ATTAINABLE IRRIGATION EFFICIENCY

By Gerald Robb and Tracy Slavin[1]

INTRODUCTION

California's hugely vibrant and diverse economy produces $600 billion in goods and services and is growing at a sustained rate of 10 percent annually making the state a magnet that both holds those who live here and attracts thousands of new residents each year. Its varied geography supports a highly productive farming sector alongside a busy tourist trade. And while national defense pumps tens of billions of dollars annually into the state's economy, California's industry remains a fountainhead of technological development.

The basis for California's healthy economy is a highly-skilled and specialized work force. Most live in urban areas, far removed from the farms which produce their basic food and fiber. However, none of this would be possible were it not for the ability of California's diverse agriculture to reliably and economically provide for their needs. And open land, air, sunlight, and an abundant but unpredictable water supply are the key ingredients.

The runoff from California's precipitation averages 75 million acre-feet (AF) annually. Sixty-one percent of this water flows into the Pacific Ocean after enhancing the environment and providing for recreation, hydroelectric power generation and navigation. All but two percent (which flows into Nevada) of the remaining 39 percent of the total runoff is used by Californians either directly or in the food and industrial products they produce and consume.

As California's population steadily increases by 700,000 people annually through birth and immigration, the need for water for food, industry, and domestic use becomes increasingly acute. The use of storage facilities allows flood waters

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from wet years to be used in dry years, ensuring a more reliable water supply. Coupled with more efficient use in the cities and on the farm, the limited water supply can be stretched to produce its maximum benefit.

In cities, efficiency is measured in reductions from historic use, without regard for basic needs. Because each user is an individual, it would be difficult to set universal standards and society does not yet seem ready to allow government to regulate the length of our showers or when we flush our toilets.

The efficiency of water use on the farm takes a different approach. It uses quantitative scientific methods to determine the percentage of applied water that is required to produce a crop. A closer look at this will help us understand the maximum irrigation efficiency attainable from production agriculture.

DISTRIBUTION UNIFORMITY

The limiting factor for the irrigation efficiency of any irrigation system is its distribution uniformity (DU). As its name implies, DU is the measure of how evenly the water is spread across the field as a ratio of the average depth of water infiltrated into the soil in the quarter of the field infiltrating the least amount, to the average depth of total irrigation water infiltrated, in percent:

$$DU = \frac{\text{Infiltration, Average Low Quarter Depth}}{\text{Infiltration, Average Field Depth}} \times 100$$

It should be emphasized that this equation presumes one half of the low quarter, or 12.5 percent of the field, is underirrigated. This results in a reduction in crop yield in this part of the field.

Natural rainfall is an example of 100 percent DU, while the best commercial irrigation systems might reach an average DU of about 80 percent. Recent investigations completed for Westlands Water District under the direction of Dr. Charles Burt of California Polytechnic State University, San Luis Obispo indicate that the highest attainable DU for a new, well-designed, well maintained hand-move sprinkler system operating under field conditions is about 76 percent.

At 80 percent DU, a farmer would need to apply an additional 25 percent to adequately irrigate those parts of the field to which the system delivers the least

amount of water. This overapplication results in losses to deep percolation below the crop root zone. A farmer can improve his DU through proper system design and management, but no irrigation system's efficiency can exceed its inherent DU unless the field is intentionally underirrigated thus sacrificing crop yields. By way of example, a furrow system's DU may be improved by increasing the advance ratio (AR) of the water to at least two by increasing furrow flow rate, or shortening run lengths where:

$$AR = \frac{\text{Set Time}}{\text{Advance Time}}$$

IRRIGATION EFFICIENCY

With DU establishing the maximum possible efficiency, there are minor losses to consider that the farmer can do little about such as evaporation during irrigation and conveyance and storage losses. The farmer's focus is to apply the correct amount of water to meet his plant's needs. Too much water applied means losses to deep percolation or a rising shallow groundwater table, while too little leads to plant stress and decreased yields. Irrigation efficiency is used to measure the efficiency of a single irrigation and is the ratio of the depth of beneficially used water (BU) to the depth of water applied (AW), expressed as a percentage:

$$IE = \frac{BU}{AW} \times 100$$

Beneficially used water satisfies all or a portion of the following requirements: evapotranspiration, leaching, special cultural practices (i.e. weed and temperature control), or water stored in the soil for later use by the crop. For instance, if the farmer calculates that his plants need four-inches of water and his system DU is 80 percent, he must apply five-inches to ensure that most (87.5 percent) of his plants receive at least four-inches. If he succeeds in applying exactly five-inches to his field, his IE would be 80 percent.

The measure of the efficiency with which water is applied to a field over a full growing season is called annual irrigation efficiency (AIE). AIE is used to determine the efficiency of all irrigations during a season as the ratio of the sum of the soil moisture replacement (SMR) water and water used for cultural practices (CP) for all

irrigations plus the water to satisfy the seasonal leaching requirement (LR), to the sum of the depths of water applied during all irrigations, expressed as a percentage:

$$AIE = \frac{SMR_1 + CP_1 + SMR_2 + CP_2 \ldots + SMR_n + CP_n + LR}{AW_1 + AW_2 + \ldots + AW_n} \times 100$$

Unfortunately, in the field, things are not always this cut and dried. First, the farmer must decide when it is time to irrigate. Since it may take 10 days or more to irrigate a field, it is not possible to irrigate the entire field at the optimum time. If the farmer irrigates too often, he will need to apply less water with each irrigation, which is less efficient than fewer, larger irrigations. If he waits too long, he may stress his crop and yield may suffer. For this reason, the tendency is to irrigate sooner and more frequently, hence less efficiently than desirable.

Second, the farmer must determine the required quantity of water to apply. To do this he must determine the exact soil moisture deficit (SMD) using hand probes, neutron probes, gypsum blocks, computer models and personal experience or professional advice, or these resources in combination. The farmer may also lack the measuring equipment to determine the precise amount of water required to refill the crop root zone or he may employ irrigation labor that is less capable than desired. Common sense would dictate that he overirrigate slightly to provide a margin of safety.

Inaccuracies in either the timing or amount of water applied can add up throughout the growing season, resulting in an AIE that may be several percentage points less than the irrigation system's potential efficiency.

ATTAINABLE IRRIGATION EFFICIENCY

In November 1989, Westlands Water District published a report on the results of the Water Conservation and Drainage Reduction (WC&DR) Program for the years 1987 and 1988 (Westlands Water District, 1989). The Program provided funding to allow farmers to hire District-approved irrigation consultants to help them improve on-farm irrigation efficiency. During 1987-88, 75 farmers participated in the Program, enrolling 335 fields encompassing 44,686 acres. From analysis of data gathered by the Program consultants it was concluded that a maximum average attainable annual irrigation efficiency for production agriculture today in Westlands is about 75 percent. As previously noted, this would leave 12.5 percent of the field

underirrigated. To attain maximum crop yields, additional water would need to be applied to the entire field in order to adequately irrigate the underirrigated area, resulting in a lower attainable irrigation efficiency. To reach this figure, a maximum attainable average DU of 80 percent was used and minor losses due to evaporation, uncollected surface runoff, and conveyance and storage losses of 6 percent were considered:

$$AIE = DU \times \left(1 - \frac{ML}{100}\right)$$
$$= 80\% \times (1 - .06) = 75\%$$

This conclusion is supported by the data contained in the WC&DR Program report for Westlands tomatoes on which an average AIE of 75 percent was attained. This is due in part to their relatively high-value and the need for intense water management to increase yields while reducing operating costs such as water, energy and fertilizer.

CONCLUSIONS

Attainable irrigation efficiency is limited by the distribution uniformity of the irrigation system and unavoidable minor losses.

The distribution uniformity of the best commercial irrigation systems might average 80 percent with half of the low quarter (12.5 percent) underirrigated. An attainable annual irrigation efficiency of 75 percent is possible after minor losses of 6 percent of applied water are considered.

The farmer should first consider improvement of his existing irrigation system to attain its maximum potential distribution uniformity and improve his irrigation practices to attain the maximum potential irrigation efficiency.

DEFINITION OF TERMS

Applied Water (AW): Water applied to a field by irrigation, excluding the tailwater which runs off the field and is collected for reuse in the irrigation of another field on that farm, expressed as a depth of water in inches or feet.

Advance Ratio (AR): For furrow irrigation, the ratio of the total time irrigation water is applied to the furrow (set time) and the time needed for irrigation water to reach the lower end of a sloping furrow (advance time).

$$AR = \frac{\text{Set Time}}{\text{Advance Time}}$$

Available Soil Moisture: The difference in soil moisture content between Field Capacity and Permanent Wilting Point. This represents the moisture which can be stored in the root zone for use by crops, expressed as a depth of water in inches or feet (Israelson & Hanson, 1979).

Beneficially Used Water (BU): Irrigation water used to satisfy a portion or all of the following: evapotranspiration, leaching requirement, special cultural practices, and/or water stored in the soil for use by crops, expressed as a depth of water in inches or feet (ASAE, 1988; Burt, et al., 1988).

Cultural Practices (CP): Irrigation water which is used for necessary farming practices such as soil reclamation, climate control, crop quality, and weed germination, as opposed to being used for evapotranspiration of a crop or leaching, expressed as a depth of water in inches or feet (Burt, et al., 1988).

Deep Percolation (DP): The amount of irrigation water that flows below the crop root zone and is unavailable for evapotranspiration, i.e., the infiltrated amount less soil moisture replacement, expressed as a depth of water in inches or feet (Merriam & Keller, 1978).

Distribution Uniformity (DU): The ratio of the average low-quarter depth of irrigation water infiltrated to the average depth of irrigation water infiltrated, expressed as a percent (ASAE, 1988).

Electrical Conductivity (EC): The property of a substance to transfer an electrical charge and a measure of the salt content of water. ECw is the term used as a measure of the salt content of irrigation water, ECe is the term used as a measure of the salt content of an extract from a soil when saturated with water, expressed as decisiemens per meter (dS/m) (Doorenbos & Pruitt, 1984).

Groundwater Table: The upper boundary of groundwater where water pressure is equal to atmospheric pressure, i.e., water level in a bore hole after equilibrium when groundwater can freely enter the hole from the sides and bottom (Doorenbos & Pruitt, 1984).

Infiltration Rate: The rate of water entry into the soil expressed as a depth of water per unit of time in inches per hour or feet per day. The infiltration rate changes with time during irrigation (Burt, et al., 1988).

Irrigation Efficiencies: Irrigation efficiencies may be calculated for single or multiple irrigations.

1. Irrigation Efficiency (IE): This general definition is used to calculate the efficiency of a single on-farm irrigation and is the ratio of the depth of water beneficially used to the depth of applied water, expressed as a percentage (Burt, et al., 1988):

$$IE = \frac{BU}{AW} \times 100$$

2. Preirrigation Efficiency (PIE): This definition is used to calculate the efficiency of an on-farm preirrigation and is the ratio of the sum of the depth of water used for soil moisture replacement and cultural practices to the depth of applied water, expressed as a percentage. No leaching requirement is included (Burt, et al., 1988).

$$PIE = \frac{SMR_1 + CP_1}{AW_1} \times 100$$

3. Regular Season Irrigation Efficiency (RIE): This definition is used to calculate the efficiency of one or more regular season on-farm irrigations and is the ratio of the sum of the depth of soil moisture replacement water and water used for cultural practices for each irrigation after the preirrigation to the sum of the depths of water applied during these irrigations, expressed as a percentage. No leaching requirement is included (Burt, et al., 1988).

$$RIE = \frac{SMR_2 + CP_2 + SMR_3 + CP_3 + \ldots + SMR_n + CP_n}{AW_2 + AW_3 + \ldots + AW_n} \times 100$$

4. Annual Irrigation Efficiency (AIE): This definition is used to calculate the efficiency of all on-farm irrigations and is the ratio of the sum of the soil moisture replacement water and water used for cultural practices for all irrigations plus the water to satisfy the seasonal leaching requirement to the sum of the depths of water applied during all irrigations, including the preirrigation, expressed as a percentage (Burt, et al., 1988):

$$AIE = \frac{SMR_1 + CP_1 + SMR_2 + CP_2 + \ldots + SMR_n + CP_n + LR}{AW_1 + AW_2 + \ldots + AW_n} \times 100$$

Where n = total number of irrigations, n = 1 is the preirrigation.

Leaching Fraction (LF): The incremental water, beyond that required for crop evapotranspiration, that must pass through the root zone to prevent harmful salt accumulations in the soil (U.S. Salinity Lab Staff, 1954). The necessary leaching requirement expressed as a fraction can be calculated as:

$$LF = \frac{ECw}{5ECe - ECw}$$

Where ECw is the electrical conductivity of the applied water and ECe is the maximum electrical conductivity of the saturated extract of the soil at which 100 percent yield is maintained (Doorenbos and Pruitt, 1984).

Leaching Requirement (LR): The incremental water necessary to satisfy the leaching requirement, expressed as a depth of water in inches, feet, acre-inches per acre, or acre-feet per acre.

$$LR = \frac{(ETAW)}{DU \div 100} \times \frac{LF}{(1-LF)}$$

Low Quarter Depth: The average depth of water infiltrated into the quarter of the field infiltrating the least amount, expressed in inches or feet.

Minor losses (ML): Water losses due to evaporation during irrigation, uncollected surface runoff from the field, and on-farm conveyance and storage systems expressed as a depth of water in inches or feet.

Soil Moisture Deficit (SMD): The amount of water needed to refill the crop root zone to field capacity at the time of irrigation, expressed as a depth of water in inches or feet (Westlands Water District, 1985).

Soil Moisture Replacement (SMR): The amount of water that is used to replace a portion or all of the soil moisture deficit, expressed as a depth of water in inches or feet.

Underirrigation: The difference between the water actually stored in the crop root zone during an irrigation (soil moisture replacement) and the water needed to refill the root zone to field capacity (soil moisture deficit) in all or part of the field, expressed as a depth of water in inches or feet, averaged over the entire field area.

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