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Irrigation Efficiency and Uniformity, and Crop Water Use Efficiency

Suat Irmak
University of Nebraska-Lincoln, suat.irmak@unl.edu

Lameck O. Odhiambo
University of Nebraska-Lincoln, lodhiambo2@unl.edu

William L. Kranz
University of Nebraska-Lincoln, wkranz1@unl.edu

Dean E. Eisenhauer
University of Nebraska-Lincoln, deisenhauer1@unl.edu

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Irrigation Efficiency and Uniformity, and Crop Water Use Efficiency

Suat Irmak, Extension Soil and Water Resources and Irrigation Engineering Specialist, Professor

Lameck O. Odhiambo, Research Assistant Professor
William L. Kranz, Extension Irrigation Specialist and Associate Professor
Dean E. Eisenhauer, Professor
Department of Biological Systems Engineering

This Extension Circular describes various irrigation efficiency, crop water use efficiency, and irrigation uniformity evaluation terms that are relevant to irrigation systems and management practices currently used in Nebraska, in other states, and around the world. The definitions and equations described can be used by crop consultants, irrigation district personnel, and university, state, and federal agency personnel to evaluate how efficiently irrigation water is applied and/or used by the crop, and can help to promote better or improved use of water resources in agriculture.

As available water resources become scarcer, more emphasis is given to efficient use of irrigation water for maximum economic return and water resources sustainability. This requires appropriate methods of measuring and evaluating how effectively water extracted from a water source is used to produce crop yield. Inadequate irrigation application results in crop water stress and yield reduction. Excess irrigation application can result in pollution of water sources due to the loss of plant nutrients through leaching, runoff, and soil erosion.

The efficiency of irrigation water use varies across Nebraska. In areas where water is limited, available water is used more carefully. Whereas, in areas of abundant water, the value put on conserving water is less and the tendency to over irrigate exists. Efficient use of water is also influenced by cost of labor, ease of controlling water, crops being irrigated, type of irrigation system, and soil characteristics. Various terms are used to describe how efficiently irrigation water is applied and/or used by the crop. Incorrect usage of these terms is common and can lead to a misrepresentation of how well an irrigation system is performing.

Nebraska has more than 8.6 million acres under irrigation with approximately 80 percent under sprinkler (mainly center pivot) irrigation systems, about 19 percent under surface (mainly furrow) irrigation systems, and less than 1 percent under microirrigation (subsurface drip) irrigation systems. In practice, it is seldom possible to deliver every drop of irrigation water to the crop due to water losses between the source and the delivery point. Irrigation water losses include spray droplet evaporation, weed water use, soil evaporation, furrow evaporation, leaks in pipelines, seepage and evaporation from irrigation ditches, surface runoff, and deep percolation. The magnitude of each loss is dependent on the characteristics and management of each type of irrigation system.

In Nebraska, the main beneficial use of irrigation water is to meet crop evapotranspiration (ET) requirements. Another beneficial use is water used for

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chemigation. In some areas, leaching of salt from the soil is also an important beneficial use. Perhaps the most non-beneficial use of water is evaporation from water and soil surface, which does not contribute to crop productivity.

Irrigation efficiency is generally defined from three points of view: (1) the irrigation system performance, (2) the uniformity of water application, and (3) the response of the crop to irrigation. These irrigation efficiency measures are interrelated and vary on a spatial and temporal scale. The spatial scale may be defined for a single field, or on a larger scale up to a whole irrigation district or watershed. The temporal scale can vary from a single irrigation event to a longer period such as part of the growing season, or a period of years.

Evaluating Irrigation System Performance

Irrigation system performance describes the effectiveness of the physical system and operating decisions to deliver irrigation water from a water source to the crop. Several efficiency terms are used to evaluate irrigation system performance. These include water conveyance efficiency, water application efficiency, soil water storage efficiency, irrigation efficiency, overall irrigation efficiency, and effective irrigation efficiency.

Water Conveyance Efficiency (E_c)

Irrigation water is normally conveyed from a water source to the farm or field through natural drainage ways, constructed earthen or lined canals, or pipelines. Many conveyance systems have transmission losses, meaning that water delivered to the farm or field is usually less than the water diverted from the source. Water losses in the conveyance system include canal seepage, canal spills (operational or accidental), evaporation losses from canals, and leaks in pipelines. The water conveyance efficiency is typically defined as the ratio between the irrigation water that reaches a farm or field to that diverted from the water source. It is expressed as:

$$E_c = (V_f / V_t) \text{ x } 100 \qquad (1)$$

E_c = water conveyance efficiency (%)
V_f = volume of irrigation water that reaches the farm or field (acre-inch)
V_t = volume of irrigation water diverted from the water source (acre-inch)

The water conveyance efficiency also can be applied to evaluate individual segments of canals or pipelines. Typically, conveyance losses are much lower for pipelines due to reduced evaporation and seepage losses. In Nebraska, irrigation water is frequently pumped from wells located in the field and carried in pipelines. Water delivery through open canals is also common, especially in the central and western parts of the state. Since there is minimal water loss in closed/pressurized conveyance systems, the conveyance efficiency can be as high as 100 percent.

Water Application Efficiency (E_a)

Water application efficiency (E_a) provides a general indication of how well an irrigation system performs its primary task of delivering water from the conveyance system to the crop. The objective is to apply the water and store it in the crop root zone to meet the crop water requirement. E_a is a measure of the fraction of the total volume of water delivered to the farm or field to that which is stored in the root zone to meet the crop evapotranspiration (ET) needs. E_a is expressed as:

$$E_a = (V_s / V_f) \text{ x } 100 \qquad (2)$$

E_a = water application efficiency (%)
V_s = volume of irrigation water stored in the root zone (acre-inch)
V_f = volume of irrigation water delivered to the farm or field (acre-inch)

Water losses during sprinkler irrigation include wind drift and evaporation from droplets in the air, from the crop canopy, and from the soil surface. Wind drift loss is water that is transported from the target area by wind, while droplet evaporation is water loss by direct evaporation of water while in transit from the nozzle to the crop or soil surface. Wind drift and droplet evaporation losses can be large if the sprinkler design or pressure produces a high percentage of very fine droplets. In Nebraska, many center pivot systems are designed to operate on low-pressure drop tubes below the center pivot lateral and close to the crop canopy. Because wind speeds are reduced close to the crop canopy, placing low-pressure sprinkler devices just above the crop canopy reduces the amount of water lost through wind drift and droplet evaporation. Canopy losses include water that is intercepted by the plant foliage and evaporated back to the air. When water reaches the soil surface, losses can occur from soil evaporation, runoff, or percolation below the root zone.

Presented in *Table 1* are the results of estimates of application water losses in three different sprinkler devices (low-angle impact, spray head, and LEPA) based on research conducted at the USDA-ARS Conservation and Production Laboratory in Bushland, Texas. The low-angle impact sprinkler was located on top of the sprinkler main lateral, the spray heads were operated at 5 ft above the canopy, and the LEPA system using bubblers was operated at 1 ft above the ground. The water loss estimates are based on the irrigation amount of 1 in to mature corn under minimal wind conditions.

Table 1. Estimates of sprinkler application water losses for 1-inch water application.

Water Loss Component	*Low-Angle Impact Sprinkler Water Loss*	*Spray Head Water Loss*	*LEPA Water Loss*
Drift and droplet evaporation	0.03 in	0.01 in	0.00 in
Plant interception	0.04 in	0.04 in	0.00 in
Net canopy evaporation	0.08 in	0.03 in	0.00 in
Soil evaporation during irrigation	Negligible	Negligible	0.02 in
Total water loss	0.15 in	0.08 in	0.02 in

Water losses during surface (furrow) irrigation include runoff, evaporation from water in the furrow channels, evaporation from the soil surface, and percolation below the root zone. Runoff losses can be significant if tailwater is not controlled and reused. In cases where runoff water is recovered and reused, the volume of irrigation water delivered to the farm or field (V_f) should be adjusted to account for the net recovered tailwater. In Nebraska, irrigators commonly block the lower end of furrows to prevent runoff. Blocking furrow ends, however, can result in nonuniform water distribution and excessive deep percolation at both the upstream and downstream ends of the field. Shown in *Figure 1* are examples of infiltration profiles under conventional furrow and blocked-end furrow irrigation. The application efficiency of furrow irrigation is impacted by management practices, stream size, soil characteristics, and field slope. The normal practice is to supply continuous flow for the entire irrigation set time. Some farmers use surge irrigation to reduce overall application depths and improve infiltration uniformity along the furrow. In surge irrigation, water is intermittently applied to the furrows, usually resulting in less runoff and more consistent opportunity time along the furrow.

Because of the losses during application, water application efficiency is always less than 100 percent. Presented in *Table 2* are "*potential*" values of water application efficiencies for well-designed and managed irrigation systems. It is possible to have a high E_a and yet have unsatisfactory irrigation performance. For example, the amounts of irrigation water applied (V_f) may be small to minimize deep percolation and surface runoff losses, but insufficient to satisfy crop ET requirements, causing yield reductions. It is also possible to apply the correct amount of water (V_f) and have very low application losses, but still have yield reduction if the irrigation water is poorly distributed. Poor water distribution causes water stress in areas receiving relatively low amounts of water and oxygen stress in areas that are waterlogged for several days. For E_a to have practical meaning, V_s needs to be sufficient and well distributed to avoid undesirable water stress and oxygen stress (in the root zone) in the farm or field. Thus, reporting of both application efficiency and water distribution uniformity would provide a better indication of overall irrigation system performance. It should be noted that "*potential*" application efficiency values presented in *Table 2* are a strong function of how a given irrigation system is managed (e.g., a subsurface drip irrigation system, which has the highest "*potential*" application efficiency, if poorly managed, can have a lower efficiency than other irrigation methods). The efficiency values presented in *Table 2* are also strong functions of soil type, slope, crop growth stage, system/water delivery capacity, and many other management factors and field and irrigation method characteristics. Thus, for the same irrigation method, these values can vary substantially from one field or location to another. Proper irrigation management can increase the

Table 2. "*Potential*" application efficiencies for well-designed and well-managed irrigation systems.

Irrigation System	*"Potential" Application Efficiency (%)*
Sprinkler Irrigation Systems	
LEPA	80 - 90
Linear move	75 - 85
Center pivot	75 - 85
Traveling gun	65 - 75
Side roll	65 - 85
Hand move	65 - 85
Solid set	70 - 85
Surface Irrigation Systems	
Furrow (conventional)	45 - 65
Furrow (surge)	55 - 75
Furrow (with tailwater reuse)	60 - 80
Basin (with or without furrow)	60 - 75
Basin (paddy)	40 - 60
Precision level basin	65 - 80
Microirrigation Systems	
Bubbler (low head)	80 - 90
Microspray	85 - 90
Micro-point source	85 - 90
Micro-line source	85 - 90
Subsurface drip	> 95
Surface drip	85 - 95

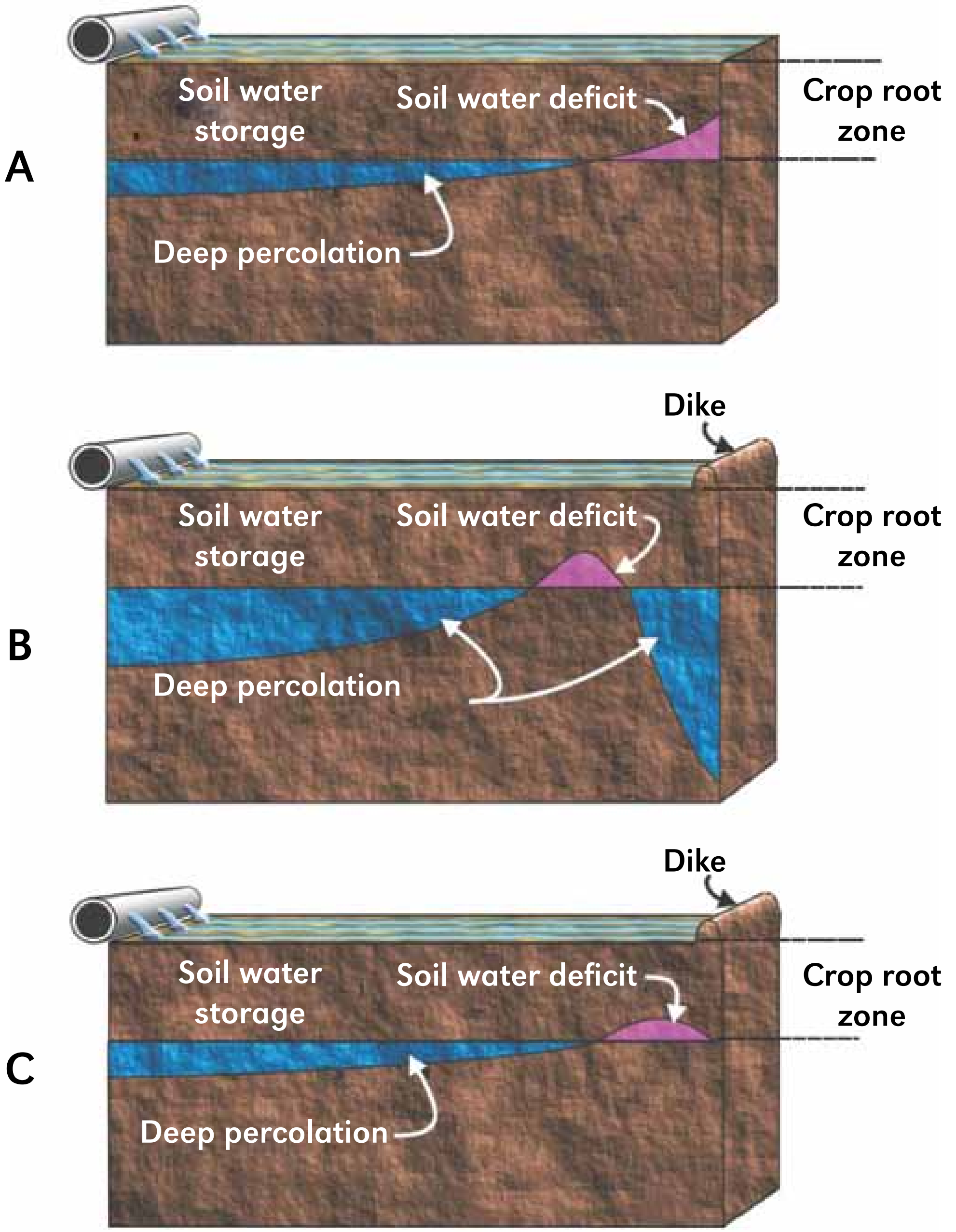

Figure 1. Example of infiltration profiles under (A) conventional furrow irrigation, (B) typical blocked-end furrow irrigation, and (C) well-managed blocked-end furrow irrigation.

increase the application efficiency, and poor irrigation management can result in inefficient use of water and reduce application efficiency. Overirrigation may result in leaching chemicals below the crop root zone, cause yield reduction, and result in wasting water resources. Improper timing and inadequate irrigation applications that do not meet the crop water requirement may impose stress to the crop and reduce grain yield and yield quality.

The calculation of water application efficiency and other efficiency terms requires measurement of irrigation water stored in the root zone, which requires measurement of soil water status. There are many ways of measuring soil water status and crop water use that are explained in other UNL Extension publications (e.g., EC783, *Watermark Granular Matrix Sensor to Measure Soil Matric Potential for Irrigation Management*; G1579, *Using Atmometers (ET_{gage}) for Irrigation Management*; EC709, *Irrigation Scheduling: Checkbook Method*; G1994, *Estimating Crop Evapotranspiration from Reference Evapotranspiration and Crop Coefficients*). For the purpose of irrigation efficiency calculations, the soil-water content is then expressed as an equivalent depth. Producers in Nebraska are increasingly using soil moisture monitoring devices for irrigation management. These sensors also can be used to determine the volume of water added to the soil during irrigation.

Soil Water Storage Efficiency (E_s)

The main goal in most irrigation applications is to maximize water storage in the soil root zone to satisfy crop ET while minimizing deep percolation and surface runoff. The soil water storage efficiency indicates how well the system uses the available root zone storage capacity to store water to meet crop needs. Thus, in most cases, maximizing water storage from irrigation is beneficial. Soil water storage efficiency (E_s) is defined as the ratio of the volume of water stored in the root zone to the volume of water required to fill the root zone to near field capacity. It is expressed as:

$$Es = [Vs / (Vfc - Va)] \times 100 \quad (3)$$

E_s = soil water storage efficiency (%)
V_s = volume of water stored in the soil root zone from an irrigation event (acre-inch)
V_{fc} = volume capacity at field capacity in the crop root zone (acre-inch)
V_a = volume of water in the soil root zone prior to an irrigation event (acre-inch)

The maximum amount of water that should be applied to achieve high E_s for a given irrigation event is the difference between the field capacity and average water content in the soil root zone prior to the irrigation event. A high E_s means that the irrigation brings the soil root zone to field capacity, but does not lead to deep percolation. In most cases, it is suggested not to refill the soil profile to the field capacity, but rather to leave some storage capacity for a potential rainfall event. Thus, refilling the soil profile to about 90 percent of the field capacity can be a good strategy. Sprinkler and microirrigation systems usually supply only sufficient water to satisfy crop ET needs without filling the soil root zone. In furrow irrigation, the usual practice is to irrigate every other furrow to provide more storage space within the root zone for potential rainfall. In such cases, the use of E_s may be meaningless because the goal with E_a is not to maximize root zone water storage. Depending on the soil type and other factors, an average root zone depth of 36 in for soybean and 48 in for corn is commonly used for irrigation management.

Irrigation Efficiency (E_i)

Sometimes, irrigation water may be applied for uses other than simply satisfying water used by crop for ET. Other beneficial uses include water used for removal of salts (leaching requirement), microclimate control (evaporative cooling during extreme heat or frost protection), seedbed preparation, germination of seeds, softening of a soil crust for seedling emergence, and ET from plants beneficial to the crop (windbreaks or cover crops for orchards). Some water also may be beneficially applied for chemigation. When more than ET water used is considered, the term irrigation efficiency (E_i) is used to define the effectiveness of the irrigation system in delivering all the water beneficially used to produce the crop. Irrigation efficiency is defined as the ratio of the volume of water that is beneficially used to the volume of irrigation water applied. It is expressed as:

$$E_i = (V_b / V_f) \times 100 \quad (4)$$

E_i = irrigation efficiency (%)
V_b = volume of water beneficially used (acre-inch)
V_f = volume of water delivered to the field (acre-inch)

Water losses that occur as a result of excessive deep percolation, runoff, weed ET, wind drift, and spray droplet evaporation are normally not considered as beneficial uses, and thus tend to decrease irrigation efficiency. A major problem with using irrigation efficiency as a performance parameter is the subjectivity involved in the definition of beneficial use. Some irrigation practitioners consider spray droplet evaporation losses as beneficial since evaporation during sprinkling cools the crop canopy and is partially compensated for by transpiration reduction. Most irrigation systems in Nebraska are operated primarily to supply water for crop ET, which allows water application efficiency (E_a) and irrigation efficiency (E_i) to be used interchangeably. Other factors that impact beneficial uses and, thus, irrigation efficiency are local water regulation agency allocation rules and farmer-practiced irrigation management strategies.

Overall Irrigation Efficiency (E_o)

The overall irrigation efficiency (E_o) represents the efficiency of the entire physical system and operating decisions in delivering irrigation water from a water supply source to the target crop. It is calculated by multiplying the efficiencies of water conveyance and water application:

$$E_o = (E_c \times E_a) \times 100 \quad (5)$$

E_o = overall irrigation efficiency (%)
E_c = water conveyance efficiency (decimal)
E_a = water application efficiency (decimal)

Effective Irrigation Efficiency (E_e)

Reuse of runoff water decreases the amount of water pumped from a source and can improve overall irrigation efficiency. Effective irrigation efficiency (E_e) is the overall irrigation efficiency corrected for runoff and deep percolation water that is recovered and reused or restored to the water source without reduction in water quality. It is expressed as:

$$E_e = [E_o + (FR) \times (1.0 - E_o)] \text{ x } 100 \qquad (6)$$

FR = fraction of surface runoff, seepage, and/or deep percolation that is recovered

In some areas, water regulations prohibit irrigation water pumped from groundwater to leave the field as runoff. Producers are, therefore, more motivated to reuse irrigation runoff to prevent it from leaving the field. Irrigators who do not have reuse systems often reduce the stream size in the furrow to minimize runoff. While this practice can reduce runoff, it generally results in poorer distribution of water and deeper percolation. Another way to reduce runoff while improving water distribution is to use surge-flow irrigation. Blocking the furrow ends is yet another way of reducing runoff. Losses due to wind drift, evaporation, and transpiration by weeds cannot be recovered.

Evaluating the Uniformity of Water Application

All irrigation systems apply water nonuniformly to a varying degree. The irrigation system performance efficiency terms described previously do not directly account for the uniformity or nonuniformity of irrigation application within a given field. Yet, the nonuniformity of the applied water can significantly affect irrigation performance. Nonuniform irrigation application results in areas that are under-watered or over-watered. Crops may experience water stress in areas that are under-watered, and oxygen stress in areas that are waterlogged for several days. Over-watering also may cause surface runoff and/or leaching of nutrients below the root zone. Thus, both under- and over-watered areas may experience yield reduction. With favorable climate conditions, optimum crop growth and yield are obtained with high uniformity of irrigation application in which each plant has an equal opportunity to access the applied water and nutrients.

The uniformity of irrigation application depends on many factors that are related to the method of irrigation, topography, soil (infiltration) characteristics, and the irrigation system's pressure and flow rate. For a sprinkler irrigation system, nonuniformity can be due to numerous factors: (1) improper selection of delivery pipe diameters (sub-main, manifolds, and lateral), (2) too high or too low operating pressure, (3) improper selection of sprinkler heads and nozzles, (4) inadequate sprinkler overlap, (5) wind effects on water distribution, (6) wear and tear on system components with time, such as pump impellers, pressure regulators, or nozzle size, and (7) nozzle clogging.

For surface irrigation, nonuniformity can be caused by: (i) differences in opportunity time for infiltration caused by advance and recession, (ii) spatial variability of soil-infiltration properties, and (iii) non-uniform grades. For micro-irrigation, nonuniformity can be due to: (i) variations in pressure caused by pipe friction and topography, (ii) variations in hydraulic properties of emitters or emission points (from clogging or other reasons), (iii) variations in soil wetting from emission points, and (iv) variations in application timing. For all irrigation methods, poor management also can cause nonuniformity.

Generally, irrigation uniformity is calculated based on indirect measurements. For example, the uniformity of water that enters the soil is assumed to be related to that collected in catch cans for sprinkler systems, to intake opportunity time and infiltration rates for surface systems, and to emitter discharge for microirrigation systems. The common uniformity measures for sprinkler, surface, and microirrigation systems are described in the next section.

Christiansen's Uniformity Coefficient (C_u) for Sprinkler Systems

Christiansen's Uniformity Coefficient (C_u) is commonly used to describe uniformity for stationary sprinkler irrigation systems and is based on the catch volumes (or depth):

$$C_u = 100\,[1 - (\sum|X_i - X_m|) / \sum X_i] \qquad (7)$$

C_u = Christiansen's uniformity coefficient (%)
X_i = measured depth water in equally spaced catch cans on a grid arrangement (inch)
X_m = mean depth of water of the catch in all cans (inch)
$\sum$ = indicates that all measured depths are summed (inch)

The C_u method assumes that each can represents the depth applied to equal areas. This is not true for data collected under center pivots where the catch cans are equally spaced along a radial line from the pivot to the outer end. For center pivot systems, it is necessary to adjust and weigh each measurement based on the area it represents.

Adjusted Uniformity Coefficient ($C_{u(a)}$) for Center Pivot Systems

The adjusted uniformity coefficient for center pivots reflects the weighted area for catch cans that are uniformly spaced and, thus, represent unequal land areas:

$$C_{u(a)} = 100\{1\text{-}[(\Sigma S_i V_i - (\Sigma V_i S_i / \Sigma S_i)\Sigma) / \Sigma(V_i S_i)]\} \qquad (8)$$

$C_{u(a)}$ = adjusted uniformity coefficient for center pivots (%)
S_i = distance from the pivot to the i^{th} equally spaced catch container (ft)
V_i = volume of the catch in the i^{th} container (inch)

Low-Quarter Distribution Uniformity (D_U) for Surface Irrigation Systems

The distribution uniformity is more commonly used to characterize the irrigation water distribution over the field in surface irrigation systems, but it also can be applied to micro and sprinkler irrigation systems. The low-quarter distribution uniformity (D_U) is defined as the average depth infiltrated in the low one-quarter of the field divided by the average depth infiltrated over the entire field. It is expressed as:

$$D_U = (D_{lq} / D_{av}) \text{ x } 100 \qquad (9)$$

D_U = distribution uniformity (%)
D_{lq} = average depth of water infiltrated in the low one-quarter of the field (inch)
D_{av} = average depth of water infiltrated over the field (inch)

Typically, D_U is based on the post-irrigation measurement of water depth that infiltrates the soil because it can be more easily measured and better represents the water available to the crop. However, using post-irrigation measurements of infiltrated water to evaluate D_U ignores any water intercepted by the crop and evaporated, and any soil water evaporation that occurs before the measurement. Any water that percolates below the root zone or the sampling depth also will be ignored. A low D_U ($\leq 60\%$) indicates that the irrigation water is unevenly distributed, while a high D_U ($\leq 80\%$) indicates that the application is relatively uniform over the entire field.

Emission Uniformity (E_U) for Microirrigation Systems

For microirrigation systems [trickle (surface drip), subsurface drip, microspray], both C_U and D_U concepts are impractical because the entire soil surface is not wetted. Microirrigation uniformity is affected by the variability in emitter discharge rates. Variability can be caused by manufacturing variations in orifice size and shape, clogging of the orifices, topographic factors, and hydraulic characteristics of the irrigation system. Uniformity of irrigation water application in microirrigation systems is defined by emission uniformity (E_U) expressed by the empirical formula:

$$E_U = [[1 - 1.27\ (C_{vm})\ n^{-1/2}]\ (q_{min} / q_{avg})] \text{ x } 100 \qquad (10)$$

E_U = emission uniformity (%)
C_{vm} = manufacturer's coefficient of uniformity (unitless)
n = the number of emitters per plant
q_{min} = minimum emitter discharge rate at minimum system pressure (gpm)
q_{avg} = average emitter discharge rate (gpm)

The definition of E_U is based on the ratio of the discharge rate for the lowest quarter of emitters to the average discharge rate, and includes the influence of multiple emitters per plant so that each may have a flow rate from a population of random flow rates based on the emitter variations from manufacturing.

Coefficient of Design Uniformity (C_{Ud}) for Microirrigation Systems

Another parameter commonly used to evaluate the uniformity of water distribution in microirrigation systems is the coefficient of design uniformity (C_{Ud}), which is based on the emitter discharge rate deviations from the average rate:

$$C_{Ud} = [(1 - 0.798(C_{vm})n^{-1/2})] \text{ x } 100 \qquad (11)$$

C_{Ud} = coefficient of design uniformity (%)
C_{vm} = manufacturer's coefficient of uniformity
n = the number of emitters per plant

Evaluating the Response of the Crop to Irrigation

Irrigation system performance and irrigation uniformity parameters discussed previously evaluate the engineering and operational aspects of the irrigation system. Different parameters are used to evaluate the response of the crop to irrigation water. The three most commonly used parameters for evaluating the response of the crop to water are crop water use efficiency, irrigation water use efficiency, and water use efficiency.

Crop Water Use Efficiency (CWU_E)

Crop water use efficiency (CWU_E) is mostly used to describe irrigation effectiveness in terms of crop yield (crop productivity). It is defined as the ratio of the mass of economic yield or biomass produced per unit of irrigation water used in ET. It is expressed as:

$$CWU_E = (Y_i - Y_d) / (ET_i - ET_d) \qquad (12)$$

CWU_E = crop water use efficiency (bu/acre-inch)
Y_i = yield of the irrigated crop (bu/acre)
Y_d = yield for an equivalent rainfed crop (bu/acre)
ET_i = ET for irrigated crop (inch)
ET_d = ET for rainfed crop (inch)

From the above definition, crop water use efficiency has units of production per unit of water used in ET. Units typically used are ton per acre-inch, pound per acre-inch, or bushels per acre-inch.

Irrigation Water Use Efficiency (IWU_E)

Irrigation water use efficiency (IWU_E) is used to characterize crop yield in relation to total depth of water applied for irrigation. It is expressed as follows:

$$IWU_E = (Y_i - Y_d)/IR_i \qquad (13)$$

IWU_E = irrigation water use efficiency (bu/acre-inch)
Y_i = economic yield of the irrigation level crop (bu/acre)
Y_d = economic yield for an equivalent rainfed crop (bu/acre)
IR_i = depth of irrigation water applied for irrigation (inch)

The CWU_E is a better indicator when quantifying the efficiency of a crop production system because it directly reflects the amount of grain yield produced per amount of water used rather than per depth of water applied, which is the case with the IWU_E. This is because not all irrigation water applied to the field is used for crop ET. Thus, IWU_E does not account for the irrigation application losses and actual water used by the crop.

Crop Water Use Efficiency

Benchmark water use efficiency looks at the total amount of water used to produce the yield and is expressed as:

$$WUE_b = Y_i / (P_e + IR + \Delta SW) \qquad (14)$$

WUE_b = benchmark water use efficiency
Y_i = yield of irrigated crop (bu/acre)
P_e = effective rainfall (inch)
IR = irrigation applied (inch)
ΔSW = change in soil water content in the root zone during the growing season (inch)

The denominator of equation 14 is a surrogate estimate for the water used to produce yield. It neglects deep percolation losses, groundwater use, and surface runoff. Experienced irrigation practitioners use WUE_b for a specific region and to identify differences between irrigation methods, irrigation management, or both.

Summary

Irrigation efficiency is described by several terms used to measure how efficiently irrigation water is applied to the field and/or used by the crop. High irrigation efficiency translates into lower operating costs, improved production per unit of water delivered, and improved environmental benefit and management. Incorrect use of efficiency terms can lead to misrepresentation of how well an irrigation system is performing. Therefore, it is important for both producers and irrigation management professionals to select the appropriate efficiency and uniformity parameters when evaluating irrigation systems. Several adjustments can be made to the volume of water delivered to the field to increase irrigation efficiency or uniformity. However, efficiencies of 100 percent are not always desirable or practical. The efficiency and uniformity indices described in this publication can provide the measure to achieve more efficient irrigation management that will lead to conserving water and protecting environmental quality in irrigated agriculture.

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