Irrigation Efficiency

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INTRODUCTION

Irrigation efficiency is a critical measure of irrigation performance in terms of the water required to irrigate a field, farm, basin, irrigation district, or an entire watershed. The value of irrigation efficiency and its definition are important to the societal views of irrigated agriculture and its benefit in supplying the high quality, abundant food supply required to meet our growing world's population. "Irrigation efficiency" is a basic engineering term used in irrigation science to characterize irrigation performance, evaluate irrigation water use, and to promote better or improved use of water resources, particularly those used in agriculture and turf/landscape management.[1–4] Irrigation efficiency is defined in terms of: 1) the irrigation system performance, 2) the uniformity of the water application, and 3) the response of the crop to irrigation. Each of these irrigation efficiency measures is interrelated and will vary with scale and time. Fig. 1 illustrates several of the water transport components involved in defining various irrigation performance measures. The spatial scale can vary from a single irrigation application device (a siphon tube, a gated pipe gate, a sprinkler, a microirrigation emitter) to an irrigation set (basin plot, a furrow set, a single sprinkler lateral, or a microirrigation lateral) to broader land scales (field, farm, an irrigation canal lateral, a whole irrigation district, a basin or watershed, a river system, or an aquifer). The timescale can vary from a single application (or irrigation set), a part of the crop season (preplanting, emergence to bloom or pollination, or reproduction to maturity), the irrigation season, to a crop season, or a year, partial year (premonsoon season, summer, etc.), or a water year (typically from the beginning of spring snow melt through the end of irrigation diversion, or a rainy or monsoon season), or a period of years (a drought or a "wet" cycle). Irrigation efficiency affects the economics of irrigation, the amount of water needed to irrigate a specific land area, the spatial uniformity of the crop and its yield, the amount of water that might percolate beneath the crop root zone, the amount of water that can return to surface sources for downstream uses or to groundwater aquifers that might supply other water uses, and the amount of water lost to unrecoverable sources (salt sink, saline aquifer, ocean, or unsaturated vadose zone).

The volumes of the water for the various irrigation components are typically given in units of depth (volume per unit area) or simply the volume for the area being evaluated. Irrigation water application volume is difficult to measure, so it is usually computed as the product of water flow rate and time. This places emphasis on accurately measuring the flow rate. It remains difficult to accurately measure water percolation volumes groundwater flow volumes, and water uptake from shallow groundwater.

IRRIGATION SYSTEM PERFORMANCE EFFICIENCY

Irrigation water can be diverted from a storage reservoir and transported to the field or farm through a system of canals or pipelines; it can be pumped from a reservoir on the farm and transported through a system of farm canals or pipelines; or it might be pumped from a single well or a series of wells through farm canals or pipelines. Irrigation districts often include small to moderate size reservoirs to regulate flow and to provide short-term storage to manage the diverted water with the on-farm demand. Some on-farm systems include reservoirs for storage or regulation of flows from multiple wells.

Water Conveyance Efficiency

The conveyance efficiency is typically defined as the ratio between the water that reaches a farm or field and that diverted from the irrigation water source.[1,3,4] It is defined as

$$E_c = 100\frac{V_f}{V_t} \qquad (1)$$

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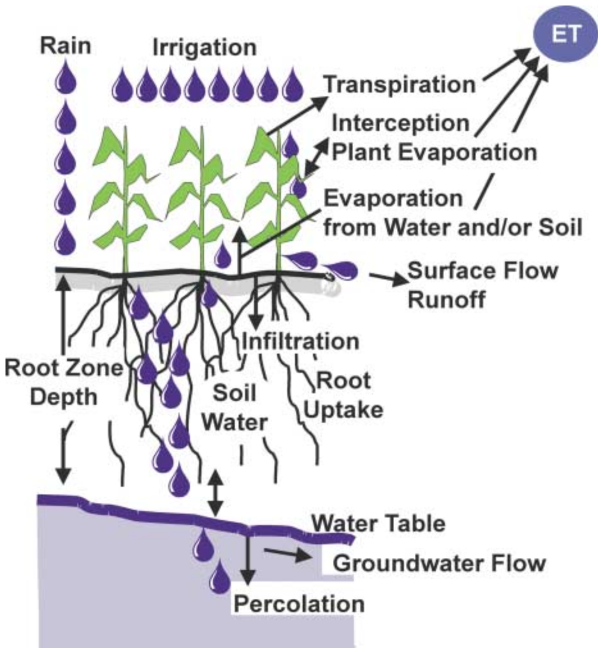

Fig. 1 Illustration of the various water transport components needed to characterize irrigation efficiency.

where E_c is the conveyance efficiency (%), V_f is the volume of water that reaches the farm or field (m^3), and V_t is the volume of water diverted (m^3) from the source. E_c also applies to segments of canals or pipelines, where the water losses include canal seepage or leaks in pipelines. The global E_c can be computed as the product of the individual component efficiencies, E_{ci}, where i represents the segment number. Conveyance losses include any canal spills (operational or accidental) and reservoir seepage and evaporation that might result from management as well as losses resulting from the physical configuration or condition of the irrigation system. Typically, conveyance losses are much lower for closed conduits or pipelines[4] compared with unlined or lined canals. Even the conveyance efficiency of lined canals may decline over time due to material deterioration or poor maintenance.

Application Efficiency

Application efficiency relates to the actual storage of water in the root zone to meet the crop water needs in relation to the water applied to the field. It might be defined for individual irrigation or parts of irrigations (irrigation sets).

Table 1 Example of farm and field irrigation application efficiency and attainable efficiencies

	Field efficiency (%)			Farm efficiency (%)		
Irrigation method	Attainable	Range	Average	Attainable	Range	Average
Surface						
Graded furrow	75	50–80	65	70	40–70	65
w/tailwater reuse	85	60–90	75	85	—	—
Level furrow	85	65–95	80	85	—	—
Graded border	80	50–80	65	75	—	—
Level basins	90	80–95	85	80	—	—
Sprinkler						
Periodic move	80	60–85	75	80	60–90	80
Side roll	80	60–85	75	80	60–85	80
Moving big gun	75	55–75	65	80	60–80	70
Center pivot						
Impact heads w/end gun	85	75–90	80	85	75–90	80
Spray heads wo/end gun	95	75–95	90	85	75–95	90
LEPA[a] wo/end gun	98	80–98	95	95	80–98	92
Lateral move						
Spray heads w/hose feed	95	75–95	90	85	80–98	90
Spray heads w/canal feed	90	70–95	85	90	75–95	85
Microirrigation						
Trickle	95	70–95	85	95	75–95	85
Subsurface drip	95	75–95	90	95	75–95	90
Microspray	95	70–95	85	95	70–95	85
Water table control						
Surface ditch	80	50–80	65	80	50–80	60
Subsurface drain lines	85	60–80	75	85	65–85	70

[a] LEPA is low energy precision application.
(From Refs. 6,7,11.)

Application efficiency includes any application losses to evaporation or seepage from surface water channels or furrows, any leaks from sprinkler or drip pipelines, percolation beneath the root zone, drift from sprinklers, evaporation of droplets in the air, or runoff from the field. Application efficiency is defined as

$$E_a = 100\frac{V_s}{V_f} \tag{2}$$

where E_a is the application efficiency (%), V_s is the irrigation needed by the crop (m^3), and V_f is the water delivered to the field or farm (m^3). The root zone may not need to be fully refilled, particularly if some root zone water-holding capacity is needed to store possible or likely rainfall. Often, V_s is characterized as the volume of water stored in the root zone from the irrigation application. Some irrigations may be applied for reasons other than meeting the crop water requirement (germination, frost control, crop cooling, chemigation, fertigation, or weed germination). The crop need is often based on the "beneficial water needs."[5] In some surface irrigation systems, the runoff water that is necessary to achieve good uniformity across the field can be recovered in a "tailwater pit" and recirculated with the current irrigation or used for later irrigations, and V_f should be adjusted to account for the "net" recovered tailwater. Efficiency values are typically site specific. Table 1 provides a range of typical farm and field irrigation application efficiencies[6–8] and potential or attainable efficiencies for different irrigation methods that assumes irrigations are applied to meet the crop need.

Storage Efficiency

Since the crop root zone may not need to be refilled with each irrigation, the storage efficiency has been defined.[4] The storage efficiency is given as

$$E_s = 100\frac{V_s}{V_{rz}} \tag{3}$$

where E_s is the storage efficiency (%) and V_{rz} is the root zone storage capacity (m^3). The root zone depth and the water-holding capacity of the root zone determine V_{rz}. The storage efficiency has little utility for sprinkler or microirrigation because these irrigation methods seldom refill the root zone, while it is more often applied to surface irrigation methods.[4]

Seasonal Irrigation Efficiency

The seasonal irrigation efficiency is defined as

$$E_i = 100\frac{V_b}{V_f} \tag{4}$$

where E_i is the seasonal irrigation efficiency (%) and V_b is the water volume beneficially used by the crop (m^3). V_b is somewhat subjective,[4,5] but it basically includes the required crop evapotranspiration (ET_c) plus any required leaching water (V_l) for salinity management of the crop root zone.

Leaching requirement (or the leaching fraction)

The leaching requirement,[9] also called the leaching fraction, is defined as

$$L_r = \frac{V_d}{V_f} = \frac{EC_i}{EC_d} \tag{5}$$

where L_r is the leaching requirement, V_d is the volume of drainage water (m^3), V_f is the volume of irrigation (m^3) applied to the farm or field, EC_i is the electrical conductivity of the irrigation water ($dS\,m^{-1}$), and EC_d is the electrical conductivity of the drainage water ($dS\,m^{-1}$). The L_r is related to the irrigation application efficiency, particularly when drainage is the primary irrigation loss component. The L_r would be required "beneficial" irrigation use ($V_l \equiv L_r V_i$), so only V_d greater than the minimum required leaching should reduce irrigation efficiency. Then, the irrigation efficiency can be determined by combining Eqs. (4) and (5)

$$E_i = 100\left(\frac{V_b}{V_f} + L_r\right) \tag{6}$$

Burt et al.[5] defined the "beneficial" water use to include possible off-site needs to benefit society (riparian needs or wildlife or fishery needs). They also indicated that V_f should not include the change in the field or farm storage of water, principally soil water but it could include field (tailwater pits) or farm water storage (a reservoir) that wasn't used within the time frame that was used to define E_i.

IRRIGATION UNIFORMITY

The fraction of water used efficiently and beneficially is important for improved irrigation practice. The uniformity of the applied water significantly affects irrigation efficiency. The uniformity is a statistical property of the

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applied water's distribution. This distribution depends on many factors that are related to the method of irrigation, soil topography, soil hydraulic or infiltration characteristics, and hydraulic characteristics (pressure, flow rate, etc.) of the irrigation system. Irrigation application distributions are usually based on depths of water (volume per unit area); however, for microirrigation systems they are usually based on emitter flow volumes because the entire land area is not typically wetted.

Christiansen's Uniformity Coefficient

Christiansen[10] proposed a coefficient intended mainly for sprinkler system based on the catch volumes given as

$$C_{\mathrm{U}} = 100\left[\frac{1-(\sum|X-\bar{x}|)}{\sum X}\right] \tag{7}$$

where C_{U} is the Christiansen's uniformity coefficient in percent, X is the depth (or volume) of water in each of the equally spaced catch containers in mm or ml, and $\bar{x}$ is the mean depth (volume) of the catch (mm or ml). For C_{U} values $>70\%$, Hart[11] and Keller and Bliesner[8] presented

$$C_{\mathrm{U}} = 100\left[1-\left(\frac{\sigma}{x}\right)\left(\frac{2}{\pi}\right)^{0.5}\right] \tag{8}$$

where σ is the standard deviation of the catch depth (mm) or volume (ml). Eq. 8 approximates the normal distribution for the catch amounts.

The C_{U} should be weighted by the area represented by the container[12] when the sprinkler catch containers intentionally represent unequal land areas, as is the case for catch containers beneath a center pivot. Heermann and Hein[12] revised the C_{U} formula (Eq. 8) to reflect the weighted area, particularly intended for a center pivot sprinkler, as follows:

$$C_{\mathrm{U(H\&H)}} = 100\left\{1-\left[\frac{\left(\sum S_i\left|V_i-\left(\frac{\sum V_iS_i}{\sum S_i}\right)\right|\right)}{\sum(V_iS_i)}\right]\right\} \tag{9}$$

where S_i is the distance (m) from the pivot to the ith equally spaced catch container and V_i is the volume of the catch in the ith container (mm or ml).

Low-Quarter Distribution Uniformity

The distribution uniformity represents the spatial evenness of the applied water across a field or a farm as well as within a field or farm. The general form of the distribution uniformity can be given as

$$D_{U_p} = 100\left(\frac{\bar{V}_p}{\bar{V}_{\mathrm{f}}}\right) \tag{10}$$

where D_{U_p} is the distribution uniformity (%) for the lowest p fraction of the field or farm (lowest one-half $p=1/2$, lowest one-quarter $p=1/4$), $\bar{V}_p$ is the mean application volume (m^3), and $\bar{V}_f$ is the mean application volume (m^3) for the whole field or farm. When $p=1/2$ and $C_{\mathrm{U}}>70\%$, then the D_{U} and C_{U} are essentially equal.[13] The USDA-NRCS (formerly, the Soil Conservation Service) has widely used D_{Ulq} ($p=1/4$) for surface irrigation to access the uniformity applied to a field, i.e., by the irrigation volume (amount) received by the lowest one-quarter of the field from applications for the whole field. Typically, D_{U_p} is based on the postirrigation measurement[5] of water volume that infiltrates the soil because it can more easily be measured and better represents the water available to the crop. However, the postirrigation infiltrated water ignores any water intercepted by the crop and evaporated and any soil water evaporation that occurs before the measurement. Any water that percolates beneath the root zone or the sampling depth will also be ignored.

The D_{U} and C_{U} coefficients are mathematically interrelated through the statistical variation (coefficient of variation, $\sigma/\bar{x}$, C_{v}) and the type of distribution. Warrick[13] presented relationships between D_{U} and C_{U} for normal, log-normal, uniform, specialized power, beta- and gamma-distributions of applied irrigations.

Emission Uniformity

For microirrigation systems, both the C_{U} and D_{U} concepts are impractical because the entire soil surface is not wetted. Keller and Karmeli[14] developed an equation for microirrigation design as follows

$$E_{\mathrm{U}} = 100[1-1.27(C_{\mathrm{vm}})n^{-1/2}]\left(\frac{q_{\mathrm{m}}}{\bar{q}}\right) \tag{11}$$

where E_{U} is the design emission uniformity (%), C_{vm} is the manufacturer's coefficient of variability in emission device flow rate (1/h), n is the number of emitters per plant, q_{m} is the minimum emission device flow rate (1/h) at the minimum system pressure, and $\bar{q}$ is the mean emission device flow rate (1/h). This equation is based on the D_{Ulq} concept,[4] and includes the influence of multiple emitters per plant that each may have a flow rate from a population of random flow rates based on the emission device manufacturing variation. Nakayama, Bucks, and Clemmens[15] developed a design coefficient based more closely on the C_{U} concept for emission device flow rates

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from a normal distribution given as

$$C_{\mathrm{Ud}} = 100(1 - 0.798(C_{\mathrm{vm}})n^{-1/2}) \qquad (12)$$

where C_{Ud} is the coefficient of design uniformity in percent and the numerical value, 0.798, is

$$\left(\frac{2}{\pi}\right)^{0.5}$$

from Eq. 8.

Many additional factors affect microirrigation uniformity including hydraulic factors, topographic factors, and emitter plugging or clogging.

WATER USE EFFICIENCY

The previous sections discussed the engineering aspects of irrigation efficiency. Irrigation efficiency is clearly influenced by the amount of water used in relation to the irrigation water applied to the crop and the uniformity of the applied water. These efficiency factors impact irrigation costs, irrigation design, and more important, in some cases, the crop productivity. Water use efficiency (WUE) has been the most widely used parameter to describe irrigation effectiveness in terms of crop yield. Viets[16] defined WUE as

$$\mathrm{WUE} = \frac{Y_{\mathrm{g}}}{\mathrm{ET}} \qquad (13)$$

where WUE is water use efficiency (kg m^{-3}), Y_{g} is the economic yield (g m^{-2}), and ET is the crop water use (mm). Water use efficiency is usually expressed by the economic yield, but it has been historically expressed as well in terms of the crop dry matter yield (either total biomass or aboveground dry matter). These two WUE bases (economic yield or dry matter yield) have led to some inconsistencies in the use of the WUE concept. The transpiration ratio (transpiration per unit dry matter) is a more consistent value that depends primarily on crop species and the environmental evaporative demand,[17] and it is simply the inverse of WUE expressed on a dry matter basis.

Irrigation Water Use Efficiency

The previous discussion of WUE does not explicitly explain the crop yield response to irrigation. Water use efficiency is influenced by the crop water use (ET). Bos[3] defined a term for WUE to characterize the influence of irrigation on WUE as

$$\mathrm{WUE} = \frac{(Y_{gi} - Y_{\mathrm{gd}})}{(\mathrm{ET}_i - \mathrm{ET}_d)} \qquad (14)$$

where WUE is irrigation water use efficiency (kg m^{-3}), Y_{gi} is the economic yield (g m^{-2}) for irrigation level i, Y_{gd} is the dryland yield (g m^{-2}; actually, the crop yield without irrigation), ET_i is the evapotranspiration (mm) for irrigation level i, and ET_{d} is the evapotranspiration of the dryland crops (or of the ET without irrigation). Although Eq. 14 seems easy to use, both Y_{gd} and ET_{d} are difficult to evaluate. If the purpose is to compare irrigation and dryland production systems, then dryland rather than nonirrigated conditions should be used. If the purpose is to compare irrigated regimes with an unirrigated regime, then appropriate values for Y_{gd} and ET_{d} should be used. Often, in most semiarid to arid locations, Y_{gd} may be zero. Bos[3] defined irrigation WUE as

$$\mathrm{IWUE} = \frac{(Y_{gi} - Y_{\mathrm{gd}})}{\mathrm{IRR}_i} \qquad (15)$$

where IWUE is the irrigation efficiency (kg m^{-3}) and IRR_i is the irrigation water applied (mm) for irrigation level i. In Eq. 15, Y_{gd} may be often zero in many arid situations.

CONCLUSION

Irrigation efficiency is an important engineering term that involves understanding soil and agronomic sciences to achieve the greatest benefit from irrigation. The enhanced understanding of irrigation efficiency can improve the beneficial use of limited and declining water resources needed to enhance crop and food production from irrigated lands.

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