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EVALUATING IRRIGATION EFFICIENCY[a]

By Marvin E. Jensen,[1] M. ASCE

INTRODUCTION

Irrigated agriculture is and has been the largest user of fresh water, but it also has been accused of being an inefficient and uneconomical user. A major part of the water used by irrigated agriculture is vaporized (evapotranspiration), in contrast to other uses that do not "consume" water. Evapotranspiration is largely controlled by meteorological conditions when adequate water is provided, and a full crop canopy exists. Significant reductions in evapotranspiration, without corresponding yield reductions, on the bulk of the 44,000,000 acres of irrigated land in the United States is possible, but is not economically feasible now (in 1967), or in the near future. In contrast, significant reductions in canal seepage, deep percolation, runoff, and operational wastes may be economically feasible now.

The agricultural industry has, during the past two decades, increased its efficiency of producing food and fiber per unit of water vaporized by using better crop varieties, insect control, improved irrigation and agronomic practices, and inorganic fertilizers. Further increases are possible and are being developed through research, but additional increases are not expected to be proportionally as great as those that have occurred during the past quarter century (since the 1940's).

Improvements in the efficiency of the physical control of irrigation water have been evident, but these improvements often are not as easily put into effect as merely changing the crop variety, or applying fertilizer. For example, a reduction in canal seepage may require large expenditures of money and major construction programs. Similarly, an increase in the irrigation

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[1] Research Investigations Leader, Water Mgt., Northwest Branch, Snake River Conservation Research Center, Kimberly, Idaho.

efficiency on the farm would require the installation and use of water-measuring devices or controls that limit the volume of water delivered to each field. A farmer recognizes the necessity of measuring or controlling the amount of seed planted, or the amount of fertilizer used because costs are proportional to the amount used. In contrast, the necessity of measuring or controlling the amount of water used for irrigation is often ignored because of habit, and water costs generally are not distributed in direct proportion to the volume used. Under good irrigation practices, crop yields are not proportional to the amount of water used. In many cases, yields actually decrease when excessive water is applied.

Data reflecting all of the economic losses caused by excessive water use are meager and difficult to secure, and available data are commonly de-emphasized by the users' water-right. Thus, the incentive to increase irrigation efficiency on the farm "appears" to be small or, in many cases, even absent at the present time. Economic incentives are becoming more apparent, however.

In some areas, legal action has forced the water user to improve irrigation efficiency. Voluntary improvement by the irrigator, project, or river basin is preferred. Voluntary improvement measures will require self-evaluation by the projects to delineate the sources of waste. Uniform evaluation procedures—including agreement on what constitutes necessary and beneficial water use—are prerequisite to the determination of the magnitudes of these wastes.

The writer's objectives are to delineate necessary and beneficial uses of water, and to describe practical and economical methods for evaluating the efficiency of irrigation systems and projects.

IRRIGATION: ITS PURPOSE AND EFFECTIVENESS

The purpose and need for irrigation must be understood before necessary and beneficial uses of water can be defined. Irrigation is generally considered as the application of water to the soil, supplementing natural precipitation for the purpose of supplying water essential to plant growth.[2]

Plants extract water from the soil but leave behind most of the dissolved salts. Water evaporating from the soil surface is salt free. Sustained crop production in an irrigation project requires the maintenance of both a favorable soil moisture tension and a favorable salt concentration. The only practical means of controlling the salt concentration in the soil today is to allow a fraction of the water applied to the soil to pass through the root zone (leaching). The quantity of water that must be allocated to leaching is proportional to the weighted average concentration of soluble salts in the applied water, C_{aw}, the volume of water vaporized by evapotranspiration, W_{et} and inversely proportional to the concentration that can be tolerated in the root zone, C_r (which varies with soil moisture content; for convenience, let C_r = the concentration near field capacity). Where rainfall is light or negligible, the salt concentration in the applied water (rainfall + irrigation water) is essentially the same as in the irrigation water, C_{iw}.

[2] Israelsen, O. W., "Irrigation Principles and Practices," 2nd Edition, John Wiley & Sons, Inc., New York, N. Y., 1950, 405 pp.

Irrigation Efficiency.—The quantity of water that is essential and effectively used to control salts must be recognized as a beneficial and necessary use of water in order to evaluate the efficiency of irrigation systems. Thus, irrigation efficiency should be defined as follows:

> Irrigation Efficiency, E_i, is the ratio of the volume of irrigation water transpired by plants and evaporated from the soil and plant surfaces, plus that necessary to regulate the salt concentration in the soil solution, and that used by the plant in building plant tissue, to the total volume of water diverted, stored, or pumped for irrigation.

This definition takes into account all losses of water that occur after the water in a natural stream or aquifer is controlled or removed specifically for irrigation purposes. The theoretical maximum efficiency for sustained high crop yields in an arid area with this definition is 100%. Expressed analytically per unit area of irrigated land, and neglecting the water in the plant tissue, irrigation efficiency under steady-state conditions, or for long periods of time such as crop seasons, becomes

$$E_i = \frac{W_{et} + W_L - R_e}{W_i} 100 \qquad (1a)$$

in which E_i = over-all irrigation efficiency in percent for the farm, project, or basin as specified; W_{et} = the volume of water vaporized by evapotranspiration; W_L = the volume of water necessary for leaching on a steady-state basis; R_e = the volume of effective rainfall; and W_i = the volume of water that is diverted, stored, or pumped specifically for irrigation.

If the time period used is not long and a change in water stored in the soil root zone during the period is large enough to affect the computed irrigation efficiency, then the change in water stored in the soil must also be considered. Thus,

$$E_i = \frac{W_{et} + W_L - R_e + \Delta W_s}{W_i} 100 \qquad (1b)$$

The change in stored soil water, ΔW_s, will be negative if there is a decrease and positive if there is an increase from the beginning to the end of the time period used.

Effective rainfall is total rainfall minus runoff and deep percolation that may occur during heavy rains or rains following a thorough irrigation. If deep percolation due to rainfall during the growing season satisfies part of the water required for leaching, then it is also part of effective rainfall.

This definition of irrigation efficiency differs from the commonly used definition by the inclusion of W_L in the numerator of Eq. 1. Other writers have also expressed the need to define irrigation efficiency in order to recognize operational procedures that are essential in providing a soil environment favorable to a crop when considering both soil moisture tension and salinity.[3,4]

[3] Reeve, R. C., "The Relation of Salinity to Irrigation and Drainage Requirements," Proceedings, 3rd Congress of the Internatl. Comm. on Irrig. and Drainage, R. 10, Q. 10, 1957, pp. 10.175-10.187.

[4] Hall, W. A., "Performance Parameters of Irrigation Systems," Transactions, Amer. Soc. of Agric. Engrs., Vol. 3, No. 1, 1960, pp. 75-76, and 81.

Eq. 1 can be applied to any irrigated unit such as a project or segment thereof. A question may arise when water lost from canals by seepage and surface runoff from farms is relifted or rediverted into the distribution system. How should this water be treated when comparing the irrigation efficiency of two projects? A simple rule can be used for this purpose. When the entire project is being evaluated to determine its ability to use water effectively, then water that is relifted or diverted should not be added to W_i if it was diverted or pumped within the same season and has a salt concentration essentially the same as the irrigation water. The larger the volume of water that is relifted or rediverted within a project, the smaller the required value of W_i. A higher over-all irrigation efficiency can be obtained for the project if W_i is reduced, but not if W_i remains the same. When drainage water is reused within a project and has a salt concentration that is significantly greater than the irrigation water, then the computation of irrigation efficiency becomes more complex because the water required for leaching also changes. Under these conditions a nonsteady-state analysis should be considered.

COMPONENTS OF IRRIGATION EFFICIENCY

The over-all irrigation efficiency is often subdivided into several components in order to evaluate the efficiency of segments of the system. Component analysis may be necessary where systems are not comparable in their entirety. The efficiencies of segments of the system are also usually expressed as percentages. These are defined beginning with the reservoir used to store irrigation water.

Reservoir storage efficiency, E_s, is the ratio of the volume of water delivered from the reservoir for irrigation, to the volume of water delivered to the storage reservoir—surface or underground—for irrigation.

Water conveyance efficiency, E_c, is the ratio of the volume of water delivered by an open or closed conveyance system to the volume of water delivered to the conveyance system at the supply source or sources.

Unit irrigation efficiency, E_u, is the ratio of the volume of irrigation water used in evaportranspiration in the specified irrigated area, plus that necessary to maintain a favorable salt concentration in the soil solution, to the volume of water delivered to this area.

The efficiencies of components of an irrigation system are defined so that the product of the component efficiency terms, expressed as ratios, gives the over-all irrigation efficiency.

$$E_i = \frac{E_s}{100} \frac{E_c}{100} \frac{E_u}{100} 100 \qquad (2)$$

The component efficiency terms also may be applied to any project or segment thereof for any specified period of time. For clarity and comparative purposes, all efficiency values reported should be identified as to the size of the unit, the period of time or number of irrigations involved, the adequacy

of irrigations, and the computational procedure used in obtaining the efficiency values.

Variation in operational procedures can cause marked differences in irrigation efficiencies of identical field systems. Reliable evaluation of the basic capabilities of two systems can be made only when the systems are operated to give the same adequacy of irrigation over the same percentage of the fields, and when operated as the designer intended.

Leaching Requirement and Irrigation Efficiency.—The water used to maintain a favorable salt concentration is considered necessary and beneficial herein. The volume of water required for leaching under steady-state conditions, or when considering the total depths of water applied over a long period of time, can be expressed as a function of W_{et} and the salt concentrations in the water, as shown in Eq. 3. This equation is applicable when the precipitation of salts or the reduction in crystalline materials in the soil is negligible during the time period.

$$W_L = \frac{C_{aw}}{\alpha\, C_r} W_{et} \qquad (3)$$

In Eq. 3, α = the leaching efficiency expressed as a fraction, and C_r = the average concentration of salts in the water in the root zone. The average concentration of salts in the drains may not be representative of the average salt concentrations of the water in the root zone near field capacity because of nonuniformity in leaching. (Excessive percolation in sandy areas or through large cracks and pores, and, in some cases, drain water also may be diluted with surface runoff.) The nonuniformity, represented by α, is a coefficient expressing the ratio of the average salt concentration in the drainage water to the average concentration of the soil water in the root zone at a water content near field capacity. Expressed analytically,

$$\alpha = \frac{C_{dw}}{C_r} \qquad (4)$$

The ratio C_{aw}/C_{dw} is the same as the "leaching requirement" when the salt concentration in the irrigation water is taken as the weighted average of rainwater and irrigation water. A more complete description of this ratio, its limitations, and the significance of the assumptions involved can be found in other references.[5,6]

The concentration of salts in the water is commonly indicated by its electrical conductivity, *EC*. The salt concentration values in Eqs. 3 and 4 can be replaced by electrical conductivity values. An examination of the tolerance of various species of plants to salinity, the influence of specific ions, stage of growth, climate, and the influence of the minimum soil water level maintained has been presented by Bernstein.[7] On new lands or on lands in which excessive amounts of salts have accumulated, the volume of water required for initial leaching should be based on a non-steady-state analysis.

[5] "Diagnosis and Improvement of Saline and Alkali Soils," Agriculture Handbook No. 60, Salinity Lab., U. S. Dept. of Agric., Washington, D. C., 1954, 160 pp.

[6] Wilcox, L. V., "Salt Balance and Leaching Requirement in Irrigated Lands," Technical Bulletin 1290, U. S. Dept. of Agric., Washington, D. C., 1963, 23 pp.

[7] Bernstein, L., "Tolerance of Plants to Salinity," Journal of the Irrigation and Drainage Division, ASCE, Vol. 87, No. IR4, Proc. Paper 3005, December, 1961, pp. 1-12.

A simple example will illustrate the importance of considering leaching as a necessary and beneficial use of water.

Example 1.—Comparing the irrigation efficiency of two field systems:

Data.

Field A, W_{et} = 36 acre-in. per acre, R_e = 10 acre-in. per acre, W_i = 40 acre-in. per acre, EC_{iw} = 0.5 mmhos per cm, EC_r = 10 mmhos per cm, α = 0.9.

Field B, W_{et} = 36 acre-in. per acre, R_e = 10 acre-in. per acre, W_i = 50 acre-in. per acre, EC_{iw} = 3 mmhos per cm, EC_r = 10 mmhos per cm, α = 0.9.

Calculations.

Field A, $EC_{aw} = [(10)(0) + (40)(0.5)]/50 = 0.4$ mmhos per cm, W_L = 1.6 acre-in. per acre (Eq. 3), field E_i = 69% (Eq. 1).

Field B, $EC_{aw} = [(10)(0) + (50)(3)]/60 = 2.5$ mmhos per cm, W_L = 10 acre-in. per acre (Eq. 3), field E_i = 72%.

The major difference between these two fields is the quality of irrigation water being used. The efficiencies are 69% and 72% for fields A and B, respectively, when considering the leaching requirement as a beneficial use. If the water required for leaching is not considered a beneficial use, as is often done, the calculated field irrigation efficiencies would have been 65% for field A and 52% for B, indicating that in field B, water was not being used as efficiently as the first when, in essence, water was actually being used more efficiently.

EVALUATING IRRIGATION EFFICIENCIES

The key to evaluating irrigation efficiency is accurate water measurement. Many irrigation projects do not have adequate facilities for measuring water diverted, stored, transported, and delivered to the irrigated farm. Likewise, many irrigation farms have no provisions for measuring water delivered to various fields. In some cases, the disposition of water can be estimated with accuracy comparable to actual measurement, and often at only a fraction of the cost. A brief summary of the probable accuracy of component efficiency terms is presented to illustrate when water measurement may be economical and practical in the evaluation of irrigation efficiency. A diagrammatic sketch illustrating the disposition of water diverted for irrigation is presented in Fig. 1.

Reservoir Storage Efficiency.—An example will be used to illustrate the accuracy of determining reservoir storage efficiency. If common water-measuring structures are installed at points 2 and 3 in Fig. 1, and these structures are capable of an accuracy of ± 3%, what will be the accuracy of the calculated reservoir storage efficiency?

Example 2.—Evaluating the accuracy of reservoir storage efficiency determinations:

Data.—Working storage capacity 100,000 acre-ft, surface area 2,000 acres, seepage loss 5,000 acre-ft, evaporation loss 6,000 acre-ft, water measurement accuracy ± 3%.

Calculations.—Inflow = 100,000 ± 3,000 acre-ft, outflow = 89,000 ± 2,670 acre-ft, reservoir storage efficiency = 89 ± 5%.

The calculated reservoir storage efficiency in example 2 is 89 ± 5%. The water lost from the reservoir would be measured within about ± 52%. Using an alternate approach, the evaporation from the reservoir can be estimated within about 10%. Assume a measuring structure at point 3 capable of an absolute accuracy of 3% as before, and that all of the seepage returns to the stream in such a manner that it can be measured within 5% with a small structure. The calculated reservoir storage efficiency would now be 89 ± 1.1%, and the estimated water loss from the reservoir would be within about ± 8% (example 3).

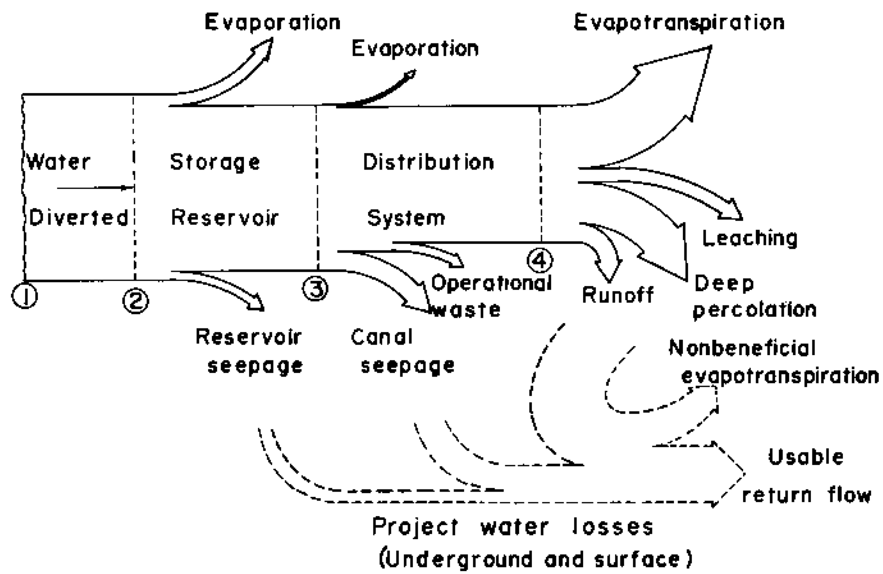

FIG. 1.—DISPOSITION OF WATER DIVERTED FOR IRRIGATION

Example 3.—Alternate approach to evaluating the accuracy of reservoir storage efficiency determinations:

Data.—Same as in example 2.

Calculations.—Estimated evaporation loss = 6,000 ± 600 acre-ft, seepage flow to the stream = 5,000 ± 250 acre-ft, total loss from the reservoir = 11,000 ± 850 acre-ft, inflow = 100,000 ± 3,520 acre-ft, reservoir storage efficiency = 89 ± 1.1%.

These simple examples illustrate that, in some cases, estimates are completely adequate and justifiable for evaluating reservoir storage efficiency.

Water Conveyance Efficiency.—The problems encountered in evaluating water conveyance efficiency also involve water measurement. The example project used in the previous section can be used to illustrate the probable accuracy of calculated water conveyance efficiencies. Assume that a total of 89,000 acre-ft of water, W_c, was diverted or released from storage during a growing season, and this water was measured at point 3 in Fig. 1 with an accurate flow measuring structure. For illustrative purposes, the errors involved in all water measuring structures used in the remainder of this discussion are assumed to be random, proportional to the flow rate, and normally distributed. The coefficient of variability is (σ/μ) 100, in which σ = the standard deviation and μ = the mean. If a 95% confidence level is selected, ($\pm$ 2 σ), 95% of the time the volume of water measured will be $W \pm 2\sigma$. If there are n farm combination turnout-measurement structures, the average amount of water delivered to each farm during the season would be $W_1, W_2, \ldots, W_n$ acre-ft. If the volumes of water measured by these structures are independent and the errors are random and normally distributed, then the sum of the individual measurements also will have errors that are normally distributed. The total volume of water delivered to the n farms, W_f, will be

$$W_f = W_1 + W_2 + \ldots + W_n \quad (5)$$

The standard deviation of the total volume of water delivered will be

$$\sigma_f = \sqrt{\sigma_1^2 + \sigma_2^2 + \ldots + \sigma_n^2} \quad (6)$$

If the flow measurement at point 3 and the flow measurements at the farms are independent, the standard deviation of the loss in the distribution system will be

$$\sigma_{(W_c - W_f)} = \sqrt{\sigma_{W_c}^2 + \sigma_{W_f}^2} \quad (7)$$

These equations would also be applicable to flow rate values. However, changes in water stored in the distribution system may become significant and should be considered.

An example will illustrate the probable accuracy of determining losses by inflow-outflow procedures.

Example 4.—Evaluating the accuracy of water conveyance efficiency determinations:

Data.—Coefficient of variability of the water measurement structure at point 3 = 1.5%, 200 farm turnout-measurement structures, each delivering 400 acre-ft with a coefficient of variability of 2.5%.

Calculations.—Total water delivered = 80,000 acre-ft (Eq. 5), σ_{W_c} = 1,335 acre-ft, $\sigma_1, \sigma_2, \ldots, \sigma_n$ = 10 acre-ft, σ_{W_f} = 141 acre-ft (Eq. 6), $\sigma_{(W_c - W_f)}$ = 1.342 acre-ft (Eq. 7).

If, as illustrated in example 4, there are 200 farm combination turnout-measurement structures, each delivering 400 acre-ft during the season, the standard deviation of the total water delivered to the farms will be 141 acre-ft, and 95% of the time the total measured flow will be 80,000 ± 282 acre-ft. The true distribution system loss in this example would be 9,000 acre-ft or 10.1 percent of the flow delivered to the system. The standard deviation of the loss would be 1,342 acre-ft and 95% of the time, measured loss would be 10.1 ± 3.0% of the flow delivered to the system. Thus, even with better-than-average water measuring devices the loss in this example could be measured with an

accuracy of only ± 30% by this inflow-outflow method. If the errors are random and there is no bias, then repeated measurements will improve the accuracy.

In practice, water measurement at individual turnouts all may be biased in one direction because of several factors; e.g., the ditch rider may deliver slightly more water than reported in order to maintain good working arrangements with the unit operator, sediment may accumulate ahead of weirs, etc. Under these conditions, the errors in measurement would be biased in addition to random errors. For example, if there was an average bias of 3% in favor of the unit operator, 80,000 acre-ft would have been delivered and only 77,600 acre-ft reported. The calculated loss would now be 11,400 ± 2,684 acre-ft. The loss measurement in this case would be between −3 to +56% of the true value. The relative accuracy of inflow-outflow measurements would improve with more loss and decrease with less loss.

These examples illustrate two significant points: (1) the accuracy of the main water measuring structure at point 3 is the primary factor determining the accuracy of calculated water loss if the water measurement errors at each farm delivery are random; and (2) if the errors in the farm water measurements are not random, but are all biased in one direction, then the accuracy of water measurement to individual farms may be just as important as the accuracy of the main measuring structure when calculating distribution system losses.

The coefficient of variability of many water measuring structures in use may be closer to 5% for the main structure and 10% for individual farm turnouts. Under these conditions the accuracy of loss measurements in example 4 would be 9,000 ± 8,972 acre-ft or ± 100%.

These examples illustrate that other methods of determining losses such as seepage may be just as reliable and more versatile unless accurate field calibrations can be obtained for the measuring structure. Seepage measurements (including nonbeneficial use by phreatophytes) are desired during the irrigation season when the canals are in use. Ponding tests in specific sections of the canals often cannot be made except at the beginning and end of the season. Direct measurements of seepage do not require as much accuracy to provide results comparable with inflow-outflow methods.

Recent studies in southern Idaho indicated that only eighteen seepage measurements using an improved seepage meter[8] would have given a seepage value having an estimated standard error of the mean of 15%. This indicates that 95% of the time, this value would have been within 30% of the true mean if the seepage measured at individual points was representative of the true value at that point. Similarly, 40 measurements would have given an estimated standard error of the mean of about 10%. The elimination of about two to four unusually high values would have reduced the estimated standard error of the mean by one-half.[9]

Some evaporation takes place directly from the water surfaces in the distribution system (Fig. 1), but these losses generally are negligible. For example, if the project being considered had 20 miles of canals with an average surface width of 15 ft, the surface area would be about 36 acres. If the annual lake

[8] Bouwer, H., and Rice, R. C., "Seepage Meters in Seepage and Recharge Studies," Journal of the Irrigation and Drainage Division, ASCE, Vol. 89, No. IR1, Proc. Paper 3448, March, 1963, pp. 17-42.

[9] Brockway, C. E., and Worstell, R. V., personal communication, May, 1965.

evaporation in the area was 3 acre-ft per acre, approximately 108 acre-ft or 0.1% of the inflow would be lost by direct evaporation from the water surfaces.

Operational wastes, such as leakage at canal gates and water that must be released at the lower end of the canal because of unpredictable changes in water deliveries, are usually small. Operational wastes of about 5% are not considered unreasonable, although in example 4, a 5% operational waste would have provided enough water for ten farm units. When operational wastes and evaporation occur, the standard deviation of seepage measurements can also be estimated using Eq. 7, provided these losses are considered as part of W_f calculated using Eqs. 5 and 6.

The combined water storage and conveyance efficiency of the previous example at the point of water delivery to the farm would be 80% if there were no operational waste, and 76% if 5% of the flow into distribution system were wasted and evaporation losses were negligible.

Unit Irrigation Efficiency.—Unit irrigation efficiency can be calculated using Eq. 1. The major problem associated with the evaluation of irrigation efficiency for a unit is determining the magnitude of W_{et} for the season between irrigations. A detailed examination of this problem is pertinent herein, and various methods of determining W_{et} are briefly described subsequently.

Farm and Field Irrigation Efficiency.—Farm and field irrigation efficiencies are commonly based on seasonal evapotranspiration and water deliveries. In addition, only the evapotranspiration from planting to harvest is used, although some evaporation takes place from the soil before the crop is planted and some evapotranspiration occurs after harvest because of weeds and regrowth. The irrigation efficiency calculations made using Eq. 1 reflect all nonbeneficial uses of water on the farm or field, e.g., seepage from farm ditches, unnecessary deep percolation, and runoff.

Project Irrigation Efficiency.—When considering all factors influencing annual irrigation efficiency on the farm, it is not uncommon to find that runoff may average 15%, and deep percolation above leaching requirements (including farm ditch losses) averaging 30% of the water delivered to the farm. The farm irrigation efficiency in this case would be 55%. The project irrigation efficiency, using data from example 2 with a reservoir storage efficiency of 89%, a water conveyance efficiency of 85%, and a farm irrigation efficiency of 55%, would be 42% (Eq. 2).

In the example (illustrated in Fig. 1), a part of the water lost from the reservoir by seepage, 5,000 acre-ft, the water lost by canal seepage, 9,000 acre-ft, the farm runoff, 11,333 acre-ft, and the deep percolation, 22,665 acre-ft, could be recirculated and reused within the project (assuming negligible additional evaporation and operational waste). However, the project irrigation efficiency could not be increased unless the water was applied to new land or W_i was reduced because W_{et} and W_L requirements would not change materially. If 60% of these losses were recovered (28,800 acre-ft) and delivered to additional farm land and used at the same farm irrigation efficiency, the project irrigation efficiency could be increased to 57%.

If most of the seepage and surface runoff is recovered in the river channel and reused on another project downstream, then the river basin irrigation efficiency would reflect this reuse. Under these conditions, large expenditures of funds to improve irrigation efficiency within a project may not seem justified because most of the water is still being put to beneficial use. However, the advantages of using gravity distribution—an important economic factor—may be lost, and operational costs, maintenance, and drainage costs within a project may be higher than necessary.

Nonbeneficial water use by phreatophytes may occur along the stream channel. If nonbeneficial use of waste water from a project is large, then the improvement of project irrigation efficiency may be necessary and economical for a river basin. Other economical benefits from improved project irrigation efficiency are often derived by the project because of reduced drainage costs, improvement of wet lands, and lower general maintenance costs.

DETERMINING EVAPOTRANSPIRATION

Techniques are now available for determining W_{et} under natural conditions on a daily basis, but only at one location in the field, border, or irrigation set for each set of instruments unless remote sampling sites are connected to a central unit. The method uses the energy balance and Bowen ratio technique. It is reliable and portable, but is generally beyond the means of many engineering studies.[10] Lysimeters provide similar data, but at fixed positions in the field. Also lysimeter methods are not as readily adaptable for use in operator-controlled fields.

Soil Sampling.—The most common method of determining W_{et} and the one that has been used extensively in irrigated areas of the Western United States for over 70 yr is soil sampling. The major problems involved in soil sampling for determining evapotranspiration have been recognized for many years. For example, drainage from the soil profile and deep percolation and their effect on W_{et} determinations were described in the mid-twenties, but they still are often ignored. Similarly, the error caused by movement of water upward from a saturated zone is well known, but it also is often overlooked.

The current general limitations and requirements for accurate determinations of W_{et} do not differ significantly from the concepts presented 40 yr ago, and subsequently published by the Duty of Water Committee of the Irrigation Division, ASCE.[11] A diagrammatic sketch is presented in Fig. 2 to illustrate the dynamic aspects of evapotranspiration and drainage, and the problems of determining W_{et} by soil sampling or neutron moderation techniques. This sketch does not illustrate minor items such as accumulation of dew, the change in water content of plants, water vapor movement into and out of the root zone due to thermal gradients, etc. The upper part of the sketch illustrates a typical rate of drainage from the soil that can occur when evapotranspiration is prevented, and a lower rate of drainage when evapotranspiration occurs. The lower part of the sketch illustrates near maximum evapotranspiration rates. The amount of drainage after an irrigation can easily be of the same order of magnitude as evapotranspiration when evapotranspiration rates, *ET*, are high. When *ET* is small, drainage from the soil may be several times larger than evapotranspiration. Obviously, large errors in W_{et} determinations can occur unless precautions are taken.

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[10] Fritschen, L. J., "Accuracy of Evapotranspiration Determinations by the Bowen Ratio Method," Bulletin of the International Association of Scientific Hydrology, Vol. X, No. 2, 1965, pp. 38–48.

[11] "Consumptive Use of Water in Irrigation," Progress Report of the Duty of Water Committee of the Irrigation Div., Transactions, ASCE, Vol. 94, 1930, pp. 1349–1399.

Gravimetric soil sampling (or the neutron technique) measures the change in soil moisture during a given time interval (t_1 to t_2 in Fig. 2). This change, expressed in units of water depth, can be written as

$$\frac{-\sum_{0}^{S_r} \Delta\theta \ \Delta S}{\Delta t} = \frac{W_{et} + W_d - R_e}{\Delta t} \quad \ldots \quad (8a)$$

or
$$ET = \frac{W_{et}}{\Delta t} = \frac{-\sum_{0}^{S_r} \Delta\theta \ \Delta S + R_e - W_d}{\Delta t} \quad \ldots \quad (8b)$$

in which S = the distance from the soil surface, S_r = the depth of the effective root zone, $\Delta\theta$ = the volumetric change in soil moisture (a negative sign indicating a decrease), Δt = the time interval between sampling dates (usually days), ET = the average evapotranspiration rate, and W_d = the water drained from the 0 to S_r depth.

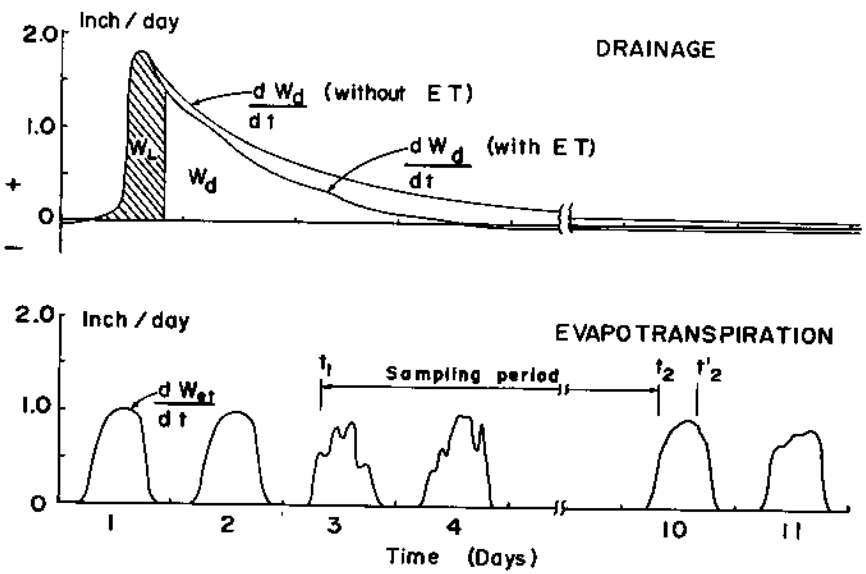

FIG. 2.—EXAMPLE DRAINAGE AND EVAPOTRANSPIRATION RATES

Drainage From the Root Zone.—Drainage from the root zone is a major unknown in Eq. 8a. It can be expressed as a function of two variables, the hydraulic gradient and the hydraulic conductivity of the unsaturated soil. When considering a horizontal plane just below the root zone, the amount of drainage that occurs between sampling dates is represented by the following equation in which the value of W_d is positive when flow is downward.

$$W_d = \int_{t_1}^{t_2} K\left(\frac{dH}{dz}\right) dt \quad \ldots \quad (9)$$

In Eq. 9, t_1 and t_2 = the dates of the first and second sampling, respectively (see Fig. 2), K = the unsaturated hydraulic conductivity (a nonlinear function of water content), and dH/dz = the hydraulic gradient.

The hydraulic head, H, consists of two components; i.e.,

$$H = h + z \quad \ldots \quad (10)$$

in which h = the water pressure head (soil moisture tension), and z = the elevation above some datum. The hydraulic gradient positive in a downward direction is

$$\frac{dH}{dz} = \frac{d(h+z)}{dz} = \frac{dh}{dz} + 1 \quad \ldots \quad (11)$$

A qualitative evaluation of whether drainage is occurring can be made by installing tensiometers in a layer of uniform soil a short distance below the root zone (see Fig. 3).

The hydraulic gradient determined by the tensiometers is

$$\frac{\Delta H}{\Delta z} = \frac{H_2 - H_1}{z_2 - z_1} = \frac{h_2 - h_1}{z_2 - z_1} + 1 \quad \ldots \quad (12)$$

Eq. 12 illustrates that a downward gradient of 1 can exist even when the soil moisture tension (or negative water pressure) is the same at points 1 and 2 (dH/dz = 0). When tension (or moisture content) does not change between sampling dates, a steady-state condition exists, but drainage may still be occurring. In order for the hydraulic gradient to be zero, the tension at position 1 must be greater than at 2 by an amount equal to Δz, $[(h_2 - h_1)/(z_2 - z_1) = -1]$. When the soil moisture below the root zone is less than the value

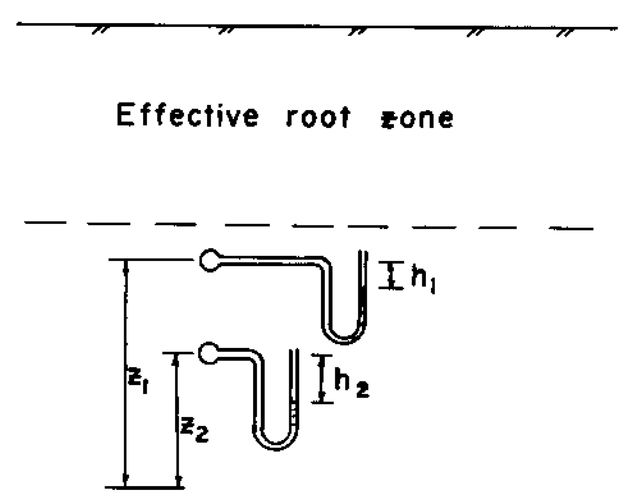

FIG. 3.—EVALUATING HYDRAULIC GRADIENT

reached after several months of drainage, then the hydraulic conductivity may be so small that W_d can be considered negligible. This condition would occur only where the water table is not close to the surface.

Minimum Time Limitations and Computational Errors.—One source of error that is frequently overlooked when determining ET by soil sampling is disregarding the time during the day when the soil samples are taken. For example, if the second sample was taken at t_2' instead of t_2 in Fig. 2, the error in calculated ET for the period $t_2 - t_1$ would be almost as great as a Δt error of one day. Obviously, the determination of ET by soil sampling for 3- to 5-day periods can include errors of 15 to 30% if the time of sampling during the day is ignored. In practice, many determinations of ET are made without considering the time of sampling.

Other Sources of Error.—Other potential sources of error in computed ET that are recognized as existing, but usually ignored, are (1) changes in bulk density and errors in bulk density measurements, (2) nonuniform root distribution, (3) drying of samples before they can be weighed, (4) contamination of soil samples with dry surface soil, and (5) damaged crop in the sampling area resulting in a nonrepresentative site (this can be critical for neutron sites because they are used all season), etc. Precautions should be taken to minimize all errors in the sampling program.

Confidence Limits.—When determining ET by soil sampling, the change in soil moisture at specific sites is measured rather than determining the average soil moisture at random sites at each sampling date. By determining the changes in soil moisture at a given site, errors due to variability between locations within the field are minimized. The neutron technique eliminates this source of error because the same sites are used all season. With gravimetric soil sampling, the second sample after an irrigation is usually taken within 1 ft from the previous site. Under these conditions, it is essential to fill and tamp the holes after removing the soil cores to avoid excessive soil drying or uneven penetration of rainfall.

The results obtained from studies in California[12] indicate that the variability in ET determinations between sites using the neutron technique to determine soil moisture is lower than in those based on gravimetric soil samples. The coefficient of variability of the mean ranged from about 4 to 2% for six to twelve sites with a 2-in. change in soil moisture between sampling dates. Neutron methods are subject to the same errors caused by not observing the time of sampling, drainage, and use of water from the saturated zone. However, the neutron method essentially eliminates the error incurred due to changes or variability in bulk density.

Minimizing ET Errors.—A number of precautions should be taken in all field or plot studies when determining evapotranspiration rates. Observance of the following precautions should result in more reliable ET data: (1) the sampling sites must be representative of the general field conditions; (2) depth of the water table should be much greater than the root zone depth; (3) only those sampling periods where rainfall is light should be used—all others being questionable because W_d may be excessive; and (4) drainage, W_d, can be minimized by (a) giving the preplant irrigation at least 10 to 30 days before planting, (b) controlling irrigation so as to apply less water than the amount that can be retained, (c) waiting at least 2 days after a normal light irrigation before taking the first sample (longer periods being required if excessive irrigations or high soil moisture levels are involved and when ET is small), and (d) using only the active root zone depth or the depth to the plane of zero hydraulic gradient for ET computations.

[12] "Vegetative Water Use Studies 1954–1960," Bulletin No. 113, Interim Report of the California Dept. of Water Resources, Sacramento, Calif., August, 1963.

Estimating Evapotranspiration.—Previously, the writer has illustrated that when a comprehensive study is undertaken to evaluate the irrigation efficiency of a project, farm, or a field for a season, the time and cost of determining evapotranspiration may be large. In contrast, estimates of ET can often be made at a small fraction of the cost of direct determinations. Actually, limited soil sampling may not provide more accurate ET data in areas where estimating procedures have been verified. Under these conditions, the use of reliable estimating procedures is justifiable. However, estimating procedures must not be used in a manner for which they were not intended. For example, empirical procedures should not be used in climatic conditions that are vastly different from those in which the relationships were developed unless they can be "calibrated" in the new area. Estimating procedures developed and tested for seasonal estimates should not be used for 2-week, or even monthly, periods if reasonable accuracy is needed because time averaging over the season may be essential. For example, if a procedure provides seasonal estimates that are within 5 to 10% of the true values, it would not be uncommon for this method to give monthly estimates that are within only 15 to 20% of the true values. When used for 10-day periods, such as between irrigations, errors up to 30% are not uncommon, especially if stage of growth is not considered and if a climatic parameter only partly related to ET is the primary or only variable involved. In contrast, procedures that are reliable for daily estimates will generally be more accurate for 5-day, 10-day, 30-day or seasonal periods.

SUMMARY AND CONCLUSIONS

The evaluation of irrigation efficiency requires the delineation of necessary and beneficial water uses in irrigation projects, uniform evaluation procedures, and acceptable standards for comparative purposes. Necessary and beneficial uses of water are defined, together with practical and economical methods for evaluating irrigation efficiency. Examples are presented to illustrate the probable accuracy of various measurements used to evaluate irrigation efficiency.

APPENDIX.—NOTATION

The following symbols are used in this paper:

C_{aw} = concentration of soluble salts in applied water;
C_{dw} = concentration of soluble salts in drainage water;
C_{iw} = concentration of soluble salts in irrigation water;
C_r = average concentration of soluble salts in the soil water in the root zone (for convenience considered as the concentration near field capacity);

E_u = unit irrigation efficiency;
E_c = water conveyance efficiency;
E_i = irrigation efficiency;
E_s = reservoir storage efficiency;
EC = electrical conductivity;
ET = average evapotranspiration rate;
h = water pressure head (soil moisture tension);
H = hydraulic head, $H = h + z$;
K = unsaturated hydraulic conductivity;
R_e = total rainfall minus runoff and deep percolation that may occur during heavy rains, or rains following a thorough irrigation;
S_r = effective depth of the root zone;
t = time;
W_c = volume of water turned into a canal system;
W_d = volume of drainage water;
W_{et} = volume of water used in evapotranspiration;
W_f = volume of water delivered to the farms;
W_i = volume of water that is diverted, stored, or pumped for irrigation;
W_L = volume of water necessary for leaching;
W_r = volume of runoff water;
W_s = volume of water stored in the soil root zone;
z = vertical coordinate;
α = leaching efficiency, $\alpha = C_{dw}/C_r$;
θ = volumetric water content; and
σ = standard deviation (subscripts denote specific values).