UNITED STATES DEPARTMENT OF COMMERCE
WEATHER BUREAU

COMPUTATION OF EVAPORATION AND EVAPOTRANSPIRATION FROM METEOROLOGICAL OBSERVATIONS*

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INTRODUCTION

The increasing importance of water in our economy and the growing seriousness of consequent shortages of water supply have led to renewed interest in the evaporation process. Extensive research is underway in an attempt to find practical means of reducing reservoir losses and many recent studies have been directed toward improved estimates of the actual losses involved. Although estimates of evaporation from proposed reservoirs have long been considered in designing water-supply projects in arid and semi-arid regions, little was known of the relative reliability of the several techniques employed until the inter-agency study[1] was conducted at Lake Hefner, Oklahoma, in 1950-51. This particular lake was selected after extensive investigation, primarily because circumstances assured accurate water-budget data for testing the reliability of energy-budget, mass-transfer and pan approaches. Inter-agency activities were subsequently transferred to Lake Mead[2], Arizona-Nevada. These two experiments proved rather conclusively that monthly evaporation from an existing reservoir can be reliably determined by application of an energy budget, and that the day-to-day variations in evaporation are in accord with an empirical mass-transfer equation.

The U. S. Weather Bureau participation in these two projects was directed toward an evaluation of techniques using Class A pan and related meteorological data to estimate evaporation from existing and proposed reservoirs. To further substantiate the findings at Lakes Hefner and Mead, a third experiment was conducted under contract with Stanford University** at Felt Lake, California.

As a result of these recent experiments, we now are quite certain that sufficiently precise estimates of reservoir evaporation can be made from pan evaporation and related meteorological data. Procedures were also derived for estimating pan and lake evaporation from observations of solar radiation, air temperature, dewpoint and wind. We are now attempting to develop a procedure for estimating soil-moisture deficiency, day-by-day, from precipitation, runoff and computed free-water evaporation for use in the preparation of river forecasts.

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**Observations were made at Felt Lake during the period January 1954 through December 1955. Analysis of the data is still in progress.

LAKE EVAPORATION

No attempt is made to discuss here the development of the techniques used for computing free-water evaporation, since this material is readily available in published form[3]. The results are summarized, however, because such computations constitute an integral part of the proposed procedure for maintaining an accounting of moisture deficiency and evapotranspiration.

It was found that pan evaporation could be reliably computed from dewpoint, wind and surface water temperature. Combining this empirical equation with one expressing an energy balance[4], a relation was derived for computing pan evaporation using air temperature and solar radiation (or percent sunshine[5]) instead of water temperature -- a factor not regularly observed. Moreover, it was found that a simple transformation of this relation would lead to the direct computation of lake evaporation from a shallow, free-water surface of extended proportions (Fig. 1). Entering the upper left-hand chart of this figure with air temperature, dewpoint and wind yields the computed pan evaporation ($\underline{E}_a$), assuming air and water temperature are equal. Entering the remaining charts with air temperature, solar radiation and $\underline{E}_a$, as indicated by the arrows, provides the estimated lake evaporation. It should be emphasized that this relation is applicable to shallow water bodies for which changes in heat storage can be neglected -- if changes in heat storage are appreciable, and known, proper adjustment can be made.

The studies reported in Research Paper 38 also showed that lake evaporation (neglecting changes in heat storage) is equivalent to about 0.7 pan evaporation when there is no net convective heat transfer at the pan-air interface, i.e., when air and pan water temperatures are equal. Moreover, a technique was developed for taking into account these variable effects. Thus, lake evaporation can also be computed by entering Fig. 2 with wind movement, elevation, α_p, difference in water ($\underline{T}_o$) and air ($\underline{T}_a$) temperatures, and pan evaporation. The factor α_p in this relation is the portion of advected energy through the pan which is utilized for evaporation (Fig. 3). It depends primarily upon the water temperature and wind movement (Fig. 3). Two separate relations are shown to indicate the effect of pressure (elevation).

Thus, it is seen that free-water evaporation can be estimated from either of two relations (Figs. 1 and 2). To assure proper interpretation, it is important that the Research Paper describing the development of these relations be consulted before attempting their application.

EXISTING EVAPOTRANSPIRATION CONCEPTS

Numerous techniques have been developed for estimating evapotranspiration from meteorological and/or pan evaporation data[4,6,7,8] to serve a variety of purposes. Although a description of each cannot be presented here, the salient features of several widely used methods are subsequently discussed.

Potential Evapotranspiration. Since any reduction in evapotranspiration brought about by a soil-moisture deficiency is essentially independent of concurrent meteorological conditions, it is found convenient to introduce the concept "potential evapotranspiration." Thornthwaite[9] defines potential evapotranspiration as "the water loss which will occur if at no time there is a deficiency of water in the soil for the use of vegetation," and states further that consumptive use "is equivalent to potential evapotranspiration." Blaney[10] has found that consumptive use depends upon the type of vegetative cover, while Penman contends that potential evapotranspiration is essentially independent of this factor. This apparent contradiction is believed largely the result of the misconception that consumptive use (as now computed) is always equivalent to potential evapotranspiration. To serve the purpose, potential evapotranspiration must either be independent of the nature and condition of the surface, or it must be defined in terms of a particular surface.

In the interest of clarity and reproducible results, it is proposed that potential evapotranspiration be defined as the evaporation from a free-water surface of extended proportions, but independent of any heat storage effects. The obvious advantages of the proposed definition are strongly believed to outweigh initial concern over any resulting confusion. By this definition, potential evapotranspiration becomes an element which can be determined and verified the world over. It is believed potential evapotranspiration so defined is essentially equivalent to that conceived by Thornthwaite, provided the area under consideration has complete vegetal cover and maximum usable water supply. Blaney[10] finds that the consumptive use of alfalfa* is approximately equivalent to free-water evaporation, and there is reason to believe that this type of cover approaches the optimum in its utilization of available energy. Although Penman has concluded that potential evapotranspiration is only 0.75 of the free-water evaporation, a plausible explanation of this apparent inconsistency is presented under the subsequent description of his approach.

<u>Penman Approach</u>. As discussed earlier, Penman uses an equation derived by simultaneous solution of the energy-budget and mass-transfer equations, the second of which is empirically derived. Moreover, the net radiation is normally determined by an empirical equation. Basically, the approach involves estimating free-water evaporation and applying coefficients to obtain potential evapotranspiration. When employing the method on a continuing basis, Penman[11] assumes that actual and potential evapotranspiration are equivalent so long as the moisture deficiency is less than some limiting value (root-zone constant), after which the actual evapotranspiration drops to 1/12 the potential value. In the accounting procedure, rainfall in excess of the moisture deficiency is considered as runoff, and it is assumed that no runoff occurs until the moisture deficiency is satisfied.

In deriving and verifying the empirical aspects of the method, a sunken pan (2.5 ft. in diameter by 2 ft. deep) constituted the "free-water surface." He later revised the equation[10], thus reducing the computed free-water evapo-

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*Although Blaney concludes that consumptive use for tules is about 40% greater, energy considerations lead one to question the validity of this estimate.

ration by about 10%, but the derived coefficients (0.75 annual) for converting "free-water" to "potential evapotranspiration" were based on the original equation. In applying the revised equation to data for Asheville, N. C., he computed[10] a mean annual free-water evaporation of 40 inches, which is virtually equivalent to the Class A pan evaporation. Based on computations at a limited number of other points, it appears that Penman's original equation yields free-water evaporation not greatly different than that observed for the Class A pan. Moreover, past verification of his 0.75 potential evapotranspiration coefficient from mean annual rainfall and runoff data is not independent of his assumption that actual and potential evapotranspiration are equivalent so long as the moisture deficiency in the root zone does not exceed four or five inches.

Thornthwaite Approach. In developing his method, Thornthwaite limited the study to those types of data observed at the standard climatological station -- rainfall and temperature. Consequently, it is assumed that potential evapotranspiration depends only on temperature, latitude and time of year. The deficiencies inherent in an empirical relation neglecting wind, humidity and solar radiation, in particular, are, of course, well recognized[12].

When applying the method on a monthly or normal monthly basis, Thornthwaite originally assumed actual and potential evapotranspiration to be equivalent[9] so long as the moisture deficiency was less than 4 inches. In subsequent studies employing day-by-day accounting[13], he assumes that actual evapotranspiration is proportional to the potential value and the portion of usable moisture (4 inches) remaining. In other words, evapotranspiration drops to half the potential when half the usable moisture is depleted. He also assumes that no runoff can occur until the moisture deficiency is satisfied, after which rainfall equals runoff, and that runoff increments so computed can be converted to streamflow by an arbitrary lagging procedure.

Blaney-Criddle Approach. This method[7] was designed to provide a basis for transposing consumptive use data for irrigated crops. Much the same as the Thornthwaite method, it is based on the assumption that the use (for a particular type of crop or vegetative cover) is dependent upon temperature, latitude and time of year. As originally derived, the equation included mean relative humidity as an additional factor, but this term is now customarily omitted.

CURRENT EVAPOTRANSPIRATION STUDIES

The effects of local weather on evapotranspiration are pronounced and obvious. Conversely, the broad-scale and local effects of evapotranspiration on weather, though perhaps not as well understood, are of such magnitude that the weather forecaster can ill afford their neglect. In maintaining a balance of rainfall, evapotranspiration and runoff, the moisture deficiency of a basin fluctuates widely. It is a true measure of drought severity, and is the principal factor determining the flood hydrograph of a particular storm. Thus, it is evident that any accounting procedure which will provide reliable and continuing estimates of evapotranspiration and moisture deficiency should aid Weather Bureau activities in a number of ways. Actually, the studies reported here are being undertaken by the Hydrologic Services Division in an attempt to increase the accuracy of river forecasts. The moisture deficiency index[14] used in the rainfall-runoff relations at the present time involves only precipitation and season, wherein it is assumed that evapotranspiration is at all times seasonable.

Concepts and Assumptions. The items in a basin accounting procedure are rainfall*, runoff, evapotranspiration, and moisture storage (or deficiency). In analyzing past records on a day-by-day basis, only rainfall and runoff (streamflow) are known. Storm by storm, the difference between rainfall and runoff yields the net change in moisture storage and this same difference on a mean annual basis is, by definition, evapotranspiration. Since the basin moisture deficiency as of any date is not known, it must be derived in conjunction with evapotranspiration. In the treatment here, moisture storage (or deficiency) includes surface depression and interception storage, as well as soil moisture storage. It does not include gravity water in temporary storage, since all water which eventually contributes to streamflow is treated as runoff.

Mean-basin daily precipitation is readily computed from records published in Climatological Data, but corresponding increments of runoff must be derived through hydrograph analysis of streamflow data published in the U. S. Geological Survey "Water Supply Papers." Assuming that the volume of water in groundwater storage is a function only of groundwater discharge, which is the same at times t_1 and t_2 in Fig. 4, the intervening area under the the hydrograph (expressed in inches depth over the basin) constitutes the total runoff from the storm producing the rise. For storms lasting over one day, this total is portioned among the days subjectively. It should be pointed out that the usual accounting procedure erroneously assumes that no runoff can occur until the moisture deficiency is satisfied, after which runoff equals rainfall -- available streamflow data are sometimes used to verify the procedure on a monthly or annual basis. For flood forecasting purposes, it can be assumed that runoff data up to the beginning of the storm are available. Accordingly, we can use actual increments of runoff in the accounting procedure.

Reasons were advanced earlier for considering free-water evaporation (Fig. 1 or 2) to represent potential evapotranspiration, and this assumption is made in the analysis. The method of obtaining actual from potential evapotranspiration and moisture deficiency is undoubtedly the most perplexing phase of the problem. It seems there is no agreement among authorities[15] on the manner in which moisture deficiency affects transpiration. Some investigators state that transpiration from a homogeneous plot continues at an undiminished rate until moisture content throughout the root zone drops to the wilting point, while others are equally certain that the rate is approximately proportional to the remaining available water. Be this as it may, the rate at which moisture storage is depleted from an initially saturated basin does decrease with time and approximates a log recession. This function can readily be used in an accounting procedure and would be wholly satisfactory if each storm saturated the basin. Unfortunately, it cannot properly provide

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*Snowfall requires special treatment not considered here.

for the increased evaporation immediately following a moderate storm on a dry basin. We have been unable to devise a single workable function for the purpose, and have resorted to an arbitrary separation of moisture storage into two categories. It is visualized that a portion of the moisture (say 1.0-inch capacity and termed "upper level" for convenience) is always depleted at the potential rate, and any deficiency in this type moisture must be satisfied before rainfall begins to recharge the "lower level." Depletion in the lower level occurs only when there is no remaining moisture in the upper level, in which case the rate of evapotranspiration is assumed to be proportional to the available moisture in the lower level. The equations used in daily accounting are:

$$(1)\quad d_2 = d_1 + T_p - (P-Q) \text{ when } 0 \leq d_2 \leq s$$

$$(2)\quad D_2 = D_1 + (1 - \frac{D_1}{S})T_p - (P-Q) \text{ when } d_2 > s \text{ or } d_2 < 0$$

where d and D designate moisture deficiency in the upper and lower levels, respectively; T_p is the potential evapotranspiration; P is precipitation; Q is the contribution to runoff; s and S are the storage capacities of the upper and lower levels, respectively; and the numeral subscripts 1 and 2 designate the beginning and end of the daily period. Any portion of potential evapotranspiration remaining after d has reached s (Eq. 1) is applied to Eq. (2). Likewise, any recharge ($P-Q$) above that required to reduce d to zero is carried on to Eq. (2).

Accounting Procedure. Table 1 shows the method of maintaining the water budget on a day-by-day basis as set forth in Eqs. (1) and (2), assuming $s = 1.0$ and $S = 10.0$. On days with rain, the recharge R is simply the difference between basin rainfall and the derived runoff increment ($P-Q$). The potential evapotranspiration T_p is computed from either of the lake evaporation relations, depending upon the types of data available. Values of d are derived from Eq. (1). If the recharge on a particular day is greater than that required to saturate the upper level ($d = 0$), the difference ($0 - d_2$, or simply $-d_2$) is entered in column (8) as shown for June 9th. Similarly, if there is insufficient moisture in the upper level to accomodate the potential evapotranspiration, i.e., when $T_p > (1.00 - d_1)$, then the difference (Eq. 1) is entered in column (9) as shown for June 6th. The evapotranspiration from the lower level, column (10), is taken from a graph by entering with applicable values of T_p' and D_1. Finally, D_2 is computed from D_1 and the data in column (8) or (10) in accordance with Eq. (2).

It should be emphasized that the procedure used provides a complete check over any selected period. Thus,

$$(3)\quad \sum P - \sum Q = \sum R = \sum T_E + (d_o - d_n) + (D_o - D_n)$$

where T_E, the total evapotranspiration, is (from Table 1)

$$(4)\quad \sum T_E = \sum[\text{col } (5) + \text{col } (10) - \text{col } (9)]$$

Although rainfall and runoff are based on observations, Eq. (3) is not to be construed as assuring realistic values of either evapotranspiration or moisture storage. Actually, it means only that any errors in estimated evapotranspiration are reflected (equal and opposite in sign) in the computed storage change.

There is, of course, no direct, feasible means of evaluating the moisture storage capacity of a natural basin, but soil moisture observations under wet and dry conditions are helpful. Although the capacity will vary from basin to basin, limited studies to date indicate that 8 to 12 inches is reasonable, and the assumption that 1.0 inch of this ($\underline{s}$) can be depleted at the potential rate seems satisfactory. Fortunately, neither basin constant appears to be critical in nature. If the selected capacities are too low, however, the observed recharge will sometimes exceed the deficiency -- an unrealistic consequence which should be avoided.

To determine the effect of varying the assumed storage capacities, computations were made for Rock Creek Basin in Maryland, using three different values for lower-level capacity. Although 3 years of computations were performed, error in the assumed initial moisture deficiencies renders most of the first year's results inconsistent. For the period November 1, 1951, through September 30, 1953, the computed evapotranspiration was 62.9, 62.2 and 60.0 inches when capacities of 20", 10" and 5", respectively, were assumed (Fig. 5). In the computations for $\underline{S}$ = 5", 2.4 inches of recharge occurred at times of zero moisture deficiency and, thus, produced a bias of this magnitude. The remaining minor differences result from differences in net moisture depletion during the period as derived by the three sets of computations. Thus, it is seen that the derived evapotranspiration data, after adjustment for change in moisture storage, are independent of the assumed capacity, provided the selected capacity is sufficiently large that the observed recharge never exceeds the moisture deficiency. The change in moisture storage over short periods is slightly dependent on the assumed capacity, but the deficiency at any time tends to differ by a constant when the capacity is changed. Using a capacity of 20" yields moisture deficiencies 3 to 4 inches greater than when a 10" capacity is assumed (Fig. 6) in the case analyzed, but this relationship is not independent of the climate in the area. The nature of the function is such that successive deficiencies plotted in Fig. 6 tend to follow a curve during depletion and a straight line during recharge.

Rainfall-Runoff Relations. Three types of runoff relations are feasible from the hydrologic point of view -- storm runoff, groundwater runoff and total runoff. Groundwater normally has little influence on flood peaks, and flood forecasts are, accordingly, based on predicted increments of storm runoff. In routine forecasting of the entire hydrograph, both groundwater and storm runoff are required, but each is treated separately. If computed runoff is to be used in maintaining the accounting, then total runoff is required. Even though all three values may be required to serve the intended purposes, any one can be computed by direct addition (or subtraction) of the other two.

The runoff relations are developed by coaxial correlation[16] of the pertinent factors reflecting moisture conditions in the basin and storm characteristics. It has been found that while the moisture deficiency (d and D) constitutes a good index to the runoff produced by a particular storm, there is a residual bias which is seasonal in nature. Accordingly, d, D and week of year are introduced in the correlation to provide an integrated index to moisture conditions within the basin (Fig. 7). Storm rainfall is introduced as the final variable in the correlation. Other factors remaining the same, there is a tendency for greater runoff to occur from a short, intense storm, but this effect can usually be neglected for basins several hundred square miles or greater in drainage area.

Application of Accounting Technique when Streamflow Data are not Available. Much of the interest in basin accounting procedures stems from the need for estimates of streamflow and evapotranspiration. If one is interested only in extending or extrapolating the discharge record for a particular basin, then the available records can be used to develop a runoff relation and the accounting procedure would then be applied using computed runoff. For an area void of streamflow data, one is forced to employ a runoff relation derived from data for a basin judged to be climatically and physiographically comparable. Transposition in this manner is admittedly undesirable, but it certainly constitutes an improvement over the usual method in which it is assumed that no runoff occurs until the basin is saturated, after which runoff equals rainfall.

Another purpose to be served by accounting techniques is the derivation of soil-moisture deficiency data for use in irrigation studies. Although derived values of d and D depend on the assumed capacities, they should adequately reflect changes in basin soil-moisture. Perhaps field calibration based on a few soil-moisture observations would lead to the determination of irrigation requirements throughout an extended period of time. Moreover, the runoff relation might be used to estimate the maximum quantity of irrigation water the soil can absorb without loss to runoff.

CONCLUSIONS

Our studies have not yet advanced to a point justifying evaluation of the proposed techniques. In terms of improved river forecasts, however, preliminary results are extremely encouraging. The standard error of the runoff relation in Fig. 7 is only two-thirds as large as that of the relation used in the past. Should this improvement prove indicative, the approach will very probably be applied to much of the continental United States as rapidly as feasible. This would mean that daily mean-basin values of moisture deficiency and evapotranspiration would become available for other purposes.

No attempt has been made to consider heat storage changes in the soil, and this factor may be significant on a seasonal basis. It is also to be expected that the relation between "free-water" evaporation and actual evapotranspiration varies with season. For river forecasting purposes, these effects can be adequately treated by introducing "season" in the runoff relation, but this does not assure that the derived moisture-deficiency and evapotranspiration data are free of seasonal bias. If observations show that a seasonal bias exists, correction could perhaps best be made by applying coefficients to the derived potential evapotranspiration data.

It is believed the approach under study is more realistic in several important respects than water-balance techniques now in use. Hydrologic congruity is assured when keying the daily accounting procedure to observed streamflow and, in the absence of discharge data, a crude rainfall-runoff relation should be better than assuming a "saturation threshold." In the proposed approach, on the other hand, a storage capacity is selected such that the basin neither reaches saturation nor total depletion. It would also seem that free-water evaporation derived from Fig. 1 or 2 should constitute a better measure of evapotranspiration potential than can be derived from temperature, latitude and time of year.

Washington, D. C.
March 5, 1957

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Table 1. Example of daily accounting procedure

Date	Precip- itation (P)	Runoff (Q)	Recharge (R)	Potential Evapotr. (T_p)	Moisture Deficiency Upper (d)	Moisture Deficiency Lower (D)	Lower Level R'	Lower Level T_p'	$(1 - \frac{D_1}{10})T_p'$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
					.55	4.40			
6/5/51				.24	.79	4.40			
6				.26	1.00	4.43		.05	.03
7				.25	1.00	4.57		.25	.14
8	.75	0	.75	.12	.37	4.57			
9	2.43	.15	2.28	.15	0	2.81	1.76		
10				.22	.22	2.81			
11				.26	.48	2.81			
12				.21	.69	2.81			
13	.42	.02	.40	.13	.42	2.81			
14				.24	.66	2.81			
15				.26	.92	2.81			
16				.21	1.00	2.90		.13	.09
17				.15	1.00	3.01		.15	.11
18	1.35	.09	1.26	.11	0	2.86	.15		
19	.42	.03	.39	.13	0	2.60	.26		
Σ	5.37	.29	5.08	2.94			2.17	.58	.37

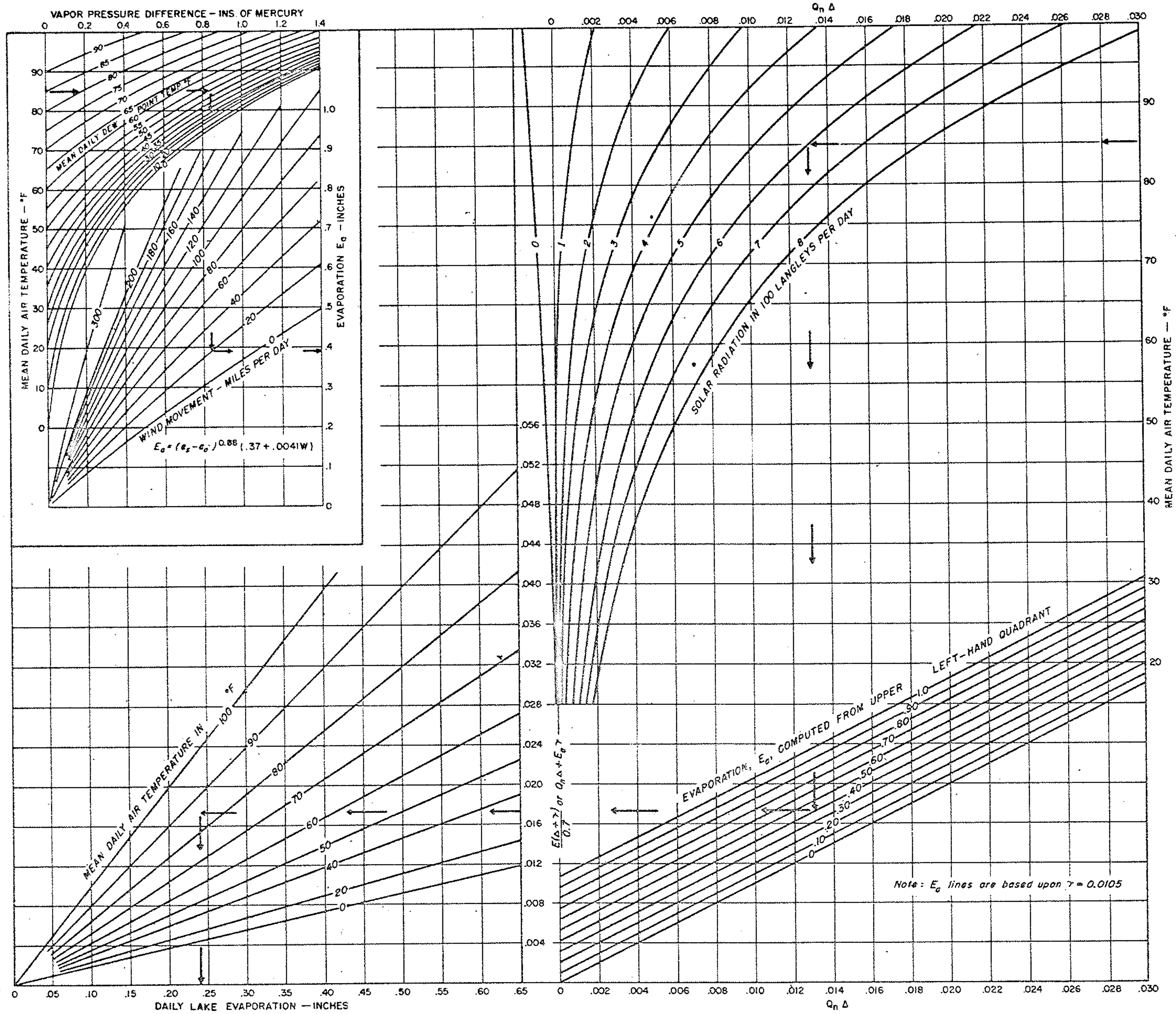

FIG. 1. FREE-WATER EVAPORATION AS A FUNCTION OF METEOROLOGICAL FACTORS.

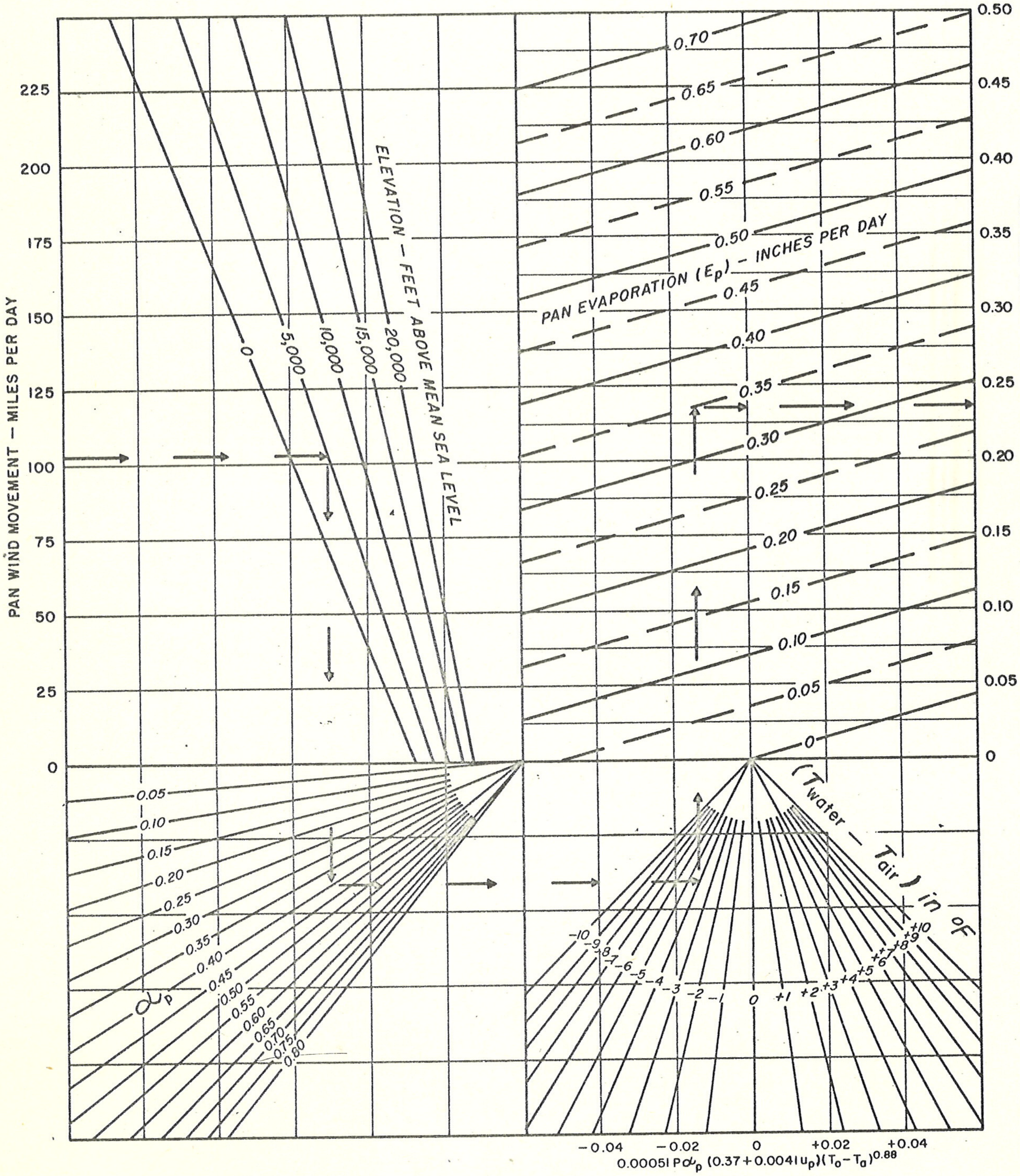

FIGURE 7. GRAPHICAL PRESENTATION OF EQUATION 14.

Fig. 2. Free-Water Evaporation As A Function Of Class A Pan Evaporation And Factors Determing Heat Flow Through The Pan.

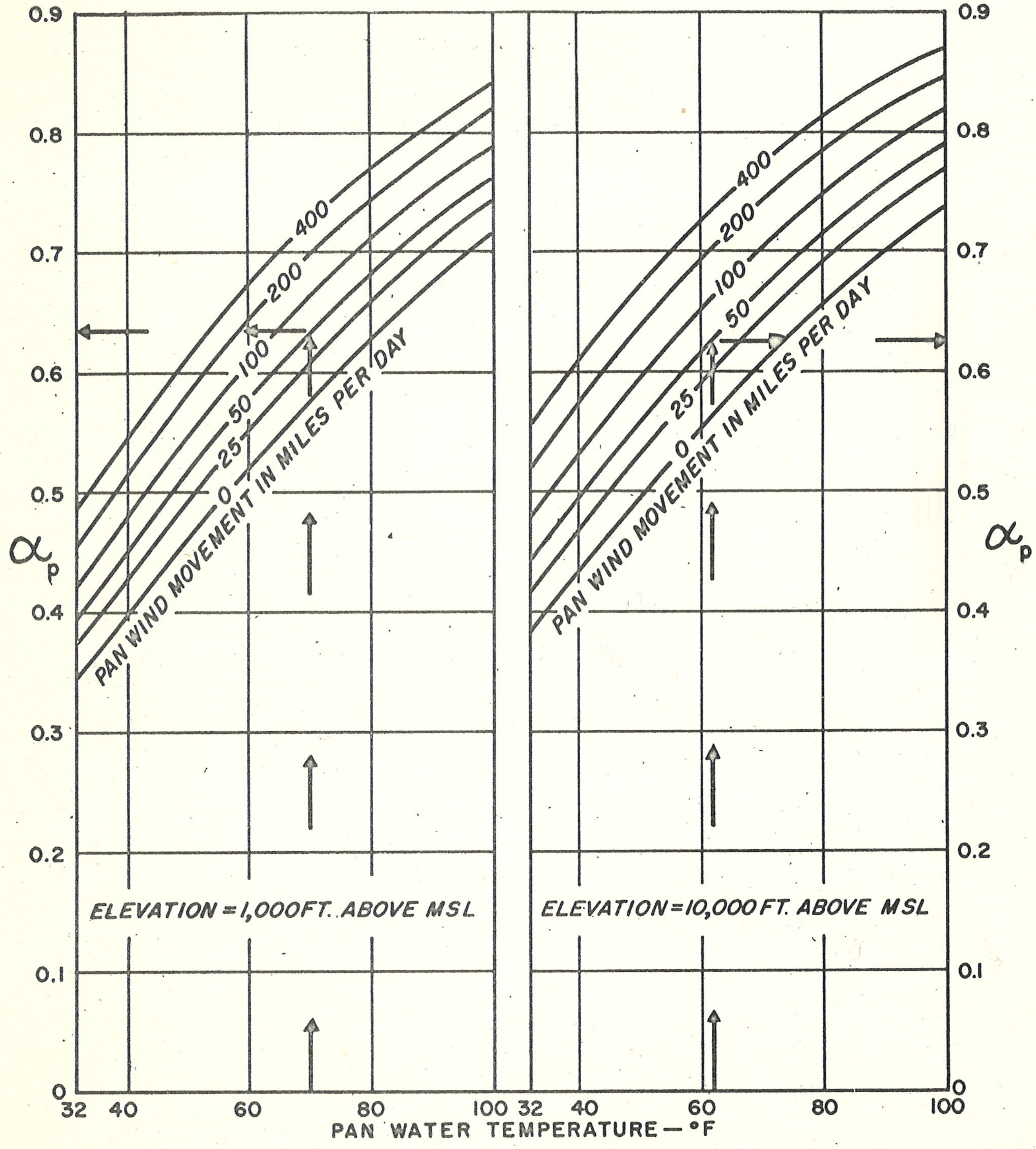

Fig. 3. PROPORTION OF ADVECTED ENERGY (INTO CLASS A PAN) UTILIZED FOR EVAPORATION.

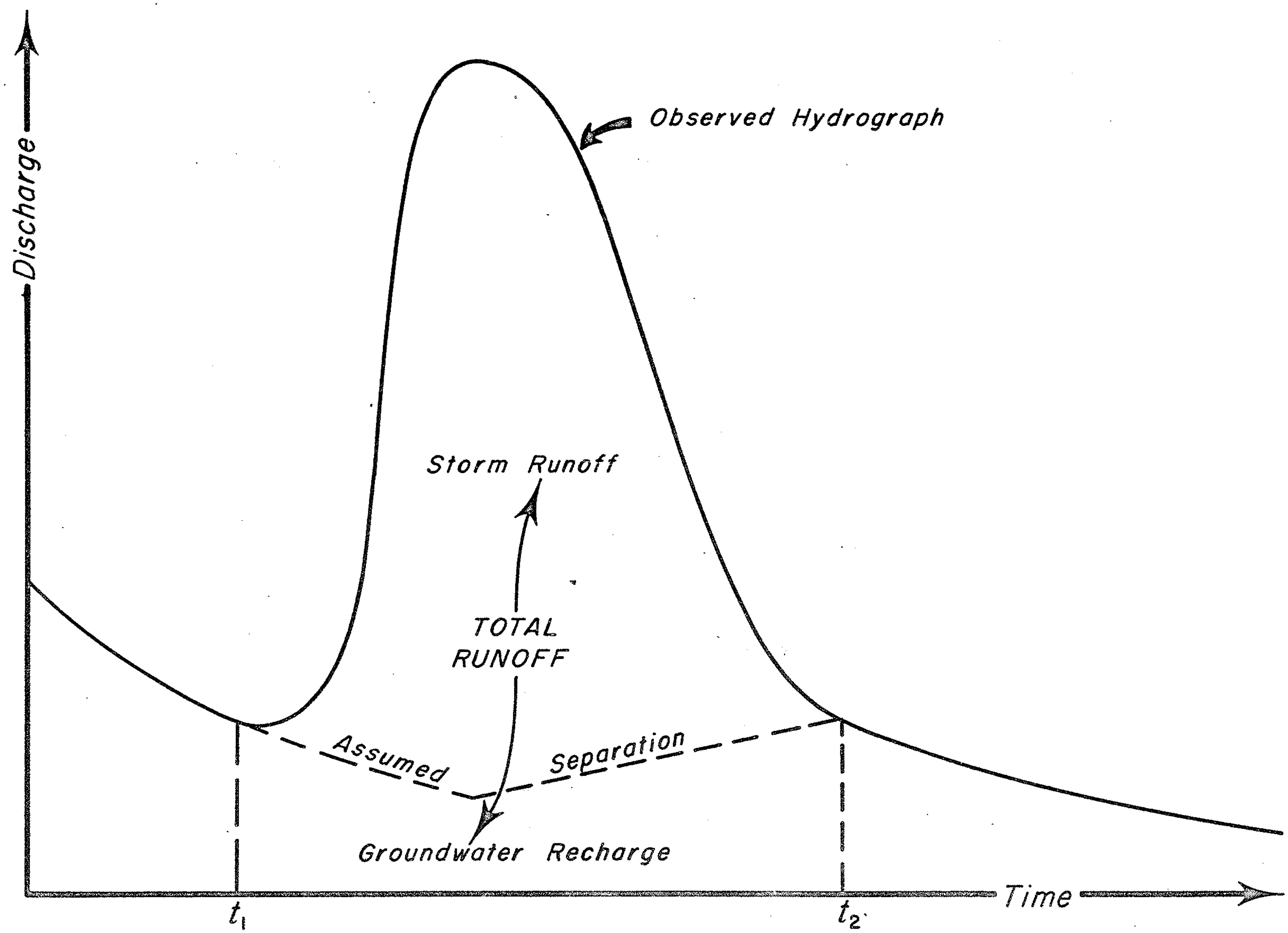

Fig. 4. METHOD OF HYDROGRAPH SEPARATION

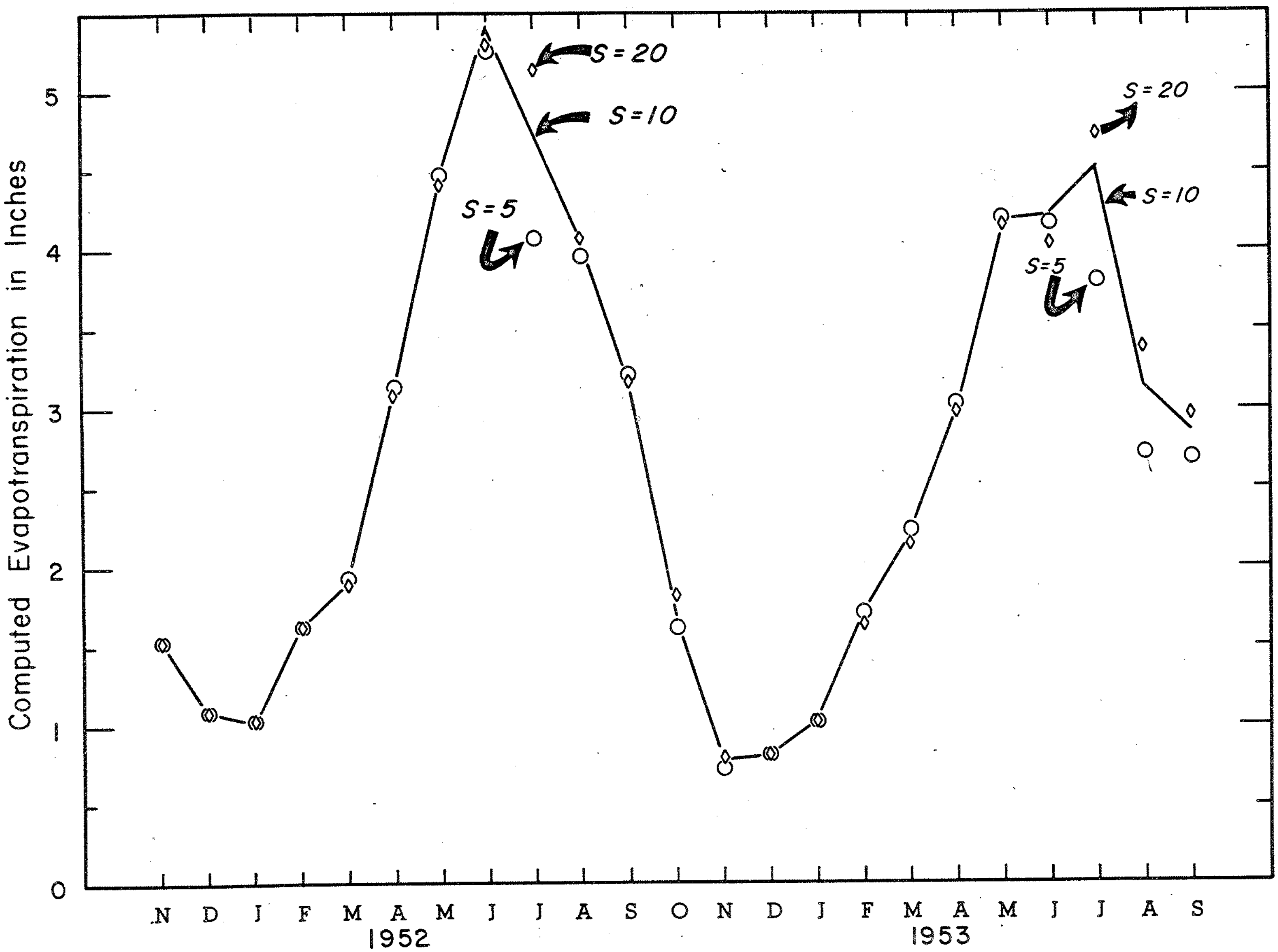

Fig. 5. EVAPOTRANSPIRATION FOR ROCK CREEK BASIN, MD., USING LOWER-LEVEL CAPACITIES OF 5, 10 AND 20-INCHES.

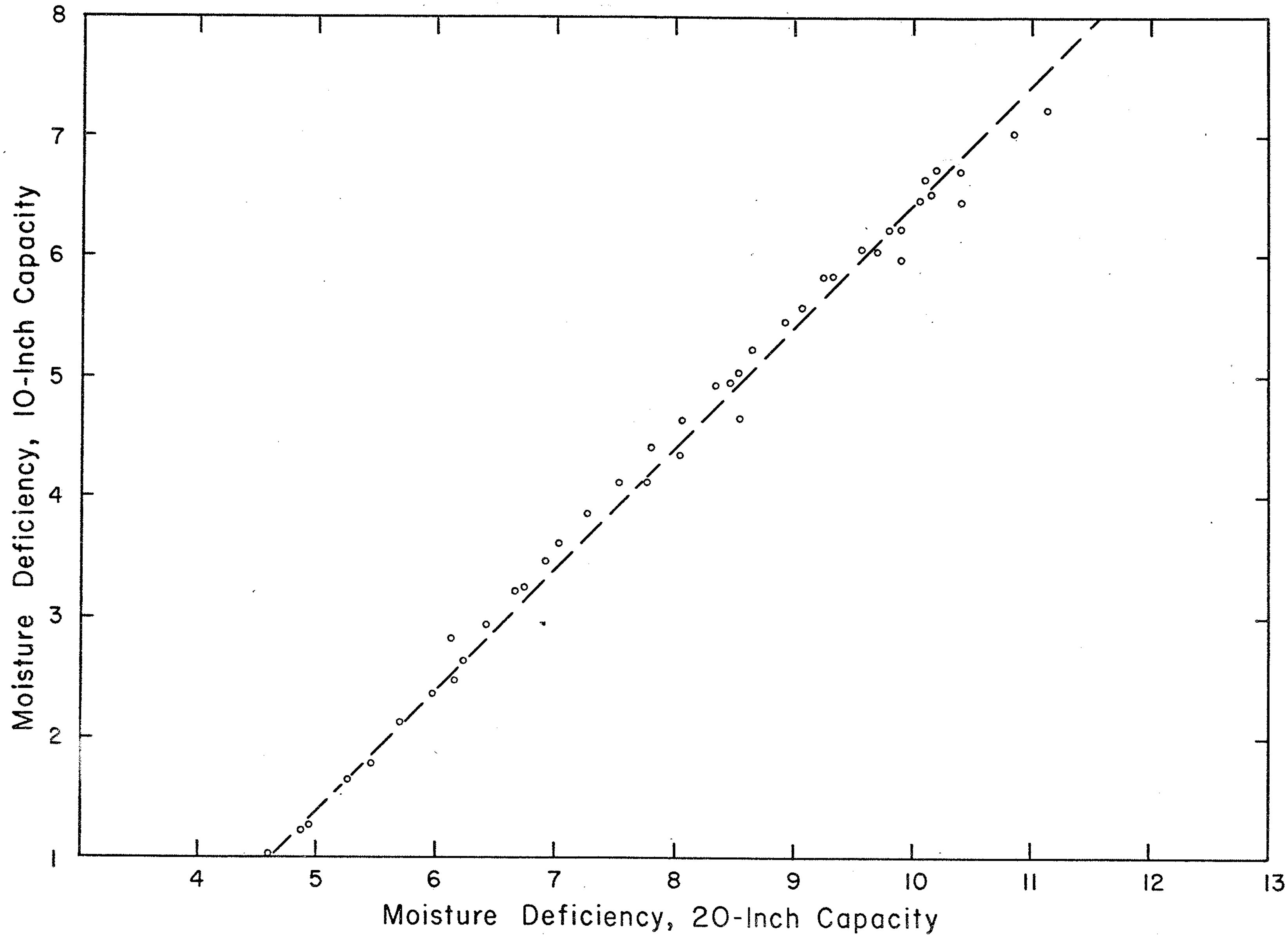

Fig. 6. The Effect Of Assumed Lower-Level Capacity On Derived Moisture Deficiency

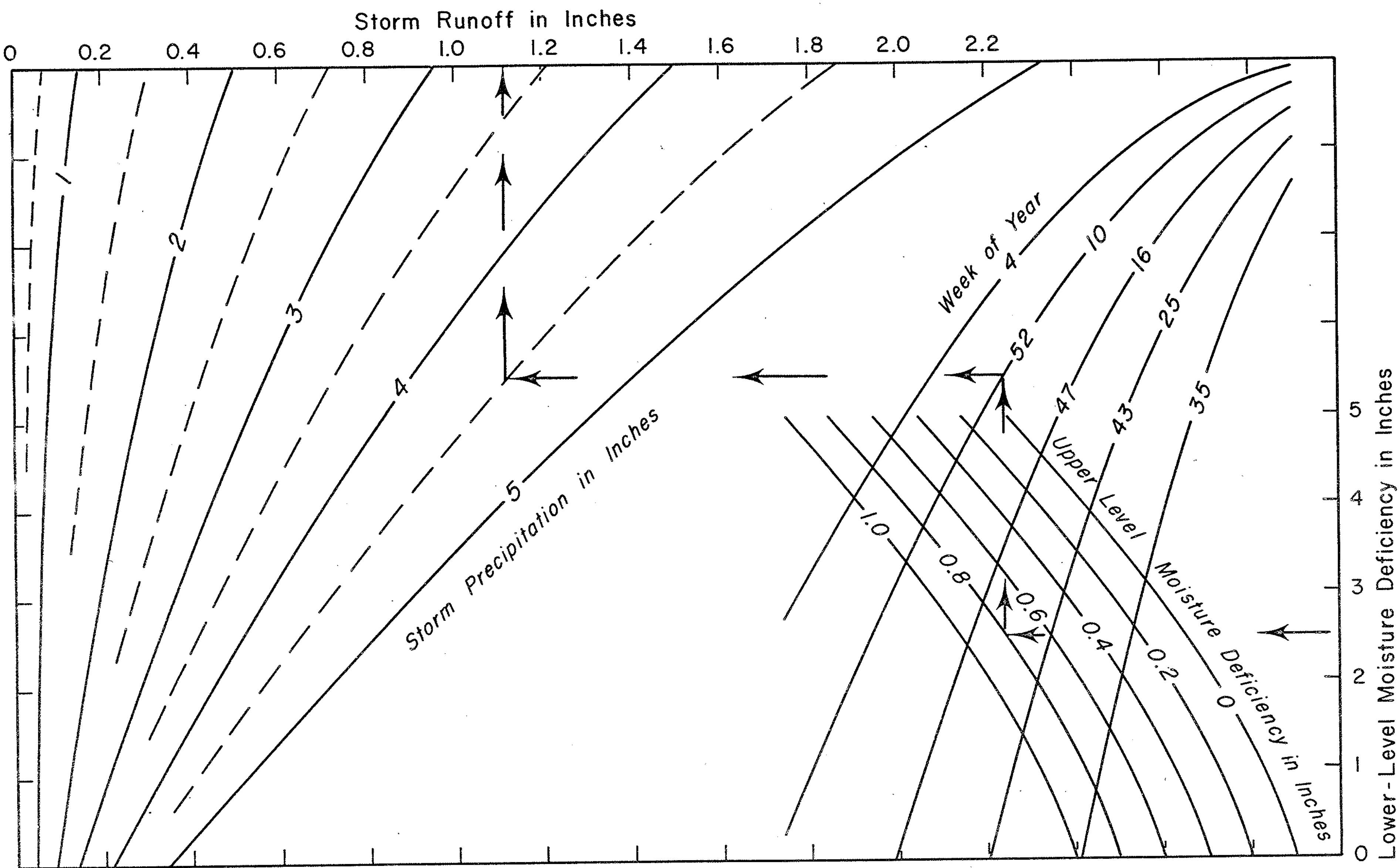

Fig. 7. Runoff Relation For Valley River Basin Above Tomotla, N.C., (104 Sq. Miles)