IRRIGATION MANAGEMENT SERIES

EFFICIENCIES AND WATER LOSSES OF IRRIGATION SYSTEMS

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Efficiency ratings receive a lot of attention. We like efficient engines, air conditioners, water heaters and furnaces. Conservationists like efficient water systems that deliver water for its intended use without loss due to leakage, spills or contamination. Since irrigation is the largest appropriated water user in Kansas, irrigation systems also receive merit based on how efficient they are reported to be. While this might sound straightforward and simple, there is room for confusion because there are different ways to define efficiency. Efficiencies also vary in time and with management. Very "efficient" systems by some definitions can be very poor performers by other definitions, for example, if distribution uniformity and delivery amount are inadequate to fulfill crop need. This bulletin will define and explain several common efficiency terms in use for irrigation systems and show how these terms apply to some common irrigation situations.

DEFINITIONS

Water Conveyance Efficiency (E_c): The percentage of source water that reaches the field.

$E_c = 100\ (W_f / W_s)$
W_f = Water delivered to field
W_s = Water diverted from source

Conveyance efficiency is generally a concern for irrigation districts that supply a group of farmers through a system of canals and open ditches. Since most Kansas irrigation water pumped and carried in closed conduits, conveyance efficiency should be nearly 100 percent.

Water Application Efficiency (E_a): The percentage of water delivered to the field is used by the crop.

$E_a = 100\ (W_c / W_f)$
W_c = Water available for use by the crop
W_f = Water delivered to field

Water application efficiency gives a general sense of how well an irrigation system performs its primary task of getting water to the plant roots. However, it is possible to have a high E_a but have the irrigation water so poorly distributed that crop stress exists in areas of the field. It is also possible to have nearly 100 percent E_a but have crop failure if the soil profile is not filled sufficiently to meet crop water requirements. It is easy to manipulate W_f so that E_a can be nearly 100 percent. Any irrigation system from the worst to the best can be operated in a fashion to achieve nearly 100 percent E_a if W_f is sufficiently low. Increasing E_a in this manner totally ignores the need for irrigation uniformity. For E_a to have practical meaning, W_c needs to be sufficient to avoid undesirable water stress.

Water application efficiency sometimes is incorrectly used to refer to the amount of water delivered to the surface of the soil in an irrigated field by a sprinkler system. Water losses can occur after reaching the soil surface, leading to overestimation of the application efficiency. E_a is often confused with water storage efficiency (E_s), which is the fraction of an irrigation amount stored in the crop root zone. The use of this term is discouraged because of the difficulty in determining the crop root zone and because E_s can be very low while sufficient water is provided to the crop.

Water losses include surface runoff and deep percolation. If a center pivot is equipped with a properly designed nozzle package and operated using best management practices and irrigation scheduling, these losses can be negligible. However, for many systems, these losses can be large and result in poorly distributed or nonuniform irrigation.

Irrigation Efficiency (E_i): The percentage of water delivered to the field that is used beneficially.

$E_i = 100\ (W_b / W_f)$
W_b = Water used beneficially
W_f = Water delivered to field

Irrigation efficiency is more broadly defined than water application efficiency in that irrigation water may have more uses than simply satisfying crop water requirements. Other beneficial uses could include salt leaching, crop cooling, pesticide or fertilizer applications, or frost protection. However, most Kansas irrigation systems are single-purpose, that is to supply water for crop use, which allows water application efficiency and irrigation efficiency to be used interchangeably.

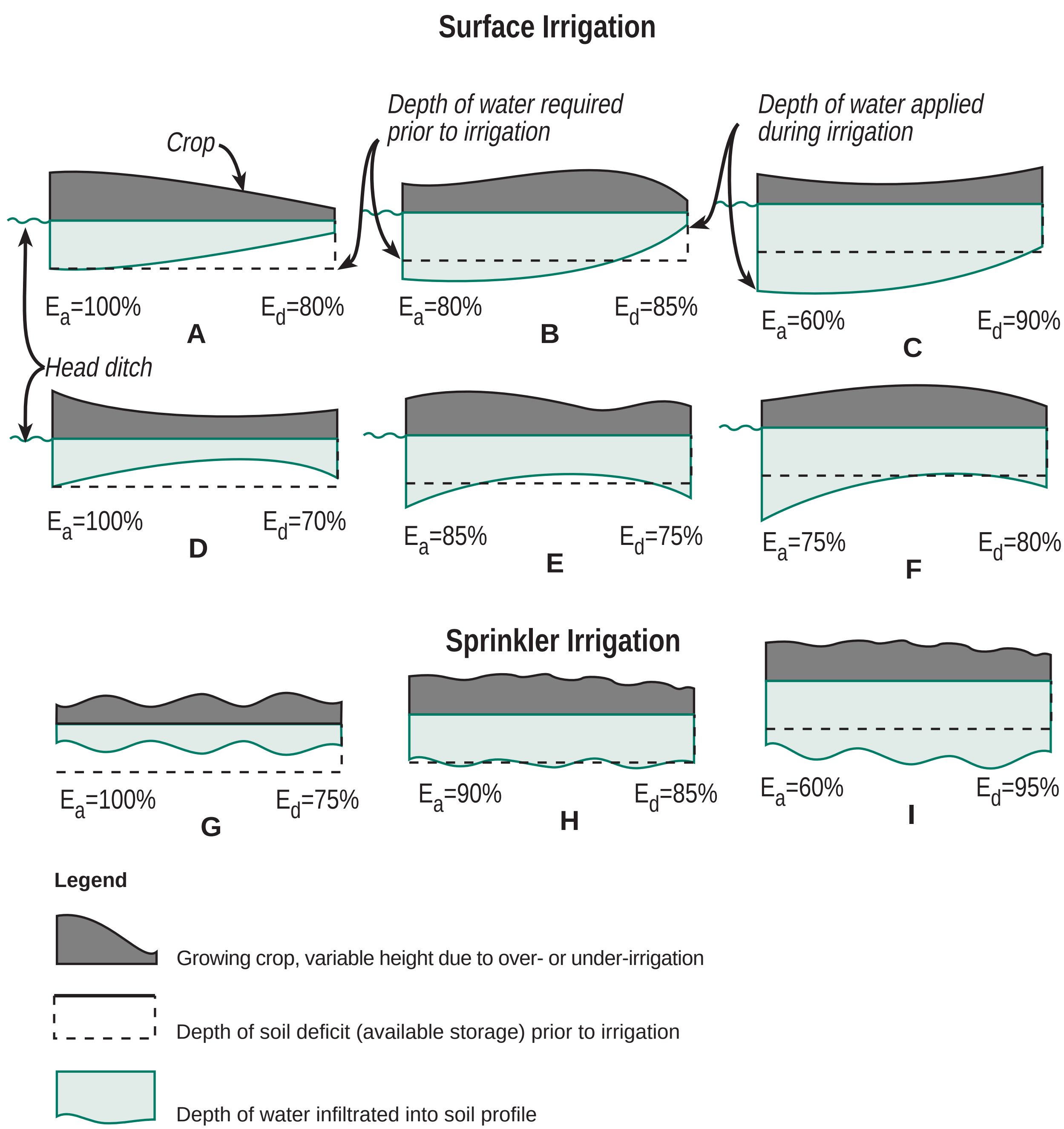
Water lost to percolation below the root zone due to nonuniform application or over-application water runoff from the field, wind drift and spray droplet evaporation all reduce irrigation efficiency. For a better insight of the system performance, water distribution should also be considered.

Water Distribution Efficiency (E_d): The percentage of the average application depth delivered to the least-watered part of the field.

E_d = 100 [1- (y/d)]
y = Average absolute numerical deviation in depth of water stored from average depth stored during the irrigation
d = Average depth of water stored during irrigation

The water distribution efficiency indicates the degree of uniformity in the amount of the water infiltrated into the soil. It also could be defined as the uniformity in depths applied at the surface based on catch-can measures for sprinkler systems. This concept for uniformity was originally developed by Christiansen in 1942 for sprinkler systems.

Figure 1. Application, E_a, and distribution, E_d, efficiencies and the effect on crop production illustrated by two-dimensional soil profiles. For these examples, E_a, estimates are made assuming no runoff. (Hansen, 1960)



Generally, high uniformity is associated with the best crop growth conditions since each plant has an equal opportunity to access applied water. Non-uniformity results in areas that are under-watered or over-watered.

Distribution Uniformity (U_d): The percentage of average application amount received in the least-watered quarter of the field.

$U_d = 100\ (L_q / X_m)$

L_q = Average low-quarter depth of water infiltrated (or caught)

X_m = Average depth of water infiltrated (or caught)

The distribution uniformity gives an indication of the magnitude of the distribution problem. It can be defined as the percent of average application amount in the lowest quarter of the field. U_d is less tedious to calculate than the E_d.

IRRIGATION EFFICIENCY EXAMPLES

Irrigation efficiency examples are shown in Figure 1 for surface and sprinkler irrigation. Examples (A), (B) and (C) show a series with increasing application depth for a field with the heaviest application occurring at the top of the field. The dashed line in the profile represents the depth of water needed to meet crop requirements until the next irrigation event. When the shaded application depth does not reach this line, that portion of the field would be under water stress. Example (A) illustrates how a portion of a crop can be under stress with 100 percent application efficiency, while example (C) shows a crop with no stress but a low application efficiency. Notice crop vigor is represented as less than optimum for areas with heavy deep percolation. Excess water can leach needed nutrients or cause waterlogged growing conditions.

The application efficiencies in Figure 1 are made using a no-runoff assumption, although for the surface irrigation example (A), (B), and (C), this might be better represented as complete tailwater capture and reuse. Example (D), (E) and (F) could be thought of as blocked-end or diked surface irrigated fields. Blocking the end of the field generally results in the driest portion of the field being about $^2/_3$ to $^4/_5$ of the length of run with wettest conditions and the potential for deep percolation losses split between the upper and lower portion ends of the field.

Sprinkler irrigation illustrations are shown in examples (G), (H), and (I). Example (H) is the desirable situation while (G) illustrates crop stress due to under-irrigation and (I) shows over-irrigation.

Center pivot sprinkler packages, even if properly designed, do not have perfect distribution uniformity. Each nozzle outlet progressively has to cover a larger land area (concentric circles) with increasing distance from the center pivot point. Each outlet has a unique and specific discharge rate requirement. However, nozzle outlets are not manufactured in an infinite number of sizes. For a specific nozzle outlet, the designer will select the nozzle outlet size that most closely matches the design specification. Sprinkler spacing must also be consistent with the manufacturer's recommendations to avoid distribution problems. Good designs should have distribution uniformities of approximately 90 percent. In Figure 2, the average design application depth is represented by the solid green line above the soil surface. The dotted black line that moves above and below the design depth represents what actual measured results might look like.

Figure 2. Illustration of sprinkler package water distribution uniformity versus infiltrated water distribution uniformity in soil.

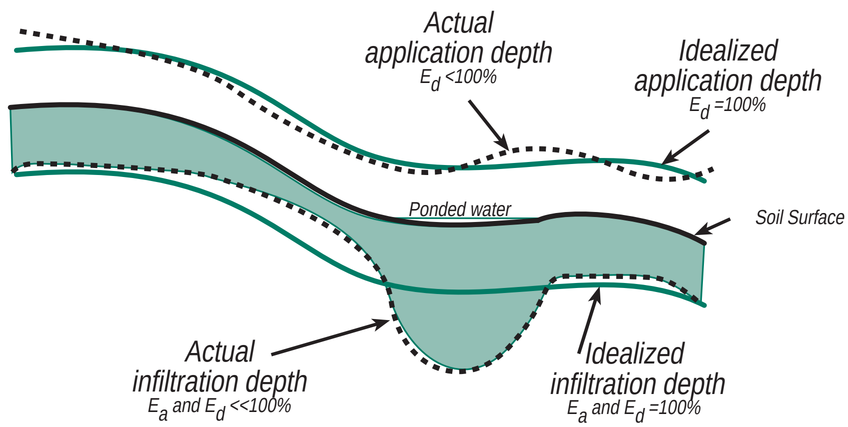


Table 1. Range of Application Efficiencies for Various Irrigation Systems

System Type	Application Efficiency Range* (%)
Surface Irrigation	
Basin	60 - 95
Border	60 - 90
Furrow	50 - 90
Surge	60 - 90
Sprinkler Irrigation	
Handmove	65 - 80
Traveling Gun	60 - 70
Center Pivot & Linear	70 - 95
Solid Set	70 - 85
Microirrigation	
Point source emitters	75 - 95
Line source emitter	70 - 95

** Efficiencies can be much lower due to poor design or management. These values are intended for general system type comparisons and should not be used for specific systems.*

Figure 3. Irrigation water loss and storage locations.

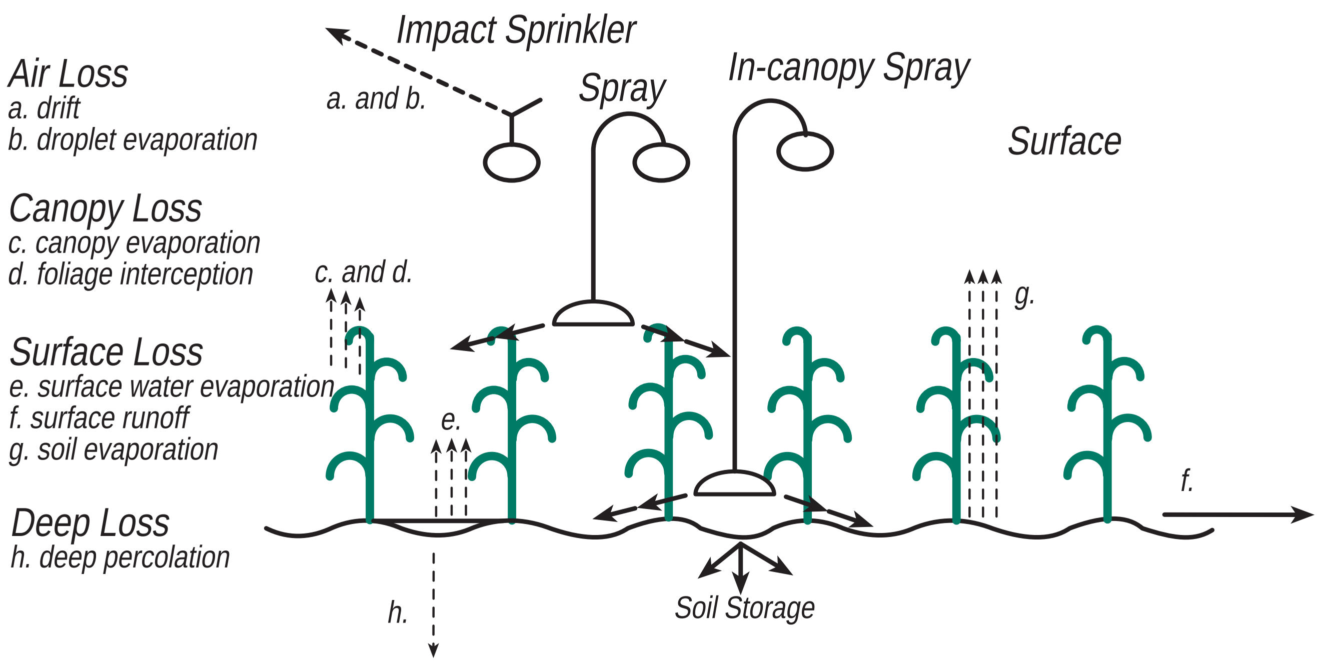


Table 2. Estimated Sprinkler Water Loss Components for a 1-inch Irrigation. Ground evaporation, runoff, and deep percolation were negligible (Schneider and Howell, 1993)

System	Air Loss	Canopy Loss	Surface Loss	Total Loss	Surface Application Efficiency*
Impact Sprinkler	0.03	0.12	-	0.15	85%
Spray Head at Truss	0.01	0.07	-	0.08	92%
LEPA	-	-	0.02	0.02	98%

**Runoff within field, distribution, or deep percolation loss are not considered.*

Table 3. Surface Irrigation Loss Estimates*

Loss	Estimate Method	Percentage of 4 Acre-inch Irrigation Applied
Furrow Water Evaporation	(0.01 in/hr × 8 hr) = 0.08 inches**	2.00
Runoff Water Evaporation	(0.3 in/day × 0.6 ac)*** = 0.18 ac-in/day	0.28
Tailwater Pit Evaporation	(0.3 in/day × 2 acres) = 0.60 ac-in/day	0.94
Tailwater Pit Leakage	(0.25 in/day × 2 acres) = 0.5 ac-in/day	0.78
Total		4.00

* *Distribution or deep percolation loss not considered*
** *Same rate as LEPA. 8 hours represents watered furrow conditions during advance and recession. Every other row irrigation.*
*** *20 ft. strip, 1320 ft. long.*

If the soil surface is sloped and the application rate exceeds the soil intake rate and surface storage capability, then water movement in the field will occur. If this water moves off the field as runoff, water application efficiency is reduced. Within the field, water movement can cause nonuniform storage, resulting in under-watering on slopes and over-watering in flat areas. This illustrates why application efficiency alone does not always indicate the irrigation condition in a field. Slope, surface condition, and infiltration capacity all affect the depth and uniformity of water delivery to the roots.

Determination of application efficiency of a specific irrigation system is generally time consuming and often difficult. One difficulty is that efficiency varies in time due to changing soil, crop and climatic conditions. Table 1 lists typical ranges of reported application efficiency (E_a). Of course, poorly designed or operated systems can have efficiencies even lower than the shown values. In general, sprinkler systems in Kansas are operated at higher application efficiency than surface flood systems. Although a well designed and managed surface system can be quite efficient, in general these systems have lower efficiency due to length of runs that are too long and incorrect set times. Most set times, in order to minimize labor input, are fixed at 12 or 24 hours intervals.

IRRIGATION WATER LOSSES

Irrigation water losses, illustrated in Figure 3, include air losses, canopy losses, soil and water surface evaporation, runoff, and deep percolation. The magnitude of each loss is dependent on the design and operation of each type of irrigation system. Table 2 shows an estimate of the application efficiency of three sprinkler packages, assuming ground evaporation, runoff and deep percolation are negligible. Ground evaporation may be an important component early in the season, before the crop canopy covers the surface.

SPRINKLER IRRIGATION LOSSES

Air losses include drift and droplet evaporation. Air losses can be very large if the sprinkler design or excessive pressure produce a high percentage of very fine droplets. Drift is normally considered to be water particles that are removed from the target area, while droplet evaporation would be the loss of water by evaporation directly from the drop of water while in flight. Direct movement and droplet evaporation vary, but the general estimate of droplet evaporation is small, probably less than 1 percent of the output. Total air loss under properly-operating sprinklers and low wind conditions is likely to be in the 1 to 3 percent range, although some older publications, have much higher values. Table 2 assumes 3 percent for the impact sprinkler and 1 percent for the spray head at a 5 foot height. Air losses were assumed to be negligible for the bubble mode LEPA head.

Canopy losses include losses due to water held on the plant (foliage interception) and canopy evaporation during the irrigation. Water evaporation from the wetted surface of the plant does reduce transpiration by the plant. However, evaporation from a free water surface is faster than transpiration through plant stomates. Net canopy evaporation loss estimates range from 0.02 to 0.04 inch per hour. Two hours of wetting was assumed for the impact sprinkler and 45 minutes for the spray nozzle. Plant interception loss estimates range from 0.04 to 0.08 inches. The 0.04 inches loss estimate was used in Table 2.

The only loss shown for the bubble mode LEPA nozzle is surface water evaporation. Since the LEPA system uses an application rate in excess of soil intake capabilities, the free water surface must be held on the soil surface until it can be infiltrated. The surface water evaporation loss estimate is 0.01 inch/hour over the two hours estimated for intake to be complete.

In all examples of Table 2, water movement as runoff or redistribution of the surface water, deep percolation, and ground evaporation were considered to be negligible. Any runoff from the field or deep percolation would reduce application efficiency by a percentage of the total application amount. Runoff of up to 60 percent of the application amount has been measured for in-canopy sprinkler heads on sloping ground.

SURFACE IRRIGATION LOSSES

Surface irrigation losses include runoff, deep percolation, ground evaporation and surface water evaporation. Runoff losses can be significant if tailwater is not controlled and reused. Although use of tailwater reuse pits could generally increase surface application efficiency, many surface irrigators use a blocked furrow to prevent runoff. Usually the lower portion of the field is leveled to redistribute the tailwater over that portion. While runoff may be reduced to near zero, deep percolation losses may still be high with this practice.

Surge irrigation can accomplish faster furrow advances. To further improve an advance time, large furrow flows may be used. However, care should be taken to avoid furrow erosion. Some chemicals (polymers) have been reported to be useful in reducing erosion. Rapid advance allows better water distribution efficiency and smaller application amounts, which can reduce deep percolation losses and improve overall irrigation efficiency.

Evaporation loss percentages from a surface irrigated field are small. The components of the loss are furrow-water evaporation (under canopy), tailwater evaporation (where there is no canopy protection) and tailwater pit evaporation, and are dependent on system operation. Loss estimates are shown in Table 3 assuming a 4-inch gross application depth is applied to a 160-acre surface irrigated field using 12-hour sets on a 10-day irrigation interval. Some loss components were estimated on a daily basis, so the percent loss was dictated by the daily application amount (64 acre-inches). Tailwater pit leakage is also a potential loss and is shown in Table 3.

SUMMARY

Various terms exist 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 misrepresentation of how well an irrigation system is performing.

Reporting of both application efficiency and water distribution uniformity would provide a better indication of overall irrigation system performance. However, these values are often difficult to measure in the field. They also vary over time and with operating conditions.

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