PATHWAYS TO EFFECTIVE APPLICATIONS

Terry A. Howell, Ph.D., P.E.
Research Leader (Agric. Engr.)
USDA-Agricultural Research Service
P.O. Drawer 10
Bushland, Texas 79012-0010
Voice: 806-356-5746
Fax: 806-356-5750
Email: tahowell@cprl.ars.usda.gov

Steven R. Evett, Ph.D.
Lead Scientist (Soil Scientist)
USDA-Agricultural Research Service
P.O. Drawer 10
Bushland, Texas 79012-0010
Voice: 806-356-5775
Fax: 806-356-5750
Email: srevett@cprl.ars.usda.gov

INTRODUCTION

Sprinkler systems, primarily center pivot systems, are widely used in the Great Plains of the United States. Methods of irrigation application using sprinklers vary considerably and include high-angle, high-pressure impact sprinklers, low-angle, medium- to low-pressure impact sprinklers, medium- to low-pressure spray nozzles, medium- to low-pressure rotary nozzles, ground-level LEPA (low-energy precision application) bubblers or drag socks or multi-mode LEPA devices (chemigation), and various LESA (low elevation spray applicators) or LPIC (low-pressure, in-canopy) application systems. Graded furrow irrigation, typically from gated pipelines, is still widely used in the Great Plains. Some of these systems utilize tailwater recovery to recirculate field runoff water. Microirrigation, especially SDI (subsurface drip irrigation), is growing in use in the Great Plains, although still not a widely adopted application technology, but one that can fit many situations with a high potential for effective irrigation. To achieve effective applications, the irrigation technology must fit the soil, crop, and irrigation water supply. Optimum irrigation water management must then be coupled with the chosen irrigation application technology to achieve effective applications to the crop.

Effective application is the terminology chosen to describe efficiency both in terms of water applications and crop productivity. In prior Central Plains Irrigation conferences (Howell, 2002; Martin, 2004), concepts of irrigation efficiency and water use efficiency were described and discussed. The purpose of this paper is to briefly outline choices for irrigation application technology and irrigation water management that can lead to *effective applications* that minimize inefficient uses of water and that can lead to near optimum crop profitability.

FRAMEWORK

The outline concepts from Purcell and Currey (2003) provide a useful tool in evaluating likely processes to achieve “effective applications.” Figure 1 illustrates the water flow pathway from its source to the crop and then through the process of obtaining a yield from the crop. In order to calculate the differences between water inputs, losses and uses, all the items in Fig. 1 must have compatible temporal and spatial scales. Determining some of the water pathway components may be difficult or highly uncertain for some time and space situations. In broad terms, this concept of effective water use is often described as “water use efficiency” (WUE) although Howell (2002) and Lamm (1997) point out the differences between WUE and irrigation efficiency (E_i) or irrigation application efficiency (E_a). For many reasons as discussed in Purcell and Currey (2003), WUE and either E_a or E_i cannot individually determine effective applications, but collectively they can distinguish irrigation technology and management that will have “effective applications.”

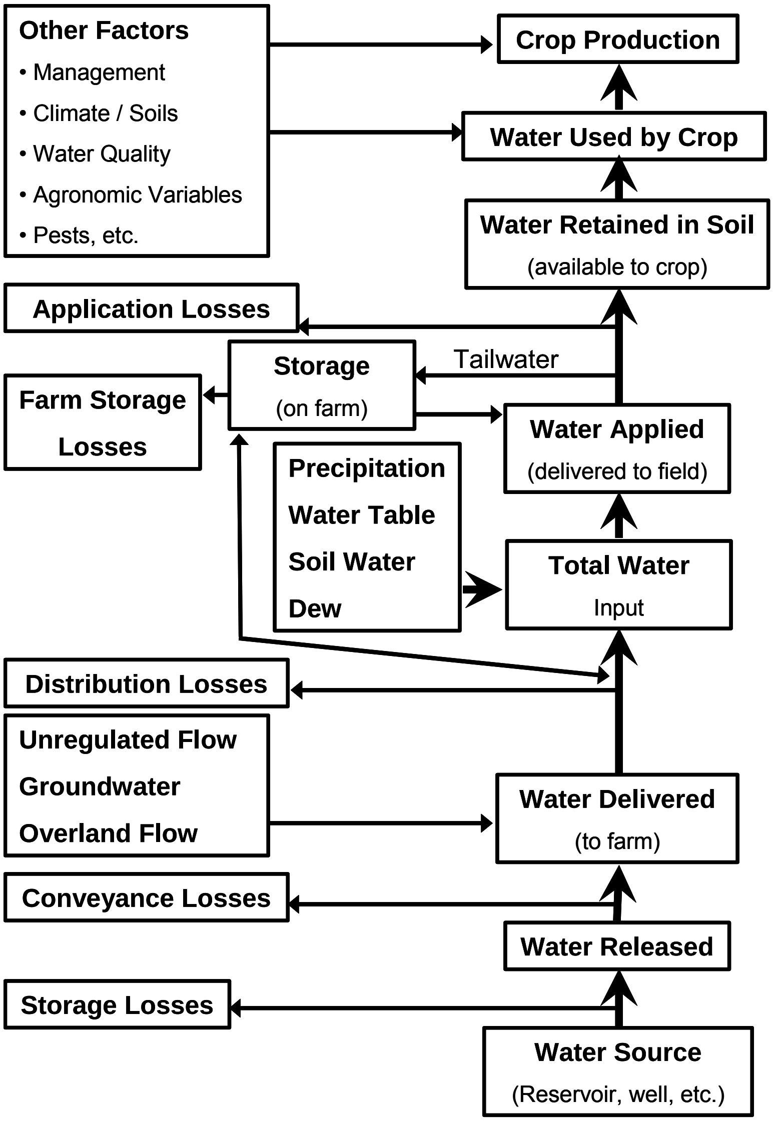

Figure 1. Illustration framework of water flow pathway from source to crop for producing yield adapted from Purcell and Currey (2003).

IRRIGATION EFFICIENCY CONCEPTS

Traditional concepts of irrigation efficiency (Heermann et al., 1990) are based on engineering concepts of the fraction of water being diverted that is then available for useful and beneficial needs of the crop. Of course, the catch in these engineering definitions is characterizing what constitutes a “required” and/or “beneficial” use of the water (Burt et al., 1997), which may be determined by outside institutions (legal or regulatory) and/or other societal issues (wetlands, wildlife habitat, etc.). Figure 2 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 (a basin plot or set, a furrow set, a single sprinkler lateral, a microirrigation lateral) to broader land scales (field, farm, an irrigation canal lateral, a whole irrigation district, a basin or watershed, or a river system, or an aquifer). The time scale can vary and may include periods from as short as a single application (or irrigation set), to a part of the crop season (preplanting, emergence to bloom or pollination, reproduction to maturity), or the irrigation season, crop season, or a year, partial year (pre-monsoon season, summer, etc.), a water year (typically from the beginning of spring snow melt through the end of irrigation diversion, or a rainy or monsoon season), or even 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, and the amount of water that might percolate beneath the crop root zone. It can also affect the amount of water that can return to surface sources for downstream uses or to ground water aquifers that might supply other water uses, and the amount of water lost to unrecoverable sources (salt sinks, saline aquifer, or an unsaturated vadose zone). Return flow of water is not a loss in terms of the larger scale (water district, hydrologic basin, etc.) and will not reduce overall efficiency unless the water quality is unsuitable for irrigation use or the returned water is not available within the irrigation season under consideration. Spears and Snyder (2004) discuss the added energy needed to recover this return water and the concepts of efficiency on the basin scale.

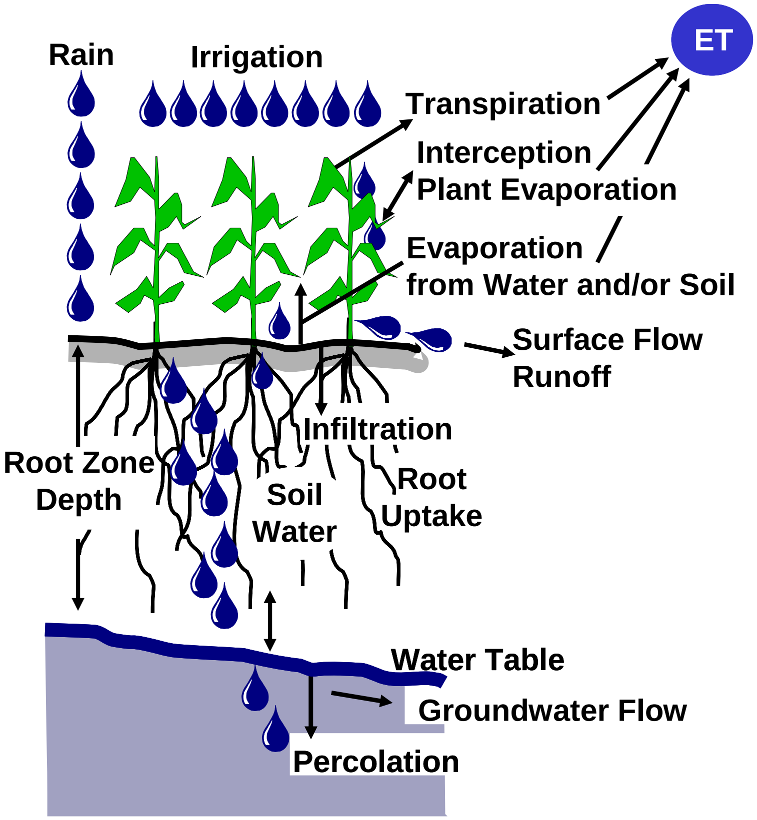

Figure 2. Illustration of various water transport components needed to characterize irrigation efficiency.

The volumes of water for the various irrigation components are typically expressed 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. The accurate measurement of water percolation volumes, ground water flow volumes, and water uptake from shallow ground water remain nearly impossible under most circumstances.

We are prone to speak and characterize some water components as losses, although they are not lost but just unavailable for use (Fig. 1). From the water supply (reservoir, ground water aquifer, river, etc.), water can be a lost due to evaporation (e.g. evaporation from a reservoir), transpiration (e.g., water consumed by phreatophytes or weeds along the water course), vertical seepage or horizontal flow beyond the “control boundaries” (will depend on the spatial scale of interest), and any operational losses or leakages from the source that can’t be recovered. From the source to the farm, there may be conveyance losses which might be evaporation from any open water conveyances (e.g., canals), leakages (e.g., vertical seepage from a canal or pipeline leaks), operational spills, as well as transpiration by phreatophytes or weeds along the water route. There could be gains in water from the release point to the farm if water is recovered from drainage ditches, groundwater inflows, as well as regional surface water recovery from runoff. Each of these water sources is subject to various State, water district, and environmental laws or regulations that might restrict their use either by permit, custom, or legal restrictions. In the Great Plains, we find limited on-farm storage of water because the majority of irrigation water is supplied directly to the farm through wells into a aquifer [usually the High Plains Aquifer or Ogallala Aquifer although some alluvial aquifers are of major importance (e.g. the Arkansas River, the South and North Platte Rivers). In some cases, small holding reservoirs are utilized with larger center pivot systems or with some microirrigation systems for short-term storage and flow regulation when several wells are needed to supply water to the field at a rate that exceeds an individual well’s flow rate. In these cases, a submersible turbine pump (desired for automation reasons) or a centrifugal pump will be used to lift the water from the shallow storage reservoir (usually these are an acre or less in area with a volume capacity of 2-5 ac-ft) to the irrigation system and to provide the system operating pressurization. These on-farm storage ponds have similar potential water loss components as those discussed above for conveyance and water supply.

On the farm or field, the net irrigation supply is augmented by water sources that are specific to individual regions (e.g., rainfall or shallow water tables) and available soil water (that may be recharged from off-season precipitation). The amount of irrigation water required by the crop is the net difference between the crop evapotranspiration (ET) and the net “effective” precipitation during a specific period, and “readily” available soil water (typically defined as a portion of the stored or retained soil water between the upper limit of “field capacity” and the “wilting point”). The available water is generally a property of the soil texture (its physical particle size distribution, bulk density, mineralogy, chemical characteristics, etc.). This "net" Irrigation requirement is typically expressed as

$$I_i = ET_i - \left(Pe_i + SW_i\right) \qquad \text{... [1]}$$

where I is the "net" irrigation requirement for period i, ET is the evapotranspiration during the period, Pe is the "effective" precipitation during the period, and SW is "available" soil water used (soil water depletion) during the period with all parameters expressed in units of depth (mm or in.). Equation 1 neglects or ignores percolation below the root zone and possible water table uptake, too. Various procedures are used to estimate Pe, and for simplicity at a given location (farm or field) SW might be assumed to be a constant value dependent on the soil texture at the site, the ET rate, and the length of specific period "i". The "gross" irrigation requirement is simply estimated as the "net" requirement (I) divided by an estimated or known irrigation application efficiency (E_a; expressed as a fraction).

IRRIGATION APPLICATION EFFICIENCY

Although E_a (irrigation application efficiency) is a widely used concept (Heermann et al., 1990; Howell, 2002), it also quite suspect and often difficult to know precisely (Lamm, 1997 & 2002). E_a is generally defined as the fraction of the "gross" irrigation amount that is stored in the root zone. It is determined by measuring or estimating

- "gross" application (volume/rate/time and the area irrigated)
- off-target water (drift, etc.)
- percolation below the root zone
- evaporation from applied water (wetted soil and/or foliage or droplets)
- runoff from irrigation
- infiltrated soil water
- change in water stored in the root zone

all of which are difficult to quantify precisely. In addition, the exact crop root zone may not be known precisely. The "gross" irrigation application may not be known with great precision owing to the myriad techniques utilized to either measure flow rate or volume or indirect measures (e.g., electrical power consumption, fuel consumption, etc.). Measuring soil water is nearly a complete science unto itself. If one assumes that off-target losses are minimal, we are left with what many call the "*Big Three*" losses:

- D or percolation (drainage) from the root zone
- E or evaporation, and
- Q or runoff

Effective applications must minimize these, so called "*Big Three*," losses, particularly where irrigation water costs are directly linked to the volume of water diverted (either pumped from a well or purchased from a water district). As Lamm (2002) emphasized, E_a is often misused and incorrectly used in comparing or ranking irrigation application technologies. It certainly has its place in irrigation science as a performance measure, but it is, perhaps, better utilized as a tool to indicate means to improve specific irrigation systems rather than a tool to judge systems. Certainly, specific irrigation application technologies will have a "potential" to be more efficient than other technologies. But, a conversion from one technology to another solely to improve efficiency is usually "suspect", as far as "saving water", without a concurrent irrigation water management technology or training investment.

Percolation Losses

Percolation losses are more easily controlled with the smaller, more frequent applications from center pivot systems or SDI (or microirrigation, in general) compared with the typically larger, less frequent surface irrigations. However, even SDI can have significant percolation losses from the root zone if not managed carefully (Darusman et al., 1997a & 1997b). Surge flow furrow irrigation has been one of the more effective technologies to reduce excessive infiltration and percolation with graded furrow systems (Allen and Schneider, 1992; Musick et al., 1987). Furrow packing or "slicking" has been used effectively with graded furrow irrigation to reduce excessive infiltration (Allen and Musick, 1992; Allen and Schneider, 1992). PAM (Polyacrylamide) polymers have been effective in reducing graded furrow percolation losses (Lentz et al., 2001).

Even if no apparent percolation loss is perceived from smaller, frequent applications, surface redistribution from higher application rate technologies (LESA, LPIC, LEPA, etc.) can result in "potential" percolation losses in lower lying areas that might accumulate runoff. Besides the loss of water available to the crop, percolation losses invariably also include nutrient leaching that can reduce available crop nutrients within the root zone, which increases costs for crop nutrients (fertilizers) and has water quality and environmental concerns.

Evaporation Losses

Evaporation losses are reduced by not irrigating bare soil, using alternate furrow irrigation, lowering center pivot system applicators nearer the ground to reduce wind effects together with utilizing various choices of spray/rotator plate deflectors (flat, grooved, concave, convex, etc.), sprinkler applicators, spacing, etc. (Howell, 2004) together with optimum operating pressure for the nozzle size to reduce small droplets. Sprinkler evaporation losses, particularly for center pivot systems, are generally perceived to be greater than measurements indicate [see Howell et al. (1991) for a current review up to that time, and Schneider (2000) for a later review]. Tolk et al. (1995) and Thompson et al. (1997) discuss measurements and modeling of center pivot system water losses from evaporation in more detail. However, for "gross" applications of 25 mm (1.0 in.), evaporative losses from center pivot systems with sprinklers or spray heads can as large as 10 to 20% of the applied water depending on the specific circumstances of the application. LEPA applications under "optimum" cases (e.g., good furrow dikes, alternate row applications with drag socks, circular rows for a center pivot system, etc.) may be less than 5-6% of the application amount. The main evaporation loss from most sprinkler or spray technologies is the "net" canopy evaporation, which is influenced by the wetting duration. The wetting duration depends on distance from the center pivot point and "gross" application amount, and on the wetted diameter of the application technology (e.g., pipeline low-angle impact sprinklers may have wetted diameters greater than 9 to 30 m or 15 to 100 ft). Of course, end guns will have a much greater "potential" evaporation loss (when operating; even if just operated in the corners) due to both the larger wetted diameter of the end gun and the greater droplet transit times and greater exposure to the wind/atmospheric factors. In order to spread evaporative losses evenly around the field, the center pivot irrigation frequency (or full rotation time) is generally desired to be a non day integer (e.g., not 24, 48, or 72 hrs), but a fraction of an even day integer so the system will irrigate differing zones of the field at the same time of the diurnal cycle (e.g., 38, 54, etc. hrs per revolution).

Crop residues effectively reduce evaporation from the soil. They also improve soil tilth and, generally, increase infiltration if the residue mass amount is significant (~3 to 4 Mg ha^{-1} or 1.5 to 3 tons ac^{-1}). Ridge till or strip till has been effective in preserving soil cover using previous crop residues while utilizing a reduced or conservation tillage system.

Runoff Losses

Runoff from graded furrow systems can exceed 30 to 60% of the applied water (Lentz et al., 1992). PAM (Polyacrylamide) polymers have been effective in reducing the runoff fraction of surface irrigation (Lentz et al., 1992; Lentz et al., 2001) but sometimes at the expense of increased percolation losses. Runoff with surface irrigation and center pivot systems (Schneider and Howell, 2000) can be a significant loss of water and cause ineffective applications. Generally, no irrigation runoff should occur with SDI or microirrigation unless a pipeline leaks or breaks. LEPA requires surface storage from furrow dikes or dammer diker implements to provide temporary surface storage for application volumes that exceed the soil infiltration capacity (Kincaid et al., 1990; Kranz and

Eisenhauer, 1990; Coelho et al., 1996; Howell et al., 2002). Furrow diking and dammer diking serve dual purposes in storing irrigation applications as well as rainfall (Lyle and Dixon, 1977; Jones and Stewart, 1990) for infiltration and reducing/eliminating runoff from the field. It is a well known practice in dryland cultures (Jones and Clark, 1987). Furrow diking can be particularly important with center pivot systems when deficit irrigation is planned or water deficits result from regional/local droughts when irrigation capacity (irrigation volume per unit area) is insufficient to meet the crop irrigation need. Figure 3 illustrates the potential surface storage needed for impact sprinklers and LESA/LPIC with center pivot systems. Systems with high instantaneous application rates, particularly LEPA, LESA, or LPIC systems, must utilize a surface storage tillage technology or an effective conservation tillage system (e.g., ridge till or strip till) to minimize surface water redistribution and possible runoff or percolation from down slope areas.

IRRIGATION WATER MANAGEMENT

Irrigation water management is the integration of irrigation scheduling or automation with the application technology. Basically, irrigation scheduling is making decisions on irrigation timing and irrigation amount subject to the irrigation supply constraints (legal and physical) in concert with the operational constraints (labor, crop cultural operations, etc.). The goal is often to produce the greatest profit within the land, labor, capital, and water restrictions of the farm or operation.

Water Balance

Most irrigation scheduling involves the application of Eqn. 1 to estimate the irrigation amount needed to refill a portion of the soil water reservoir. The irrigation amount is constrained by both the irrigation capacity (gpm ac^{-1} or mm d^{-1}) [also considering the irrigation frequency or interval] and the irrigation application technology. Most irrigation timing decisions are based on estimated (modeled) or measured soil water. By recognizing that in Eqn. 1 that $SW = \bar{\theta}_k - \bar{\theta}_j$, Eqn. 1 can be rearranged as follows:

$$\bar{\theta}_k = \bar{\theta}_j + Pe_i + I_i - ET_i \qquad \text{... [2]}$$

where $\bar{\theta}_k$ is the mean or total “available” soil water within the root zone on the end day “k” of period “i”, $\bar{\theta}_j$ is the mean or total “available” soil water on the beginning day “j” of the period, and Pe_i, I_i, and ET_i were previously defined. All terms in Eqn. 2 are in depth units (mm or in.). Typically, $\bar{\theta}_j$ is taken as $\bar{\theta}_{fc}$ (water content of the root zone at “field capacity”) minus a desired soil water storage term to allow intermediate rainfall storage to minimize runoff and/or percolation. The

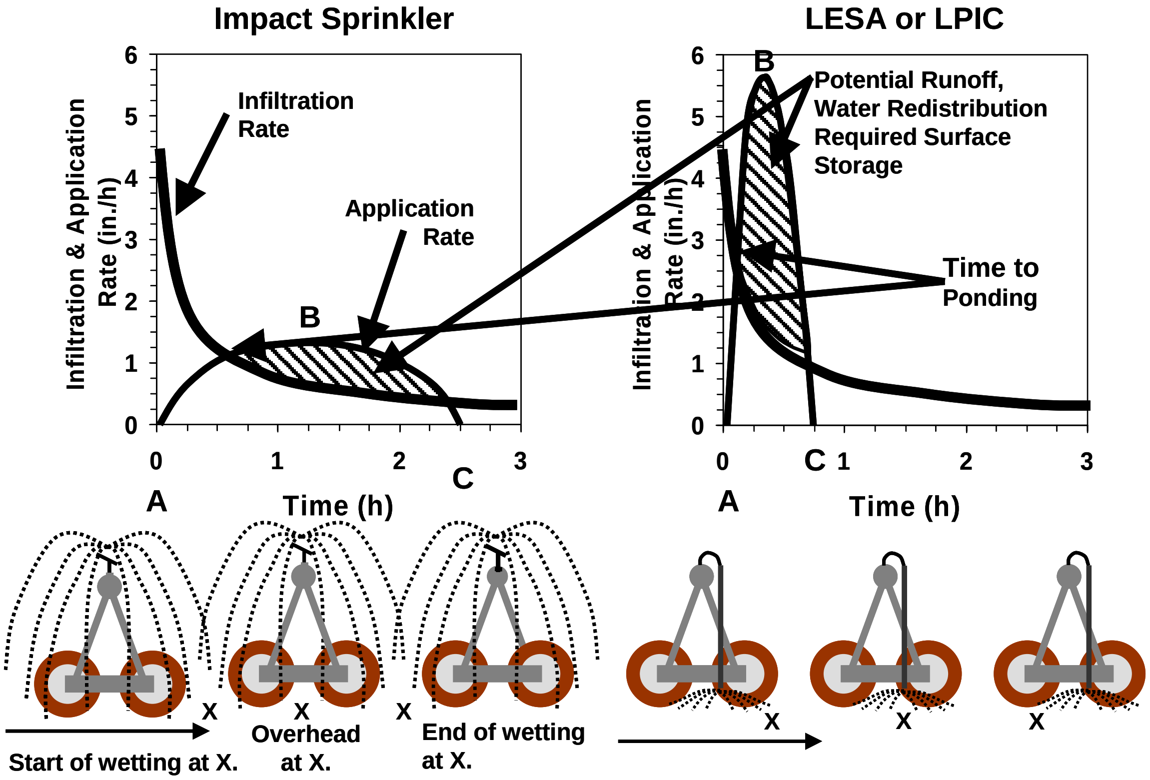

Figure 3. Illustration of runoff or surface water redistribution potential for impact sprinkler and spray (LESA or LPIC) center application packages for an example soil. (A) represents the start of the irrigation, (B) is the peak application rate (usually when the system is directly overhead), and (C) is the completion of the irrigation. The first intersection point of the infiltration curve and the application rate curve represents the first ponding on the soil surface.

goal of most irrigation decisions is to maintain the root zone soil water within the defined limits given as

$$\left(\bar{\theta}_{fc} - C\right) \ge \bar{\theta} \ge \bar{\theta}_c \qquad \text{... [3]}$$

where C is the allowed storage for intermediate rainfall and $\bar{\theta}_c$ is a "critical" lower limit of soil water that will reduce yield or crop quality. The value of $\bar{\theta}_c$ depends on the soil texture and other factors such as crop growth stage, atmospheric water demand, etc. (Lamm et al., 1994; English et al., 1990). For lighter textured soils (e.g., sands, loamy sands, or sandy loams), C may be very small or impractical to utilize due to the lower "available" soil water content.

Martin et al. (1990) defined the irrigation dates in the terms of “earliest date” [irrigation depth typically applied will just refill the root zone without excessive runoff or percolation] and the “latest date” [amount if irrigation was delayed until θ was near θ_c]. Both of these irrigation dates bracket the optimum irrigation timing decision date expressed as $D_e \leq D_o \leq D_l$, where the subscripts denote “e” for early, “o” for optimum, and “l” for latest. The decision to postpone irrigations from D_e to D_l considers rainfall forecasts, ET rates, labor and farm operation decisions and the risk assumed by the producer. As the date is postponed to near D_l, some reduction in yield may be anticipated.

SUMMARY

Effective irrigations must consider the application technology and the irrigation water management. Table 1 gives an outline of technologies that can be effective in achieving irrigations that are aimed to achieve high profits within producer constraints. No single irrigation application technology or management technology will insure “effective applications”, but an integration of “Best Management Practices” (BMPs) involving technology and management can offer pathways to achieve ”effective applications” and wise utilization of our limited water supplies for profitable irrigated agriculture.

Table 1. Example irrigation concepts for “effective applications” emphasizing “Big Three” water loss components.

IRRIGATION TECHNOLOGY			
Surface Irrigation			
Surge Flow	Percolation	+[†]	Reduced by more uniform infiltration “opportunity” times
	Evaporation		
	Runoff	+	Reduced by runoff flows and “cut-back” controls
	This technology has relatively low costs and can be easily adopted into most existing gated pipe systems.		
Tailwater Recovery	Percolation	+ -	Reduces field percolation but greater seepage losses from reservoir.
	Evaporation		
	Runoff	+	Recycles runoff water.
	This technology can be adopted for most furrow systems, but it adds additional pumping and capital costs to return the water.		
PAM (Polyacrylamide)	Percolation	+	Reduced by more uniform infiltration “opportunity” times
	Evaporation		
	Runoff	+	Reduced by reduced flows and “cut-back” controls
	This technology is relatively low cost, although repeated applications may be required, and is easily adopted to most furrow systems.		
Center Pivot Sprinkler Irrigation			
Low-Angle Impact Sprinklers	Percolation	+	Reduced by lowered application amounts.
	Evaporation	+	Reduced by lowered wind effects.
	Runoff	+	Reduced by usually having a lower peak application rate.
	Easily adopted to existing high angle sprinkler systems.		
Low Pressure Applicators	Percolation	-	In some cases, can have significant surface water movement.
	Evaporation	+	Reduced by having smaller wetted diameter and selection options for spray applicators, plate grooves, and groove shapes.
	Runoff	-	Increased if reduced wetted diameter and higher peak application rate exceed soil infiltration and surface storage capacity.
	Moderate capital costs if retrofitting older machines with wider drop spacing and greater number of heads that are more closely spaced.		

[†] The “+” symbols indicate a generally recognized practice to reduce losses for that component and the “-” symbol indicates either no improvement or possibly greater loss for that component.

Table 1. Part II.			
IRRIGATION TECHNOLOGY			
Center Pivot Sprinkler Irrigation, *continued*			
LEPA	Percolation	+	Reduced by lowered application amounts.
	Evaporation	+	Reduced by reduced wetted area (minimal canopy wetting).
	Runoff	+ -	Reduced if furrow dikes retain all applied water. Can be a significant water loss if dikes can't contain the applied water.
	Easily adapted to newer pivots with closely spaced outlets. Can add increased costs for the greater number of applicator heads and diking machinery. Requires furrow diking and circular planting to be most effective.		
LESA / LPIC	Percolation	+	Reduced by lowered application amounts.
	Evaporation	+	Reduced by reduced wetted area.
	Runoff	-	Can be a significant water loss if reduced wetted diameter and higher peak application rate exceed soil infiltration and surface storage capacity.
	Easily adapted to newer pivots with closely spaced outlets. Can add increased costs for the greater number of applicator heads and diking machinery, if needed. Easily compatible with conservation tillage systems when diking not required or furrow dikes used with ridge till.		
Microirrigation			
SDI	Percolation	+ -	Reduced by lowered application amounts, but can be a significant loss if water profile is maintained at a high soil water content.
	Evaporation	+	Reduced by smaller wetted area (only water that moves upward readily can evaporate.
	Runoff	+	Reduced by lowered application amounts.
	Technology is rapidly advancing. It remains relatively expensive but is easily automated. Adaptable with ridge till and/or strip till systems. Fits odd or irregular shaped fields.		
TILLAGE TECHNOLOGY			
Ridge Till	Percolation		
	Evaporation	+	Reduced by crop residues shading the soil and by reduced heating of the soil.
	Runoff	+	Reduced by crop residues enhancing soil infiltration rates ad increasing surface detention water storage.
	Requires planting and cultivating machinery retrofitting or changing. May require some individual equipment adoptions. Adapted to SDI as well as LEPA/LESA/LPIC.		

Table 1. Part III.			
TILLAGE TECHNOLOGY, *continued.*			
Strip Till	Percolation		
	Evaporation	+	Reduced by crop residues shading the soil and by reduced heating of the soil.
	Runoff	+	Reduced by crop residues enhancing soil infiltration rates ad increasing surface detention water storage.
	Requires planting and cultivating machinery retrofitting or changing. May require some individual equipment adoptions. Well adapted to LESA/LPIC but can be used effectively with SDI.		
WATER MANAGEMENT TECHNOLOGY			
Irrigation Scheduling			
ET Based	Percolation	+	Reduced by decisions to time and size events to match soil water holding capacity.
	Evaporation	+	Reduced by using a later day scheduling timing to lengthen event cycles.
	Runoff	+	Reduced by using timing to consider rainfall probabilities.
	Easily adapted to all irrigation application technologies. Requires training and field observations and measurements. Can be contracted through private consultants.		
Soil Sensor Based	Percolation	+	Reduced by decisions to time and size events to match soil water holding capacity. Can actually monitor lower root zone.
	Evaporation	+	Reduced by using a later day scheduling timing to lengthen event cycles.
	Runoff	+	Reduced by automated irrigation shut-down.
	Easily adapted to all irrigation application technologies. Requires modest to significant capital investment and some training. Can be contracted through private consultants. Can be easily integrated with center pivots or SDI into automated controls.		
Plant Sensor Based	Percolation		
	Evaporation	+	Reduced by using a later day scheduling timing to lengthen event cycles.
	Runoff		
	Easily adapted to most irrigation application technologies. Requires modest capital investment and some training. Can be contracted through private consultants. Can be integrated with center pivots or SDI into automated controls.		

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