivalent tile drain system.

The cost study has to be based on the combined system used in the experiments because its performance is known, which makes the determination for the details of the equivalent tile drain possible. If the other combined system is used in the analysis, the problem will arise regarding the details of the equivalent tile drain system since the performance of the other combined system is not known.

General equations for cost analysis

The following equations, derived for the analysis by the author, will be used to determine the annual costs of both systems:

$$At = Lt \cdot Ct \cdot \left[\frac{i}{(1+i)^N - 1} + i\right] \tag{8}$$

$$Ac(n) = Ltc \cdot Ctc \cdot \left[\frac{i}{(1+i)^N - 1} + i\right] + Lm \cdot Cm \cdot \left[\frac{i}{(1+i)^n - 1} + i\right] \tag{9}$$

in which

At is an annual cost of an equivalent tile drain system

Ac is an annual cost of a combined system

Lt is a total length of tile drains required for the equivalent system

Ltc is a total length of tile drains required for the combined system

Lm is a total length of mole drains in the combined system

Ct is a cost per unit length of the tile drain

Ctc is a cost per unit length of tile drain in the combined system

Cm is a cost per unit length of the mole drain

N is the life of tile drain in years

n is the life of mole drain in years

i is an interest rate per year

Subtracting equation (8) by equation (9) and dividing by Ct,

$$\frac{S(n)}{Ct} = (Lt - C \cdot Ltc)\left[\frac{i}{(1+i)^N - 1} + i\right] - \frac{Lm \cdot Cm}{Ct} \cdot \left[\frac{i}{(1+i)^n - 1} + i\right] \tag{10}$$

in which

$S(n) = At - Ac(n)$

= annual saving if the combined system is used instead of the equivalent tile drain

$C = Ctc/Ct$

Dividing equation (10) by equation (8) and multiplying by 100,

$$SP(n) = 100\left\{1 - \frac{C \cdot Ltc}{Lt} - \frac{Lm \cdot Cm \cdot [(1+i)^N - 1]}{Lt \cdot Ct \cdot [(1+i)^n - 1]\,(1+i)^{N-n}}\right\} \tag{11}$$

in which

$$SP(n) = \frac{At - Ac(n)}{At} \cdot 100$$

= annual saving in percent of the annual cost of the equivalent tile drain if a combined system is used instead of an equivalent tile drain.

Application of the equations

The equations, as shown in the prior section, will be applied, and the information obtained from the experiment will be used.

Data used in the determination of the spacing of the equivalent tile drain system are as follows:

1. The water table is to be lowered by 1 foot in 2.7 days, and the initial water table is 2.75 feet above tile drains.

2. The average hydraulic conductivity of the soil is 0.74 feet per day, as obtained from the field measurement (the resutls of the measurement are shown in Appendix C).

3. The specific yield is 5.5%, as read from Figure 10-10 (Luthin, 1966).

4. The depth of the tile drain is 2.77 feet.

5. The impermeable layer is 6 feet below the ground surface.

The spacing of the equivalent tile drain computed by the USBR method (1964) and Jenab's method (1967) using the data given above was found to be 52 and 49 feet, respectively (calculation is shown in Appendix D). The spacing of 50 feet will be used for the cost analysis of the equivalent tile drain in this study.

For the combined system, the actual spacings and details as constructed for the experment will be used in the analysis.

In this study, the equivalent tile drain requires 871 feet of tile drains, and the combined system uses 363 feet of tile drains and 7,260 feet of mole drains per acre. To further investigate the saving which results from the use of the combined system in place of the equivalent tile drain, assume i = 10% per year, N = 30 years and C = 1.10.

Substituting the above values of the variables in Equations 10 and 11, Ct/Cm, S(n)/Ct and SP(n) are computed for the values of n from 1 to 10. The results are shown in Table 2 and drawn in Figure 34.

Discussion of results

Many reports (Hamblyn, 1950; Piper, 1958; Theobald, 1963; and Trafford, 1971) stated that the life of mole drain ranges from 2 to 15 years. The ratio of costs per foot of tile drain and mole drain (Ct/Cm), as reported by Trafford (1971), Baitch and Rieser (1971), varies approximately from 200 to 800. With ranges of n and Ct/Cm above, Figure 34 shows that the annual saving could be from 31% to 53% of the cost of the equivalent tile drain. In order to demonstrate numerically the actual annual saving, let us consider the case where the life of the mole drain is 3 years, the costs per foot of mole and tile drain are 0.2 cents and one dollar, respectively. The annual saving will be 44 dollars per acre or 48% of the cost of the equivalent tile drain system.

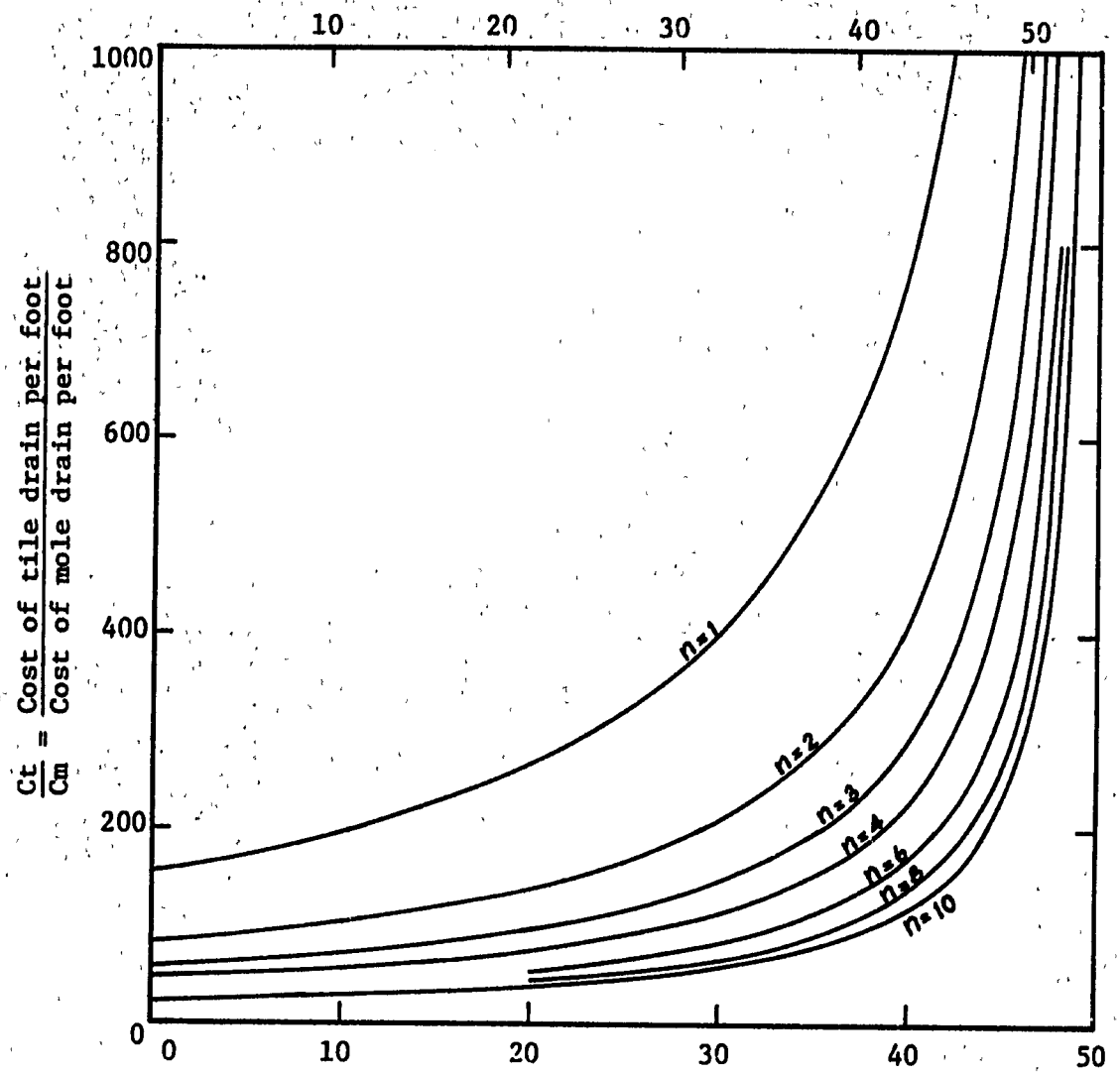
Figure 34 indicates that the saving is always obtained if Ct/Cm is greater than 160, even if the mole drain has to be redrawn every year. All curves are flat in the region of small Ct/Cm and become very steep when this ratio is greater than 200. This could be interpreted that the ratio of the unit cost of tile drain and mole drain needs not be too high in order to gain an appreciable amount of saving by using the combined system instead of a tile drain system, even when the life of the

Table 2. Saving per acre and saving in percent of the cost of an equivalent tile drain.

	Life of Mole Drain in Years													
	1		2		3		4		6		8		10	
Ct/Cm	S(1)/Ct	SP(1) %	S(2)/Ct	SP(2) %	S(3)/Ct	SP(3) %	S(4)/Ct	SP(4) %	S(6)/Ct	SP(6) %	S(8)/Ct	SP(8) %	S(10)/Ct	SP(10) %
50			-33.7	-36.4	-8.4	-9.1	4.2	4.6	16.7	18.1	22.8	24.7	26.4	28.4
100			8.2	8.9	20.8	22.5	27.1	29.4	33.3	36.1	36.4	39.4	38.2	41.2
150	-3.2	-3.4	22.1	24.0	30.5	33.1	34.7	37.6	38.9	42.1	40.9	44.3	42.1	45.6
200	10.1	10.9	29.1	31.5	35.4	38.3	38.6	41.8	41.7	45.1	43.2	46.8	44.1	47.8
250	18.3	19.8	33.3	36.0	38.3	41.5	40.8	44.2	43.3	46.9	44.6	48.2	45.3	49.0
300	23.4	25.3	36.1	39.1	40.3	43.6	42.4	45.9	44.5	48.1	45.5	49.2	46.1	49.9
350	27.2	29.4	38.1	41.2	41.7	45.1	43.5	46.1	45.2	49.0	46.1	49.9	46.6	50.5
400	30.0	32.5	39.6	42.8	42.7	46.2	44.3	47.9	45.8	49.6	46.6	50.5	47.2	51.1
500	34.0	36.9	41.6	45.1	44.2	47.8	45.4	49.2	46.7	50.5	47.3	51.2	47.6	51.6
600	36.7	39.7	43.0	46.6	45.1	48.9	46.2	50.0	47.2	51.1	47.7	51.7	48.0	52.0
700	38.6	41.8	44.0	47.7	45.8	49.6	46.7	50.6	47.6	51.6	48.1	52.1	48.3	52.3
800	40.0	43.3	44.8	48.5	46.4	50.2	47.2	51.0	47.9	51.9	48.3	52.3	48.5	52.5
900	41.1	44.5	45.4	49.1	46.8	50.6	47.5	51.4	48.2	52.1	48.5	52.5	48.7	52.7
1000	42.0	45.5	45.8	49.6	47.1	51.0	47.7	51.7	48.3	52.3	48.7	52.7	48.8	52.9

Notes: Ct = cost of tile drain per foot S = saving obtained per acre
Cm = cost of mole drain per foot SP = saving obtained in per cent

SP(n) = Annual saving in percent of the cost of an equivalent tile drain



$$\frac{S(n)}{Ct} = \frac{\text{Annual saving per acre}}{\text{Cost of tile drain per foot}}$$

Note: n = Life of mole drain in years

Figure 34. Curves showing the saving in construction cost obtained if a combined mole tile drain system is used instead of an equivalent tile drain system.

mole drains is short. For example, for the life of mole drain of two years, with the increase of Ct/Cm from 85 to 200, the annual saving increases from 0 to 32%. In other words, it might be suggested that the life and cost of the mole drain does not influence significantly the percent of saving as long as the mole channels last two years or more and the ratio of Ct/Cm is greater than 200.

In addition to the saving in construction cost discussed above, mole drains also give subsoiling effect which allows a better air circulation through the soil and increases its water holding capacity. Mole drains have been found to make leaching in heavy soil more effective (Rapp, 1968).

SUMMARY AND CONCLUSIONS

An investigation was conducted to evaluate the field performance and economic feasibility of the combined mole-tile drain system in heavy soils in comparison with a similar tile drain system. Two combined systems were constructed, the double mole and single mole. The mole drains, drawn at a depth of about 19 inches and with a spacing of 6 feet, were constructed above and orthogonal to the tile drains 2.77 feet deep spaced at 120 feet. The field performances were investigated by comparing the rate of recession of water table at midpoints between tile drains, the accumulative drops, the drawdown curves and the discharge rates of the three systems. The investigation on the deterioration of mole drains during the period of two years was done by comparing the rate of recession of the water table at midpoints obtained in the 1972 and 1973 experiments.

The economic analysis was conducted by comparing the cost of the combined systems to that of an equivalent tile drain based on the total and annual costs. The results of the experiments may be concluded as follows:

1. The combined systems were more effective than the tile drain system in lowering the water table.

2. The difference in the effectiveness between the combined systems using the single and double mole drains in lowering the water table was not distinctly apparent.

3. There was no conclusive indication of the deterioration of the mole channels during the period of two years.

4. The construction cost of a combined system is always lower than that of an equivalent tile drain system even if the mole drains in the combined system have to be redrawn every year.

SUGGESTIONS FOR FURTHER STUDY

The following laboratory and field investigations should be considered:

1. Model studies may be used to investigate the performance of the combined system as affected by different variable parameters, such as hydraulic conductivity, depth to the impermeable layer, spacing of mole drains, depth of mole drains, and spacing and depth of tile drains. From the studies, empirical formulas for the combined systems may be developed by means of the method of the dimensional analysis. Also, a verification of the results from the studies above by field experiment may be conducted.

2. Further investigation on the effective life of mole drains in various types of soils should be made. The information from this investigation are useful for the economic analysis of the combined system.

3. An extensive study should be conducted by using the combined system and an equivalent tile drain system in the areas where crops are to be grown. A comparison of crop yields from each area should be made in order to investigate the subsoiling effect of mole drains.

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Appendix A

Record of Soil Boring on USU Drainage Farm

Station # 17

0 - 1'	dark gray moist silty clay loam
1 - 3 1/2'	gray moist clay loam
3 1/2 - 5'	gleyed light gray clay, moist
5 - 7 1/2'	gray clay, brown, some green mottles, moist clay
7 1/2 - 10'	brown mottled, moist clay
10 - 12'	stratified clay loam, clay and sandy layers

Couldn't determine free water

Station # 18

0 - 2 1/2'	dark gray moist clay loam
2 1/2 - 4 1/2'	gray gleyed clay, moist
4 1/2 - 9 1/2'	stratified clay loam and sandy layers

Free water 10 1/2'

Note: This data was taken from Perez, Mario, 1969. Unpublished M.S. Report, Utah State University, Logan, Utah.

Appendix B

Data of the Water Table Elevations Measured During the Experiments in 1972 and 1973

Observation Well No.	Sept. 21, 72 A.M.	(ft.)	Sept. 21, 72 A.M.	(ft.)	Sept. 21, 72 P.M.	(ft.)	Sept. 21, 72 P.M.	(ft.)
R	09:00	100.37	11:30	100.28	02:42	100.18	06:35	100.10
1	09:24	100.47P	12:03	100.45P	03:17	100.45P	07:05	100.42PP
6	09:24	100.44	12:02	100.42	03:16	100.36	07:05	100.30
11	09:23	100.32P	12:01	100.32P	03:15	100.31P	07:04	100.30P
5	08:55	100.23	12:05	100.24P	03:19	100.21	07:07	100.17
10	08:55	100.36P	12:06	100.36P	03:20	100.35PP	07:08	100.34PP
15	08:57	100.26P	12:07	100.25P	03:21	100.24P	07:09	100.23P
SD1	09:03	100.29	11:33	100.11	02:44	99.81	06:39	99.67
2	09:04	100.45P	11:36	100.45P	02:45	100.43P	06:40	100.41P
3	09:05	100.42	11:39	100.41	02:48	100.31	06:42	100.16
4	09:06	100.38	11:42	100.02	02:51	99.73	06:45	99.62
ND1	09:08	100.34	11:43	100.06	02:54	99.61	06:48	99.37
SD2	09:14	100.37	11:53	99.75	03:04	99.58	06:57	99.47
7	09:13	100.46P	11:50	100.44P	03:02	100.43P	06:55	100.39PP
8	09:12	100.43	11:48	100.42	02:59	100.39	06:51	100.35
9	09:11	100.44P	11:46	100.43P	02:57	100.42P	06:49	100.39P
ND2	09:10	100.38	11:44	99.87	02:54	99.56	06:49	99.43
SD3	09:16	100.30P	11:55	100.29P	03:07	100.28P	06:58	100.27P
12	09:17	100.28P	11:56	100.27P	03:07	100.26P	06:59	100.25P
13	09:17	100.28P	11:56	100.27P	03:08	100.26P	07:00	100.24P
14	09:18	100.27P	11:57	100.26P	03:09	100.24P	07:01	100.22P
ND3	09:18	100.29	11:57	99.64	03:10	99.28	07:02	99.11
16	09:21	100.14	12:00	100.12	03:13	100.04	07:03	100.02
17	09:20	100.10	11:59	100.06	03:12	100.03	07:03	100.03
18	09:19	100.2[illegible]	11:58	100.17	03:12	100.07	07:02	100.04

Note: P = ponding; PP = partially ponding

Observation Well No.	Sept. 22, 72 A.M.	(ft.)	Sept. 22, 72 A.M.	(ft.)	Sept. 22, 72 P.M.	(ft.)	Sept. 22, 72 P.M.	(ft.)
R	00:35	100.03	10:41	99.91	02:00	99.84	06:26	99.75
1	01:15	100.42PP	11:15	100.39PP	02:30	100.32	06:57	100.19
6	01:13	100.29	11:15	100.21	02:29	100.10	06:56	99.88
11	01:12	100.29P	11:14	100.27P	02:28	100.27P	06:55	100.26P
5	01:17	100.12	11:19	100.06	02:31	100.03	06:59	99.99
10	01:18	100.32	11:20	100.28PP	02:32	100.23PP	07:00	100.16
15	01:19	100.22P	11:21	100.20P	02:32	100.19P	07:00	100.17P
SD1	00:39	99.57	10:47	99.50	02:02	99.50	06:27	99.44
2	00:40	100.39P	10:46	100.37P	02:02	100.35P	06:28	100.33P
3	00:44	100.03	10:50	99.85	02:05	99.76	06:31	99.61
4	00:46	99.56	10:54	99.47	02:07	99.41	06:34	99.34
ND1	00:50	99.25	10:55	99.16	02:10	99.14	06:36	99.12
SD2	01:02	99.34	11:04	99.21	02:19	99.20	06:47	99.15
7	00:59	100.19	11:01	100.02	02:16	99.90	06:45	99.64
8	00:55	100.35	10:59	100.32	02:14	100.22	06:42	100.07
9	00:52	100.37	10:56	100.22	02:12	100.09	06:39	99.89
ND2	00:51	99.29	10:55	99.17	02:11	99.15	06:38	99.07
SD3	01:04	100.25P	11:05	100.05	02:21	100.22PP	06:48	100.20PP
12	01:05	100.25P	11:06	100.22P	02:22	100.20P	06:48	100.19P
13	01:06	100.23P	11:07	100.22P	02:22	100.20P	06:49	100.18P
14	01:07	100.20P	11:08	100.18P	02:23	100.14	06:50	99.89
ND3	01:08	98.91	11:08	98.87	02:24	98.86	06:51	98.60
16	01:11	100.02	11:12	99.98	02:27	99.94	06:54	99.93
17	01:10	100.04	11:11	100.02	02:26	100.00	06:54	100.00
18	01:09	100.05	11:10	100.01	02:25	99.95	06:52	99.94

Note: P = ponding; PP = partially ponding

Observation Well No.	Sept. 23, 72 A.M.	(ft.)	Sept. 23, 72 P.M.	(ft.)	Sept. 24, 72 A.M.	(ft.)	Sept. 24, 72 P.M.	(ft.)
R	08:26	99.56	07:06	99.38	09:06	99.24	06:16	99.12
1	08:55	100.04	07:34	99.61	09:26	99.41	06:46	99.18
6	08:54	99.63	07:33	99.17	09:25	99.03	06:46	98.93
11	08:53	100.24P	07:33	100.20P	09:24	100.18P	06:45	100.15P
5	08:55	99.87	07:35	99.78	09:28	99.64	06:48	99.55
10	08:56	99.99	07:36	99.46	09:29	99.28	06:49	99.04
15	08:56	100.16P	07:37	100.01PP	09:30	99.84	06:50	99.57
SD1	08:27	99.30	07:07	99.27	09:06	99.21	06:18	99.18
2	08:27	99.83	07:08	99.43	09:07	99.31	06:22	99.16
3	08:30	99.54	07:11	99.27	09:08	99.21	06:22	99.09
4	08:34	99.31	07:13	99.07	09:09	98.98	06:25	98.87
ND1	08:35	99.04	07:17	98.98	09:10	98.89	06:29	98.84
SD2	08:45	99.03	07:26	98.96	09:17	98.83	06:38	98.78
7	08:42	99.48	07:24	99.07	09:16	99.00	06:35	98.86
8	08:40	99.91	07:21	99.40	09:15	99.26	06:32	99.07
9	08:37	99.65	07:18	99.22	09:14	99.12	06:30	98.93
ND2	08:37	98.97	07:17	99.88	09:14	98.77	06:29	98.72
SD3	08:46	99.33	07:27	99.02	09:18	98.84	06:39	98.79
12	08:47	100.07	07:28	99.62	09:19	99.26	06:40	99.01
13	08:47	100.15P	07:29	100.08	09:20	99.50	06:40	99.12
14	08:48	99.55	07:29	99.12	09:21	98.95	06:41	98.80
ND3	08:49	98.57	07:30	98.56	09:22	98.55	06:42	98.54
16	08:52	99.87	07:32	99.70	09:24	99.57	06:44	99.36
17	08:51	99.98	07:31	99.92	09:23	99.84	06:43	99.63
18	08:50	99.90	07:30	99.73	09:23	99.52	06:43	99.41

Note: P = ponding; PP = partially ponding

Observation Well No.	Sept. 25, 72 A.M.	(ft.)	Sept. 25, 72 P.M.	(ft.)	Sept. 26, 72 A.M.	(ft.)	Sept. 26, 72 P.M.	(ft.)
R	10:57	98.99	06:44	98.93	11:07	98.88	06:04	98.83
1	11:21	99.04	07:12	98.93	11:37	98.88	06:36	98.82
6	11:21	98.80	07:11	98.74	11:36	98.68	06:36	98.65
11	11:20	100.09P	07:10	100.06P	11:36	99.86PP	06:35	99.60
5	10:54	99.40	07:12	99.32	11:40	99.19	06:00	99.15
10	10:54	98.92	07:13	98.80	11:40	98.77	06:00	98.74
15	10:55	99.49	07:14	99.47	11:41	99.44	06:01	99.43
SD1	10:58	99.13	06:45	99.10	11:09	99.06	06:05	99.04
2	10:59	98.98	06:45	98.91	11:10	98.83	06:06	98.79
3	11:01	99.00	06:46	98.89	11:12	98.87	06:10	98.81
4	11:04	98.75	06:49	98.72	11:15	98.65	06:10	98.63
ND1	11:06	98.74	06:53	98.70	11:19	98.63	06:14	98.60
SD2	11:14	98.67	07:02	98.63	11:29	98.57	06:27	98.55
7	11:12	98.74	06:59	98.69	11:25	98.65	06:26	98.64
8	11:10	98.96	06:56	98.85	11:23	98.83	06:20	98.77
9	11:08	98.84	06:54	98.74	11:21	98.70	06:16	98.67
ND2	11:07	98.60	06:54	98.56	11:20	98.51	06:15	98.48
SD3	11:15	98.69	07:03	98.65	11:29	98.59	06:24	98.56
12	11:15	98.86	07:04	98.73	11:30	98.68	06:29	98.62
13	11:16	98.96	07:05	98.83	11:30	98.78	06:30	98.72
14	11:16	98.68	07:05	98.58	11:31	98.54	06:31	98.49
ND3	11:17	98.52	07:05	98.52	11:31	98.51	06:32	98.51
16	11:19	99.05	07:08	98.94	11:34	98.81	06:34	98.74
17	11:19	99.33	07:07	99.20	11:33	99.00	06:33	98.92
18	11:18	99.14	07:06	99.00	11:32	98.87	06:33	98.80

Note: P = ponding; PP = partially ponding

Observation Well No.	Sept. 27, 72		Sept. 28, 72		Sept. 29, 72		Oct. 4, 72	
	P.M.	(ft.)	P.M.	(ft.)	A.M.	(ft.)	P.M.	(ft.)
R	05:08	98.78	04:45	98.75	06:01	98.63	03:17	dry
1	05:31	98.89	05:11	98.94	06:20	98.69	03:49	98.29
6	05:30	98.63	05:10	98.78	06:19	98.65	03:48	98.27
11	05:28	99.45	05:09	99.28	06:18	99.01	03:47	98.59
5	05:05	99.00	04:40	98.85	06:22	98.73	03:11	98.39
10	05:06	98.83	04:40	98.85	06:23	98.61	03:12	98.29
15	05:06	99.39	04:41	99.35	06:24	99.30	03:13	98.99
SD1	05:09	98.99	04:46	98.95	06:02	98.28	03:19	98.11
2	05:10	98.81	04:50	98.94	06:03	98.69	03:22	98.22
3	05:11	98.90	04:51	98.88	06:04	98.66	03:24	98.32
4	05:12	98.56	04:52	98.64	06:05	98.45	03:26	98.09
ND1	05:14	98.52	04:53	98.48	06:06	98.40	03:27	98.14
SD2	05:20	98.49	04:57	98.52	06:10	98.49	03:34	98.26
7	05:19	98.60	04:56	98.75	06:09	98.55	03:32	98.16
8	05:18	98.87	04:55	98.88	06:08	98.62	03:31	98.21
9	05:17	98.77	04:54	98.79	06:07	98.56	03:30	98.21
ND2	05:15	98.44	04:53	98.54	06:07	98.47	03:28	98.08
SD3	05:20	98.54	05:00	98.54	06:11	98.47	03:35	98.40(dry)
12	05:21	98.73	05:01	98.74	06:12	98.47	03:37	98.07
13	05:22	98.82	05:02	98.82	06:13	98.54	03:38	98.09
14	05:23	98.54	05:03	98.53	06:14	18.32	03:39	98.01
ND3	05:23	98.49	05:04	98.48	06:15	98.37 (dry)	03:40	dry
16	05:26	98.70	05:08	98.67	06:18	98.48	03:45	97.93
17	05:26	98.94	05:07	98.89	06:17	98.65	03:43	98.23
18	05:25	98.81	05:06	98.76	06:16	98.54	03:42	98.13

1973

Observation Well No.	Aug. 28, 73 A.M.	(ft.)	Aug. 28, 73 A.M.	(ft.)	Aug. 28, 73 P.M.	(ft.)	Aug. 28, 73 P.M.	(ft.)
R	07:40	100.67	10:40	100.46	01:40	100.32	07:40	100.14
1	07:43	100.46P	10:43	100.44P	01:43	100.43PP	07:43	100.41PP
6	07:44	100.45PP	10:44	100.44PP	01:44	100.42PP	07:44	100.31
11	07:45	100.34P	10:45	100.32P	01:45	100.31P	07:45	100.28P
5	08:07	100.57P	11:08	100.55P	02:08	100.53PP	08:07	100.28
10	08:08	100.34P	11:09	100.32P	02:09	100.30P	08:08	100.29P
15	08:10	100.20P	11:10	100.19P	02:10	100.17P	08:10	100.14P
SD1	07:47	100.27	10:47	100.02	01:47	99.89	07:47	99.76
2	07:48	100.48P	10:48	100.45P	01:48	100.44P	07:48	100.41P
3	07:49	100.52P	10:49	100.48PP	01:49	100.42	07:49	100.29
4	07:50	100.22	10:50	99.99	01:50	99.88	07:50	99.71
ND1	07:51	99.78	10:51	99.63	01:51	99.44	07:51	99.17
SD2	07:56	100.39	10:56	100.16	01:56	99.77	07:56	99.46
7	07:55	100.46P	10:55	100.42	01:55	100.35	07:55	100.20
8	07:54	100.48	10:54	100.43	01:54	100.38	07:54	100.25
9	07:53	100.43P	10:53	100.39PP	01:53	100.33	07:53	100.18
ND2	07:52	100.35	10:52	100.28	01:52	99.80	07:52	99.49
SD3	07:57	100.30P	10:57	100.28P	01:57	100.25P	07:57	100.21P
12	07:58	100.32P	10:58	100.29P	01:58	100.27P	07:58	100.23P
13	07:59	100.30P	10:59	100.27P	01:59	100.24P	07:59	100.20P
14	08:00	100.29P	11:00	100.26P	02:00	100.23P	08:00	100.19PP
ND3	08:01	100.30P	11:01	100.28P	02:01	100.09PP	08:01	98.73
16	08:02	100.12	11:02	100.01	02:02	99.95	08:02	99.90
17	08:03	100.04	11:03	99.98	02:03	99.95	08:03	99.91
18	08:04	100.11	11:04	99.98	02:04	99.91	08:04	99.86

Note: P = ponding; PP = partially ponding

Observation Well No.	Aug. 29, 73 A.M.	(ft.)	Aug. 29, 73 P.M.	(ft.)	Aug. 30, 73 A.M.	(ft.)	Aug. 30, 73 P.M.	(ft.)
R	07:40	99.97	07:40	99.72	07:40	99.57	07:40	99.35
1	07:43	100.39PP	07:43	100.22	07:43	100.09	07:43	99.50
6	07:44	100.28	07:44	99.96	07:44	99.86	07:44	99.29
11	07:45	100.24P	07:45	100.20P	07:45	100.18P	07:45	100.15P
5	08:07	100.13	08:07	99.68	08:07	99.57	08:07	99.26
10	08:08	100.27	08:08	100.18	08:08	100.10	08:08	99.65
15	08:10	100.09	08:10	99.98	08:10	99.97	08:10	99.73
SD1	07:47	99.69	07:47	99.43	07:47	99:36	07:47	99.22
2	07:48	100.36P	07:48	100.12	07:48	99.99	07:48	99.59
3	07:49	100.07	07:49	99.70	07:49	99.61	07:49	99.31
4	07:50	99.54	07:50	99.33	07:50	99.30	07:50	99.05
ND1	07:51	98.97	07:51	98.84	07:51	98.75	07:51	98.66
SD2	07:56	99.33	07:56	99.13	07:56	99.10	07:56	98.90
7	07:55	100.10	07:55	99.79	07:55	99.67	07:55	99.17
8	07:54	100.12	07:54	99.67	07:54	99.57	07:54	99.20
9	07:53	99.92	07:53	99.48	07:53	99.36	07:53	99.02
ND2	07:52	99.22	07:52	98.93	07:52	98.88	07:52	98.69
SD3	07:57	99.36	97:57	99.00	07:57	98.91	07:57	98.74
12	07:58	100.16PP	07:58	99.88	07:58	99.59	07:58	99.21
13	07:59	100.16P	07:59	100.08	07:59	99.92	07:59	99.44
14	08:00	99.76	08:00	99.28	08:00	99.14	08:00	98.87
ND3	08:01	98.37	08:01	98.20	08:01	98.12	08:01	97.99
16	08:02	99.65	08:02	99.24	08:02	99.02	08:02	98.73
17	08:03	99.82	08:03	99.45	08:03	99.19	08:03	98.82
18	08:04	99.74	08:04	99.20	08:04	98.95	08:04	98.63

Note: P = ponding; PP = partially ponding

Observation Well No.	Aug. 31, 73		Aug. 31, 73		* Sept. 1, 73		** Sept. 1, 73	
	A.M.	(ft.)	P.M.	(ft.)	A.M.	(ft.)	P.M.	(ft.)
R	07:40	99.25	07:40	99.09	07:40	99.20	07:40	100.00
1	07:43	99.33	07:43	98.94	07:43	99.39	07:43	100.42PP
6	07:44	99.12	07:44	98.85	07:44	99.21	07:44	100.44
11	07:45	100.13P	07:45	100.09P	07:45	100.09P	07:45	100.25P
5	08:07	99.17	08:07	99.02	08:07	99.34	08:07	100.57P
10	08:08	99.45	08:08	98.95	08:08	99.48	08:08	100.30P
15	08:10	99.70	08:10	99.27	08:10	99.66	08:10	100.09P
SD1	07:47	99.12	07:47	99.04	07:47	99.07	07:47	100.06
2	07:48	99.43	07:48	99.14	07:48	99.55	07:48	100.42
3	07:49	99.27	07:49	99.09	07:49	99.39	07:49	100.43
4	07:50	98.98	07:50	98.75	07:50	99.11	07:50	99.85
ND1	07:51	98.56	07:51	98.48	07:51	98.41	07:51	99.15
SD2	07:56	98.82	07:56	98.71	07:56	98.90	07:56	99.81
7	07:55	99.10	07:55	98.83	07:55	99.22	07:55	100.40
8	07:54	99.16	07:54	98.95	07:54	99.33	07:54	100.44
9	07:53	98.97	07:53	98.75	07:53	99.15	07:53	100.34
ND2	07:52	98.62	07:52	98.51	07:52	98.67	07:52	99.67
SD3	07:57	98.69	07:57	98.56	07:57	98.80	07:57	100.15PP
12	07:58	99.11	07:58	98.90	07:58	99.25	07:58	100.19P
13	07:59	99.27	07:59	99.01	07:59	99.38	07:59	100.17P
14	08:00	98.81	08:00	98.63	08:00	98.88	08:00	100.05
ND3	08:01	97.96	08:01	97.88	08:01	97.99	08:01	98.44
16	08:02	98.63	08:02	98.42	08:02	98.55	08:02	99.48
17	08:03	98.72	08:03	98.50	08:03	98.76	08:03	99.84
18	08:04	98.53	08:04	98.32	08:04	98.49	08:04	99.47

Note: P = ponding; PP = partially ponding
* After 1/4" rainfall
** After 6/8" rainfall

Observation Well No.	Sept. 2, 73 A.M.	* (ft.)	Sept. 2, 73 P.M.	(ft.)	Sept. 3, 73 A.M.	(ft.)	Sept. 3, 73 P.M.	(ft.)
R	07:40	100.40	07:40	100.15	07:40	99.99	07:40	99.77
1	07:43	100.44PP	07:43	100.42PP	07:43	100.39PP	07:43	100.28
6	07:44	100.44PP	07:44	100.30	07:44	100.28	07:44	100.05
11	07:45	100.32P	07:45	100.28P	07:45	100.25P	07:45	100.21P
5	08:07	100.56P	08:07	100.33	08:07	100.21	08:07	99.81
10	08:08	100.32P	08:08	100.29P	08:08	100.27P	08:08	100.20
15	08:10	100.18P	08:10	100.14P	08:10	100.09PP	08:10	100.00PP
SD1	07:47	99.89	07:47	99.70	07:47	99.63	07:47	99.43
2	07:48	100.44P	07:48	100.40P	07:48	100.35P	07:48	100.10
3	07:49	100.45PP	07:49	100.18	07:49	99.99	07:49	99.67
4	07:50	99.88	07:50	99.61	07:50	99.50	07:50	99.33
ND1	07:51	99.41	07:51	99.05	07:51	98.94	07:51	98.84
SD2	07:56	99.86	07:56	99.41	07:56	99.34	07:56	99.17
7	07:55	100.39	07:55	100.19	07:55	100.11	07:55	99.84
8	07:54	100.45	07:54	100.27	07:54	100.16	07:54	99.78
9	07:53	100.35	07:53	100.16	07:53	99.90	07:53	99.53
ND2	07:52	99.79	07:52	99.43	07:52	99.22	07:52	98.98
SD3	07:57	100.26P	07:57	100.20P	07:57	99.33	07:57	99.00
12	07:58	100.29P	07:58	100.22P	07:58	100.16PP	07:58	99.90
13	07:59	100.27P	07:59	100.19P	07:59	100.16P	07:59	100.09PP
14	08:00	100.26P	08:00	100.13	08:00	99.70	08:00	99.28
ND3	08:01	100.27P	08:01	98.79	08:01	98.37	08:01	98.19
16	08:02	100.00	08:02	99.88	08:02	99.64	08:02	99.26
17	08:03	99.98	08:03	99.90	08:03	99.83	08:03	99.53
18	08:04	99.97	08:04	99.86	08:04	99.74	08:04	99.27

Note: P = ponding; PP = partially ponding

* After 6/8" rainfall

Observation Well No.	Sept. 4, 73 A.M.	(ft.)	Sept. 4, 73 P.M.	(ft.)	Sept. 5, 73 A.M.	(ft.)	Sept. 5, 73 P.M.	(ft.)
R	07:40	99.63	07:40	99.42	07:40	99.32	07:40	99.17
1	07:43	100.21	07:43	99.78	07:43	99.64	07:43	99.20
6	07:44	99.96	07:44	99.49	07:44	99.36	07:44	99.04
11	07:45	100.19P	07:45	100.16P	07:45	100.15P	07:45	100.11P
5	08:07	99.70	08:07	99.40	08:07	99.34	08:07	99.14
10	08:08	100.15	08:08	99.86	08:08	99.71	08:08	99.20
15	08:10	99.99PP	08:10	99.83	08:10	99.82	08:10	99.43
SD1	07:47	99.37	07:47	99.23	07:47	99.15	07:47	99.06
2	07:48	99.98	07:48	99.63	07:48	99.50	07:48	99.19
3	07:49	99.60	07:49	99.35	07:49	99.32	07:49	99.13
4	07:50	99.30	07:50	99.10	07:50	99.07	07:50	98.85
ND1	07:51	98.76	07:51	98.68	07:51	98.61	07:51	98.54
SD2	07:56	99.12	07:56	98.95	07:56	98.89	07:56	98.75
7	07:55	99.71	07:55	99.30	07:55	99.21	07:55	98.93
8	07:54	99.67	07:54	99.33	07:54	99.29	07:54	99.04
9	07:53	99.41	07:53	99.11	07:53	99.07	07:53	98.82
ND2	07:52	98.93	07:52	98.75	07:52	98.74	07:52	98.55
SD3	07:57	98.92	07:57	98.77	07:57	98.72	07:57	98.60
12	07:58	99.62	07:58	99.27	07:58	99.18	07:58	98.95
13	07:59	99.96	07:59	99.54	07:59	99.36	07:59	99.09
14	08:00	99.14	08:00	98.90	08:00	98.83	08:00	98.65
ND3	08:01	98.11	08:01	97.99	08:01	97.97	08:01	97.88
16	08:02	99.05	08:02	98.78	08:02	98.69	08:02	98.47
17	08:03	99.29	08:03	98.95	08:03	98.85	08:03	98.61
18	08:04	99.06	08:04	98.76	08:04	98.66	08:04	98.44

Note: P = ponding; PP = partially ponding

Observation Well No.	Sept. 6, 73 A.M.	(ft.)	Sept. 6, 73 P.M.	(ft.)	Sept. 7, 73 A.M.	(ft.)	Sept. 7, 73 P.M.	(ft.)
R	07:40	99.10	07:40	98.95	07:40	98.92	07:40	98.78
1	07:43	99.10	07:43	98.87	07:43	98.78	07:43	98.56
6	07:44	98.93	07:44	98.74	07:44	98.65	07:44	98.51
11	07:45	100.08P	07:45	100.04P	07:45	99.99	07:45	99.80
5	08:07	99.08	08:07	98.98	08:07	98.91	08:07	98.83
10	08:08	99.09	08:08	98.82	08:08	98.77	08:08	98.53
15	08:10	99.24	08:10	99.08	08:10	99.00	08:10	98.93
SD1	07:47	98.98	07:47	98:91	07:47	98.86	07:47	98.80
2	07:48	99.11	07:48	98.95	07:48	98.87	07:48	98.71
3	07:49	99.10	07:49	98.94	07:49	98.92	07:49	98.74
4	07:50	98.79	07:50	98.68	07:50	98.53	07:50	98.42
ND1	07:51	98.46	07:51	98.38	07:51	98.32	07:51	98.26
SD2	07:56	98.68	07:56	98.58	07:56	98.52	07:56	98.45
7	07:55	98.89	07:55	98.70	07:55	98.68	07:55	98.58
8	07:54	99.01	07:54	98.84	07:54	98.83	07:54	98.62
9	07:53	98.81	07:53	98.71	07:53	98.65	07:53	98.48
ND2	07:52	98.49	07:52	98.41	07:52	98.34	07:52	98.27
SD3	07:57	98.56	07:57	98.46	07:57	98.42	07:57	98.32
12	07:58	98.92	07:58	98.76	07:58	98.75	07:58	98.56
13	07:59	99.04	07:59	98.88	07:59	98.85	07:59	98.67
14	08:00	98.62	08:00	98.49	08:00	98.46	08:00	98.30
ND3	08:01	97.86	08:01	97.80	08:01	97.79	08:01	97.72
16	08:02	98.41	08:02	98.24	08:02	98.21	08:02	98.06
17	08:03	98.58	08:03	98.39	08:03	98.37	08:03	98.18
18	08:04	98.39	08:04	98.22	08:04	98.20	08:04	98.03

Note: P = ponding; PP = partially ponding

Observation Well No.	* Sept. 8, 73 A.M.	(ft.)	** Sept. 8, 73 P.M.	(ft.)	*** Sept. 9, 73 A.M.	(ft.)	Sept. 9, 73 P.M.	(ft.)
R	07:40	99.59	07:40	100.10	07:40	100.05	07:40	99.81
1	07:43	100.42P	07:43	100.44P	07:43	100.44P	07:43	100.41PP
6	07:44	100.40PP	07:44	100.42PP	07:44	100.42PP	07:44	100.23
11	07:45	100.26P	07:45	100.29P	07:45	100.27P	07:45	100.23P
5	08:07	100.57P	08:07	100.56P	08:07	100.54P	08:07	100.29
10	08:08	100.28P	08:08	100.30P	08:08	100.30P	08:08	100.28P
15	08:10	100.10PP	08:10	100.09P	08:10	100.09P	08:10	100.02
SD1	07:47	99.77	07:47	99.89	07:47	99.85	07:47	99.58
2	07:48	100.41P	07:48	100.42P	07:48	100.40P	07:48	100.29PP
3	07:49	100.46PP	07:49	100.33	07:49	100.19	07:49	99.80
4	07:50	99.97	07:50	99.74	07:50	99.66	07:50	99.41
ND1	07:51	98.45	07:51	99.28	07:51	99.08	07:51	98.93
SD2	07:56	99.60	07:56	99.70	07:56	99.54	07:56	99.30
7	07:55	100.41	07:55	100.35	07:55	100.30	07:55	100.04
8	07:54	100.46	07:54	100.41	07:54	100.39	07:54	100.10
9	07:53	100.36	07:53	100.31	07:53	100.22	07:53	99.82
ND2	07:52	98.82	07:52	99.61	07:52	99.42	07:52	99.12
SD3	07:57	99.89	07:57	100.20P	07:57	100.16P	07:57	99.26
12	07:58	100.17	07:58	100.22P	07:58	100.19P	07:58	100.10
13	07:59	100.16P	07:59	100.20P	07:59	100.17P	07:59	100.14P
14	08:00	99.77	08:00	100.12PP	08:00	99.91	08:00	99.43
ND3	08:01	98.36	08:01	98.40	08:01	98.34	08:01	98.16
16	08:02	99.02	08:02	99.65	08:02	99.60	08:02	99.27
17	08:03	99.69	08:03	99.91	08:03	99.90	08:03	99.65
18	08:04	99.26	08:04	99.82	08:04	99.78	08:04	99.34

Note: P = ponding; PP = partially ponding
* After 1" rainfall
** After 1/2" rainfall
*** After 3/16" rainfall

Observation Well No.	* Sept. 10, 73 A.M.	(ft.)	Sept. 10, 73 P.M.	(ft.)	** Sept. 11, 73 A.M.	(ft.)	Sept. 11, 73 P.M.	(ft.)
R	07:40	99.68	07:40	99.51	07:40	99.58	07:40	99.45
1	07:43	100.39PP	07:43	100.33	07:43	100.41PP	07:43	100.36
6	07:44	100.21	07:44	99.96	07:44	100.35	07:44	100.10
11	07:45	100.22P	07:45	100.20P	07:45	100.21P	07:45	100.19
5	08:07	100.19	08:07	99.85	08:07	100.38	08:07	100.01
10	08:08	100.27PP	08:08	100.20	08:08	100.27PP	08:08	100.22
15	08:10	100.00	08:10	99.84	08:10	100.05	08:10	99.93
SD1	07:47	99.50	07:47	99.38	07:47	99.57	07:47	99.43
2	07:48	100.12	07:48	99.84	07:48	100.19	07:48	99.85
3	07:49	99.71	07:49	99.53	07:49	99.90	07:49	99.52
4	07:50	99.39	07:50	99.23	07:50	99.55	07:50	99.29
ND1	07:51	98.84	07:51	98.76	07:51	98.83	07:51	98.77
SD2	07:56	99.25	07:56	99.09	07:56	99.35	07:56	99.12
7	07:55	99.97	07:55	99.63	07:55	100.15	07:55	99.67
8	07:54	99.98	07:54	99.67	07:54	100.21	07:54	99.76
9	07:53	99.67	07:53	99.38	07:53	99.89	07:53	99.42
ND2	07:52	99.05	07:52	98.89	07:52	99.06	07:52	98.94
SD3	07:57	99.09	07:57	98.95	07:57	99.17	07:57	98.92
12	07:58	99.95	07:58	99.63	07:58	100.00	07:58	99.63
13	07:59	100.10PP	07:59	99.94	07:59	100.07	07:59	99.96
14	08:00	99.26	08:00	99.05	08:00	99.35	08:00	99.03
ND3	08:01	98.10	08:01	98.01	08:01	98.11	08:01	98.00
16	08:02	99.08	08:02	98.87	08:02	98.99	08:02	98.82
17	08:03	99.46	08:03	99.17	08:03	99.46	08:03	99.15
18	08:04	99.17	08:04	98.90	08:04	99.10	08:04	98.86

Note: P = ponding; PP = partially ponding
* After unmeasurable rainfall
** After 1/4" rainfall

Observation Well No.	Sept. 12, 73 A.M.	(ft.)	Sept. 12, 73 P.M.	(ft.)	Sept. 13, 73 A.M.	(ft.)	Sept. 13, 73 P.M.	(ft.)
R	07:40	99.36	07:40	99.20	07:40	99.12	07:40	98.98
1	07:43	100.31	07:43	99.98	07:43	99.76	07:43	99.30
6	07:44	99.96	07:44	99.48	07:44	99.28	07:44	98.96
11	07:45	100.18P	07:45	100.16P	07:45	100.14P	07:45	100.11P
5	08:07	99.81	08:07	99.48	08:07	99.36	08:07	99.17
10	08:08	100.18	08:08	99.95	08:08	99.77	08:08	99.28
15	08:10	99.88	08:10	99.56	08:10	99.38	08:10	99.14
SD1	07:47	99.31	07:47	99.17	07:47	99.07	07:47	98.98
2	07:48	99.68	07:48	99.34	07:48	99.24	07:48	99.03
3	07:49	99.44	07:49	99.22	07:49	99.19	07:49	99.00
4	07:50	99.25	07:50	99.01	07:50	98.96	07:50	98.75
ND1	07:51	98.72	07:51	98.65	07:51	98.57	07:51	98.49
SD2	07:56	99.04	07:56	98.87	07:56	98.80	07:56	98.66
7	07:55	99.51	07:55	99.13	07:55	99.05	07:55	98.82
8	07:54	99.61	07:54	99.26	07:54	99.21	07:54	98.96
9	07:53	99.30	07:53	99.02	07:53	98.97	07:53	98.75
ND2	07:52	98.86	07:52	98.68	07:52	98.62	07:52	98.48
SD3	07:57	98.85	07:57	98.71	07:57	98.67	07:57	98.55
12	07:58	99.47	07:58	99.19	07:58	99.10	07:58	98.90
13	07:59	99.73	07:59	99.36	07:59	99.22	07:59	99.00
14	08:00	98.93	08:00	98.75	08:00	98.68	08:00	98.52
ND3	08:01	97.96	08:01	97.89	08:01	97.86	08:01	97.79
16	08:02	98.72	08:02	98.55	08:02	98.48	08:02	98.33
17	08:03	99.01	08:03	98.76	08:03	98.69	08:03	98.51
18	08:04	98.74	08:04	98.53	08:04	98.47	08:04	98.29

Note: P = ponding; PP = partially ponding

Observation Well No.	Sept. 14, 73 A.M.	(ft.)	Sept. 14, 73 P.M.	(ft.)	Sept. 15, 73 A.M.	(ft.)
R	07:40	98.94	07:40	98.82	07:40	98.79
1	07:43	99.15	07:43	98.83	07:43	98.76
6	07:44	98.86	07:44	98.67	07:44	98.57
11	07:45	100.09P	07:45	100.05P	07:45	99.99P
5	08:07	99.08	08:07	98.98	08:07	98.90
10	08:08	99.13	08:08	98.80	08:08	98.75
15	08:10	99.03	08:10	98.94	08:10	98.88
SD1	07:47	98.91	07:47	98.85	07:47	98.79
2	07:48	98.96	07:48	98.81	07:48	98.74
3	07:49	98.98	07:49	98.82	07:49	98.79
4	07:50	98.63	07:50	98.50	07:50	98.37
ND1	07:51	98.41	07:51	98.34	07:51	98.27
SD2	07:56	98.60	07:56	98.51	07:56	98.44
7	07:55	98.79	07:55	98.63	07:55	98.59
8	07:54	98.95	07:54	98.76	07:54	98.75
9	07:53	98.75	07:53	98.59	07:53	98.57
ND2	07:52	98.42	07:52	98.33	07:52	98.26
SD3	07:57	98.52	07:57	98.42	07:57	98.37
12	07:58	98.87	07:58	98.72	07:58	98.69
13	07:59	98.97	07:59	98.82	07:59	98.78
14	08:00	98.49	08:00	98.36	08:00	98.33
ND3	08:01	97.78	08:01	97.73	08:01	97.72
16	08:02	98.28	08:02	98.15	08:02	98.09
17	08:03	98.47	08:03	98.31	08:03	98.26
18	08:04	98.25	08:04	98.11	08:04	98.08

Note: P = ponding; PP = partially ponding

Observation Well No.	Sept. 15, 73		Sept. 16, 73		Sept. 16, 73		Sept. 17, 73	
	P.M.	(ft.)	A.M.	(ft.)	P.M.	(ft.)	A.M.	(ft.)
R	05:16	98.70	07:40	98.67	07:40	98.60	07:40	98.60
1	05:19	98.63	07:43	98.61	07:43	98.41	07:43	98.36
6	05:20	98.50	07:44	98.40	07:44	98.32	07:44	98.27
11	05:21	99.93PP	07:45	99.41	07:45	98.91	07:45	98.75
5	05:42	98.86	08:07	98.79	08:07	98.75	08:07	98.71
10	05:43	98.57	08:08	98.53	08:08	98.39	08:08	98.38
15	05:45	98.83	08:10	98.78	08:10	98.76	08:10	98.73
SD1	05:23	98.75	07:47	98.70	07:47	98.66	07:47	98.61
2	05:24	98.67	07:48	98.59	07:48	98.50	07:48	98.45
3	05:25	98.68	07:49	98.66	07:49	98.54	07:49	98.53
4	05:26	98.29	07:50	98.19	07:50	98.12	07:50	98.03
ND1	05:27	98.21	07:51	98.13	07:51	98.07	07:51	98.00
SD2	05:32	98.40	07:56	98.32	07:56	98.26	07:56	98.21
7	05:31	98.55	07:55	98.50	07:55	98.43	07:55	98.39
8	05:30	98.62	07:54	98.58	07:54	98.45	07:54	98.39
9	05:29	98.47	07:53	98.44	07:53	98.33	07:53	98.32
ND2	05:28	98.21	07:52	98.16	07:52	98.11	07:52	98.07
SD3	05:33	98.31	07:57	98.22	07:57	98.16	07:57	98.11
12	05:34	98.57	07:58	98.52	07:58	98.41	07:58	98.39
13	05:35	98.66	07:59	98.61	07:59	98.50	07:59	98.47
14	05:36	98.23	08:00	98.20	08:00	98.11	08:00	98.09
ND3	05:37	97.68	08:01	97.67	08:01	97.62	08:01	97.62
16	05:38	98.01	08:02	97.93	08:02	97.85	08:02	97.79
17	05:39	98.16	08:03	98.15	08:03	98.01	08:03	97.98
18	05:40	97.98	08:04	97.91	08:04	97.82	08:04	97.79

Observation Well No.	Sept. 18, 73		Sept. 19, 73		Sept. 20, 73	
	A.M.	(ft.)	A.M.	(ft.)	A.M.	(ft.)
R	07:40	98.53	07:40	98.44	07:40	98.36
1	07:43	98.22	07:43	98.12	07:43	98.01
6	07:44	98.18	07:44	98.13	07:44	98.07
11	07:45	98.46	07:45	98.24	07:45	98.16
5	08:07	98.64	08:07	98.57	08:07	98.49
10	08:08	98.28	08:08	98.16	08:08	98.07
15	08:10	98.68	08:10	98.64	08:10	98.59
SD1	07:47	98.54	07:47	98.48	07:47	98.42
2	07:48	98.35	07:48	98.28	07:48	98.21
3	07:49	98.44	07:49	98.33	07:49	98.23
4	07:50	97.92	07:50	97.84	07:50	97.77
ND1	07:51	97.90	07:51	97.81	07:51	97.73
SD2	07:56	98.13	07:56	98.07	07:56	98.01
7	07:55	98.31	07:55	98.24	07:55	98.17
8	07:54	98.28	07:54	98.19	07:54	98.12
9	07:53	98.21	07:53	98.11	07:53	98.03
ND2	07:52	98.01	07:52	97.95	07:52	97.89
SD3	07:57	98.02	07:57	97.94	07:57	97.87
12	07:58	98.29	07:58	98.20	07:58	98.13
13	07:59	98.37	07:59	98.26	07:59	98.19
14	08:00	98.00	08:00	97.90	08:00	97.83
ND3	08:01	97.58	08:01	97.54	08:01	97.50
16	08:02	97.65	08:02	97.54	08:02	97.41
17	08:03	97.86	08:03	97.75	08:03	97.66
18	08:04	97.67	08:04	97.57	08:04	97.46

Appendix C

Results of the Field Hydraulic Conductivity Measurements

Hole No.	Depths from Ground Surface (feet)	Hydraulic Conductivity (feet per day)
1	3	2.36
	6	0.64
	9	0.24
2	3	1.80
	6	0.57
	9	--
3	3	3.40
	6	0.93
	9	0.37
4	3	2.55
	6	0.82
	9	0.35

Appendix D

Design of an Equivalent Tile Drain System

The data obtained in this research is used to determine the spacing of an equivalent tile drain. The data were shown previously in the presentation of cost analysis. The following is the procedures showing the calculation of tile spacing from two methods, USBR and Jenab's.

USBR Method

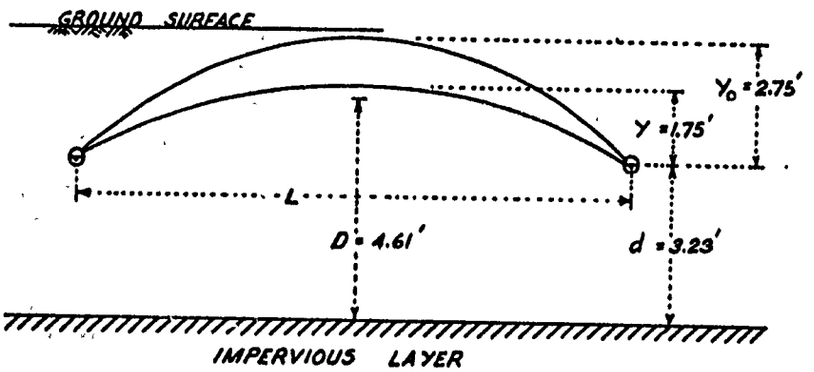

Figure 35. Design of an equivalent tile drain system.

From Figure 10-2 (Luthin, 1966), the equivalent depth (d') is equal to 3.23 feet.

Average flow depth (D) = $d' + Y_o/2$

= 4.61 feet

From Figure 35

$$Y/Y_o = \frac{1.75}{2.75} = 0.636$$

From Figure 10-8 (Luthin, 1966), when $Y/Y_o = 0.636$ it was found that

$$\frac{KDt}{SL^2} = 0.062$$

Substituting K, D, t and s, we have

$$\frac{0.74 \times 4.61 \times 2.7}{0.055 \times L^2} = 0.062$$

or

$$L = 52 \text{ feet} = \text{tile spacing}$$

Jenab's Method

From the data available, it may be found that

transmissivity (T) = 4.61 ft. x 0.74 ft./day

$$= 3.94 \times 10^{-5} \text{ ft.}^2/\text{sec.}$$

since specific yield (s) = 0.055

$$\alpha = \frac{T}{V}$$

$$= \frac{3.94 \times 10^{-5}}{0.055} = 0.716 \times 10^{-3} \text{ ft.}^2/\text{sec.}$$

From Figure 35, we have

$$Y/Y_o = \frac{1.75}{2.75} = 0.636 = D_1(u_n)$$

From Figure 6 (Jenab, 1967), when $D_1(u_n) = 0.636$, it was found that

$$\frac{\sqrt{4\alpha t}}{L} = 0.525$$

Substituting α and t,

$$L = \frac{\sqrt{4 \times 0.716 \times 10^{-3} \times 2.7 \times 24 \times 3600}}{0.525}$$

$$= 49.2 \text{ feet} = \text{tile spacing}$$

VITA

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