PERCOLATION OF SOIL WATER AS RELATED TO CONSUMPTIVE USE

by

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PERCOLATION OF SOIL WATER AS RELATED TO CONSUMPTIVE USE

INTRODUCTION

One of the problems most perplexing to soil and plant scientists interested in plant, soil and water relationships is that of evaluating the fate of water applied to a soil under crop. It is known that water applied to the soil surface will percolate downward through the soil, wetting or filling the soil as it goes, some will be lost through evaporation, some will be used by plants, some will percolate into deep soil layers beyond the reach of plants and some will be retained by the soil for long and indefinite periods of time. But what are the relationships among these various influences on soil water? What are the rates of loss by evaporation, transpiration and percolation? How much effect does the rate of water loss by one means have on another? How much water can be and will be retained by the soil? These are questions that remain unanswered or at best are only partially and arbitrarily answered.

The relationship proposed and discussed in this thesis came to light from a study which began as an attempt to evaluate the water retentive properties of soil or those properties which affect field capacity. Field capacity is commonly defined as the moisture content in the soil 24 to 48 hours after the application of water, at which time downward movement of water has materially decreased. It was realized that some measure of field capacity, in the field, was necessary before any study of the factors affecting field capacity could be made. However, in the course of this initial study no real value for field capacity but only the usual arbitrary 24 to 48 hour moisture percentage could be found. This confirmed the belief shared by many workers that in a dynamic soil system, particularly with growing plants, no fixed moisture value can be called field capacity and that what is frequently referred to as field capacity is but one point on a continuous time-drainage curve[1]. The value for soil moisture at such a point cannot be an equilibrium constant.

The type of time-drainage curves obtained in the first year's work suggested that the rate of drainage or percolation could be expressed as a function of time and that this function would be different depending upon whether the soil was clear of vegetation and covered to prevent evaporation or under the influence of a growing crop. It was felt that these functions were closely related and their functional relationship would be useful if determined. Considerable effort went into an attempt to establish this relationship mathematically but the attempts met with only partial success. A graphic analysis of the data then provided a solution to the problem of relating percolation and consumptive use[2].

[1] Time-drainage curves are the curves obtained by plotting the moisture content in the soil at various times after the soil has been irrigated, against time in hours or days or any desired time units. The curves will be frequently referred to in this thesis as moisture-time curves as the latter more aptly describes them than does the former.

[2] Consumptive use will, in this thesis, refer to the moisture utilized and transpired by plants from the soil plus the moisture lost by evaporation from the soil surface. Consumptive rate is determined directly by taking the difference between the moisture content in the soil 2 to 3 days after an irrigation and the moisture content just prior to the next irrigation and dividing this difference by the number of days between the times of sampling.

The author believes that the relationship between percolation and consumptive use is valid and can be evaluated, as will be shown in the following pages. The author also feels that with the establishment of this relationship, a new tool for the study of soil moisture movements and losses or utilization may be at hand. The relationship may also serve as a tool for the study of field capacity itself from the standpoint of when it occurs in the soil following the application of water.

In order to obtain data with which to relate percolation to consumptive use, field experiments were conducted at the Klamath Falls Experimental Area at Klamath Falls, Oregon. The work consisted of taking soil moisture samples from small plots under three distinct conditions (1) cropped, (2) cleared of vegetation and (3) cleared of vegetation and covered to prevent evaporation. The soil samples were taken at various time intervals starting soon after the plots were thoroughly irrigated. The moisture percentages of the samples were determined. These percentages plotted against the various times at which the samples were taken provided the moisture-time curves necessary to quantitatively relate percolation to consumptive use.

REVIEW OF LITERATURE

The literature pertaining to the specific problem under consideration in this thesis is apparently quite limited because relatively few workers have ever evaluated the relationship between percolation of water through the soil and consumptive use. A number of workers have made occasional studies in which percolation alone was evaluated but in these experiments consumptive use was eliminated by removing plants and covering the soil to prevent evaporation. In other studies percolation and consumptive use have been evaluated together but were not separable. Although a relationship between percolation and consumptive use has been suggested by a number of workers, dating back to 1912, when Widtsoe and McLaughlin (24, pp. 216-268) recognized that such a relationship existed, no definite studies were reported until very recently.

Widtsoe in Utah pioneered the work on consumptive use when he and his colleague McLaughlin studied the distribution of moisture after irrigation. They could not account for all of the water that they applied to field plots and attributed some of the loss to evaporation and transpiration and the remainder to deep percolation losses. They made no attempt to relate these losses of soil water to one another (24, pp. 216, 268).

In 1921 Gardner and Widtsoe (8, pp. 215, 232) reported theoretical aspects of soil moisture movement in the ideal soil. They presented a theoretical equation relating percent moisture in the soil, Q, to time, t. The parameters in the equation were evaluated from a particular soil and the equation has the form

$$Q = 14.6 + 2.7e^{-.02t} + 2.7e^{-.4t}$$

(8, p. 230). Because of the difficulty in evaluating the parameters, the equation has not been utilized in the study of the downward movement of moisture.

Generally, a parabolic curve is obtained by plotting moisture content against time following application of water in the soil. For the first 1 to 2 or 3 days from time zero the curve shows a fairly rapid decrease in moisture but as time increases the rate of decrease of moisture gradually slows down, the curve becoming asymtotic with respect to the time axis as the moisture content never reaches zero in the field. There are no sharp changes in the slope of the curve. Curves of this sort are frequently referred to in the literature as time-drainage curves, and are sometimes used to estimate the field capacity of soils.

Much of the interest in the percolation of water applied at the soil surface has centered around the soil moisture characteristic known as field capacity. Veihmeyer and Hendrickson define field capacity as "the amount of water held in the soil after excess water has drained away and the rate of downward movement materially decreased..." (22, p. 75). They state that this takes about two to three days in soils which are uniform in texture and structure (22, p. 75). They also indicate that field capacity is not an equilibrium value but a point on a time-drainage curve (22, p. 76). This latter view is supported by a number of workers (2, pp. 35-36);

4, p. 43; 6, p. 718; 7, p. 319; 13, p. 368; 17, p. 539; 18, p. 227 and 31, pp. 142-143). Israelson, on the other hand, refers to field capacity as an equilibrium value although it is influenced at any soil depth by the distance from a surface of complete saturation (11, p. 158). A definition of particular interest here is that of Edlefson and Bodman who state that field capacity is "...that moisture content for a given soil below which downward motion of water is negligible in comparison with the rate at which growing plants extract water from the soil." (6, p. 718). There is an implication in this definition that downward movement of water will decrease sooner when plants are growing on the soil than when the soil is bare, for the very obvious reason that the transpiration of plants will assist in depleting the moisture above as well as below field capacity.

Israelson and West (1922) conducted one of the earliest tests attempting to establish the field capacity in the field. They applied large amounts of water to small field plots, to insure saturation, covered the plots with straw to prevent evaporation and followed the movement of water downward by repeated soil sampling for 10 days. They also sampled periodically for a considerable time after the 10 days (2, p. 9). They were of the opinion that the downward movement of water must come to equilibrium with the water table and the results of sampling for the first 10 days appeared to confirm this opinion (12, footnote p. 9). However, even after 10 days there was some moisture movement downward, although at so slow a rate that they considered the moisture in the soil at the end of 10 days represented the effective water capacity (12, footnote p. 9). The authors do not define effective water capacity but presumably they mean the maximum amount of water the soil will hold for plant growth.

Veihmeyer and Hendrickson conducted similar tests on a number of California soils about 1930. After applying water to small field plots, they covered them with canvas and then sampled the soil at close intervals, attempting to determine the time after the application of water that the percolation became negligible (23, p. 185). It is interesting to compare their decision that in 2 to 3 days percolation becomes negligible (23, p. 192), from which they defined field capacity, with that of Israelson and West who decided that the soil reached the effective field capacity at 10 days. However, Veihmeyer and Hendrickson made their claim with reference to moisture percolating into relatively dry soil while Israelson and West referred to completely saturated soil in contact with a water table. Veihmeyer and Hendrickson made the observation that plants extract moisture rapidly enough to prevent appreciable percolation 2 to 3 days after the application of water (23, p. 192). Here again is reference to the effect of consumptive use on percolation.

Bodman, in 1936, presented data to show that in a soil saturated to 20 feet and with evaporation prevented, 60 percent of the downward movement of moisture occurred within 3 days, a further 22.5 percent in the next 55 days and still a further 17.5 percent in the next 273 days (2, pp. 35-36). This would indicate that the major portion of percolation takes place within 3 days, but whether the remaining percolation is negligible or not is questionable. If a similar test had been carried out but with plants growing, the consumptive use would likely have had a profound effect on the results Bodman obtained. Later (1941) Edlefsen and Bodman reported on tests involving plots which were thoroughly irrigated, then covered with roofing paper to prevent evaporation, and stated that "... water moves out of the soil at moisture contents much below the moisture equivalent[3] even in the lower depths. Two months had elapsed, however, before the soil at any depth had lost water in quantities sufficient to produce a relative wetness which was significantly below 1." (6, p. 719). The term relative wetness means the percentage moisture in the soil divided by the moisture equivalent (6, p. 719). A relative wetness of 1. would mean the soil is at the moisture equivalent or field capacity, less than 1. would mean the soil is below field capacity. If the moisture equivalent is taken as a measure of field capacity the indications are that percolation does indeed become small very quickly and long periods of time are needed before the downward movement loss of moisture becomes significant.

[3] Moisture Equivalent, as originated by Briggs and McLane (3, pp. 1-23), is the percentage of water, on an oven dry basis, held in a soil sample against centrifugal force of 100 times gravity. It is frequently used as a measure of field capacity.

Wilcox, in 1939, studying some of the factors affecting field capacity, made the interesting observation that the heavier the soil the longer the time it takes for gravitational water to drain away and therefore a constant or definite time of sampling for field capacity could result in considerable errors (25, p. 143). He also stated that the rapid use of water by plants added further complications to the problem by affecting the rate of drainage (25, p. 147). Wilcox again referred to this in 1949, when he considered the source of variability in field capacity determinations as variations in the time required for excess water to drain into the subsoil, variations in the rate of plant absorption of water during the drainage period and variations in the subsoil. (26, p. 573).

Other workers who have applied the technique of thoroughly irrigating a small plot, then covering the plot with canvas, tar paper or some other material and sampling at intervals to determine field capacity are Colman (1947) (5, p. 278), Hanks et al. (1954) (9, p. 253) and Biggar (1955) (1, p. 7). The work of Biggar will be referred to again. Hanks et al. approximated field capacity directly from time versus moisture content curves, using the moisture content at which drainage was negligible. This was done for a wide range of soil types (9, p. 254). Because of the nature of time-drainage curves, which are ordinarily smooth curves with no flex points of any kind, it is difficult to see how consistent approximations for field capacity could be made by this technique.

Robins et al. attacked the problem of downward movement of moisture as it affects consumptive use with the technique of sampling the soil, following irrigation, under an actively growing alfalfa crop (19, p. 344). By observing the moisture loss up to 8 days they found that the rate of loss from the 0 to 3 foot zone into lower depths was 0.20 inches per day two days after irrigation, 0.11 inches per day four days after irrigation and the total loss by percolation from 2 to 8 days was 0.58 inches (19, p. 346). They showed that this loss could result in an error of as high as 23 per-cent in consumptive use determinations over the first eight days following irrigation (19, p. 347), since consumptive use determin-ations are often begun only 2 to 3 days after an irrigation. Some of the moisture loss usually attributed to consumptive use may actually be percolation losses into lower depths.

Consumptive use data, compiled by Harrold, from the lysimeters at Coshocton, Ohio, show a rather startling change in the pattern of moisture usage by plants with a change in moisture content in the soil. Before an irrigation the rate of moisture use by corn plants from four layers, 0-7, 7-14, 14-21 and 21-28 inches was very uniform at 0.051, 0.054, 0.053, and 0.044 inches per day, respectively. After irrigation the pattern changed to 0.138, 0.122, 0.055 and 0.048 inches per day for each successive depth. The total consump-tive use for the four depths altered from 0.202 inches per day before irrigation to 0.363 inches per day after irrigation (10, pp. 99-100). This information suggests the possibility of a "luxury consumption" of water by plants when moisture is very readily available. Part of the increased consumptive use could be attributed to increased evaporation from the soil surface but it is difficult to see how evaporation could account for all of the increase, especially at the lower depths. This work would also appear to support the view that plants obtain water with increasing difficulty as the moisture content of the soil decreases. Shockley claims that most irrigated crops have about the same moisture extraction pattern (20, p. 110). He claims the extraction pattern is approximately 40 percent from the upper quarter of the root zone, 30 percent from the second, 20 percent from the third, 10 percent from the fourth or bottom quarter of the root zone (20, p. 112). If both Robins' and Shockley's claims are true, the moisture extraction by plants during the first 2 or 3 days after irrigation could undoubtedly have considerable affect on the length of time required for percolation to become negligible (field capacity).

Regarding the view that plants have more difficulty in obtaining water as the soil dries out, Widtsoe and McLaughlin showed that the total loss of moisture increases steadily with time but the rate of loss steadily decreases (24, p. 241). They go on to state "the removal of water from soil by transpiration varies with the ease with which water may be obtained ..." (24, p. 268). This latter statement, of course, simply indicates that as more and more water is removed from the soil either by consumptive use, by percolation, or by both, the plants obtain water with ever increasing difficulty. In later years Veihmeyer and Hendrickson repudiated this claim and stated that the rate of water use by plants was unaffected by the amount of water in the soil and that water was equally available to plants over the entire range from field capacity to the wilting percentage[4] (21, p. 76, 78). A controversy of long standing arose from these claims and even today there are supporters of each claim although the balance now appears to be in favor of the arguments of Widtsoe and McLaughlin.

Biggar's paper is still in press and unavailable but the abstract indicates that he studied the relative importance of transpiration, evaporation and downward movement as each effects moisture loss. He measured the soil moisture distribution with electrical resistance blocks and made predictions as to the amounts of moisture removed by the three means (1, p. 7).

It is fairly obvious from this review of literature that the problem of percolation of soil water as it affects consumptive use, as well as the reverse problem of the affect of consumptive use on percolation, remains unresolved. It appears that these two means of moisture loss, especially in the early stages following the application of water to the soil, are inseparably related to one another. This is particularly true with respect to the field deter-

[4] The wilting percentage is the percentage of moisture in the soil expressed on an oven dry basis, at the time when plants growing on the soil permanently wilt. It is approximately the same for all plants but not for all soils.

minations of the field capacity of soil and with respect to the direct soil determinations of consumptive use itself. It is the sincere hope of the author that the relationship which is developed in the following pages will shed some light on the problem and perhaps render possible the determination of consumptive use without the need for field capacity determinations. An accurate knowledge of the consumptive use is the ultimate goal which would enable soils men and farmers alike to predict the water requirements of growing crops.

SPECIFIC OBJECTIVES

The first objective of this thesis is to point out that the percolation of soil water through the soil profile is related to the consumptive use of water. The influence of consumptive use on percolation has been mentioned a number of times throughout the literature, but as far as can be ascertained no workers have ever qualitatively related one to the other. This leads directly to the second and major objective, which is to quantitatively relate percolation to consumptive use. This is to be done for only one soil type but for two crops, barley and alfalfa. First attempts at relating percolation and consumptive use will be the development of a empirical equation relating one to the other. Following this, attempts will be made to solve the mathematical function in terms of the experimental data at hand. It is felt that interpretations of material presented by other workers up to date have not fully covered the theoretical aspects of soil moisture movements under crop conditions. Some of the assumptions regarding field capacity, for instance, or consumptive use are lacking one basic essential, that of sound theoretical considerations of the assumptions. Several workers from time to time have stated or hinted that plant use of water from soil practically stops percolation in a very short time after irrigation but no basis for this belief is presented other than simple observation. A quantitative basis for some of the assumptions regarding the movement and loss of soil moisture above and below field capacity seems essential to the evaluation of postulates based on observation. This applies equally to the considerations of field capacity itself.

Present estimates of available moisture (field capacity to wilting percentage) are not precise because by taking field capacity, as it is presently defined, as the upper limit no consideration is given to consumptive use up to the time field capacity is reached following an irrigation. The lack of precision is even more apparent if the findings of Robins et al. (see page 10) and Harrold (see page 10) have any merit, that is, that the consumptive use rate is highest during this two or three days after an irrigation. The magnitude of this imprecision can be considerable, even with present estimates of consumptive use, which may be too low. For example, alfalfa can utilize up to one inch of water in three days.

The third objective of the thesis follows directly after the above arguments. Attempts will be made to show that having related percolation to consumptive use, more precise estimates of consumptive use and available moisture can be made. In addition it will be shown that the upper limit of available moisture is not field capacity as defined but is actually above it by the amount of consumptive use of the crop during the period between application of water and attainment of field capacity.

EXPERIMENTAL PROCEDURES

Field Work

The field work to obtain data was conducted during the summers of 1954 and 1955. The techniques of soil sampling to obtain time-drainage curves for different conditions will be described in this section. The data with which to compare rates of moisture loss were obtained under the following treatments: 1. actively growing crop, 2. clear of vegetation and 3. clear of vegetation and covered to prevent evaporation. The covering for the third plot was sisal-craft paper[5] which contains a tar-like moisture barrier.

Tensiometers were installed in each of the three plots to record the soil moisture tension changes with time. Soil moisture tension is defined by Richards (16, p. 95) as the pressure difference across a porous wall or membrane which is contact with soil of which the moisture content has reached an equilibrium value against a constant applied pressure[6].

In 1954 barley was the test crop and in 1955 the test crop was alfalfa which had been seeded in 1954. There was no special reason

5 Sisal-craft paper is a heavy commercially available building paper which is triple thickness with the center sheet coated with a rubber or tar-like material.

6 Soil moisture tension may be more easily visualized if it is thought of as the suction force necessary to pull water out of the soil.

for using these two crops except that in 1954 barley had been planted and was already growing where the plots were to be located and it was thought that for the 1955 tests alfalfa would provide good root distribution in the soil and would be a very actively transpiring crop.

Generally, the procedure was to prepare the plots by removing the crop where required, staking the plots leaving a one foot border around each, installing irrigation ditches and dikes where necessary and installing the tensiometers. A narrow aisle was left between plots to facilitate moving about from plot to plot. When the preparations were complete, the plots within one replication at a time were thoroughly irrigated, the paper cover was put in place and from then until the end of the experiment soil samples were taken as will be described, tensiometer readings recorded and weather records were kept.

Experimental Plot Area

The soil at the experimental site has not been classified as to soil series. It has a quite uniform sandy loam texture down to two feet but becomes a little heavier textured in the third foot. There is a relatively hard, thin layer at about 42 inches depth, but this is inconsistent or missing in places and is quite pervious to water. The sandy texture shades into a very coarse sand or fine gravel below five feet. Good drainage prevailed because of a large deep drain, situated approximately 40 feet from the experimental site, which pulled the water table down to about 14 feet at the drain. Although not determined, it is estimated that the water table would be 10-12 feet below the surface at the plot location.

Experimental Design

The plot arrangement was somewhat similar to that used by Edlefsen and Bodman (6, p. 715) in the study discussed previously (see page 8). Three plots 10 feet by 12 feet were laid out in each of three replications or blocks. Each replicate was within an area of approximately 40 feet by 60 feet. In each replicate the crop was removed with a hand hoe or rotary hoe from two of the three small plots.

To determine the sites for sampling at a specified time each plot was laid out in a grid of 2 by 2 foot squares, making 30 squares per plot. A movable grid of strings attached to small boards was constructed and moved from plot to plot as needed. Each 2 by 2 foot square of each plot was given a number between one and ten inclusive, selected from a random table. Three squares in each plot therefore had the same number and were sampled at a given scheduled time. The sampling schedule is shown in table I.

Table I

Schedule of soil sampling for moisture following irrigation.

Grid Number	Number of hours from time = 0 1954	1955
1		
2	2	2
3	4	6
4	8	24
5	24	30
6	36	48
7	48	72
8	72	144
9	144	220
10	216	410

Grid number 1 was the position selected for the tensiometers and was not sampled. Three squares were sampled each time within each plot for each of the three plots within a replication; since samples were withdrawn from 4 depths (0-12, 12-24, 24-36, and 36-42 inches), this meant a total of 36 individual samples to be handled at each sampling time. Only three depths were sampled in 1955 (0-12, 12-24, 24-36 inches), making a total of 27 samples each time. These samples had to be taken and weighed as quickly as possible, before any appreciable loss of moisture from the samples. The usual time required for the complete sampling and weighing operation was 30 to 45 minutes. It was felt that the three grid samples (not composited but weighed separately) would represent a reasonable average of the moisture content within each plot.

Tensiometers were installed at 3 random locations and at two depths, 9 inches and 18 inches, in each plot. In 1955 tensiometers were available for installation in only two replicates. In 1954 there were sufficient tensiometers for all replicates but because so many of them failed to function properly the data for that year are considered unreliable and will not be presented. The records for 1955 are more complete and will be included in this paper.

Immediately after the tensiometers were installed ~~and~~ the whole plot area was irrigated to aid in "settling" the soil around the tensiometer cups as well as to keep the soil at a fairly high moisture level before the start of the tests.

Irrigation

At the start of the test water was turned onto the plots in early morning, ponded to 4-5 inches deep in about ten minutes, then kept running for about an hour with adjustments in the flow to maintain the 4-5 inches of water. The stream of water was then closed off and the remaining water allowed to seep into the soil. The excess water disappeared in about two hours; the time of disappearance was noted and taken as time zero. No exact measurement of the amount of water applied was taken but it is estimated, from the time it took the excess to soak away and the total time the water was on the plots, that at least 6-8 inches was applied. This should be more than ample to wet the soil to four feet, particularly since the soil was already at a high moisture level.

As soon as the water had disappeared the plot selected to be the covered treatment was covered with the sisal-craft paper which was sealed down around the edges with wet soil packed firmly with a shovel. The paper extended one foot beyond the edges of the plot, to reduce border effects. Slits in the paper for the tensiometers had previously been cut so that the paper could be slipped in place quickly and with a minimum of disturbance of the soil surface. These slits were covered with an extra piece of the paper and sealed down with soil.

Because of the large number of samples involved at each sampling time, only one replicate was started at a time. The starting time for the replications therefore differed by as much as two weeks. The starting dates for each replicate each year are shown in table II. The barley (1954) was of necessity at slightly different

Table II

Starting dates for the different replications in 1954 and 1955.

	Year	
Replicate	1954	1955
1	August 9	July 19
2	August 11	July 26
3	August 17	August 2

stages of growth at the dates when the study began on the three replicates; but since the crop was well grown by the start of the tests the effect was probably slight. The alfalfa (1955) was present in a fairly good stand but was again of necessity at slightly different stages of growth when measurements were made on the different replicates. At the start of replicate 1 the alfalfa was

6-8 inches high, at the start of replicate 2, 12-14 inches and at the start of replicate 3, 18-20 inches high. It was impossible to predict what the effect these differences might have on the outcome.

Replicate 2 (1954) was lost after 72 hours sampling because of an inadvertent flooding from a broken ditch which was being used at the time for irrigation of other experimental plots.

Soil Sampling

The soil samples were withdrawn with a small screw type auger and transferred immediately to ordinary 2 pound paper bags which were of double thickness. For each depth a core of soil, one foot long and about 2 inches in diameter, was placed in the bag. The tops of the bags were quickly folded over, to prevent escape of moisture, and set aside for weighing. As soon as the samples were weighed the bags were opened at the top and placed in the greenhouse to air dry. The samples were later oven dried and the moisture percentage calculated.

As a precaution against the loss of moisture by vapor movement from deep within the soil profile the sample holes were refilled with soil from around the plots except in the case of the paper covered plot where the sample hole was left unfilled and the small hole in the paper through which the soil sample was taken simply covered over with an extra piece of paper and sealed down with soil. It would be well to note here that the paper was never moved once it was in place, but a small hole (about 2 inches square, cut on three sides, leaving a small flap which was replaced) was cut in the paper immediately before the soil sample was taken. In this regard, when the paper was finally lifted, over a month later, the soil surface was still quite moist indicating that probably not very much moisture was lost in the form of vapor.

There may be some criticism of the use of paper bags for moisture sampling but for the following reasons the author feels this was justified. First of all, the bags made it possible to use the whole one-foot core of soil, providing a bulk sample of from 400 to 500 grams as compared with a smaller subsample of 50 to 100 grams necessary for sampling cans which are commonly used for moisture sampling. It was felt that there would be less moisture loss from the paper bags during the weighing than there would be from the process of subsampling for the cans. A series of tests to determine how much moisture was lost during the weighing period showed that in 1 hour less than 1 gram of moisture was lost; this resulted in an error of under 1 percent. In addition, any such loss would be relatively constant for all samples although presumably the loss would decrease slightly as the test progressed and the soil became drier in the field. Secondly, the very large number of samples (700-800 each year) which had to be stored until taken to Oregon State College for oven drying, virtually precluded the possibility of using moisture sampling cans. Thirdly, by eliminating the need for subsampling the operation was much speedier than it could have been with subsampling.

Weather Records

Weather records in 1954 were observational only, as temperature and humidity data were not collected. However, in 1955 the recording hygrothermograph set about 100 yards away in an adjoining experimental field provided data of weather conditions throughout the experiment. The maximum and minimum temperatures and relative humidities are tabulated in the appendix.

Laboratory Work

Very little laboratory work was involved, aside from the oven drying and weighing of the samples. The samples were dried at 110° Centigrade to obtain oven dry weights for calculation of moisture percentages.

A moisture tension curve was determined by means of the pressure membrane apparatus as described by Richards (14, pp. 451-454) and the porous plate apparatus, also described by Richards (15, pp. 105-110). The former is used for high tensions and the latter for lower tensions, below one atmosphere.

RESULTS AND DISCUSSION

Weather and Crop Conditions During the Tests

In 1954 the weather for the most part warm to hot and dry with slight to moderate winds occurring occasionally. The only rain during the period of the experiment fell on August 25 and 26 with slight intermittent rain both days. At that time, however, the tests were almost completed, with only one sampling time remaining for replicate 3. The weather generally was conductive to high rates of transpiration and evaporation.

In 1955 the weather appeared generally a little hotter than in 1954 with the temperature maximums in the high 80 degrees or low 90 degrees throughout almost all the test period. Rain fell only once, on August 7, when a fairly heavy thunderstorm of short duration occurred. It was hot and dry immediately before and after the storm so it probably had little influence on the tests; at least, no appreciable affect was noted when the moisture contents of the soil was calculated later.

Moisture-Time Curves

The moisture contents of the covered, bare and cropped treatments are plotted against time in figures 1 to 8; the data from which the graphs were drawn are tabulated in the appendix. Each of figures 1 through 6 contains curves based on the average of three replicates for a particular depth and year. The three treatments are included in each figure. Figures 7 and 8 contain the average for all three depths for each treatment and each year.

Interpretation of the Moisture-Time Curves

There are several features of the moisture-time curves which bear some discussion. These observations are, for the most part, what was expected from the nature of the factors which affect moisture losses from the soil at various depths and with different crops.

It is quite obvious from the figures that the soil under crop, either barley or alfalfa, loses moisture more rapidly than the same soil under no crop, whether evaporation is prevented or not. However, it was observed that in the field, during the early stages of the experiment, the bare plot dried out on the surface more rapidly than did the plot in crop. The crop provided a shade cover which slowed up direct evaporation from the soil. The soil which was covered with paper usually lost moisture the least rapidly of all three plots although there was one case in 1954, that of the third foot, where the covered plot apparently lost moisture more rapidly than did the bare uncovered plot. Soil sampling variations may have accounted for this. This reversal of the two curves (figure 3) resulted in the curves for the two plots being virtually superimposed on one another when the average for the replicates and three depths were plotted together (figure 7).

Analysis of variance was carried out on the data from individual soil moisture samples for each of several distinct sampling times.

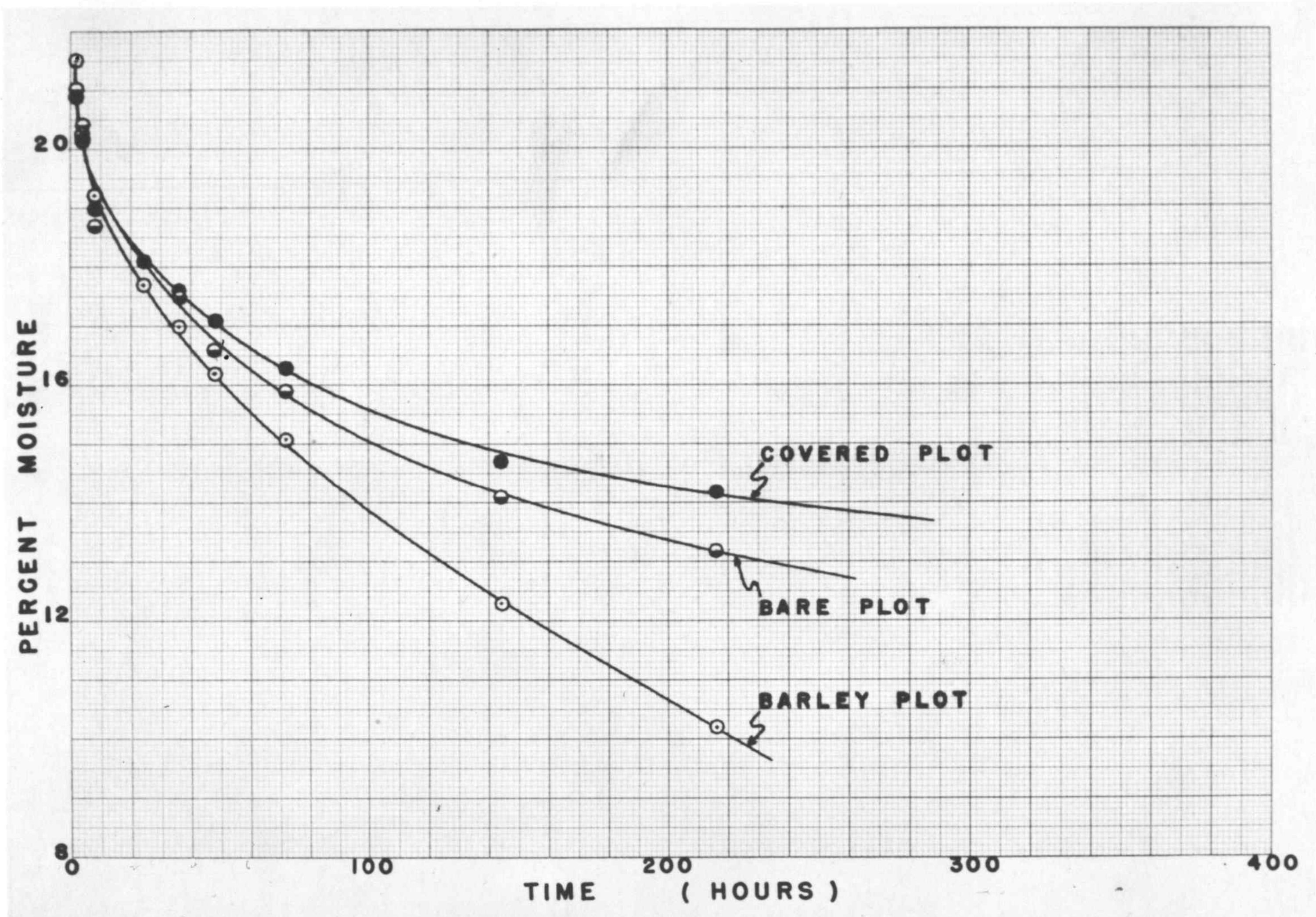

Figure 1. Moisture-time curves representing rates of soil moisture loss for three conditions from the 0 to 12-inch depth in 1954.

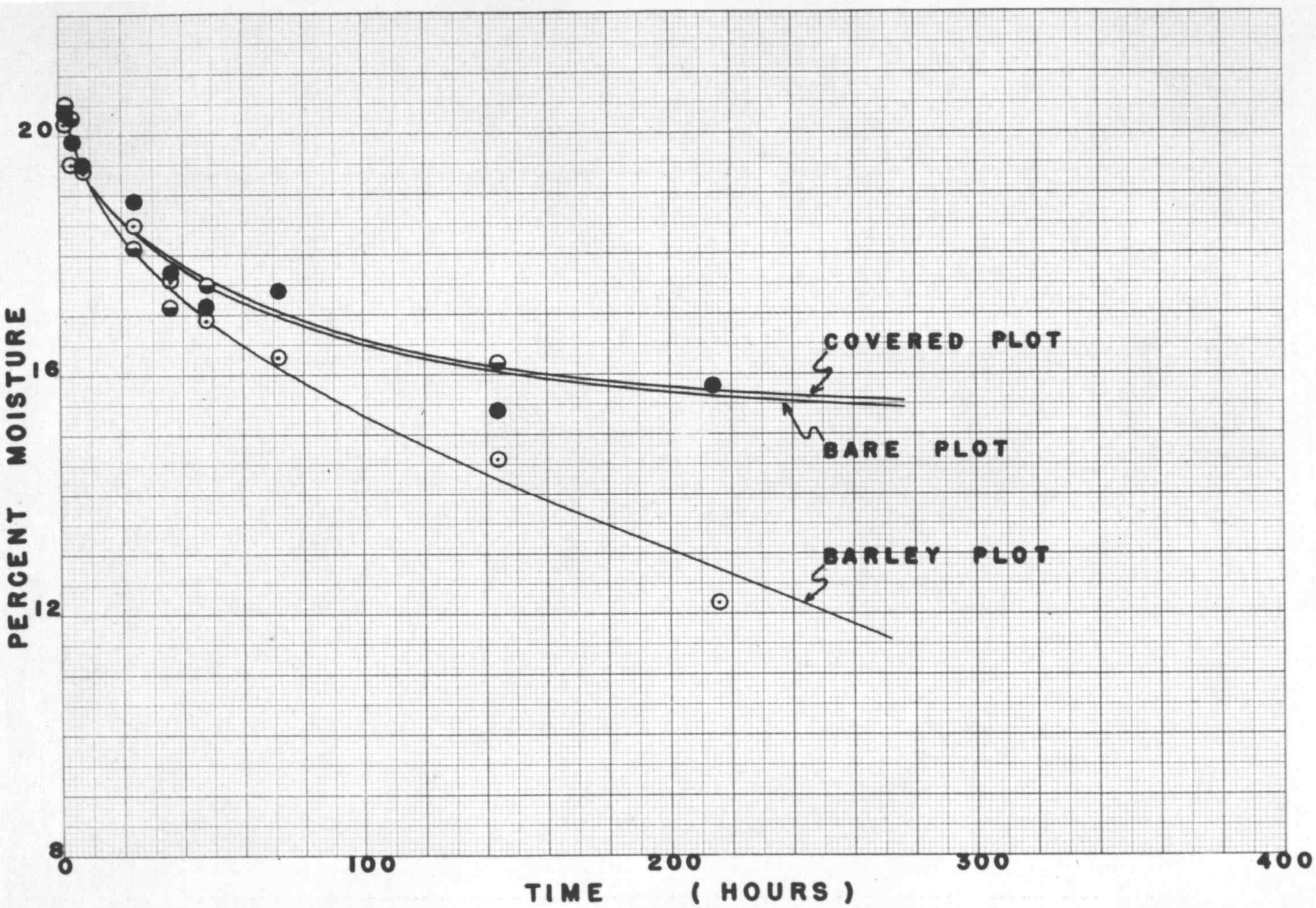

Figure 2. Moisture-time curves representing rates of soil moisture loss for three conditions from the 12 to 24-inch depth in 1954.

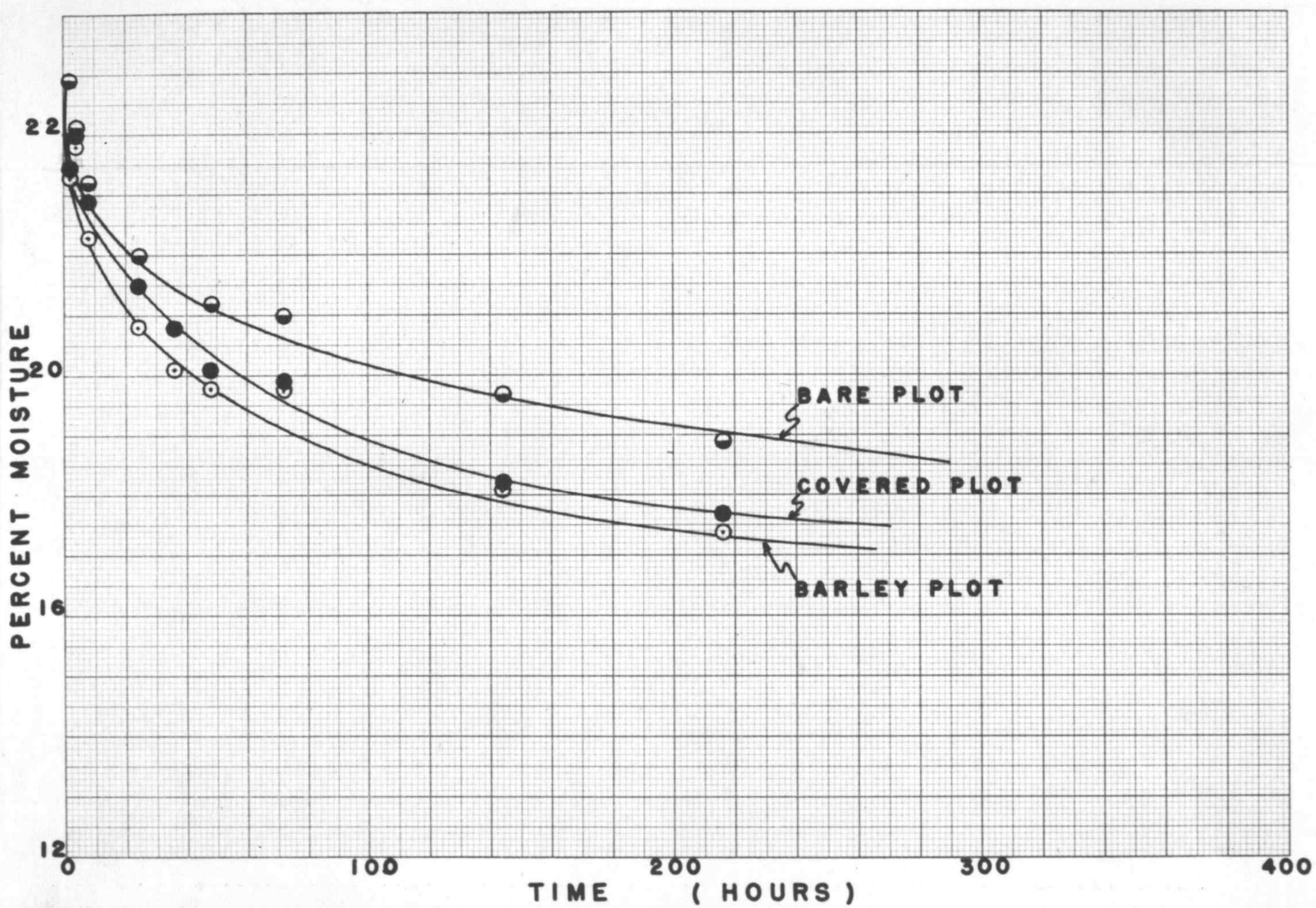

Figure 3. Moisture-time curves representing rates of soil moisture loss for three conditions from the 24 to 36-inch depth in 1954.

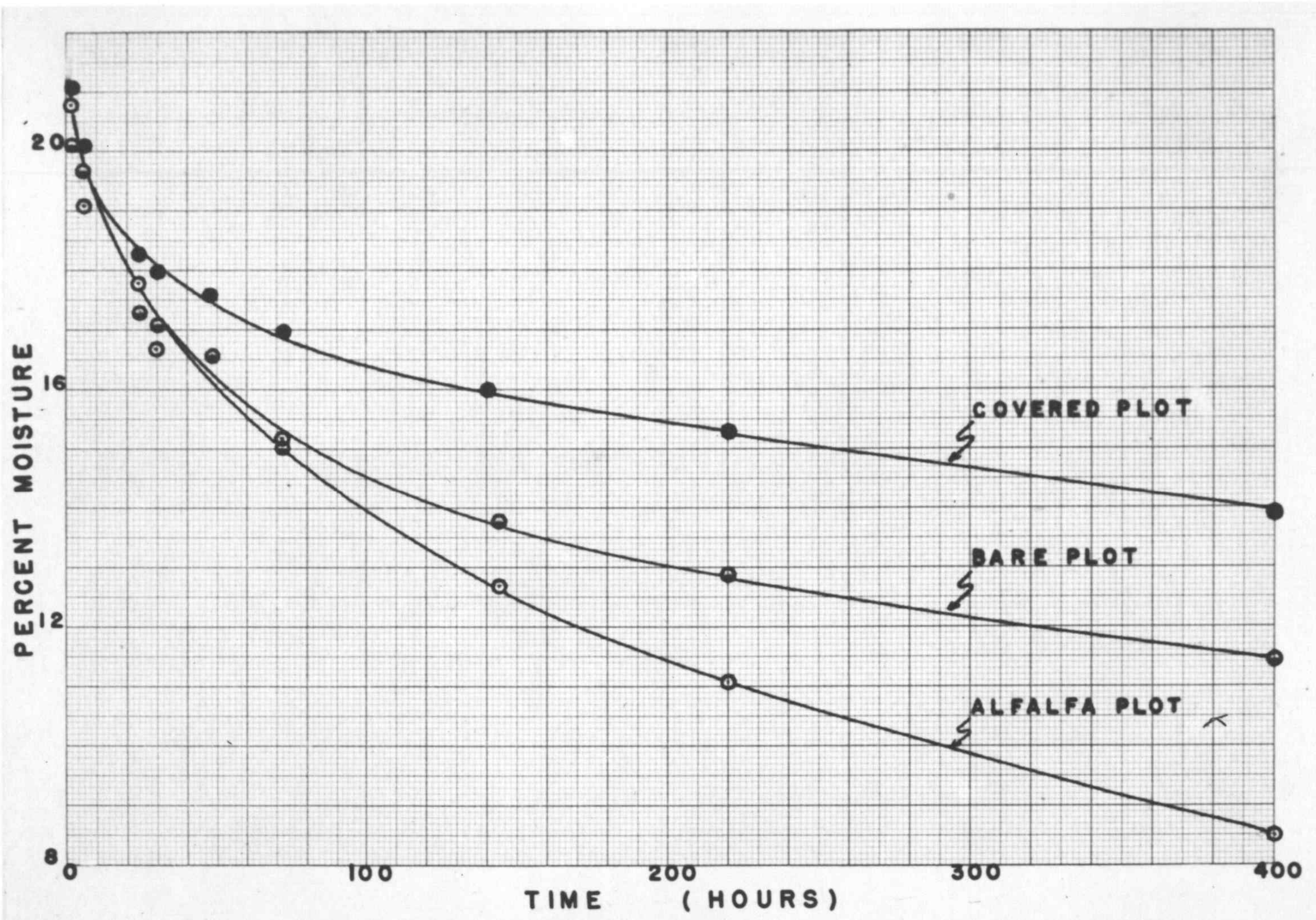

Figure 4. Moisture-time curves representing rates of soil moisture loss for three conditions from the 0 to 12-inch depth in 1955.

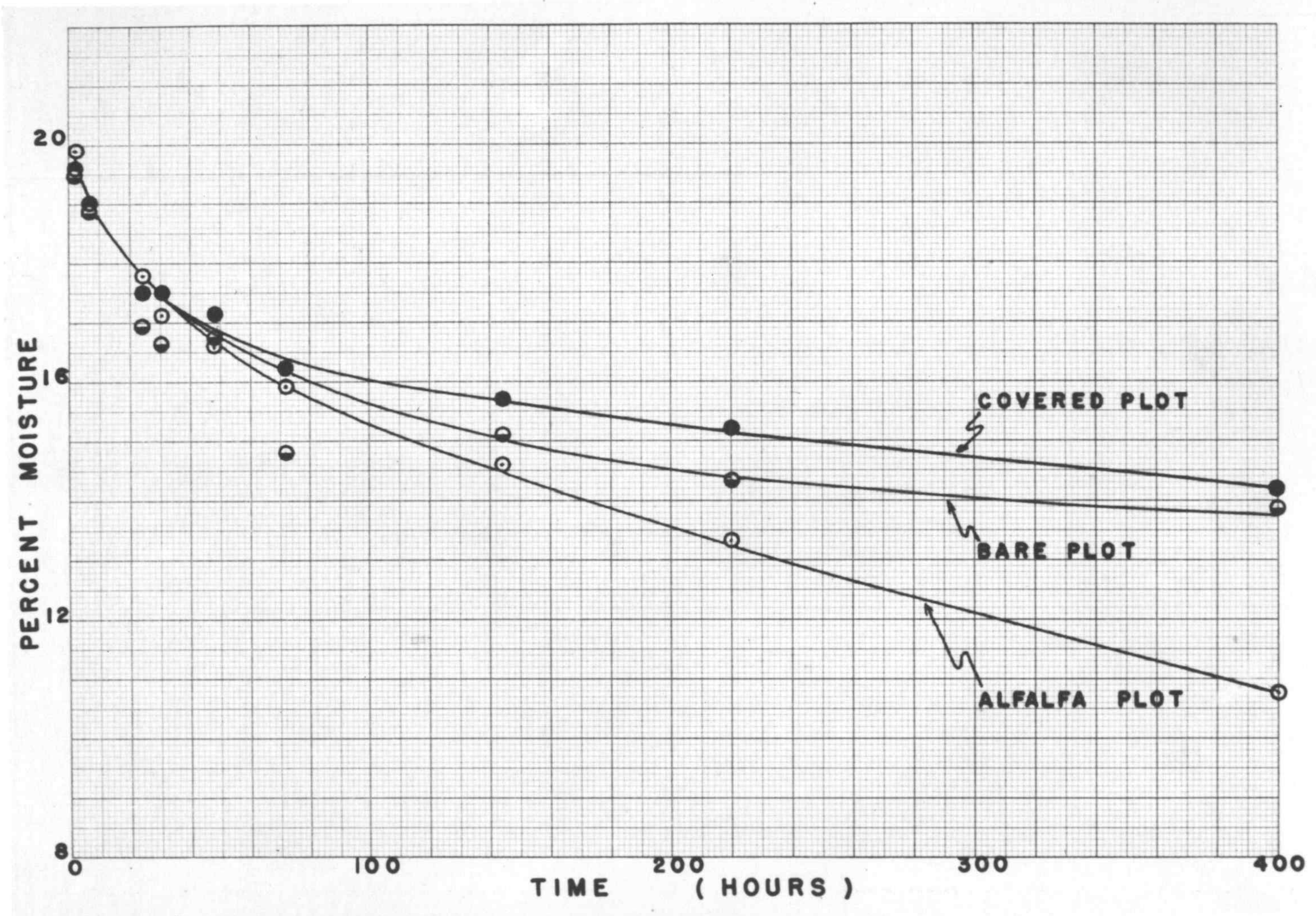

Figure 5. Moisture-time curves representing rates of soil moisture loss for three conditions from the 12 to 24-inch depth in 1955.

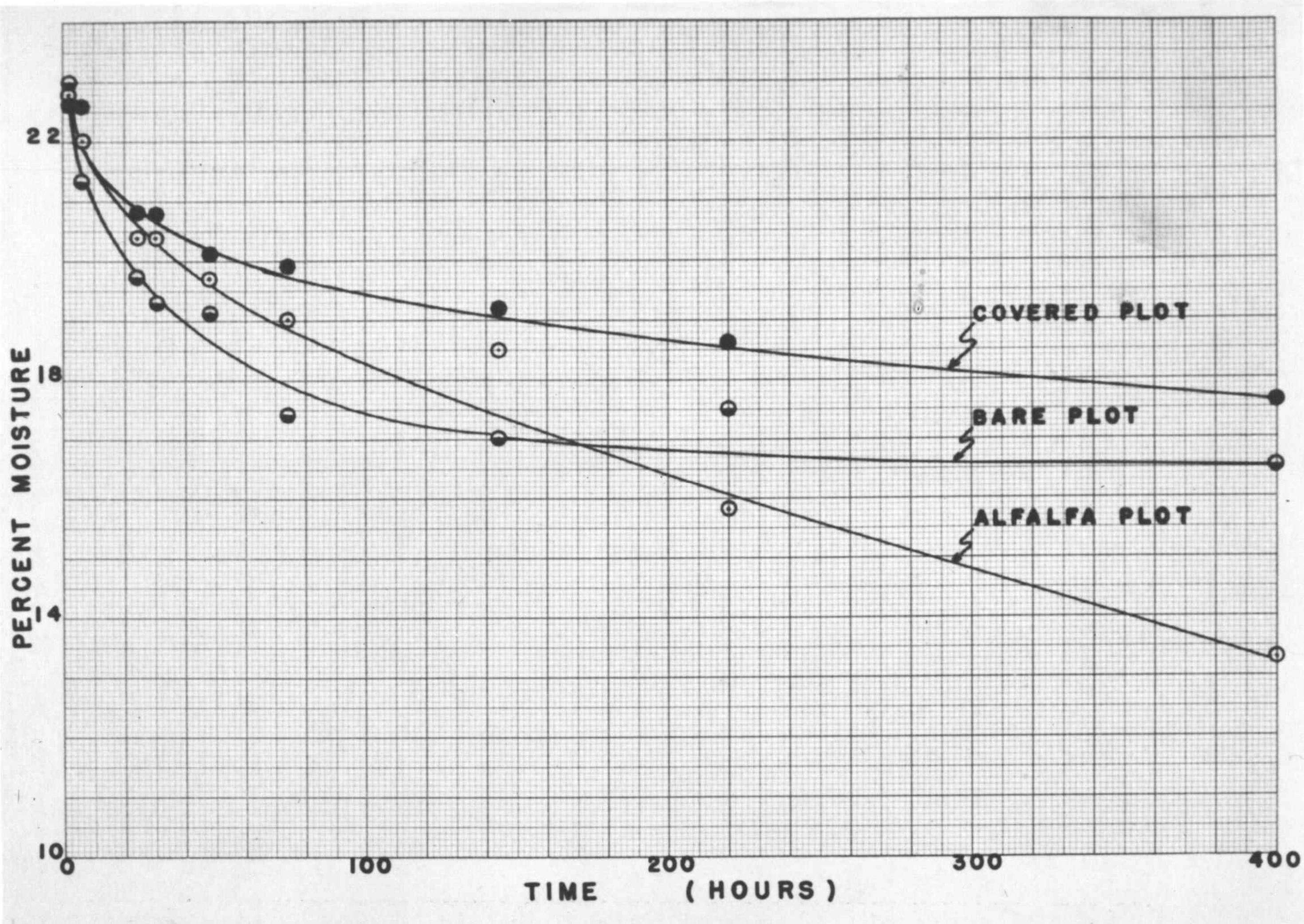

Figure 6. Moisture-time curves representing rates of soil moisture loss for three conditions from the 24 to 36-inch depth in 1955.

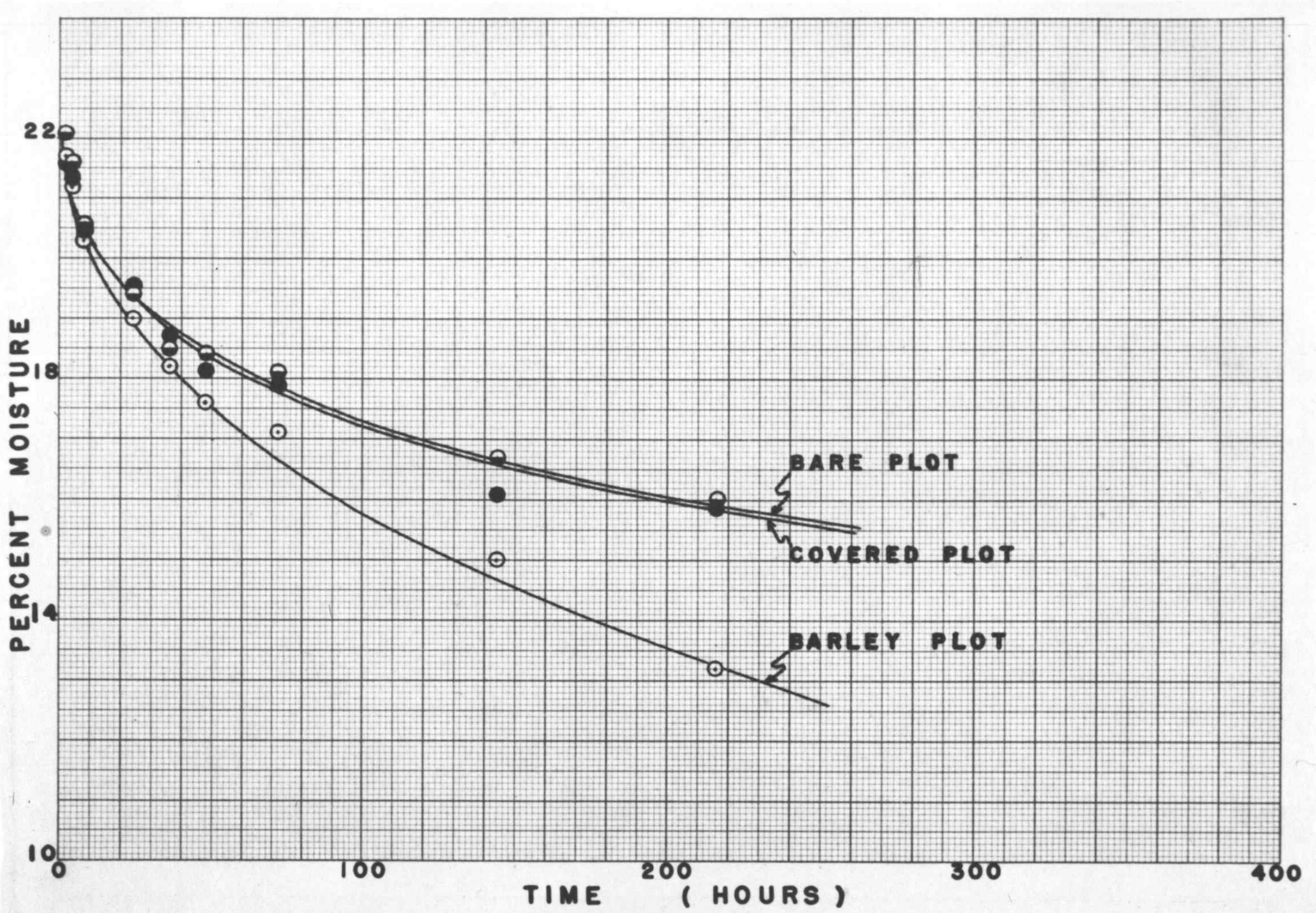

Figure 7. Moisture-time curves representing rates of soil moisture loss for three conditions from the 0 to 36-inch depth in 1954.

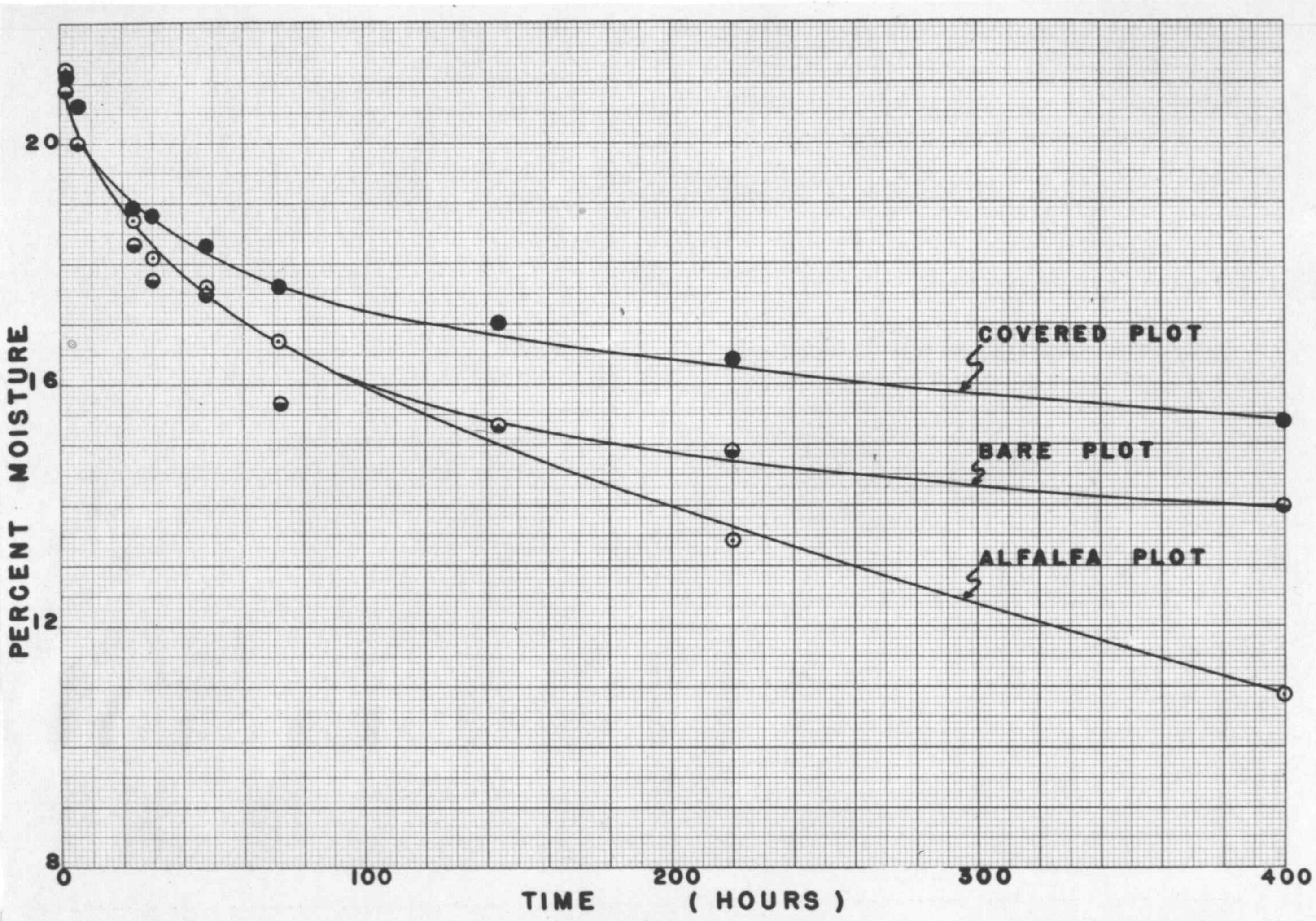

Figure 8. Moisture-time curves representing rates of soil moisture loss for three conditions from the 0 to 36-inch depth in 1955.

This was done to learn whether real differences existed between the curves and, secondly, to see at approximately what time the differences did become significant. This latter would be the time at which the divergence of the curves became statistically significant.

Comparing only the curves for the alfalfa plot and the covered plot for 1955, there were significant differences between the curves, appearing first in the 0-12 inch depth at 30 hours and later in the 12-24 and 24-36 inch depths at 144 hours. Statistically then, the two curves had diverged significantly at about these two times for the respective depths. Comparisons of the curve for the alfalfa plot with those of the bare and covered plots together showed that, generally, the latter two were significantly different from the former except where the curve for the bare plot was below that of the other two plots as occurred in 1955. It should be mentioned here that in 1955, in the third foot at 6, 30 and 72 hours the points representing the moisture contents within the bare plot were significantly below the points representing the moisture contents within the other two plots. However, the difference was not significant at 24 hours. In the second foot the point representing the moisture in the bare plot at 72 hours was the only one below the corresponding points for the other two plots. In the top foot no such differences appeared at any time. In 1954 the curve for the bare plot showed opposite behavior in the third foot, that is, from 72 hours on it was above the curves for the covered and the barley plots. These analyses confirm the apparent erratic behavior of the curves representing the bare plot. For the top foot the curves for the bare plot behaved as expected in both years since they fell between the curves for the covered and cropped plots.

The overall coefficient of variation for the individual samples was considered good. For all plots and all depths the coefficient ranged from 2.8 to 8.5 percent, depending upon the individual time of sampling. Generally, the coefficient was higher as the sampling time increased, that is, as the soil became drier.

Initially, it was expected that from these curves an estimate of relative losses of moisture by evaporation, transpiration and percolation could be made. Even a cursory examination of the curves shows that no estimate of field capacity is possible, at least with any considerable degree of accuracy. Even the curve for the covered plot shows a slow but persistent loss of moisture from downward movement throughout the time included in the experiments. If the moisture movement within the soil held precisely to the concept of field capacity equilibrium, that is, that percolation ceases or becomes negligible at field capacity, there ought to be some measureable point or narrow range on the time-drainage curve which corresponds to field capacity. The curves presented here do not show any point or range which could be considered to represent an equilibrium value. It would indeed be hazardous to attempt to arbitrarily pick even a range of moisture content or a range of time which might correspond to field capacity.

It is interesting to note the changes in the rate of moisture loss from each downward successive foot. There is very little difference between the covered and bare plots, at least for the first 200 to 300 hours, although less moisture was lost from the second and third foot than from the first foot in both plots (table 3). In 1954 the soil of the barley plots lost more moisture from the top foot than from the second, and more from the second than from the third, this third foot showing about the same loss as from the bare and covered plot. This appears to reflect the shallow rooting characteristics of the barley plants, which results in the crop withdrawing most of its moisture from the top two feet. This might not occur if moisture was somewhat less available in the upper two feet of soil. In 1955 the alfalfa plot lost more water from the top foot than from the second and third, with the latter two depths showing about the same loss over a given time interval. This may reflect the deep rooting habit of the alfalfa plant, which results in moisture withdrawal from all three feet and probably from still deeper depths. Table III will help to clarify this discussion.

Table III shows quite clearly, in addition to the observations already discussed, the marked decrease in the relative rate of moisture loss over the different time intervals. It is also of interest to note from the table that the total percent moisture loss from the two cropped plots (1954 and 1955), from each of the top two feet, was approximately the same but not the same in the case of the third foot. This is especially interesting when it is considered that the total loss for the barley plot was as much in 200 hours as the total for the alfalfa plot in 300 hours. However, taking the average loss over the entire three feet of the soil, the loss from the alfalfa plot was slightly greater than that from the barley plot. This simply means that the loss from the alfalfa from three feet of soil was about the same as the loss from the barley from the two feet of soil over the same time interval.

Table III. Loss in percent moisture over a number of time intervals starting at 2 hours after irrigation.

Depth	Time interval in hours	1954 Covered	1954 Bare	1954 Barley	1955 Covered	1955 Bare	1955 Alfalfa
	2-100	4.7	5.1	7.6	4.6	5.4	6.8
0-12	100-200	1.9	2.2	3.2	1.0	1.6	2.5
inches	200-300	-	-	- *	0.9	0.9	1.6
	Total	6.6	7.3	10.8	6.5	7.9	10.9
	2-100	3.8	3.9	5.7	3.6	3.8	4.7
12-24	100-200	0.8	0.8	1.4	0.7	1.1	1.2
inches	200-300	-	-	-	0.6	0.6	1.2
	Total	4.6	4.7	7.1	4.9	5.5	7.9
	2-100	4.4	4.7	4.8	3.0	- #	4.5
24-36	100-200	1.1	1.0	1.0	0.8	-	1.6
inches	200-300	-	-	-	0.7	-	1.6
	Total	5.5	5.7	5.8	4.5	-	7.7

* Data not reliable after 200 hours.

\# Variance among individual measurements so great that the means are unreliable.

The fact that the curve representing the moisture in the bare plot fell significantly below the other two curves warrants some discussion. It is very difficult to see why the curve behaved as it did in 1955 and especially why the effect should be greater in the third foot than in the second, and greater in the second than in the first, where it was not noticeable. Further complicating the picture is the fact that in 1954 the position of the same curve for the third foot shifted in the opposite direction, that is, above the other two curves. There is the possibility that water vapor movements as affected by temperature and humidity gradients may have had some influence. Particularly in 1955, the temperature and humidity readings were quite extreme. Daytime temperatures were in the high 80 degrees or low 90 degrees while night temperatures ranged from about 40 to 50 degrees. Relative humidities ranged from about 20 to 30 percent in the daytime to 100 percent at night. These ranges of temperature and relative humidity, along with the fact that the bare plot was subjected to the full radiation of the sun, could set up vapor pressure gradients acting upward in the soil which would bring about water vapor movements upward at night to the soil surface where the vapor condensed and was available for evaporation during the day. However, this still would not explain why the effect should be greater in the third foot than in the second or the first foot. It is incredible that the behavior of the curve for the bare plot could be due to chance error since each point on the curve represents 3 samples from each of 3 replicates, a total of 9 samples. Further study is necessary before a satisfactory answer can be found.

Soil Moisture Tension

The soil moisture-tension curves which were determined in laboratory are shown for all three soil depths in figure 9. The percent moisture is plotted against the logarithm of the tension in atmospheres. These curves are presented only to aid in characterizing the soil with respect to moisture retentive properties at various tensions. The wilting percentage, which is usually taken at 15 atmospheres, varies from 6 to 8 percent depending upon the depth, and the field capacity, frequently taken at one third atmosphere, varies from about 12.5 percent to about 14.0 percent depending upon depth. If field capacity is taken at one tenth atmosphere, as is sometimes done, it varies from about 17.5 to 23.0 percent.

The changing tensions under the various treatments during the experiment are shown by plotting tension as recorded by the tensiometers against time in figures 10 and 11. No discussion of these curves will be presented here as the behavior of tension under the various treatments is quite evident. However, the curves will be referred to from time to time in the remaining section of this thesis.

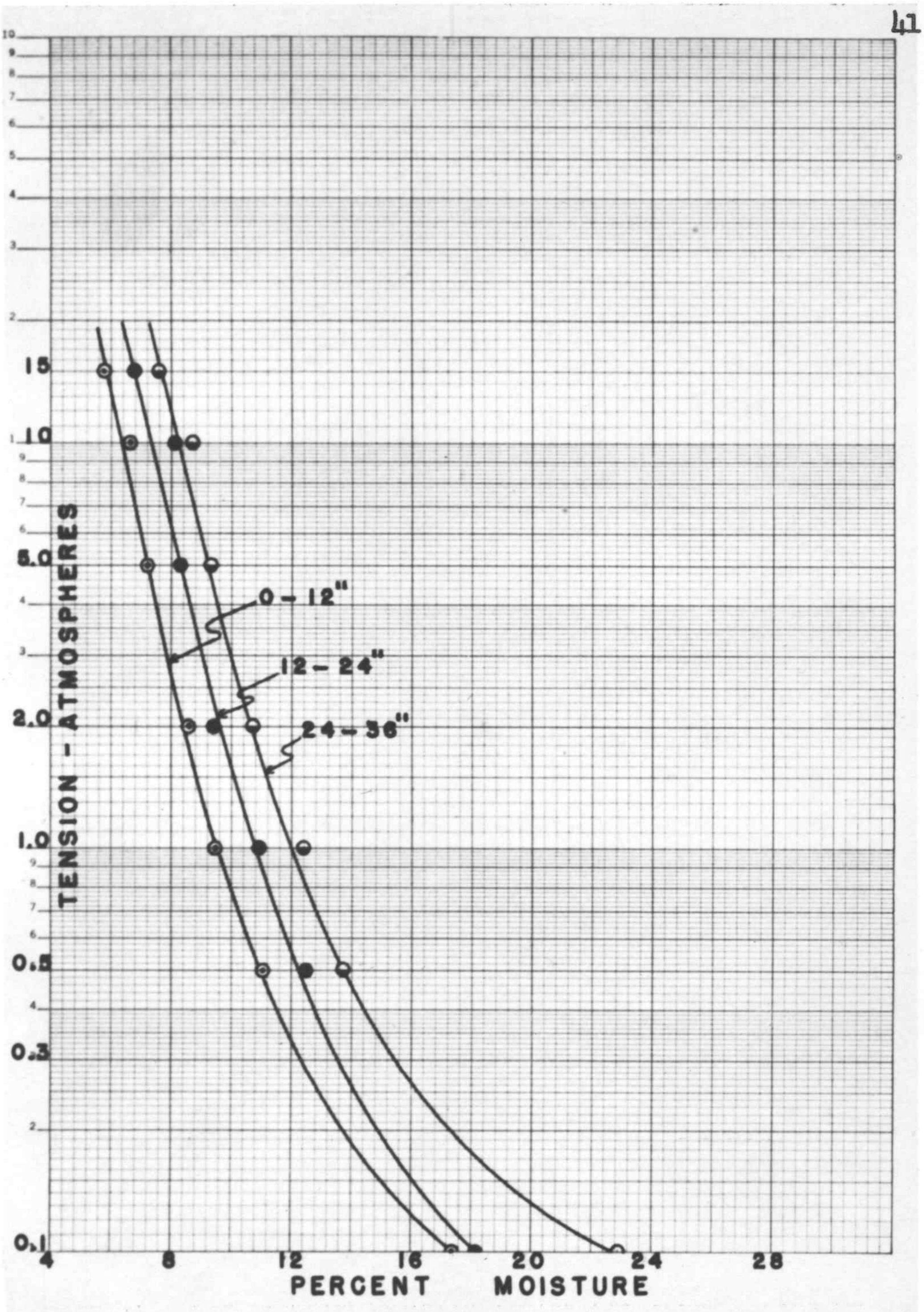

Figure 9. Soil moisture-tension curves for three depths at the experimental site.

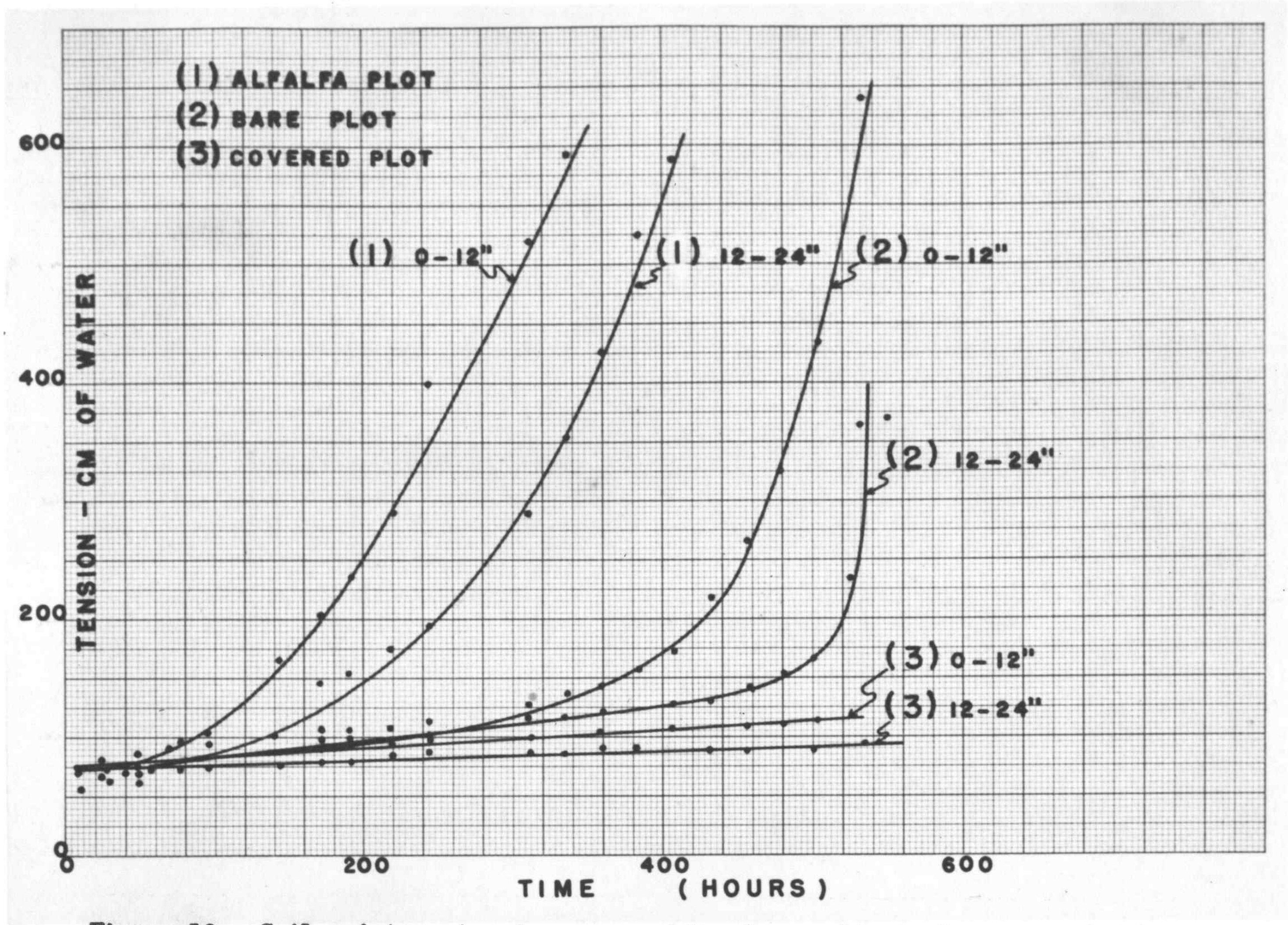

Figure 10. Soil moisture tension versus time for replicate 1 as recorded by tensiometers (1955).

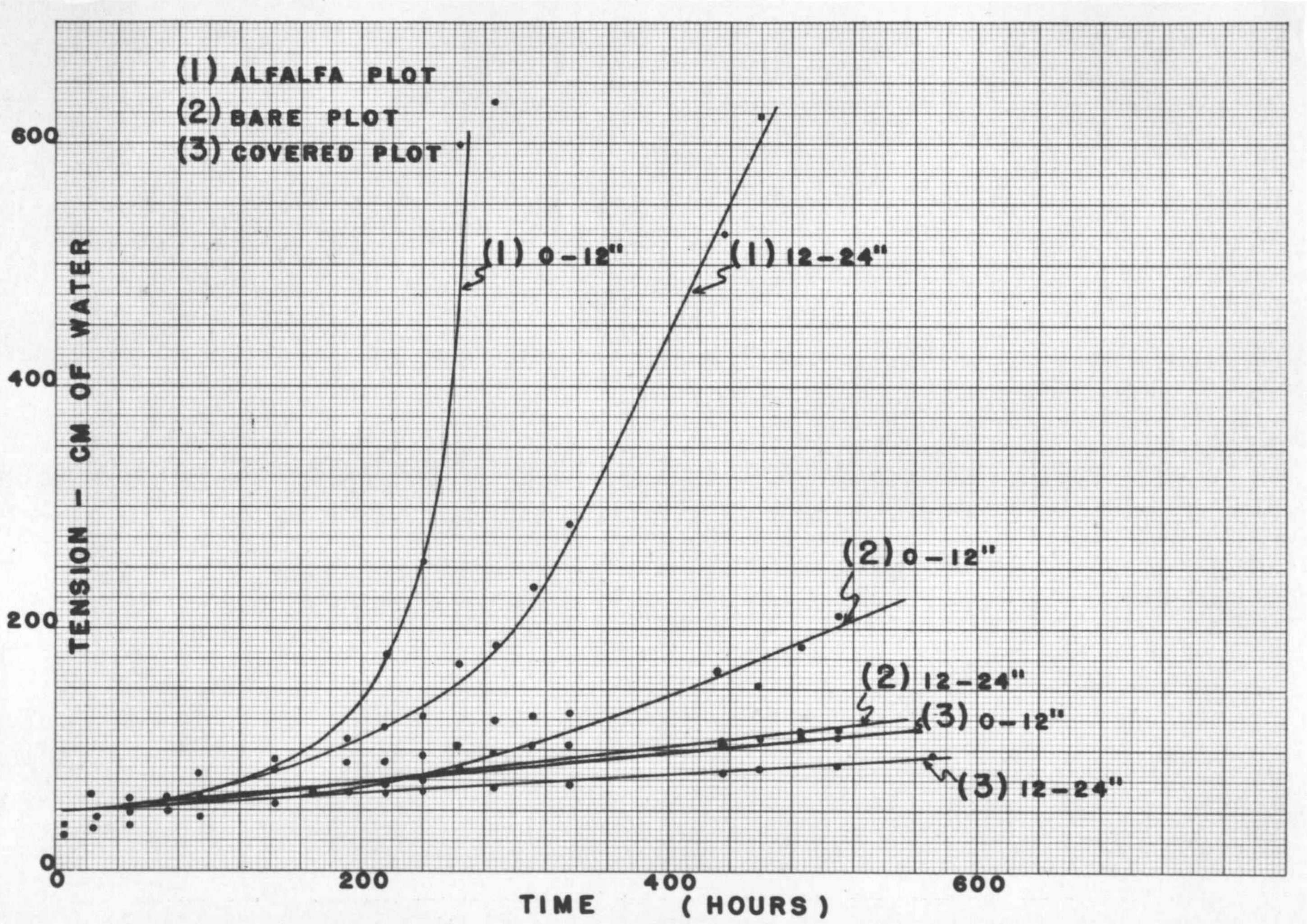

Figure 11. Soil moisture tension versus time for replicate 2 as recorded by tensiometers (1955).

Limitations of the Moisture-Time Curves

While the moisture-time curves yield very valuable information, such as relative amounts of moisture lost from the soil under the three conditions, the rate of these losses and the total losses within a given time interval, the interpretations discussed so far have some serious limitations. For example, in the case of the covered plot it may be safely said that the moisture loss results from the percolation of soil water into the subsoil, but in the case of the bare plot the amount lost from percolation and the amount lost from evaporation cannot be separated. In the case of the plot with a growing crop the amount lost by percolation, by evaporation and by plant use again cannot be separated into the component parts. It cannot even be assumed that the percolation from the covered plot equals that from the cropped plot, leaving the remainder of the loss (evaporation and plant transpiration) to be lumped together as representing consumptive use. If it is assumed that percolation is some function of the moisture content, the percolation from the plot in crop must be less than that from the covered plot and the rate of percolation must slow up sooner in the former than in the latter. This is because the plants and direct evaporation play an active part in reducing the moisture content while percolation is going on. The difference then between the curves for the covered plot and the cropped plot does not represent consumptive use, as might be suspected at first glance, but represents only the difference between the total moisture loss under the two conditions at any given time.

However, the curve for the covered plot does characterize the soil with respect to percolation and can be used to determine the percolation loss which takes place under a crop. How the curve can be so used will be shown in the following section.

DEVELOPMENT OF THE RELATIONSHIP BETWEEN PERCOLATION AND CONSUMPTIVE USE

This section is devoted to the development of theory involved in the proposed relationship between percolation and consumptive use. It has been stated that percolation, when plants are growing on the soil, will be different from percolation when no plants are growing and the plot covered over. The problem then, is to derive a function which will represent the percolation of water from soil under crop conditions. There are two possibilities, both of which will be considered. First, a purely mathematical relationship will be presented, the solution of which was found to be extremely cumbersome if not impossible. Secondly, a graphical solution will be presented which the author believes to be a valid and reasonably good approximation of soil water percolation under crop. From this approximation it will be shown that consumptive use moisture losses can be separated from percolation losses once the characteristics of the soil with respect to downward movement of water are known and represented by a curve, such as was determined for the covered plot.

Both the mathematical and the graphical solutions presented here are based on the assumption that percolation of soil water is a function of moisture content only. The assumption is subject to the criticism that as soil moisture is depleted tensions or negative pressures are set up in the soil water. Tension may be thought of as the force necessary to "pull" the water out of the soil. Tension gradients may be set up which ordinarily act upward toward the soil surface as drying proceeds. There are times when tension gradients act downward but only when dry soil is wetted only at the surface. There would be, then, a tendency for water to be pulled upward toward the soil surface since the surface soil dries out first. However, the percolation of soil water takes place at very low tensions within the wet range of soil moisture. Examination of the tension-time curves for 1955 (figures 10 and 11, pages 42 and 43) shows that over 500 hours elapsed from time zero before there was any appreciable rise in tension within the covered plot. Since the elapsed time for the experimental sampling was about 400 hours it is readily apparent that the experiment was conducted at low tensions throughout. The tension gradients would undoubtedly be small and have little or no effect on the movement of moisture. It will be apparent later why the tension within the alfalfa plot, though rising relatively soon after time zero, need not be considered at this point in the discussion. Reference to this will be made later.

Mathematical Considerations

The arbitrary curves in figure 12 represent two empirical curves (1 and 3) and one hypothetical curve (2). It was found that by plotting the logarithm of $(t + 4)$, where t = time, versus percent moisture for the experimentally determined curve 1, a straight line was obtained for all depths each year (see figure 14 page 54). Therefore, the relationship for curve 1 can be taken as

$$y_1 = A \ln (t + 4) + B \qquad (1)$$

or

$$t = e^{(y_1 - B)/A} - 4 \qquad (2)$$

where y_1 is the moisture at any time t and A and B are constants. Differentiating equation (1) shows that

$$\frac{dy_1}{dt} = \frac{A}{t + 4} \qquad (3)$$

Substituting equation (2) into equation (3) yields the function

$$\frac{dy_1}{dt} = A/(e^{(y_1 - B)/A} - 4 + 4)$$

or

$$\frac{dy_1}{dt} = A e^{B/A} e^{-y_1/A} . \qquad (4)$$

Referring again to figure 12, it is seen that at time t_2 the moisture content at M, an arbitrarily chosen point on curve 1, is equal to the moisture content at N on curve 3 at time t_1. According to the assumption discussed earlier, the rate of percolation associated with curve 3 at point N will be equal to the percolation rate at point M on curve 1. The slope of curve 1, dy_1/dt, at any time is the percolation rate. Therefore, there is a hypothetical curve associated with curve 3 with a slope at t_1 equal to the slope of curve 1 at t_2. This hypothetical curve is represented by curve 2 in figure 12 and the slope at P is equal to the slope at M. The difference (P-N) designated as U in figure 12 is then equal to consumptive use up to time t_1. Obviously, U is a function of time or, mathematically, U = f(t). By letting y_1 equal the moisture content at M, y' the moisture content at n and y" the moisture content at P,

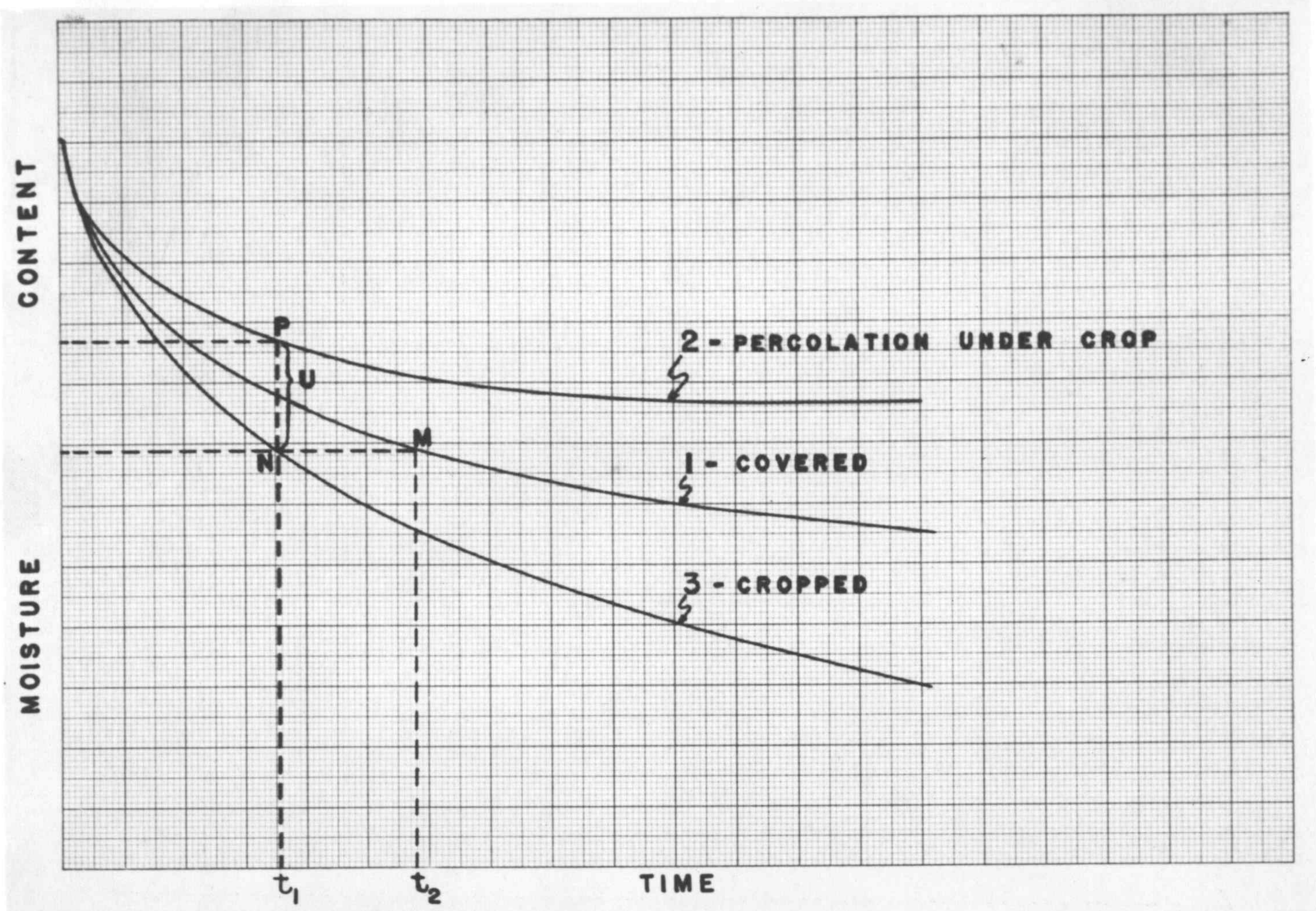

Figure 12. Arbitrary moisture-time curves to illustrate the procedure in the calculation of percolation under cropped conditions.

it can be said that $y_1 = y' = y'' - f(t)$ at t_1. Substituting in equation (4) it follows that

$$\frac{dy''}{dt} = A\, e^{B/A}\, e^{-y''/A}\, e^{f(t)/A} \qquad (5)$$

and

$$e^{y''/A}\, dy'' = A\, e^{B/A}\, e^{f(t)/A}\, dt\,. \qquad (6)$$

Since M was arbitrarily established on curve 1, equation 5 or 6 is the differential equation for curve 2. Integration of the differential equation will yield the equation for curve 2. As long as f(t) is not evaluated, equation (6) cannot be integrated. However, the assumption is now made that the rate of consumptive use is constant with time or that $U = f(t) = C\,t$ where C is a constant. This assumption, whether stated or not, has always been made by workers who sample the soil to determine the rate of consumptive use. The direct sampling method of determining the consumptive use rate (see footnote, p. 2) implies the assumption. Total consumptive use over any period of time between irrigations is simply the difference in moisture contents at the beginning and end of the period, so in this case the assumption is not necessary; however, any extrapolation of the consumptive use rate from either end of the period automatically brings in the assumption. Upon integration of the left side of equation (6) between the limits B and y'' and the right side between the limits 0 and t the function becomes

$$e^{y''/A} = e^{B/A}\; A/C\; (e^{Ct/A} - 1) + 1 \qquad (7)$$

or by taking logarithms becomes

$$y'' = A\ B/A + A \ln \left[A/C\ (e^{Ct/A} - 1) + 1 \right] \qquad (8)$$

Since point M on curve 1 was arbitrarily chosen, the general form follows from equation 8 as

$$y_2 = B + A \ln \left[A/C\ (e^{Ct/A} - 1) + 1 \right] \qquad (9)$$

where y_2 is the moisture content at any time t represented by curve 2. This, then, is the moisture content at any time which would result from percolation alone when plants are growing. The reader should realize that this is not a real situation because percolation by itself cannot be measured when there are plants also using moisture. All that remains is to subtract consumptive use (U) from equation (9) and the function for curve 3 follows as

$$y_3 = B + A \ln \left[A/C\ (e^{Ct/A} - 1) + 1 \right] - Ct \qquad (10)$$

where y_3 is the moisture content at any time t represented by curve 3.

The next step involved the evaluation of the consumptive use factor C for known values of A, B, and t. However, it became apparent immediately that C was not constant but varied with time. One of the basic assumptions in the derivation was that C was a constant. It was then realized that the function is much more complicated than equation (10) and the derivation cannot be carried beyond equation (5) where f(t) is not evaluated. It was then decided to resort to a graphical solution to the problem.

Graphical Solution

The technique presented in this section is, for the first two or three steps, essentially the same as that described in the preceding section; in addition, the graphical derivation of the hypothetical curve for percolation when plants are growing is based on the same assumption as was the mathematical derivation, that is, that percolation is a function of moisture content only. The assumption was discussed at some length in the previous section. However, the graphical analysis eliminates the need for the assumption that the rate of consumptive use is constant and in fact, as will be shown, gives a means of approximating consumptive use in terms of percent moisture. The derivation which follows shows how the theoretical considerations exemplified by the curves in figure 11 can be fitted to the experimental curves in figure 12 to derive the hypothetical curve for percolation of soil water when plants are growing. In the derivation only the data for the top foot of soil in the 1955 experiment are considered; the derivation serves as an example of the technique. The results for the remaining depths for the two years are presented in figures 16-22 in the appendix.

The first step is simply to plot the data for the covered plot and the alfalfa plot to obtain the two experimental curves shown in figure 13. The data plotted here are the averages for the three replications for the 0 to 12-inch depth.

The next step involves plotting the data for the covered plot as the logarithm of $t + 4$ (time in hours) versus percent moisture as

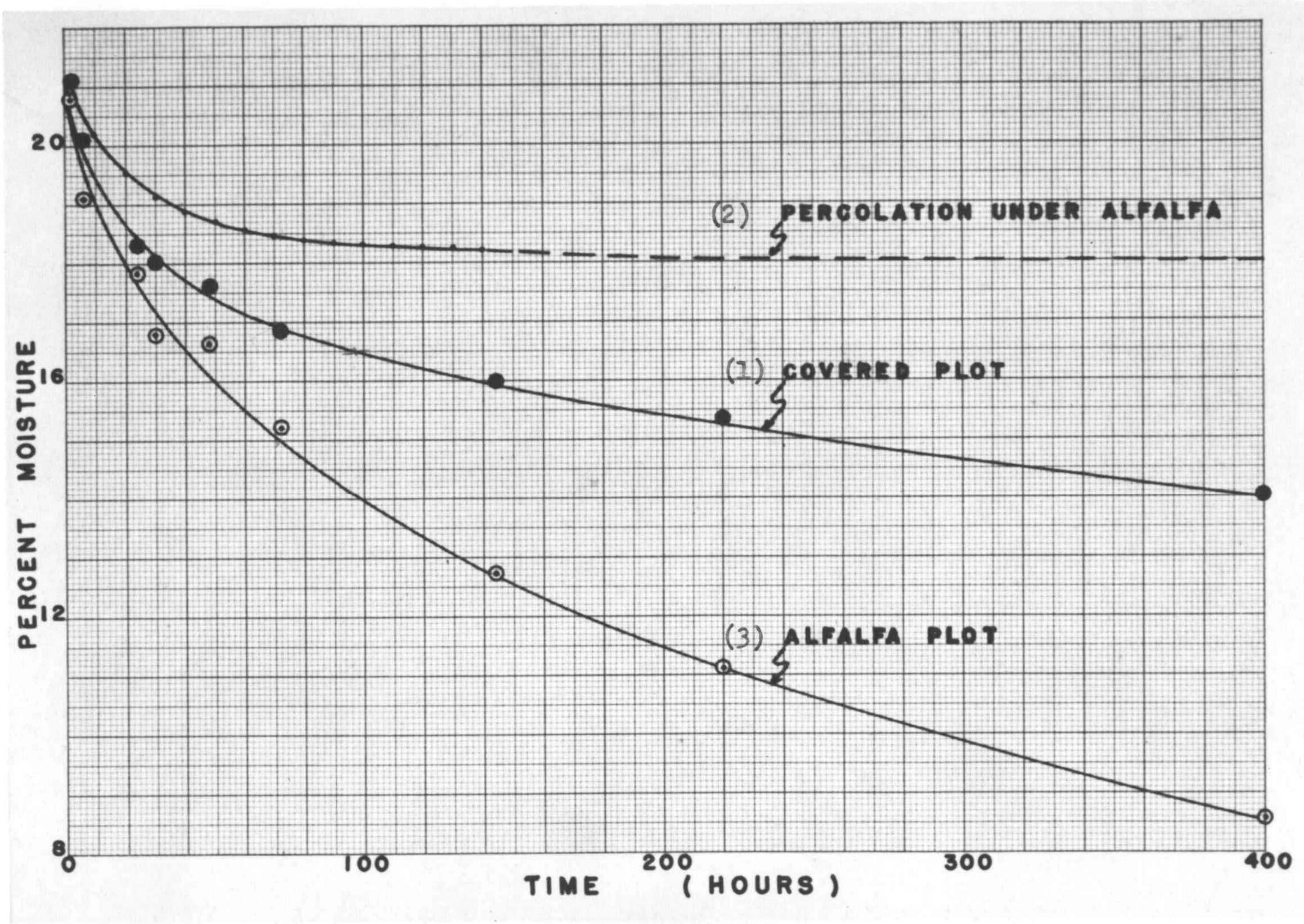

Figure 13. Moisture-time curves for the alfalfa and covered plots and the calculated curve for percolation under alfalfa (0 to 12-inch depth, 1955).

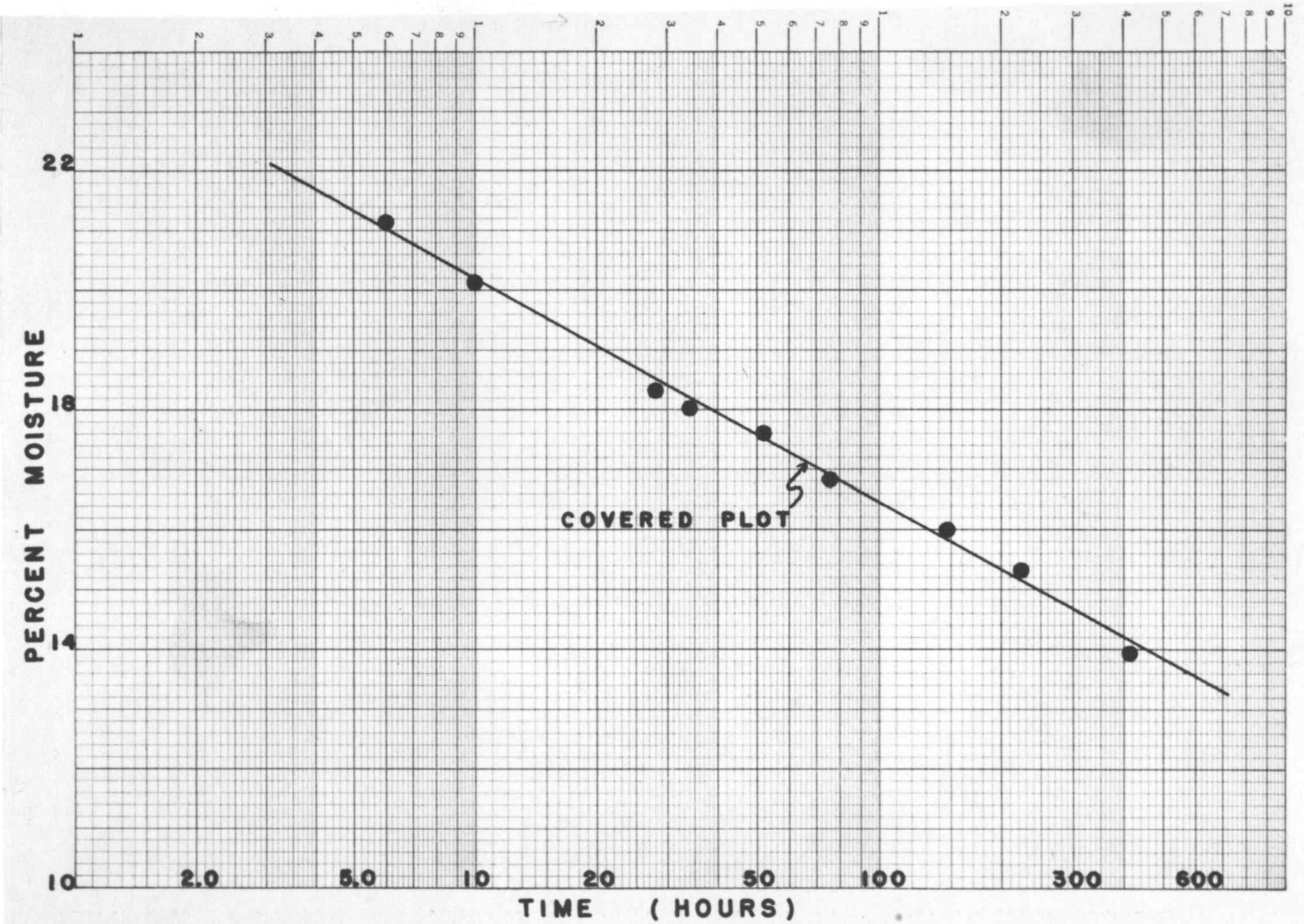

Figure 14. Data for the covered plot (0 to 12-inch depth, 1955) plotted as the logarithm of (t + 4), where t is time, versus percent moisture.

shown in figure 14. The equation for the line is

$$m_1 = A \ \ln \ (t + 4) \qquad (11)$$

where m_1 is the change in moisture percentage at any time t represented by the curve for percolation from the covered plot. The change of symbols from y_1 to m_1 was made to facilitate the ease of calculations by the elimination of the constant B in equation 1. The quantity m_1 is not equal to the quantity y_1 in the previous section on mathematical considerations but is related by the equation $m_1 = y_1 - B$. Since B is a constant m_1 and y_1 may be treated as analogous terms.

The constant A in equation (11) is evaluated from the slope of the line in figure 12. In this particular case A equals -1.65, where the minus sign indicates the negative slope. Differentiating equation (11) with respect to t,

$$\frac{dm_1}{dt} = \frac{A}{t + 4} \quad . \qquad (12)$$

Then at selected times as shown in table IV values for dm_1/dt are calculated. The value dm_1/dt is the change in moisture content per hour due to percolation from the covered plot.

Table IV

Calculated values of dm_1/dt for a number of values of t.

t hours	dm_1/dt percent per hour
10	.1178
50	.0305
100	.0159
150	.0107
200	.0081
250	.0065
300	.0055
350	.0047
400	.0041

These data are shown graphically in figure 15. It was shown in the mathematical derivation that

$$\left.\frac{dy_1}{dt}\right]_{t_2} = \left.\frac{dy_2}{dt}\right]_{t_1}$$

or simply that the slope of curve 1, figure 11 at t_2 is equal to the slope of curve 2, figure 11 at t_1. It follows that $dm_1/dt = dm_2/dt$ at the corresponding t_2 and t_1. The quantity m_2 is now the change in moisture percentage up to time t. The term m_2 bears the same relationship to y_2 as does m_1 to y_1. In other words the percolation rate, which is the slope associated with curve 3, figure 13, is the same as the percolation rate represented by curve 1, figure 13 when the moisture contents are the same. By choosing suitable times such as in table IV, selecting these points on curve 1, figure 13, and selecting the corresponding points on curve 3 where the moisture contents are the same, the times when $dm_2/dt = dm_1/dt$ can be found. These new times for dm_2/dt are plotted directly opposite the corresponding points for dm_1/dt, as shown in figure 15, giving the curve which is labeled dm_2/dt. Integration of the area under the curve with a planimeter, over suitable time intervals, yields successive changes of moisture percentage lost by percolation under the crop from the start of the experiment. The first integration interval was taken from two to ten hours because the moisture content is not known with certainty at $t = 0$ but is known at $t = 2$. The integrated changes in moisture percentage m_2 in percent moisture together with the time intervals are shown in table V. These quantities are successively subtracted from the moisture percentage at $t = 2$ hours and the points plotted to yield curve 2 shown in figure 13. This curve then, represents the percolation of soil water under crop conditions. The curve is purely hypothetical and can never be directly determined experimentally.

Table V

Changes in moisture percentage from percolation when alfalfa is growing found by integration of the curve dm_2/dt over various time intervals.

Time interval hours	Changes in moisture percentage (m_2) found by integration
2 - 10	.88
10 - 20	.72
20 - 30	.41
30 - 40	.22
40 - 50	.14
50 - 60	.10
60 - 70	.08
70 - 80	.07
80 - 90	.06
90 -100	.05

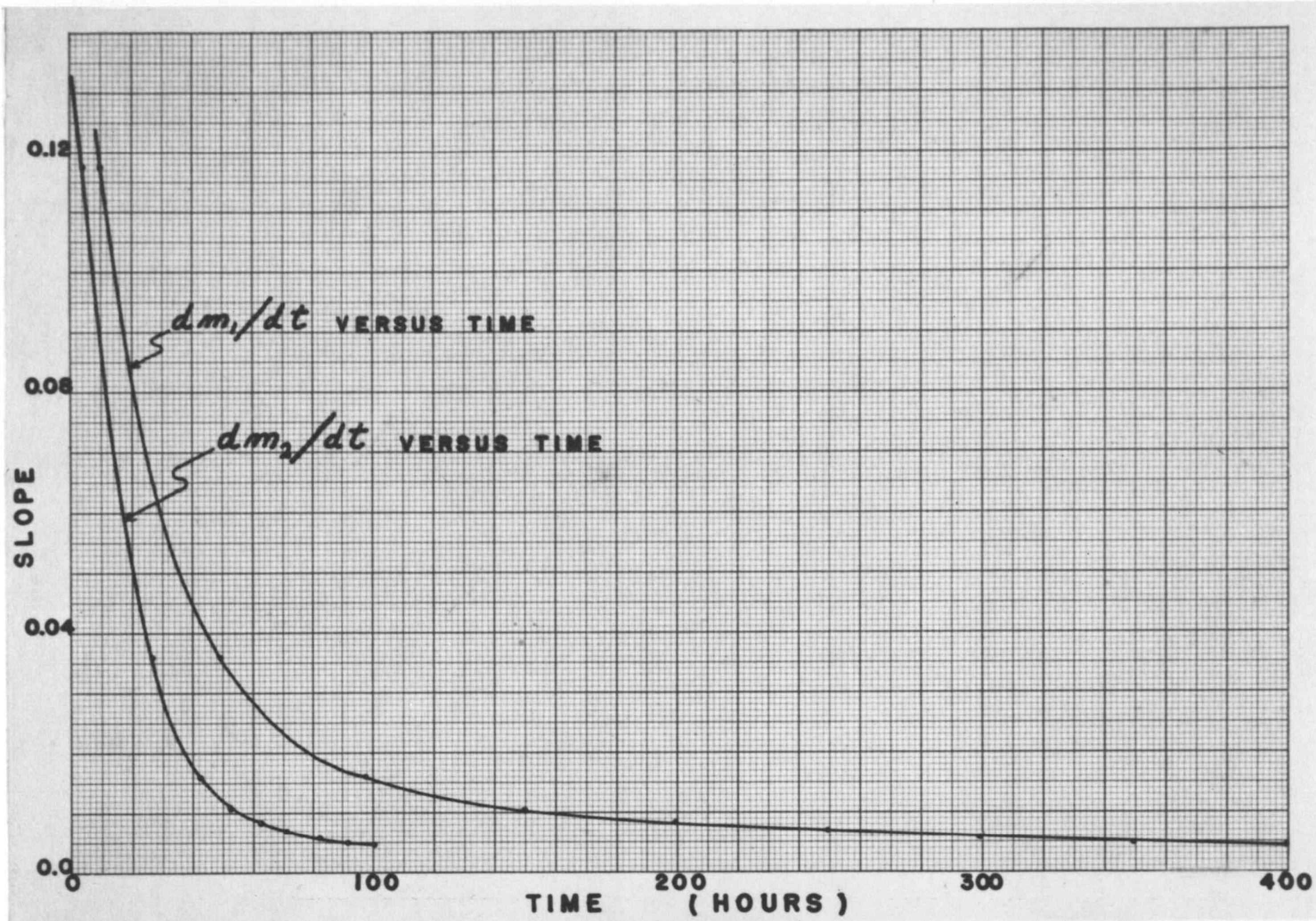

Figure 15. The rate of change of percolation under the covered plot (dm_1/dt) and under the alfalfa plot (dm_2/dt) versus time (0 to 12-inch depth, 1955).

The difference between curve 2 and curve 3 in figure 13 represents consumptive use. This is quite obvious because water is lost from the soil by only two possible means, percolation and consumptive use, which of course includes evaporation and transpiration. The remaining moisture which is not lost is that still held in the soil at any particular time and is related to curve 3 in figure 13. It follows that a table of consumptive use over any desired interval or intervals can be made. A typical example of such a table is shown in table VI. The consumptive use for all depths, each year, is shown in table IX in the appendix.

Table VI

Consumptive use with time in terms of percent moisture as determined from the curves in figure 13.

Time in hours	Accumulative consumptive use as percent moisture Curve 2 - Curve 3	Rate of consumptive use percent per hour
2	---	
20	1.50	.0830
40	2.30	.0425
60	2.99	.0345
80	3.64	.0325
100	4.28	.0320
120	4.85	.0285
140	5.36	.0255
160	5.82	.0230
180	6.25	.0215
200	6.63	.0189
220	6.99	.0180
240	7.32	.0165
260	7.63	.0155
280	7.90	.0135
300	8.17	.0135

It is interesting to note that the consumptive use rate is indeed not constant, at least until some 300 hours had elapsed. This would appear to support the conclusion, reached in the previous section, that the assumption that consumptive use was a constant or that $f(t) = Ct$ was quite unjustified. The reader will remember that this assumption was made before equation (5) of the mathematical derivation was integrated.

Referring again to the assumption that percolation is a function of moisture content only it can now be seen why consideration of the rising tension in the alfalfa plot was not necessary. The tension versus time curves in figures 10 and 11 show that the tension did not rise appreciably until after 100 hours. Curve 2, figure 13 shows that percolation under the alfalfa had practically ceased before 100 hours. Therefore, the same arguments with respect to tension gradients apply equally as well to the alfalfa plot as to the covered plot.

DISCUSSION OF THE INTERACTION BETWEEN PERCOLATION AND CONSUMPTIVE USE

The following discussion is concerned with the practical implications involved in considering the interaction between consumptive use and percolation. The practical implications apply to studies of field capacity, available moisture and consumptive use and are discussed in that order. The limitations and criticisms of the analyses presented in the previous section are also being pointed out.

Field Capacity

It will be recalled from the review of literature that quite a number of workers support the view expressed by Veihmeyer and Hendrickson (see page 5) that field capacity is not an equilibrium value but a point on a time-drainage curve. This is undoubtedly true, because in studies of soil moisture movement where no transpiration or evaporation losses occurred it was most often observed that percolation did persist for many days or even weeks without any sudden decrease in percolation rate. Curve 1, figure 13 is a typical illustration of this behavior. Selection, from such a curve, of a single point to represent field capacity is purely arbitrary.

Veihmeyer and Hendrickson also made the very pertinent observation that plants extract moisture rapidly enough to prevent appreciable percolation 2 to 3 days after the application of water (see page 5). When the interaction between percolation and consumptive use is considered, percolation can be shown to decrease much more rapidly and become negligible much sooner than when the interaction is not taken into account. This is illustrated by curves 1 and 2 in figure 13. Curve 2 indicates that percolation does become very small on about the third day after irrigation when plants are growing. The time required for the percolation rate to become small appears to be nearly independent of depth and crop as long as consumptive use is large for that depth (see appendix figures 16-22). The third day, of course, applies to the soil under study, but because of the extreme effect of consumptive use encountered, this length of time may have fairly general application to other light textured soils. Evidently, when consumptive use is very slight or absent, as appeared to be the case in the third foot in the barley plot, percolation is very similar to that from a covered plot even though plants are withdrawing moisture from the soil immediately above. The shallow rooting habit of the barley probably accounts for this.

Although percolation becomes small in 2 to 3 days the choice of the time for sampling for field capacity is still quite critical. This is because sampling at any particular time will not yield the moisture percentage represented by curve 2 (figure 13) but will yield the moisture percentage represented by curve 3. This latter curve is still changing quite rapidly 2 to 3 days after the irrigation. For example, at 48 hours curve 2 shows 18.7% moisture and curve 3 shows 16.1% moisture while at 72 hours curve 2 shows

18.4% and curve 3 shows 15%. Curve 2, then, indicates a difference of only 0.3% moisture while curve 3 indicates a difference of 1.1% over a 24 hour period. The field capacity determination would therefore differ by 1.1%, depending upon whether the sample was taken at 2 days or at 3 days. Whether this difference is important or not depends on the precision desired but the fact that there is a noticeable difference emphasizes the importance of considering the drainage characteristics of a soil and relating these to consumptive use of any particular crop before deciding when to sample for field capacity in the field.

It is difficult to make a definite recommendation as to a time of sampling for field capacity even for the soil where this experiment was conducted. Sampling at either two or three days would apparently satisfy the present definition of field capacity because percolation is small by the second day and still smaller by the third day. The question still remains, how small should percolation be when the sample is taken? In either case the result describes only the moisture content at whichever day the soil is sampled. The result does not represent the upper limit of available moisture. This is discussed in the following section.

Available Moisture

Available moisture is almost universally described as the amount of moisture between field capacity and the wilting percentage held in the soil for plant use. The wilting percentage, or lower limit of the available moisture range, is ordinarily readily obtainable as it is a relatively fixed quantity as far as plant species are concerned on any particular soil. The field capacity as ordinarily defined, that is, the moisture content in the soil 2 to 3 days after an irrigation, is most often considered the upper limit of the available moisture range. However, the nature of curves 2 and 3, figure 13 reveals that a soil with particular drainage characteristics cannot drain any further under crop than to some moisture value above field capacity as ordinarily defined, a value fixed by the consumptive use of the crop. This value can be thought of as field capacity plus consumptive use up to the time for field capacity to be reached. Therefore, this new value is really the upper limit of the available moisture. It is especially noteworthy that this limit differs very little from the second day to the third as compared with field capacity over the same period. These arguments again emphasize the necessity of knowing the drainage or percolation characteristics of the soil and relating them to the consumptive use of the crop before estimating field capacity or the available moisture range. It is again very difficult to say how much difference there would be, with regard to various soil types, in available moisture studies but the indications are that perhaps present estimates are too low. Even on the very sandy soil studied in these experiments, if available moisture is estimated from the moisture-tension curves (figure 9) between one third atmosphere and 15 atmospheres (field capacity to wilting percentage) the result is about 6 percent available moisture in the top foot, as compared with 11 to 12 percent if the estimate is made from the upper limit of available moisture from the curves in figure 13. The one-tenth atmosphere percentage which is sometimes used to determine field capacity appears to be a better estimate of the upper limit of available moisture since the estimate in this case is about 10 percent available moisture.

Consumptive Use

Perhaps the most significant outcome of this study with regard to consumptive use is the evidence that consumptive use is not constant, at least for a considerable time after an irrigation. It has long been assumed that consumptive use was relatively constant and that an average consumptive use value over some period between irrigations could apply to the entire period between the irrigations. It will be recalled from the review of literature that Robins et al. reported marked increases in consumptive use at all depths of the root zone immediately following an irrigation (see page 10). The results reported in this thesis appear to support the above claims. Consumptive use of water may be considerably higher than it is ordinarily thought to be.

The other important result of this study with respect to consumptive use is, of course, the technique for estimating consumptive use itself. The technique in using the experimental curves for this purpose has already been adequately discussed but it is worth while to point out here that the procedure may be a useful tool for obtaining more accurate estimates of consumptive use.

Limitations and Criticisms

It is fully realized that there are definite limitations to the procedure presented in this study, not the least of which is the actual physical problem of soil sampling to obtain the experimental curves. Considerable work is required, although within a relatively short time, and conditions must be controlled rather carefully. On the other hand, once the curve characterizing the percolation of water in any particular soil is obtained it can be related to the corresponding curve for any crop on the same soil. The amount of information which can be obtained this way is perhaps ample compensation for the amount of work involved.

The technique is limited to the accuracy with which the soil can be sampled. Considerable sampling variation is frequently encountered in the moisture sampling in the field, variation which makes it very difficult to estimate the mean moisture content with a desired accuracy unless an almost prohibitive number of samples are taken from a large number of replications. This entire study can be criticized on this basis, but the fact remains that, regardless of the amount of variation, the data at hand are the best estimates obtainable under the experimental conditions. The claims that are made may appear to be of doubtful importance in a practical way but in the interests of a more thorough understanding of soil-water-plant relationships the study is believed to be a worthwhile contribution. A more thorough understanding of these relationships may assist in solving some of the more practical problems now confronting soil scientists.

SUMMARY AND CONCLUSIONS

A field sampling technique was used to obtain data with which to make comparisons among evaporation, transpiration and percolation losses of soil moisture. Three treatments with which to make the comparisons were (1) a cropped plot (barley in 1954 and alfalfa in 1955), (2) a bare plot and (3) a covered plot. The soil under each of these treatments was sampled at predetermined time intervals starting at two hours after a thorough irrigation. The moisture percentage in the soil samples at the various times was plotted against time to produce a number of moisture-time curves representing the loss of moisture from each treatment at depths of 0-12, 12-24 and 24-36 inches as well as all three depths together. These curves were then compared.

Comparisons between the curves for the barley and alfalfa plots and the curves for the covered plots indicated that percolation of soil water and consumptive use were related, or more specifically, that the latter had a very marked influence on the former. By means of a graphical technique it was shown that percolation and consumptive use could be related quantitatively and from this relation more precise estimates made of consumptive use and available moisture than were previously possible.

The following conclusions were made from this study:

1. Percolation and consumptive use are related.

2. Percolation can be quantitatively related to consumptive

use by the technique described.

3. Consumptive use slows up percolation so drastically that the latter is negligible within three days, at least for light textured soils.
4. Field capacity as ordinarily defined is exactly what the definition says - the moisture content in the soil 2 or 3 days after the application of water. It does not define the upper limit of available moisture.
5. The upper limit of available moisture is above field capacity, as ordinarily defined, by an amount equal to the consumptive use up to the time referred to in the definition of field capacity.
6. The consumptive use rate was highest immediately after the irrigation and gradually decreased at all depths as the soil dried out.
7. The fact that percolation and consumptive use can be related quantitatively may provide a new tool for the evaluation of consumptive use, the available - moisture range and field capacity.

BIBLIOGRAPHY

1. Biggar, James. Moisture transfer and loss from a field soil. (Abstracted in Agronomy abstracts, p. 7, 1955).

2. Bodman, G. B. Factors affecting downward movement of water in soils. Pennsylvania state college, 1936. 190 p. (American soil survey association. Bulletin no. 17).

3. Briggs, L. J. and J. W. McLane. The moisture equivalent of soils. Washington, Government printing office, 1907. 23 p. (U. S. Dept. of agriculture. Bureau of soils. Bulletin no. 45).

4. Colman, A. E. The dependence of field capacity upon the depth of wetting of field soils. Soil science 58:43-50. July 1944.

5. ___________. A laboratory procedure for determining the field capacity of soils. Soil science 63:277-283. 1947.

6. Edlefsen, N. E. and G. B. Bodman. Field measurements of water through a silt loam soil. Journal of the American society of agronomy 33:713-731.

7. Gardner, Willard. Capillary moisture holding capacity. Soil science 7:319-324. 1919.

8. Gardner, Willard and J. A. Widtsoe. The movement of soil moisture. Soil science 11:215-232. 1921.

9. Hanks, J. R. et al. Field capacity approximation based on the moisture transmitting properties of the soil. Soil science society of America, proceedings 18:252-254. July 1954.

10. Harrold, Lloyd L. Available moisture for crops. Agricultural engineering 35:99-101. 1954.

11. Israelson, O. W. Irrigation principles and practices. New York, John Wiley and sons, 1949. 422 p.

12. Israelson, O. W. and F. L. West. Water holding capacity of irrigated soils. Logan, Utah agricultural college, 1922. 24 p. (Utah. Agricultural experiment station. Bulletin no. 183).

13. Marshall, T. J. and G. B. Stirk. Pressure potential of water moving downward into soil. Soil science 68:359-370. 1949.

14. Richards, L. A. Pressure membrane apparatus—construction and use. Agricultural engineering 28:451-454. October 1947.

15. ____________. Porous plate apparatus for measuring moisture retention and transpiration by soil. Soil science 66:105-110. 1948.

16. ____________. Methods of measuring soil moisture tension. Soil science 68:95-112. 1949.

17. Richards, L. A. and D. C. Moore. Influence of capillary conductivity and depth of wetting on moisture retention in soil. Transactions American geophysical union 33:531-540. 1952.

18. Richards, L. A. and L. R. Weaver. Moisture retention by some irrigated soils as related to soil moisture tension. Journal of agricultural research 69:215-235. 1944.

19. Robins, J. S. et al. Unsaturated flow of water in field soils and its effect on soil moisture investigations. Soil science society of America, proceedings 18:344-347. July 1954.

20. Shockley, Dale R. Capacity of soil to hold moisture. Agricultural engineering 36:109-112. February 1955.

21. Veihmeyer, F. J. and A. H. Hendrickson. Soil moisture conditions in relation to plant growth. Plant physiology 2:71-82. 1927.

22. ____________. Methods of measuring field capacity and permanent wilting percentage of soils. Soil science 68:75-94. 1949.

23. ____________. The moisture equivalent as a measure of field capacity of soils. Soil science 32:181-193. 1931.

24. Widtsoe, J. A. and W. W. McLaughlin. The movement of water in irrigated soil. Logan, Utah agricultural college, 1912. 268 p. (Utah. Agricultural experiment station. Bulletin no. 115).

25. Wilcox, J. C. Soil moisture studies. I. Some factors affecting the moisture holding capacity and its determinations. Scientific agriculture 20:140-149. October 1939.

26. ____________. Soil moisture studies. IV. Indirect determinations of field capacity for moisture. Scientific agriculture 29:563-578. December 1949.

APPENDIX

Table VII. Moisture percentage at various times after time zero for the barley, bare and covered plots. Average of three replicates. 1954

Depth Inches	Plot* No.	2	4	8	24	36	48	72	144	216
		Time in Hours								
0-12	1	21.5	20.3	19.2	17.7	17.0	16.2	15.1	12.3	10.2
	2	21.0	20.4	18.7	18.1	17.5	16.6	15.9	14.1	13.2
	3	20.9	20.2	19.0	18.1	17.6	17.1	16.3	14.7	14.2
12-24	1	20.2	19.5	19.4	18.5	17.6	16.9	16.3	14.6	12.2
	2	20.5	20.3	19.5	18.1	17.1	17.5	17.4	16.2	15.8
	3	20.4	19.9	19.5	18.9	17.7	17.1	17.4	15.4	15.8
24-36	1	23.3	23.8	22.3	20.8	20.1	19.8	19.8	18.1	17.4
	2	24.9	24.2	23.2	22.0	20.8	21.2	21.0	19.7	18.9
	3	23.4	24.0	22.9	21.5	20.8	20.1	19.9	18.2	17.7
Ave. of Three Depths	1	21.7	21.2	20.3	19.0	18.2	17.6	17.1	15.0	13.2
	2	22.1	21.6	20.5	19.4	18.5	18.4	18.1	16.7	16.0
	3	21.6	21.3	20.4	19.5	18.7	18.1	17.9	16.1	15.9

* Plot 1 - Barley; Plot 2 - Bare; Plot 3 - Covered

Table VIII. Moisture percentage at various times after time zero for the alfalfa, bare and covered plots. Average of three replicates. 1955.

Depth Inches	Plot* No.	2	6	24	30	48	72	144	220	410
		Time in Hours								
0-12	1	20.8	19.1	17.8	16.7	16.6	15.2	12.7	11.1	8.4
	2	20.1	19.7	18.3	17.1	16.6	15.1	13.8	12.9	11.3
	3	21.1	20.1	18.3	18.0	17.6	17.0	16.0	15.3	13.9
12-24	1	19.9	19.0	17.8	17.1	16.6	15.9	14.6	13.3	10.5
	2	19.5	18.9	16.9	16.6	16.7	14.8	15.1	14.3	13.8
	3	19.6	19.0	17.5	17.5	17.1	16.2	15.7	15.2	14.1
24-36	1	22.8	22.0	20.4	20.4	19.7	19.0	18.5	15.8	13.3
	2	23.0	21.3	19.7	19.3	19.1	17.4	17.0	17.5	16.5
	3	22.6	22.6	20.8	20.8	20.1	19.9	19.2	18.6	17.6
Ave. of Three Depths	1	21.2	20.0	18.7	18.1	17.6	16.7	15.3	13.4	10.7
	2	20.9	20.0	18.3	17.7	17.5	15.7	15.3	14.9	13.9
	3	21.1	20.6	18.9	18.8	18.3	17.6	17.0	16.4	15.2

* Plot 1 - Alfalfa; Plot 2 - Bare; Plot 3 - Covered

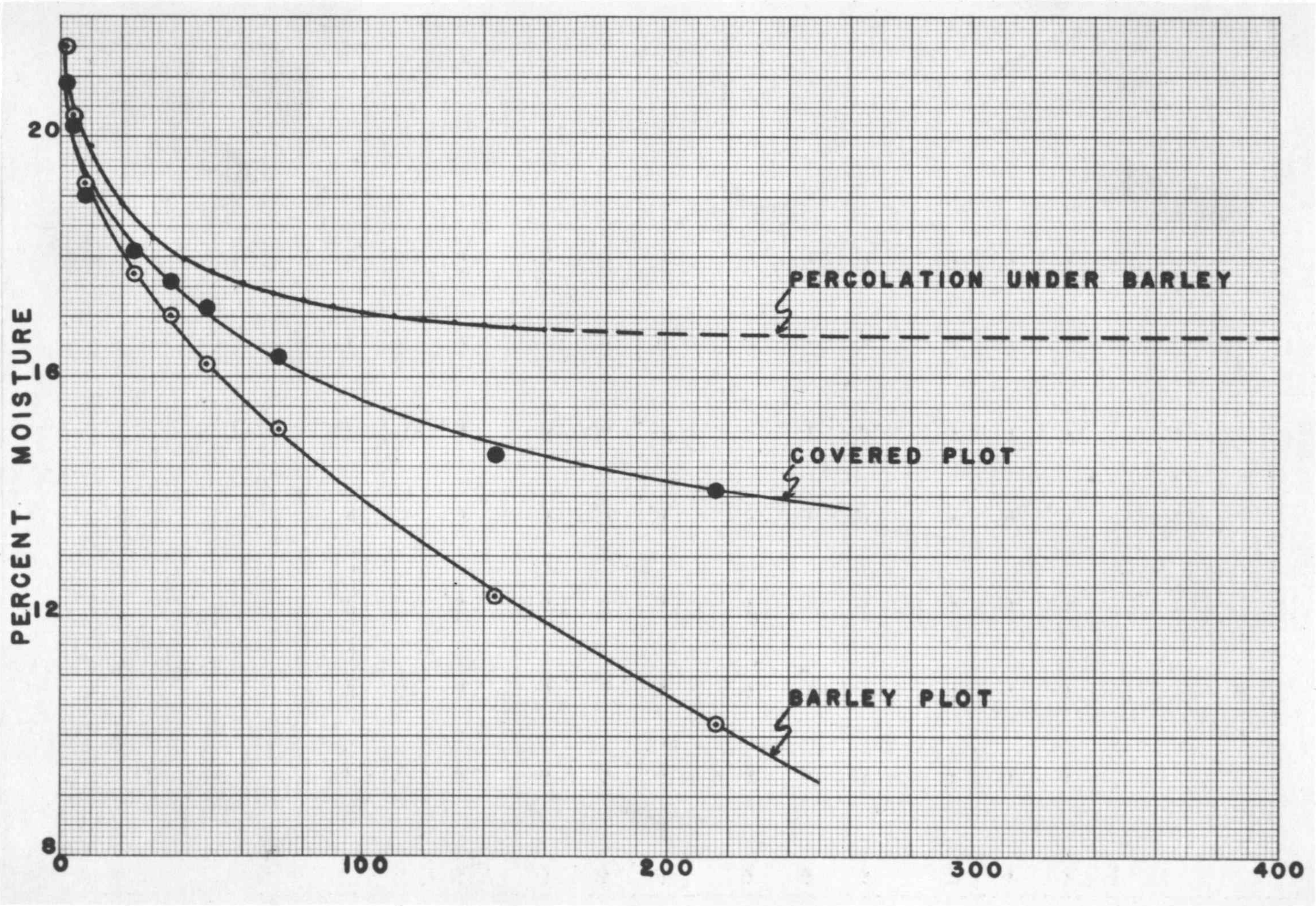

Figure 16. Moisture-time curves for the barley and covered plots and the calculated curve for percolation under barley (0 to 12-inch depth, 1954).

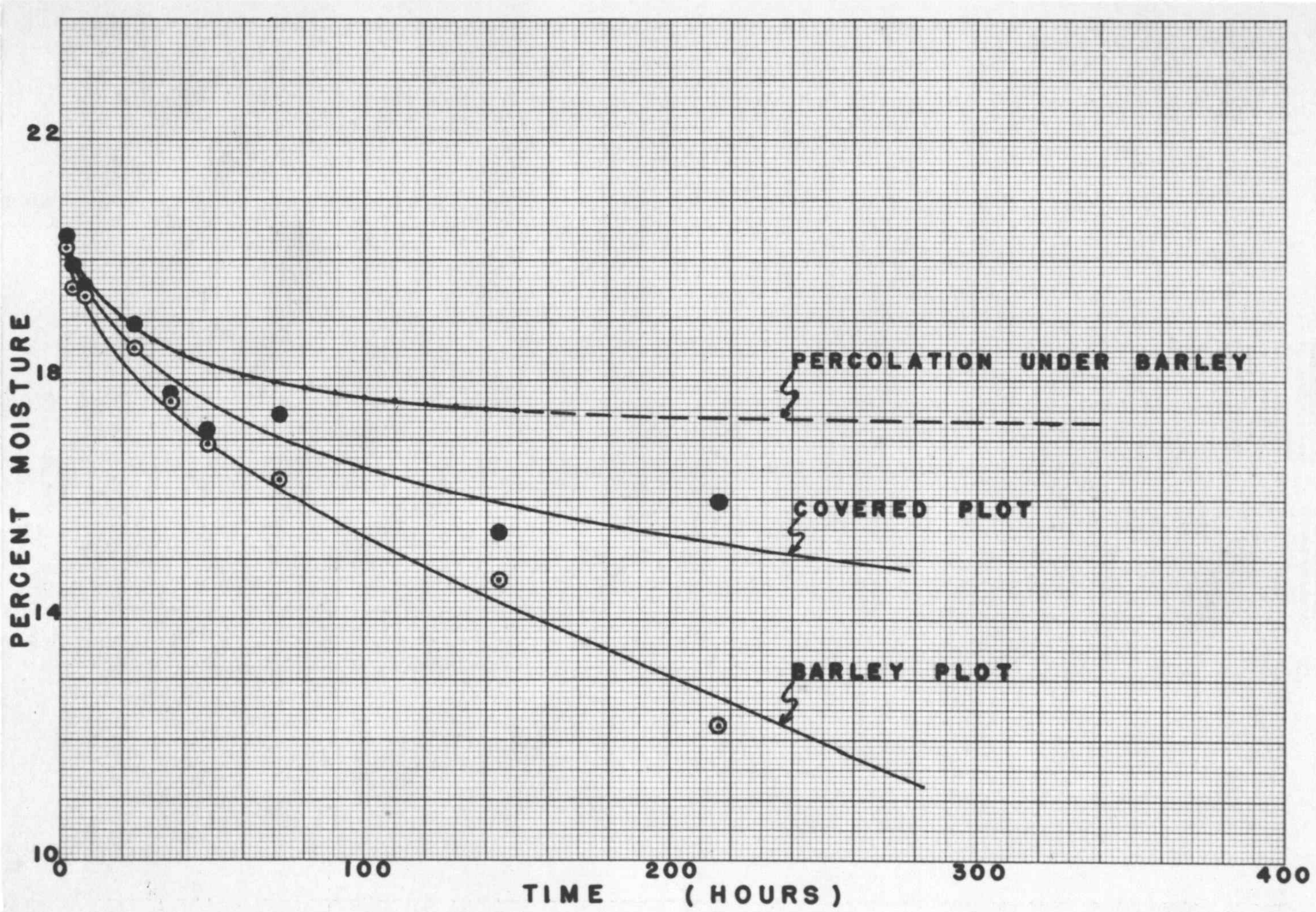

Figure 17. Moisture-time curves for the barley and covered plots and the calculated curve for percolation under barley (12 to 24-inch depth, 1954).

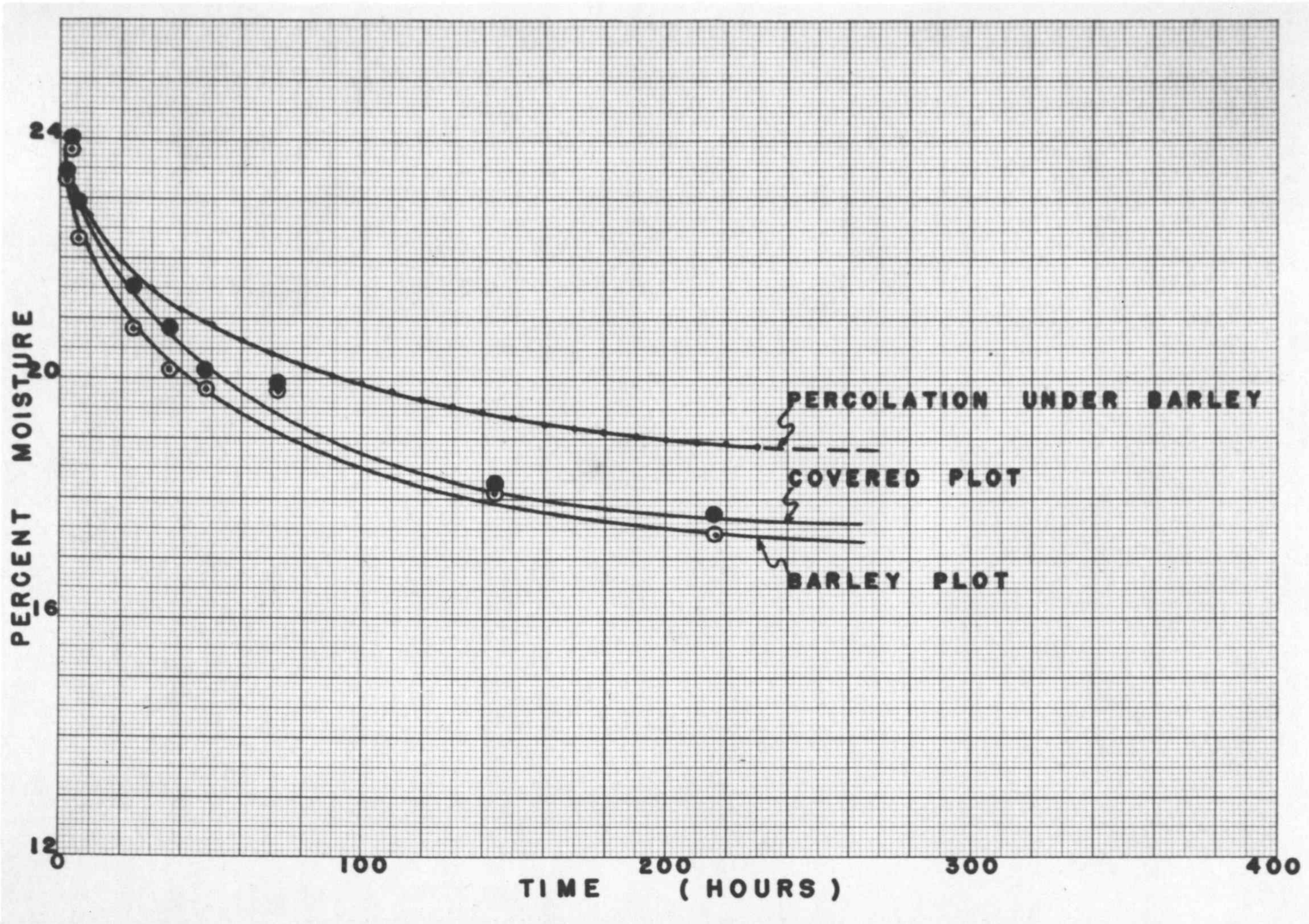

Figure 18. Moisture-time curves for the barley and covered plots and the calculated curve for percolation under barley (24 to 36-inch depth, 1954).

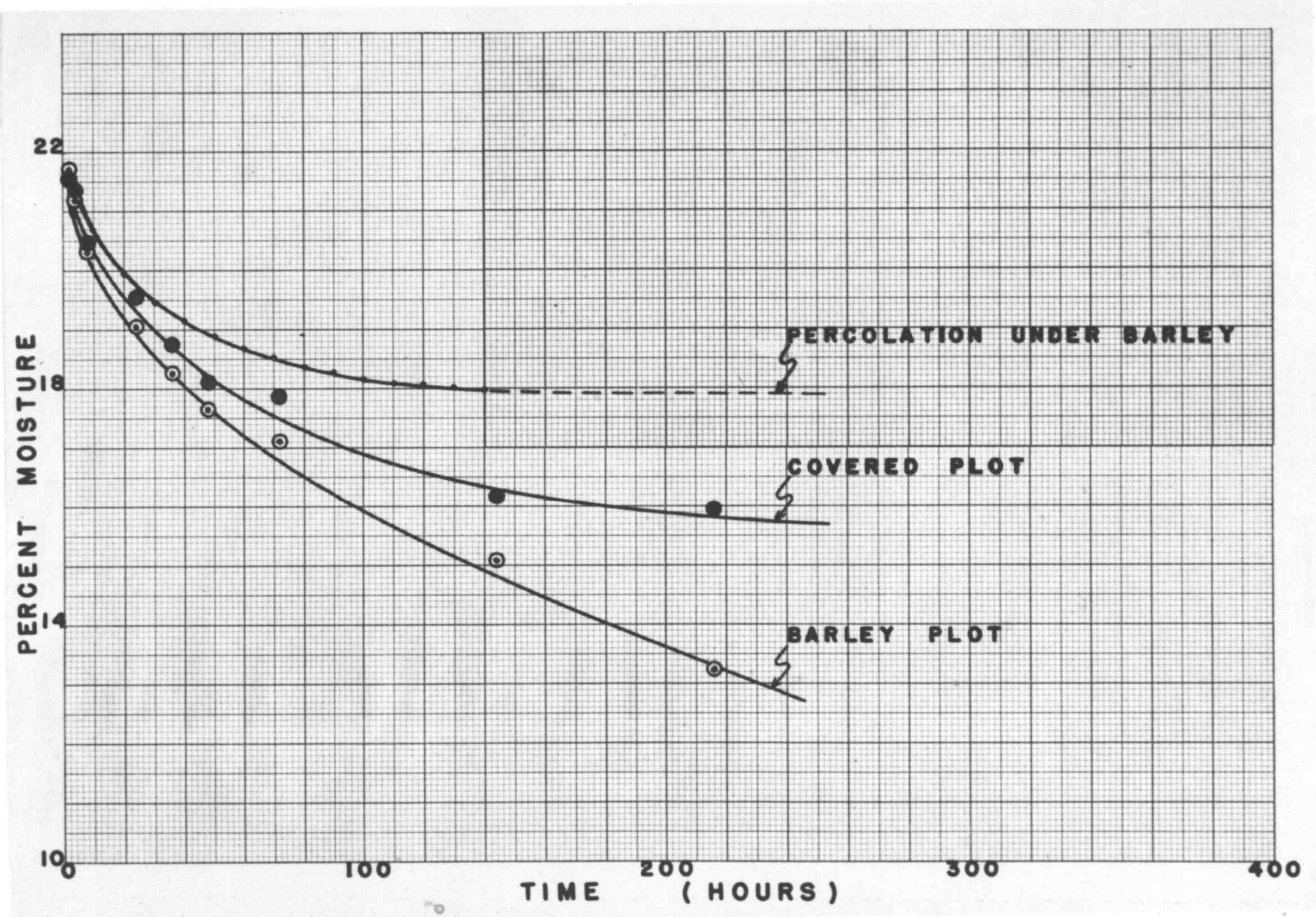

Figure 19. Moisture-time curves for the barley and covered plots and the calculated curve for percolation under barley (0 to 36-inch depth, 1954).

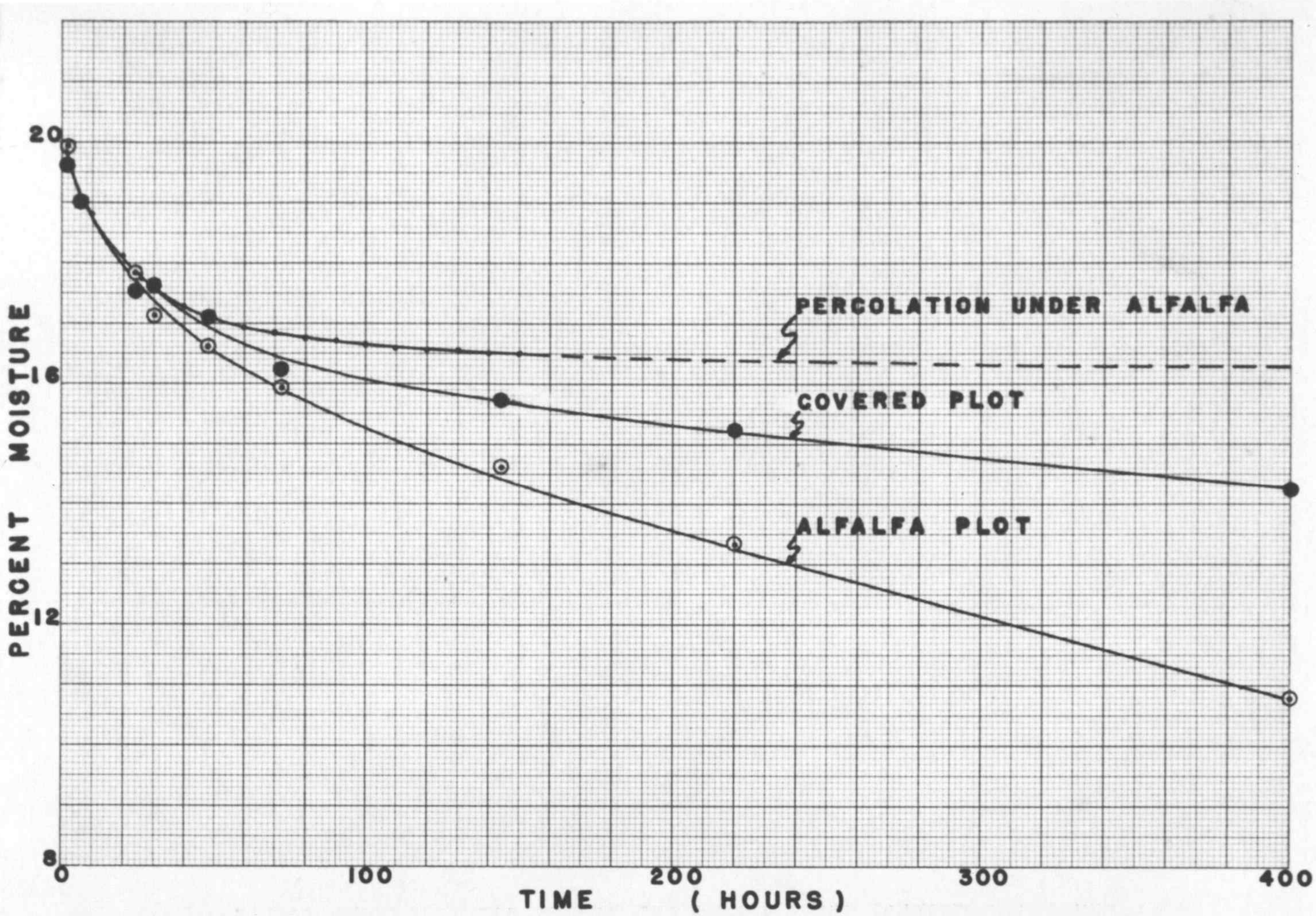

Figure 20. Moisture-time curves for the alfalfa and covered plots and the calculated curve for percolation under alfalfa (12 to 24-inch depth, 1955).

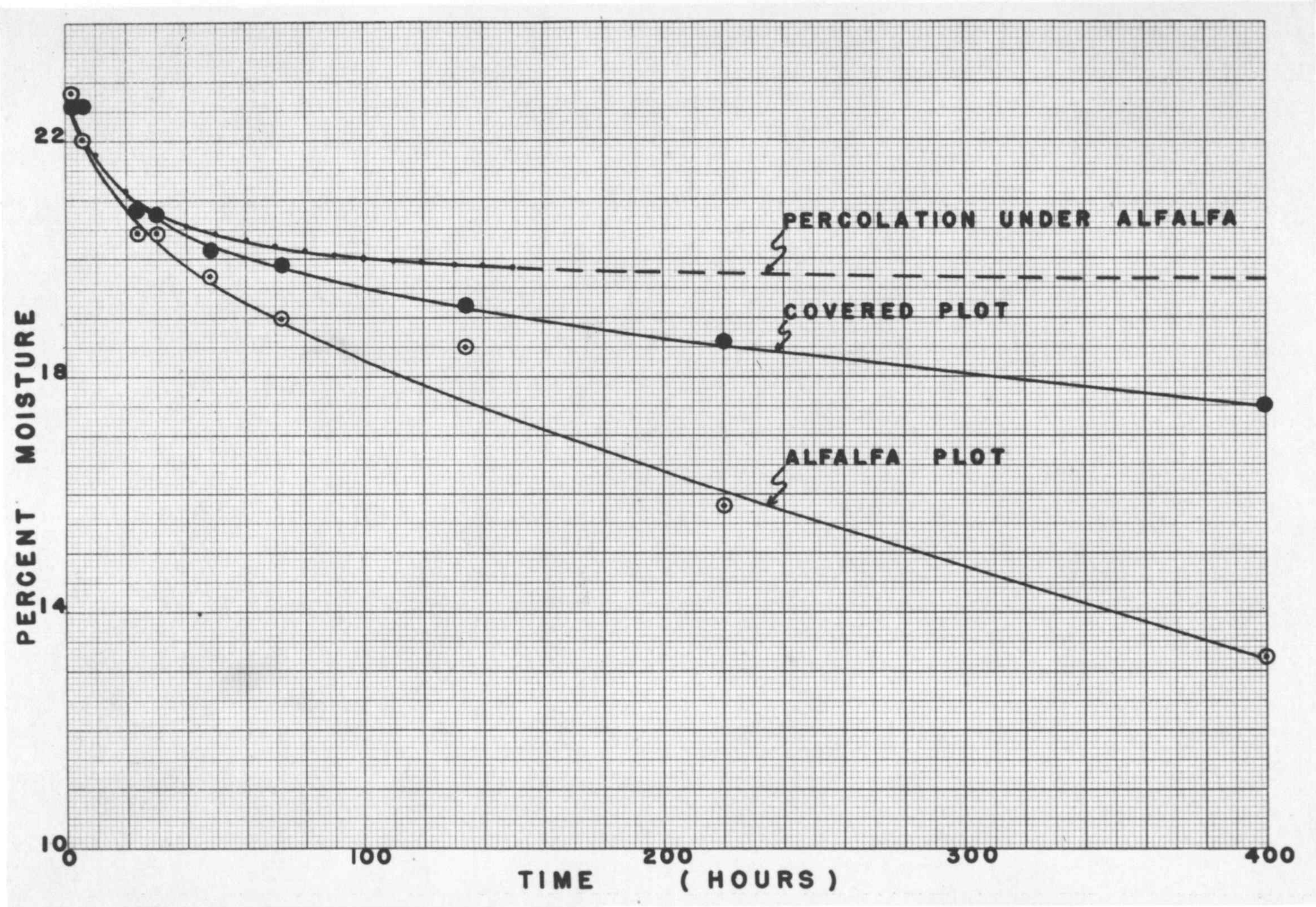

Figure 21. Moisture-time curves for the alfalfa and covered plots and the calculated curve for percolation under alfalfa (24 to 36-inch depth, 1955).

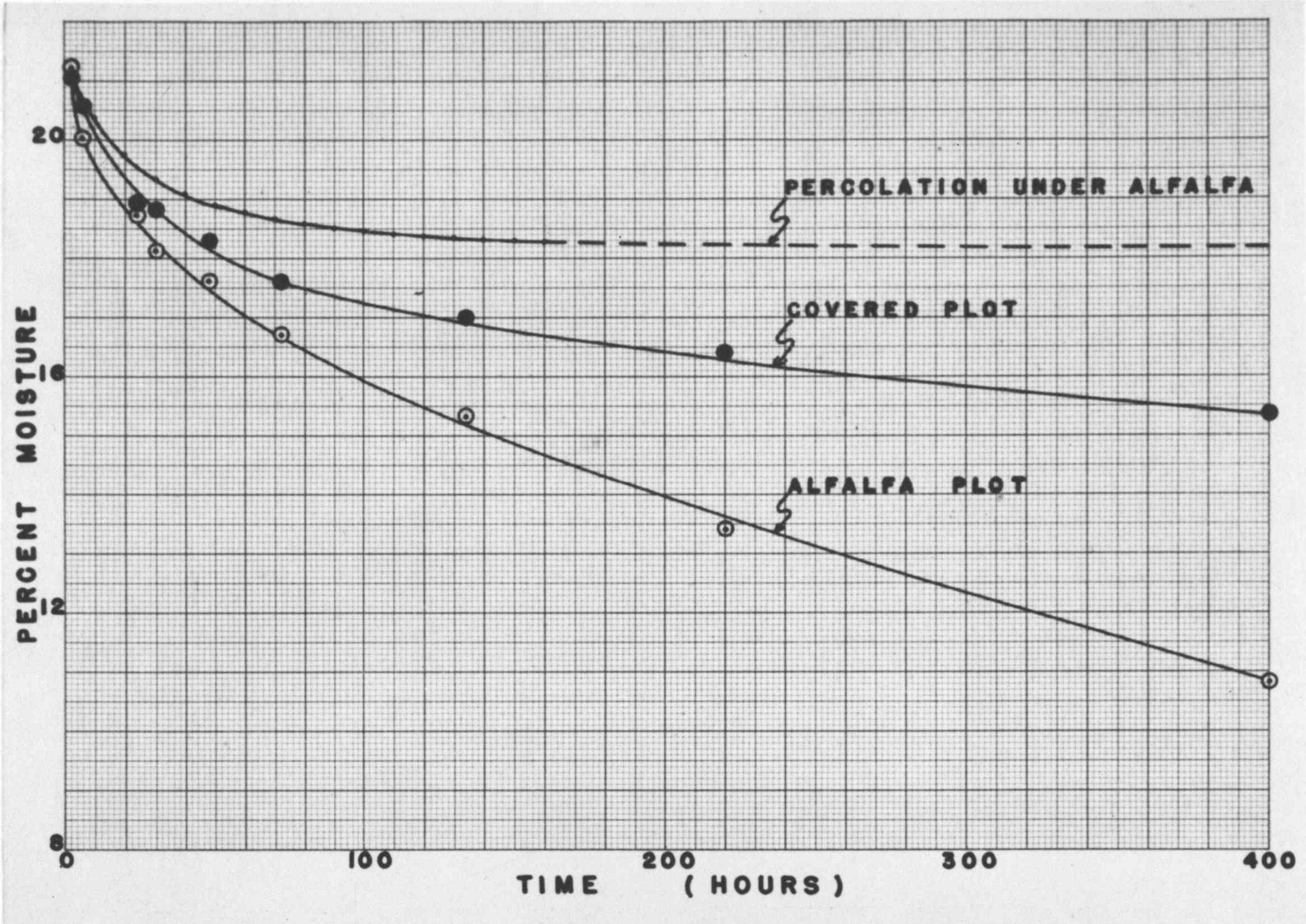

Figure 22. Moisture-time curves for the alfalfa and covered plots and the calculated curve for percolation under alfalfa (0 to 36-inch depth, 1955).

Table IX. Rate of consumptive use in terms of percent moisture per hour for all depths in 1954 and 1955.

Time Hours	1954 0-12"	12-24"	24-36"	0-36"	1955 0-12"	12-24"	24-36"	0-36"
0								
20	.0275	.0265	.0035	.0333	.0830	.0028	.0140	.0500
40	.0225	.0195	.0090	.0246	.0425	.0114	.0200	.0185
60	.0300	.0205	.0090	.0243	.0345	.0210	.0175	.0210
80	.0305	.0200	.0050	.0200	.0325	.0120	.0155	.0195
100	.0295	.0175	.0045	.0208	.0320	.0140	.0165	.0190
120	.0310	.0180	.0025	.0208	.0280	.0170	.0170	.0190
140	.0295	.0185	.0010	.0195	.0255	.0165	.0165	.0185
160	.0285	.0200		.0177	.0230	.0140	.0160	.0170
180	.0275	.0235		.0180	.0215	.0155	.0170	.0175
200	.0285	.0215		.0168	.0189	.0145	.0170	.0165
220	.0300	.0215		.0167	.0180	.0150	.0170	.0170
240	.0295	.0210		.0155	.0165	.0140	.0160	.0165
260	.0260	.0205		.0148	.0155	.0130	.0150	.0170
280	.0250	.0205		.0137	.0135	.0120	.0155	.0160
300				.0138	.0135	.0125	.0155	.0150

Table X. Hygrothermograph records of temperature and relative humidity near the experimental site in 1955.

Date		Temperature Degrees in Fahrenheit		Relative humidity Percent	
		maximum	minimum	maximum	minimum
July	19	90			30
	20	89	50	100	32
	21	90	51	100	29
	22	92	54	100	30
	23	92	52	100	28
	24	85	49	100	30
	25	80	40	100	30
	26	76	42	100	42
	27	76	43	100	38
	28	78	47	100	30
	29	85	43	100	34
	30	89	47	100	30
	31	90	49	100	31
August	1	90	48	100	24
	2	86	47	100	31
	3	85	50	92	26
	4	91	56	83	26
	5	92	51	100	26
	6	96	55	98	26
	7	87	61	100	33
	8	89	51	100	25
	9	91	51	100	28
	10	93	50	100	25
	11	94	52	100	21
	12	87	47	100	18
	13	87	46	96	24
	14	89	44	100	24
	15	90	45	100	22
	16	88	45	100	21
	17	91	49	100	22
	18	92	46	100	19
	19	89	47	100	25
	20	89	53	98	21