Irrigation Engineering, Evapotranspiration

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Glossary

Crop coefficient Ratio of evapotranspiration for a specific crop at a specific growth stage to the reference crop ET for that same time period and climatic conditions

Irrigation capacity Gross flow rate per unit land area irrigated

Irrigation scheduling Systematic determination of the need for irrigation and the timing and amount of irrigation water to apply to a specific crop and/or field with a specific irrigation system

Limited irrigation Planned irrigation management that does not meet the full crop water requirement; also called *deficit irrigation*

Lysimeter A device, generally a tank or container, that defines the soil boundaries, particularly the lower boundary, for measuring the water and/or solute movement and the soil water balance of the enclosed soil

Reference Crop ET Evapotranspiration from a specified crop (most often short grass or alfalfa) which is well supplied with water and has full ground cover (near maximum vegetative cover) and minimum exposed soil

Irrigation engineering is the application of science to irrigation design, management, and operation for the benefit of mankind. Evapotranspiration is the combined processes of water evaporation from soil, plant, or water surfaces and water evaporation from plant tissue (internal plant surfaces) by transpiration. Evapotranspiration influences irrigation design and management. Irrigation design and management directly affect plant growth processes, crop yield, environmental impact of irrigation on soil and water resources, and individual producer net profits.

I. Evapotranspiration and Irrigation Engineering

A. Description

Evaporation is the vaporization process whereby a substance, either liquid or solid, is converted into a vapor. For solids, the process is generally called *sublimation*. In agriculture and irrigation engineering, usually evaporation refers to the water vaporization from soil, plant, or water surfaces, and *transpiration* usually refers to the vaporization of water from plant tissues generally through the stomata of plant leaves. Evapotranspiration is the combined processes of water vaporization from evaporation and transpiration and is also called *consumptive use* in some literature. In addition, water retained in the living tissue is generally ignored since it is such a small amount compared to the mass and/or rates of water vaporization consumed in either evaporation or transpiration. Although evapotranspiration cannot be defined as a single process, it is considerably easier to measure than evaporation or transpiration; hence, its use as both an identifying term and a measured parameter is widespread in the agricultural and irrigation sciences to describe the use of water by vegetation.

Irrigation engineering is a specialized branch of engineering dealing with the application of science to irrigation design, management, and operation. Irrigation engineering is a subdiscipline of the larger agricultural and civil engineering fields. Traditionally, civil engineers specializing in irrigation engineering have been more directly involved with off-farm engineering applications (water supply, dams, canals, drainage, etc.) while agricultural engineers specializing in irrigation engineering have been involved with on-farm applications (application methods, system design, irrigation scheduling, etc.). An overlap of agricultural and civil engineering in irrigation engineering is widely visible. Since this encyclopedia is intended for agricultural sciences, on-farm irrigation engineering will be emphasized. [*See* IRRIGATION ENGINEERING: FARM PRACTICES, METHODS, AND SYSTEMS; WATER CONTROL AND USE.]

B. Measurement and Estimation of Evapotranspiration

1. ET Measurement

Many methods have been proposed and used to measure water use by vegetation. Generally, the lumping of evaporation and transpiration into evapotranspiration does not pose a severe theoretical restriction. However, in some cases the distinction of water use in evaporation and in transpiration (as separate physical processes) is clearly more desirable. For simplicity, the term evapotranspiration will be designated by the symbol ET, evaporation by E, and transpiration by T, henceforth in this chapter (remembering that ET = E + T).

ET can be directly measured by two means—weighing lysimeters and by eddy correlation. ET can be indirectly inferred by water balance or energy balance based on the principle of the conservation of mass and energy, respectively. Weighing lysimeters are devices with a soil container which is mounted on a scale that can precisely determine the change of the soil mass due to the vaporization of water by E and T (Fig. 1). Sometimes the lysimeter soil surface may be covered to eliminate E, and thereby permitting T to be measured. Small lysimeters (called *micro-lysimeters*), usually about 200 mm or less in diameter and 100 to 200 mm deep, have been used to manually measure E over short periods (a day to perhaps 2 or 3 days) for bare soil or beneath crop canopies. This method is basically a simple soil water balance of the surface soil water where most of the soil water evaporation occurs, and the soil water content volume change (measured as mass) is determined by removing and weighing the lysimeter containers and then replacing them back into the soil for evaporation to occur. These micro-lysimeter measurements of E require routine soil volumetric sampling to "refresh" the soil in the micro-lysimeter and to relocate the measurement sites. They cannot be used reliably during rain or irrigation events and may not correctly

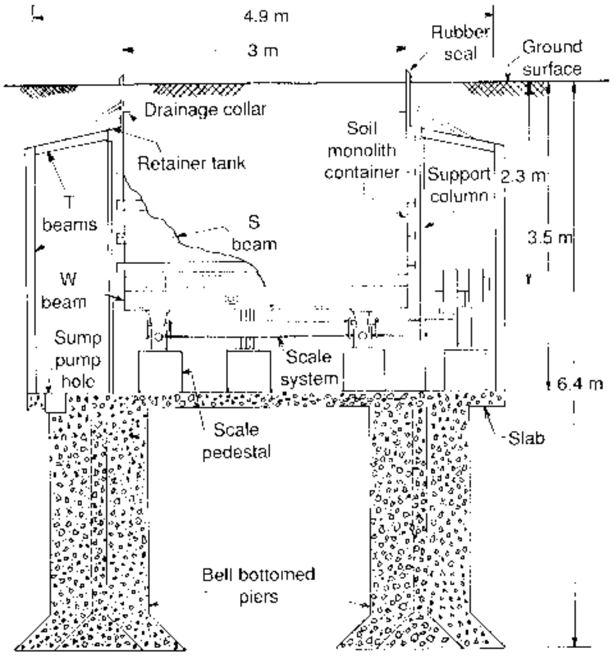

FIGURE 1 Schematic diagram of the weighing lysimeters at Bushland, Texas (USDA-ARS). [From Marek, T. H., Schneider, A. D., Howell, T. A., and Ebeling, L. L. (1988). Design and construction of large weighing monolithic lysimeters. *Trans. ASAE* **31**, 477–484; reprinted by permission of the American Society of Agricultural Engineers, St. Joseph, MI.]

represent the soil drying since plant root extraction is eliminated. Weighing lysimeters (and percolation lysimeters as well) provide a defined water flux at the lysimeter boundary (generally zero; although drainage water can be removed, water can be added to simulate upward flow from a water table, or a constant water table elevation can be maintained).

Eddy correlation measurement of ET requires precise and fast-response instruments to measure the covariance of the perturbations (fluctuations from the mean) of vertical wind and water vapor movements. With higher speed and more accurate portable, DC-powered data acquisition systems, eddy correlation methods are becoming more widely used. Eddies are gusts of wind created by the turbulent flow and mixing of the atmosphere controlled by the forces of momentum, heat, and water vapor transfer.

ET can be determined by a water balance as

$$ET_i = \overline{\Theta}_i - \overline{\Theta}_i - 1 + R_i + I_i - Q_i - D_i, \quad (1)$$

where ET_i is the water use during period i, Θ_i is the profile soil water content (over some specified depth Z as $\overline{\Theta} = \int \Theta \, dz$ from 0 to Z) at the end of period i, R_i is precipitation, I_i is irrigation, Q_i is runoff (or runon if negative), and D_i is drainage at depth Z (or upward flow if negative) during period i, and all terms are expressed in units of length (usually mm; equated to 1 kg m $^{-2}$ for water). For most agricultural applications $\overline{\Theta}$, R, and I can be measured by several methods; however, Q and certainly D are more difficult to determine. Often, Q and D can be neglected in certain situations. The ET rate is determined by dividing ET by the period length.

ET can be determined by an energy balance as

$$ET = (Rn - G - H)/\lambda, \quad (2)$$

where ET is in mm sec^{-1} (positive during evaporation or transpiration), Rn is net radiation in W m^{-2} (positive when incoming exceeds outgoing radiation), G is soil heat flux in W m^{-2} (positive when the soil is warming), H is sensible heat flux in W m^{-2} (positive when the air is warming), and λ is the latent heat of vaporization in J kg^{-1} [approximately 2.45×10^6 J kg^{-1} at 25°C]. Rn can be measured with net radiometers, and G can be measured with soil heat flux plates buried at a shallow depth (usually about 20 to 50 mm deep) and soil calorimetric correction for the thermal energy storage in the soil layer above the plates. H can be measured using profile techniques (micrometeorological methods) or using surface temperature measurements (these are usually made with infrared thermometers). In Eq. (2), ET is determined as the residual [i.e., the remainder of $(Rn - G - H)/\lambda$]. Most often, however, the Bowen ratio method is used where

$$\beta = H/(\lambda ET) = \gamma\ (K_h/K_v)\ [(\Delta T/\Delta e)] \quad (3)$$

and

$$ET = (Rn - G)/[\lambda\ (1 + \beta)], \quad (4)$$

where β is the Bowen ratio (fraction), γ is the psychrometric constant in kPa °C^{-1} (approximately (6.6×10^{-4} P, where P is barometric pressure in kPa), K_h and K_v are the eddy transfer coefficients for sensible and latent heat (usually equality between K_h and K_v is assumed), respectively, and ΔT and Δe are the vertical gradients for temperature in °C and for vapor pressure in kPa, respectively. The Bowen ratio method can reduce instrumentation detail required in the micrometeorological profile methods; however, precise measurements of ΔT and Δe are required as well as the assumption that $K_h\ K_v^{-1} = 1.0$. The Bowen ratio energy balance method cannot be used when β is equals -1.0, which occurs most often at neutral atmospheric conditions before sunrise and late evening after sunset. Often the magnitude of the energy balance fluxes at night are too small to be reliably measured by the Bowen ratio. The Bowen ratio energy balance method and other energy balance methods require highly accurate measurements of Rn and G, which commonly can contain errors of ±5% or more. These Rn and G errors directly affect the accuracy of H and λET.

Transpiration (T) can be measured using a heat balance method for certain species with a main stem (at least 5 mm in diameter for small plants to over 100 mm for trees). Figure 2 illustrates a heat-balance gauge. The gauge consists of a small heater that is placed in contact with the plant stem and several thermopiles (or thermocouples) that measure the radial and vertical heat migration from the heater. A constant power is applied to the heater and the transpiration flux through the plant stem is related to the heat migration rate along the stem accounting for radial heat dissipation away from the heater. The device is carefully insulated to avoid heat transmissions to or from the environment. The areal transpiration can be computed based on the plant or crop density. In practice, many individual gauges need to be measured and averaged to account for plant to plant variations.

2. ET Estimation

ET (as well as E and T) is influenced by many factors—climatic factors (mainly solar radiation, air temperature, relative humidity, and wind speed), soil factors (i.e., water content, thermal properties, physi-

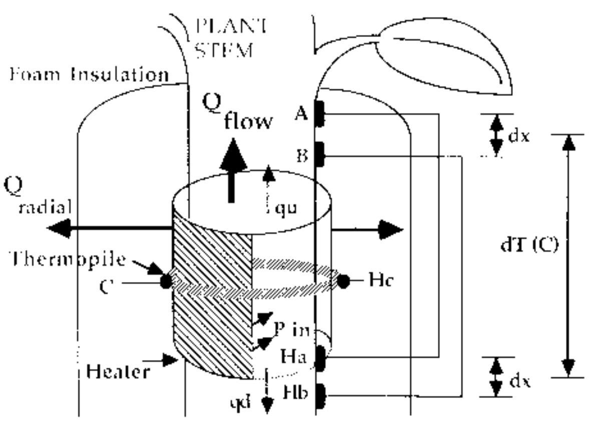

FIGURE 2 Schematic diagram of a stem heat balance gauge used to measure plant transpiration. A, B, Ha, and Hb are thermocouple temperature measurement locations; and C and Hc are radial thermopile temperature measurement locations; P is input power from the heater; qd is the downward heat flow, qu is the upward heat flow, Q_{radial} is the radial heat flow, and Q_{flow} is the net upward heat flow; dx is the increment for upward and downward temperature gradients and dT is the temperature gradient in °C measured as [(A − Ha) + (B − Hb)]/2. [*Source:* Dynamax, Inc., Houston, Texas.]

cal layers, soil strength, and root-zone salinity), and plant factors (i.e., plant density, plant height, rooting depth, leaf area, and stomatal conductance). Crop ET is often characterized for hypothetical crops called *reference crops* (ET for a reference crop will be called ET_r). Short grass (usually a cool season type species) and alfalfa are the most common reference crops. The ET of these crops when "well-supplied with water" and with a "full ground cover" generally defines ET_r. ET_r is often computed using the Penman combination type equation which is given below for a grass ET_r case as

$$\lambda ET_r = [\Delta\ (Rn - G) + (\gamma\ Ea)]/(\Delta + \gamma), \quad (5)$$

where Δ is the slope of the saturation vapor pressure curve $[\partial e\ \partial T^{-1}]$ in kPa °C^{-1} [usually evaluated at the mean air temperature, T_a, in °C] and $Ea = 74.42\ (1.0 + 0.53\ U_2)\ (e_a^* - e_a)$ in W m^{-2} for grass reference ET_r, where U_2 is the mean wind speed in m sec^{-1} at a 2 m elevation above the ground, e_a^* is the saturation vapor pressure in kPa at T_a, and e_a is the ambient vapor pressure in kPa. The Penman equation was later modified using resistance factors to apply more generally to any crop or vegetation and is known as the Penman–Monteith equation which is given as

$$\lambda ET_r = [\Delta\ (Rn - G) + (\gamma\ Ea)]/(\Delta + \gamma^*), \quad (6)$$

where $\gamma^* = \gamma\ (1 + r_c/r_a)$ where r_c is the canopy resistance to vapor transfer in sec m^{-1}, r_a is the aerodynamic resistance to vapor transfer in sec m^{-1}, and Ea is now defined as $Ea = [(m\ \rho_a\ \lambda)/P]\ [(e_a^* - e_a)]/r_a]$ in W m^{-2}, where m is the molecular mass of water vapor to air mass [0.622] and ρ_a is the air density in kg m^{-3}. The aerodynamic resistance (r_a) includes the effect of wind on the evaporation process (note: r_a is inversely related to wind speed). ET_r will be crop specific because Rn will depend on the crop and soil albedo (short-wave or solar radiation reflection ratio) and the crop and soil emissivity (long-wave emittance factor), the effects of the crop on energy flux into the soil (G), the aerodynamic factors of the crop that influence r_a (mainly crop height, crop roughness, and atmospheric stability), and the crop resistance factors that influence r_c (mainly leaf area and stomatal resistance). For time periods of a day, G is often assumed to be negligible; however, for longer periods (weeks or months) or shorter periods (hours) G can be a significant factor and should not be neglected. ET_r is defined in terms of the crop canopy resistance, r_c, for a specific reference condition.

Many other ET_r estimation methods and equations have been developed, particularly for applications where climatic data may be limited and all the parameters required for Eqs. (5) and (6) may be unavailable. A few of the more widely used empirical reference ET equations for grass are given below

Priestley-Taylor $\lambda ET_r = \alpha\ \Delta\ (Rn - G)/(\gamma + \Delta)$ (7)

Jensen-Haise $\lambda ET_r = C_T\ (T - T_x)\ R_s$ (8)

Hargreaves $\lambda ET_r = 0.0023\ R_A\ TD^{1/2}\ (T + 17.8)$, (9)

where α is an empirical coefficient (dimensionless) which is approximately 1.26 for wet surface conditions, C_T and T_x are determined by empirical equations based on site elevation and the warmest month's mean maximum and minimum temperatures, R_s is solar radiation in W m^{-2}, R_A is extraterrestrial solar radiation (solar radiation outside of the earth's atmospheric layer) in W m^{-2}, and TD is the mean monthly temperature difference (maximum minus minimum) in °C. The Priestley-Taylor equation is most often applied to more humid locations; the Jensen-Haise and Hargreaves equations are more appropriate for weekly or longer-term ET estimates. In addition, evaporation pans are widely used as methods to estimate ET_r; however, pan location and the site conditions surrounding the pan can greatly affect pan evaporation.

Empirical crop coefficients are used to compute the crop (or other vegetation as specified) water use as

$$ET = [(K_{cb}\ K_w) + K_s]\ ET_r, \quad (10)$$

where ET_r is the computed reference ET for a specified reference crop in mm d^{-1}, K_{cb} is the basal crop coefficient (fraction), K_w is a water deficit ET reduction factor (fraction), K_s is a soil evaporation factor (fraction), and ET is the actual crop water use in mm d^{-1}. Figure 3 illustrates a generalized crop coefficient curve. Ideally, the empirical factors (K_{cb}, K_w, and K_s) could be developed using Eq. (6) with appropriate

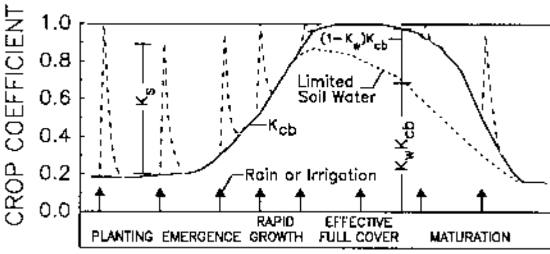

FIGURE 3 Generalized crop coefficient curve illustrating the crop coefficient parameters. [Adapted from Wright, J. L. (1982). New evapotranspiration crop coefficients. *J. Irrig. Drain. Engr. Div. ASCE* **108**(IR1), 57–74. Reprinted by permission of the American Society of Civil Engineers, New York, NY.]

values for r_a and r_c. The basal crop coefficient, K_{cb}, is defined for the case with a "well-watered" crop but dry soil surface (several days after irrigation or rainfall). K_{cb} is determined for a specific crop and for a specific method of determining ET_r. For this reason, the use of published values of K_{cb} must carefully determine the appropriate ET_r and method of estimating ET_r. K_w is defined by the reduction in ET caused by reduced soil water, may be both soil and crop specific, and normally decreases exponentially (or logarithmically) with increased soil drying. K_s is specific for a particular soil and will generally decline exponentially to zero following several days of drying.

II. Irrigation Engineering

Engineering designs for irrigation systems provide detailed information on water supply (rate and volume), application rates, hydraulic design of water delivery components, operation criteria for the systems, and maintenance schedules for the irrigation system. ET impacts the water supply or demand for the irrigation project (field, farm, or entire project on a hydrologic basin or region scale). This chapter will deal only with the effects of ET on irrigation engineering applied to on-farm irrigation design and management; however, the impact of off-farm, district, or project engineering is recognized to impact on-farm irrigation engineering.

A. Irrigation Capacity

Irrigation capacity (IC) is defined as the gross flow rate per unit land area, and it is usually characterized in units of liter sec^{-1} m^{-2} (or mm s^{-1}) or more commonly converted to mm d^{-1} (mm d^{-1} = 8.64×10^4 liter sec^{-1} m^{-2}). IC includes all the application conveyance losses (only on-farm losses are considered in this chapter). IC should be optimized through the engineering design because IC directly affects the fixed irrigation system costs since the size of the water supply and conveyance structures (pipelines, canals, pumps, valves, power demand costs, power distribution component sizes, etc.) are directly related to IC. IC is an irrigation rate constraint, and it can affect crop growth and yield performance for the particular climatic regime in which the system is intended to function as well as irrigation efficiency (fraction of applied water actually being used by the crop). IC is sometimes indirectly and/or directly constrained by regulations (i.e., well sizing, well spacing, turn-out flow controls). In certain cases, irrigation volume will also be constrained (i.e., water allotments, water depletion regulations). Generally, IC is one of the primary factors affecting variable irrigation costs, particularly when ground water is the main irrigation water supply, through the gross flow rate which is directly proportional to energy consumption where pumping is necessary.

As IC is reduced, the ability of the irrigation system (with its efficiency and uniformity) and irrigation management to meet the full crop irrigation needs is sacrificed. Irrigation capacity in excess of the minimum IC necessary to meet the crop water needs (including any necessary leaching for salinity management) in all years requires additional capital investment for irrigation equipment. Since the irrigation system peak application rate is also directly proportional to IC, runoff from irrigation applications can result if IC is too large; however, the irrigation hydrology (the partitioning of irrigation applications into infiltration, runoff, deep percolation or drainage, and ET) is complex and difficult to predict. The goal of irrigation should be to achieve a high partitioning of irrigation applications into ET (especially T) while minimizing application losses to runoff and drainage resulting in high irrigation efficiency, irrigation application efficiency (defined as the fraction of applied water actually being stored in the crop root-zone), water use efficiency (WUE is defined as the ratio of crop yield to seasonal crop water use (ET) usually expressed in units of kg m^{-3}, where 1 g m^{-2} per mm equals 1 kg m^{-3} or 10 kg ha^{-1} per mm equals 1 kg m^{-3}), and irrigation water use efficiency (IWUE is defined as the ratio of crop yield to total seasonal irrigation amount with the same units as WUE). The optimum IC is somewhat difficult to precisely determine since the acceptable risk level associated with reduced crop yields resulting from soil water deficits depends on the philosophies and financial resources of the individual grower (i.e., a particular design with a specific IC may meet the crop needs in 9 years out of 10, on the average, with a maximum yield reduction of 10%). The grower needs to specify the risk level that is acceptable, and then the IC and system design can then be determined to meet or exceed that criterion. Figure 4 illustrates the simulated effect of net sprinkler IC on corn yields at Bushland, Texas (Pullman clay loam soil), for a specific irrigation management strategy for 28 years of climatic record (1958–1985). This illustration shows for this particular case that a net IC above 8 mm d^{-1} did not improve expected corn yield. However, as net IC declined to

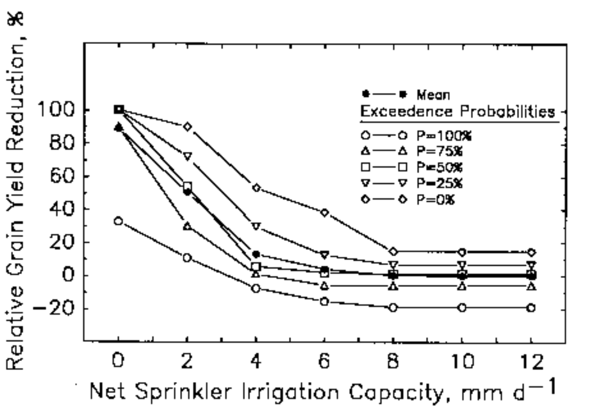

FIGURE 4 Simulated relative corn grain yield reduction for a Pullman clay loam soil at Bushland, Texas, as affected by net sprinkler irrigation capacity for 20-mm applications with a 75-mm allowable soil water depletion prior to irrigation for a 28-yr period. [From Howell, T. A., Copeland, K. S., Schneider, A. D., and Dusek, D. A. (1989). Sprinkler irrigation management for corn—Southern Great Plains. *Trans. ASAE* **32,** 147–154, 160. Reprinted by permission of the American Society of Agricultural Engineers, St. Joseph, MI.]

4 mm d^{-1} the mean corn yield would be reduced about 10% while 1 year in 4 (25% exceedence probability) the corn yield could be reduced almost 30%.

IC necessary to meet the full irrigation needs of a crop is largely based on (1) the maximum crop ET rate over some specified planning interval, (2) the plant available soil water that can be extracted by the crop without any serious yield reduction, and (3) effective precipitation during the planning interval. The first factor is well defined in many sources while the second factor is more difficult to precisely characterize for particular crops and soils. The third factor can be estimated in many ways, but it is influenced strongly by the precipitation pattern (frequency, amount, and intensity), soil factors (slope, surface cover, soil type, etc.), and normal ET rates during the specific time interval. Equation (1) can be rearranged to solve for I as the irrigation requirement. IC can be bracketed in several ways. At some soil water content level (θ_c), the crop cannot take up water from the soil at a rate sufficient to meet the atmospheric demand rate for transpiration (the value of K_w in Eq. (10) will begin declining below a value of 1.0 and the value of r_c in Eq. (6) will begin to increase above the value defined for the reference condition), and the crop will develop a water deficit which will reduce growth (and eventually yield) and ET through mechanisms that regulate the stomatal opening and biochemical processes in the leaves. This critical soil water content is not necessarily the same for these two processes—normally growth (photosynthesis) will be reduced before ET is greatly affected—and may even vary with several environmental conditions. In addition, if the soil water content is too large, exceeding some value θ_u, then water more easily moves through the profile resulting in water losses to D with its associated nutrient leaching losses and rainfall losses to Q may increase.

The irrigation management goal is therefore to maintain θ within this range ($\theta_u - \theta_c$) while minimizing irrigation application losses to D and Q with I constrained by the irrigation design to be ≤ to IC*T, where T is the design time period in days and IC is in mm d^{-1}. The maximum IC can be estimated as $\int(\mathrm{ET} - \mathrm{R})dt$ over time period T in days, when no soil water ($\theta_{i-1} = \theta_c$) can be extracted without reducing crop growth and yield, divided by the irrigation application efficiency (as a fraction). This maximum IC will clearly depend on effective rainfall. In most cases, the expected effective rainfall for short duration planning periods (one week or less) will be zero. As the soil water content increases above θ_c, available soil water can be extracted by the crop to meet its ET demand without reducing crop growth and yield, thereby reducing the irrigation amount and IC required to meet the crop water needs. Likewise precipitation, groundwater contributions (negative D), and water harvesting (negative Q) (see Eq. (1)) directly offset ET thereby reducing irrigation needs and irrigation capacity. IC can be estimated using an equation developed by the USDA-Soil Conservation Service given as

$$\mathrm{IC} = 0.034\ (\mathrm{ET}_m^{1.09}/\mathrm{AD}^{0.09}), \tag{11}$$

where IC is in mm d^{-1}, ET_m is the monthly mean ET for the peak month in mm month^{-1}, and AD is the allowable soil water depletion in mm between irrigations which avoids crop water deficits.

B. Irrigation Scheduling

Irrigation scheduling (IS) comprises of strategic (long-term) decisions (i.e., selection of methods for detecting plant water needs, planning for seasonal water allotments to specific fields or crops, etc.) and tactical (short-term) decisions that mainly determine when to irrigate and how much irrigation water to apply. In some cases, irrigation applications may be desired for reasons beyond meeting crop water needs (i.e., frost protection, crop stand establishment, salinity management, chemical applications—herbicides or pesticides, etc.). IS needs to consider the crop water needs, irrigation system constraints (IC and application rate), energy conservation, soil water contents, weather and precipitation patterns, and cultural practices like harvesting, fertilizing, etc. IS will directly affect the crop production economics through its effect on crop yield and crop quality and on irrigation costs (labor, energy, and/or water).

IS strategic decisions include the method of crop irrigation need determination, the desired range of single irrigation application amounts for best uniformity and efficiency, and the crop yield goals. Tactical IS decisions include the day-to-day integration of irrigation with other farming practices (planting, cultivation, harvesting, pest control, immediate weather forecasts, etc.).

Figure 5 illustrates a simple example crop production function (relationship between crop yield and applied irrigation water) and irrigation economics. The crop production function is assumed to follow a quadratic function in this example. The middle graph (Fig. 5A) shows a low fixed irrigation cost while the lower graph (Fig. 5B) shows a higher fixed irrigation cost. Both graphs (Figs. 5A and 5B) show low and high variable irrigation costs associated mainly with the costs of irrigation water. These examples assume that income is directly proportional to crop yield and that irrigation costs are linear. Several important points can be illustrated with this simple example. First, as either fixed or variable costs increase, the net profit (vertical distance between the income and cost curves) and range of positive net profits (horizontal distance between the points of intersection of the income and cost curves) decrease. The fixed costs do not greatly affect the optimum irrigation amount that maximizes net profit. The optimum irrigation amount (the point where the slopes of the income curve is equal to the slope of the cost line) decreases with increased variable irrigation costs. An additional point is that maximum net profit is not overly sensitive to the irrigation amount near the optimum irrigation amount (the slopes are relatively low). Of course, relationships like those illustrated here are simplified and do not consider many additional production economic and engineering parameters.

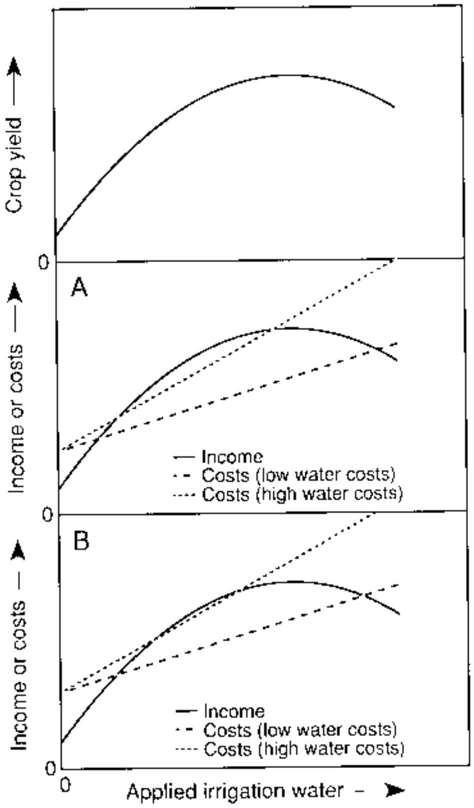

FIGURE 5 A hypothetical example of a crop production function and irrigation economics for linear irrigation costs with both low (A) and high (B) fixed and variable costs (water costs).

Many irrigation systems are designed and managed to operate near the maximum crop production level and this is usually called full irrigation. As Fig. 5 shows, this may not necessarily be the maximum net profit or the most optimum use of irrigation water; however, it may reduce the production risks that are faced by the grower. As the irrigation amount is reduced from that necessary to produce maximum crop yield, the risks (reduced net profits) increase. In addition, irrigation systems apply water with differing distributions of application amounts called application uniformity, and the application uniformity can affect irrigation economics (both net profit and system capital costs) as well. Traditionally, when lower irrigation amounts from those necessary for maximum crop yield are used, the irrigation management strategy is called limited or deficit irrigation. These strategies rely on avoidance of critical crop water stress, particularly in the sensitive crop growth phases normally associated with reproductive growth (i.e., anthesis in most cereal crops). Figure 5 illustrates that a deficit- or limited-irrigation strategy may not necessarily result in a reduced net profit. Limited- and deficit-irrigation management can be constrained by either volume or rate irrigation constraints. The rate constraint is the IC (or a well spacing or sizing regulation constraint) while a volumetric constraint could be a pumping volume regulation (i.e., so many m^3 per unit land area) or a water right constraint (legal permit).

Additional legal or regulatory constraints on drainage, runoff, or water quality (both drainage and runoff) can impact irrigation design and management. These later regulations are called nonpoint source discharge regulations. Irrigation system design affects the fixed irrigation costs though the size of pipe size, canal size, pump size, power demand charge, etc., and the variable irrigation costs through the pumping rate, pumping pressure, labor, etc. Irrigation management and IS affect net profit through the resulting crop yield and quality and the variable irrigation costs, which are proportional to the total seasonal irrigation applications.

1. Irrigation Timing

Many methods are used to aid and determine irrigation timing decisions, which are a critical component of IS. IS should be based on plant water needs rather than indirect parameters such as soil water content, etc. However, plant measurements are often less quantitative, more time consuming, and often more difficult to automate. Plant water stress symptoms include visual signs like color changes, growth patterns, leaf rolling or curling, leaf wilting, etc. Often by the time that these visual observations are evident, significant damage to the crop yield potential may have already occurred. More quantitative measures of direct plant water deficits include plant temperature, reflected or emitted radiation, stem diameter, leaf diffusion resistance, leaf water potential, plant transpiration, etc. A major difficulty in using quantitative plant water stress measurements is the separation of the influences caused by the environmental parameters and those caused by plant water deficits. Many times some of the above plant measurements are made before sunrise to determine the rehydrated level of plant water stress. Other daytime measurements of plant water deficit may rely on air temperature, relative humidity (or combined into the vapor pressure deficit), or solar radiation. In some cases, dynamic atmospheric changes (clouds, wind, etc.) greatly affect the plant water status and its measurement. In some instances, a portion of the field may be managed with low soil water deficits to serve as a check or reference field for nearby fields using plant-based IS timing. Plant-based measurements are sometimes unreliable when extrapolated for several days, which may be necessary to schedule or order irrigation water anticipating irrigation needs.

Soil water parameters are often used in IS timing. Soil water can be estimated from simple soil sampling and judgment based on visual and feel methods; gravimetric methods requiring soil samples to be weighed, dried, and reweighed; soil water potential sensors (tensiometers and thermocouple psychrometers); porous block sensors (in equilibrium with the soil of electrical resistance, capacitance, and/or heat dissipation types); neutron attenuation meters (gauges that emit low levels of nuclear radiation and count the slow neutrons that are reflected back from water or other hydrogen elements); or soil dielectric gauges (time domain reflectometry). Several of the soil water sensors can be automated for measurement speed; however, soil contact and placement are major limitations. Soil water content or potential is an indicator of expected plant water stress. Soil water content or potential will usually permit longer-range IS timing forecasts than will plant based measurements. In addition, soil water measurements can be used more directly than plant indicators to determine irrigation amounts necessary to refill the soil profile.

Irrigation timing sensing methods should be viewed as information rather than one method versus another. Each method adds potentially greater collaboration or support for each of the other measurements. The grower or irrigation consultant needs to gather sufficient information, either soil or plant based, to make the irrigation timing decisions. These decisions should be presented in the context of a scheduling opportunity window. The earliest irrigation date in this scheduling window will avoid application losses to drainage and runoff while the later date in this scheduling window will avoid the development of plant water stress and associated future yield reductions.

2. Irrigation Amount

Irrigation amount is largely dictated by the irrigation application method, application efficiency, and the available soil water storage capacity. The irrigation amount is largely constrained by the IC and the frequency of irrigation applications. The irrigation application method will have a specific range of application amounts in which its efficiency and uniformity may be optimized. This optimum range could be about 50 to 100 mm for surface irrigations, 15 to 50 mm for sprinkler irrigations, or 5 to 25 mm for microirrigation (drip, trickle, bubbler, micro-spray, etc.). Available soil water storage dictates how much water could be stored within the soil profile without excessive losses to drainage. However, it may be desirable in many cases, particularly in subhumid and semi-arid climates, to avoid refilling the soil profile to leave potential storage for precipitation to minimize precipitation runoff losses.

III. Irrigation Water Management

On-farm irrigation water management is the combined utilization of irrigation system design with IS to enhance effectiveness of irrigation. Irrigation water management involves the integration of many strategic (long-range) and tactical (short-range) decisions with the farm management decisions (again both strategic and tactical), water supply, and legal and institution constraints.

Farm management decisions of cropping sequence and variety selections affect irrigation management. In addition, farm cultural operations such as tillage, pest control (both weeds and insects), fertility, crop harvesting, and other farming activities must be integrated with irrigation management to achieve the farm production goals. In many cases, these farm and crop management decisions may be more critical than irrigation decisions. In the United States, many times these farm management decisions are constrained by government farm programs or natural resource regulations.

Irrigation water supply has additional management constraints. Off-farm water supply may involve water "ordering" (advance forecast of water demand) from a water district or a water management agency. The ET of the crops being irrigated and the irrigation methods directly affect the water order. In other cases, the control of the water supply is simply the regulation or limit on water pumping, particularly from groundwater sources. These pumping restrictions have many forms from taxes or fees to absolute water withdrawal limits or regulations. For example, in southeastern Texas, groundwater withdrawal in certain areas is subject to fees charged by ground water districts to control and reduce land subsidence; in southwest Nebraska, the local natural resource conservation districts have imposed a fixed limit over a 5-year period on irrigation pumping volume; and in many western states, rigid water right laws control the water allocations for irrigation.

Energy consumption in irrigation also has emphasized the need for integrated management of irrigation with power distribution. In many situations with electrical-powered irrigation water supplies, electrical load management integration with irrigation management is necessary to reduce energy consumption (and therefore reduce irrigation variable costs) or to control the power demand by regulation to "off-peak" time periods. In the United States during the 1970s when energy rates were rapidly escalating, electrical load management became a critical component to preserve and/or maintain irrigation power availability.

Water quality issues have become major irrigation management factors. The impact of irrigation on the sustainability of irrigated agriculture has become important globally. The increased demand for the declining developed, high-quality water resources within the United States is one example of this environmental awareness. This awareness is heightened in areas with conjunctive use of groundwater and surface water for multi-purpose use (irrigation, domestic, municipal, and industrial). For example, groundwater contamination from leached nitrogen beneath irrigated lands along the central Platte Valley in Nebraska has heightened awareness about the necessity to integrate farm fertility management with irrigation management; in the San Joaquin Valley in central California, the leaching of naturally occurring toxic elements such as selenium into drainage waters has caused farm drainage discharge elimination with its associated perched water table creation and land degradation; in the Grand Valley of Colorado, percolating waters beneath irrigated lands leach naturally occurring salts into the Colorado River with many downstream impacts all the way to California and even into Mexico, affecting international treaties and compacts.

Often irrigation management is focused on annual or shorter-term objectives—crop variety or species chosen, crop yield and/or quality, irrigation method, irrigation amount, energy costs, etc. Longer-term objectives for irrigation management include sustainability (water availability), water quality issues, and producer risk. Clearly, irrigation must be profitable or it will no longer remain viable and feasible. ET, irrigation design, and irrigation management affect both the short- and long-term value of irrigation. In many cases, the value of irrigation far exceeds its value to an individual producer extending to local, regional, national, and world economies. It remains increasingly important to conserve limited natural resources both (soils, water, and energy) and to use these resources wisely to insure long-term food and fiber production for a growing world population. Irrigation engineering will continue to serve an important function in meeting this global need.

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Bibliography

Brustart, W. (1982). "Evaporation into the Atmosphere." D. Reidel, Dordrecht, Holland.

Cuenca, R. H. (1989). "Irrigation System Design: An Engineering Approach." Prentice Hall, Englewood Cliffs, NJ.

Hagan, R. M., Haise, H. R., and Edminster, T. W. (eds.) (1967). "Irrigation of Agricultural Lands." Agronomy Monograph No. 11, Am. Soc. Agron., Madison, WI.

Hoffman, G. J., Howell, T. A., and Solomon, K. H. (eds.) (1990). "Management of Farm Irrigation Systems." ASAE Monograph, Am. Soc. Agric. Engrs., St. Joseph, MI.

James, L. G. (1988). "Principles of Farm Irrigation System Design." John Wiley & Sons, New York, NY.

Jensen, M. E. (ed.) (1980). "Design and Management of Farm Irrigation Systems." ASAE Monograph, Am. Soc. Agric. Engrs., St. Joseph, MI.

Jensen, M. E., Burman, R. D., and Allen, R. G. (eds.) (1990). "Evapotranspiration and Irrigation Water Requirements." ASCE Manual and Reports on Engineering Practice No. 70, Am. Soc. Civil Engrs., New York, NY.

Monteith, J. L., and Unsworth, M. H. (1990). "Principles of Environmental Physics," 2nd ed. Edward Arnold, London, Great Britain.

Pair, C. H., Hinze, W. H., Frost, K. R., Sneed, R. E., and Schiltz, T. J. (1983). "Irrigation" *formerly "Sprinkler Irrigation."* The Irrig. Assoc., Silver Spring, MD.

Rosenberg, N. J., Blad, B. L., and Verma, S. B. (1983). "Microclimate, the Biological Environment." John Wiley & Sons, New York, NY.

Stewart, B. A., and Nielsen, D. R. (eds.) (1990). "Irrigation of Agricultural Crops." Agronomy Monograph No. 30, Am. Soc. Agron., Crop Sci. Soc. Am., and Soil Sci. Soc. Am., Madison, WI.