CHALLENGES IN INCREASING WATER USE EFFICIENCY IN IRRIGATED AGRICULTURE

Terry A. Howell [1/]

ABSTRACT

Irrigated agriculture is a vital component of total agriculture and supplies many of the fruits, vegetables, and cereal foods consumed by humans; the grains fed to animals that are used as human food; and the feed to sustain animals for work in many parts of the world. World-wide irrigation was practiced on about 277 million ha in 2003 with about 48% of the world's irrigation in India, China, and the United States. The objectives of this paper are to review irrigation worldwide in meeting our growing needs for food production, to discuss various concepts that define water use efficiency (WUE) in irrigated agriculture from both engineering and agronomic view points, and to discuss the impacts of enhanced WUE on water conservation. Scarcely one-third of our rainfall, surface water, or groundwater is used to produce plants useful to mankind. Without appropriate management, irrigated agriculture can be detrimental to the environment and can endanger sustainability. Irrigated agriculture is facing growing competition for low-cost, high-quality water. WUE in irrigated agriculture is broader in scope than most agronomic applications and must be considered on a watershed, basin, irrigation district, or catchment scale. The main pathways for enhancing WUE in irrigated agriculture are to increase the output per unit of water (engineering and agronomic management aspects), reduce losses of water to unusable sinks and reduce water degradation (environmental aspects), and reallocate water to higher priority uses (societal aspects).

KEYWORDS

Evapotranspiration, Irrigation Efficiency, Irrigation Management, Irrigation Technology, Water Conservation, Water Use, Water Use Efficiency

INTRODUCTION

Irrigated agriculture is a vital component of total agriculture and supplies many of the fruits, vegetables, and cereal foods consumed by humans; the grains fed to animals that are used as human food; and the feed to sustain animals for work in many parts of the world. World-wide irrigation was practiced on about 277 million ha in 2003 with about 48% of the world's irrigation in India, China, and the United States [~2% in Turkey]. The objectives of this paper are to review irrigation worldwide in meeting our growing needs for food production, to discuss various concepts that define water use efficiency (WUE) in irrigated agriculture from both engineering and agronomic view points, and to discuss the impacts of challenges to increasing WUE in irrigated agriculture. Scarcely one-third of our rainfall, surface water, or groundwater is used to produce plants useful to mankind. Irrigated agriculture can be detrimental to the

[1/] Research Leader, Supervisory Agricultural Engineer, USDA-ARS, P.O. Drawer 10, 2300 Experiment Station Road (shipping), Bushland, TX 79012-0010 | (806) 356-5746 (voice) | (806) 356-5750 (fax) | tahowell@cprl.ars.usda.gov (email) | http://www.cprl.ars.usda.gov (internet).

environment which can endanger sustainability without appropriate management. Irrigated agriculture is facing growing competition for low-cost, high-quality water, and is often viewed as a water source for a world's expanding population. WUE in irrigated agriculture is broader in scope than most agronomic applications and must be considered on a watershed, basin, irrigation district, or catchment scale. The main pathways for enhancing WUE in irrigated agriculture are to increase the output per unit of water (engineering and agronomic management aspects), reduce losses of water to unusable sinks and reduce water degradation (environmental aspects), and reallocate water to higher priority uses (societal aspects).

Irrigation is vitally important in meeting the food and fiber needs for a rapidly expanding world population that reached six billion on October 12, 1999 and is currently increasing by about 80 to 85 million people each year. The United Nations projects that the world population in 2050 could be 7.3 to 10.7 billion if reproductive fertility declines and 14.4 billion if the world's population continues to increase at its present rate. Much of this growth will occur in the developing world. If the current African growth rate is maintained, its population will double in less than 25 years. While most demographers expect human reproductive fertility rates to decline, the population in south-central Asia is projected to double in 30 years, and Central America's population could double in 35 years. The income of much of the increased population and its consumption of goods and services has also increased, increasing the pressure on natural resources (soil and water) and energy supplies. While this income provides adequate nutrition for people in some regions, significant and even worsening malnutrition problems exist in others.

The purpose of the symposium is to overview recent developments and present new expectations from such developments, especially in light of continuous growth of the world population and the growing environmental concerns. The symposium aims to identify best management practices that will best harmonize sustainable use of water for agricultural production and livelihoods with well-functioning ecosystems. The symposium will also provide a platform for reviewing/discussing a number of contentious issues which concern the future of irrigated agriculture under increasing demands due to the competition for freshwater resources between different sectors.

Sinclair et al. (1984) described WUE on various scales from the leaf to the field. In its simplest terms, it is characterized as crop yield per unit water use. At a more biological level, it is the carbohydrate formed from CO2, sunlight, and water through photosynthesis per unit transpiration. Brown (1999) has proposed that the upcoming benchmark for expressing yield may be the water required to produce a unit of crop yield, which is simply the long used transpiration ratio or the inverse of WUE. Often, the term WUE becomes confounded when used in irrigated agriculture. Bos (1980 and 1985) recommended that WUE with irrigation be based on the yield produced above the rainfed or dryland yield divided by the "net" evapotranspiration difference for the irrigated crop, which he called the yield : ET ratio. He also proposed the irrigated difference from the dryland yield divided by the "gross" applied water, which he called the yield : water supply ratio that is called irrigation WUE (IWUE) here. These definitions are attractive, but difficult to apply, since many management factors could affect yield or could differ substantially between irrigated and dryland agriculture such as fertility, variety, pest management, sowing date, soil water content at planting, planting density, and row spacing. Defining WUE for irrigation is additionally complex because the scale of importance for the water resource shifts to the broader hydrologic, watershed, irrigation district, or irrigation project scale and the water components may not be so precisely defined and may become even more qualitative when such terms

as “reasonable,” “beneficial,” or “recoverable” are employed (Burt et al., 1997). The objectives of this paper are to review progress in irrigation research worldwide to help meet our growing needs for food production, review irrigation trends in the U.S., discuss concepts that define WUE in irrigated agriculture from both engineering and agronomic view points, and discuss impacts of enhanced WUE on water conservation. Irrigation can be an effective means to improve WUE through increasing crop yield especially in semi-arid and arid environments. Even in sub-humid and humid environments, irrigation is particularly effective in overcoming short-duration droughts. However, irrigation by itself may not always produce the highest WUE possible. Readers are also referred to important review articles on irrigated agriculture like Clothier (1983), Clothier and Green (1994), Pereira et al. (1996), and Howell (2001) and on agricultural water conservation like Unger and Howell (1999). Although much has changed with irrigation water management and irrigation technology in the past twenty years, Dr. Marvin Jensen’s comment, “The greatest challenge for agriculture is to develop the technology for improving water use efficiency,” (Karasov, 1982) remains true today in 2006.

WORLD IRRIGATION TRENDS

As the world’s population has increased since the 1960s, irrigated land area has also increased such that the per capita irrigated land remained relatively stable at about 0.045-0.047 ha/person (**Figure 1**) until the mid 1990s and since has declined to 0.044 ha/person in 2003 (FAOSTAT, 2005). In contrast, arable land area per capita

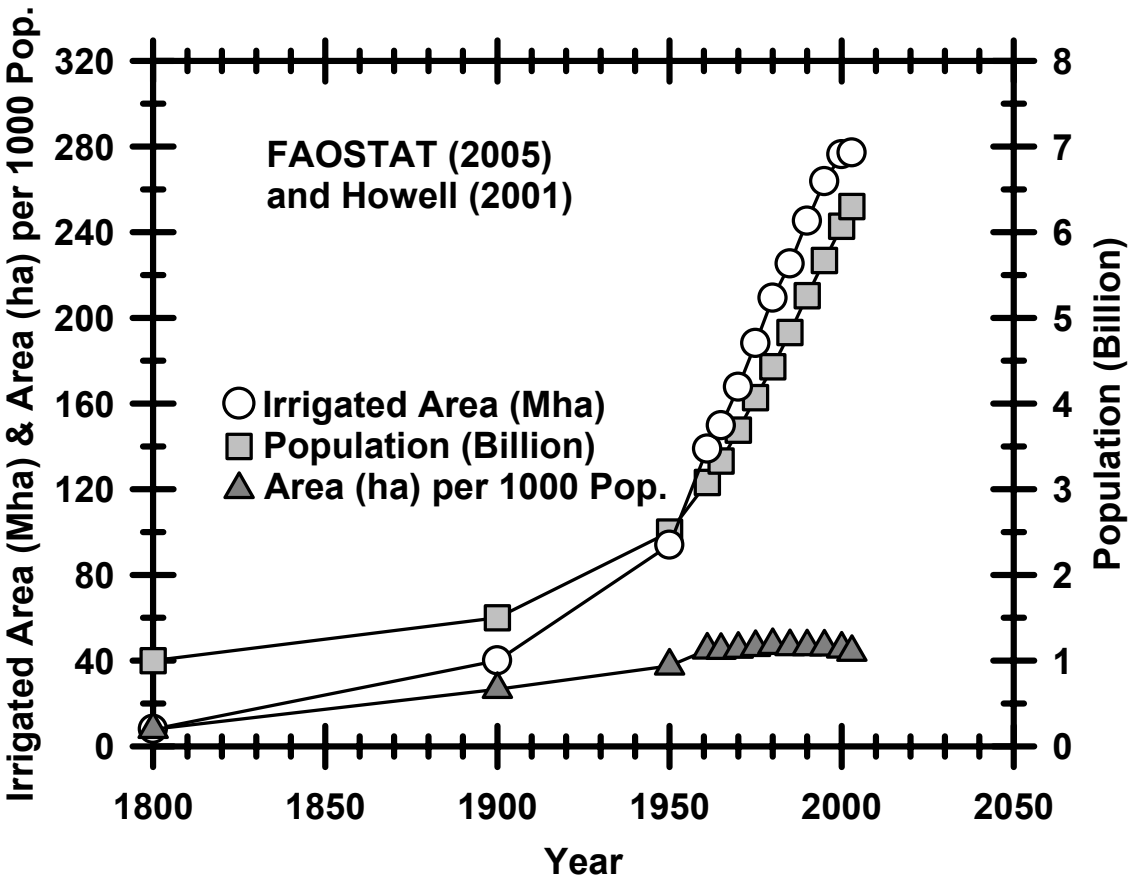

Figure 1. World irrigated area, population, and irrigation-population density.

has decreased from 0.38 ha/person in 1970 to 0.28 ha/person in 1990 (FAOSTAT, 2005). Worldwide irrigated land was about 277 Mha (FAOSTAT, 2005) in 2003 (**Figure 2**). Irrigated land comprises 15% of the arable land in the world and produces 36% of the food (FAO, 1988). Two-thirds of the world's irrigated area is in Asia. Nearly 70% of the grain in China and almost 50% in India is harvested from irrigated lands (Brown, 1999). The FAO (1988) estimated that almost two-thirds of the increase in crop production needed in developing countries in the upcoming decades must come from an increased yield per unit land area, one-fifth from increased arable land area, and the remaining one-eighth from increased cropping intensity. They attribute almost two-thirds of the increase in arable land to increased irrigated land. Rhoades (1997) similarly concluded that the required increased food production in developing countries must come primarily from irrigated land.

Asia has a high percent of the world's irrigated land, and its percent change from 1974 to 1989 was similar to the change worldwide. In projecting global water demands, Seckler et al. (1998) concluded that one-half of the increase in demand for water by the year 2025 could be met by increasing the effectiveness of irrigation. While the remaining water needs could be met by small dams and conjunctive use of aquifers, medium sized dams will certainly be needed. Postel (1993) noted the slow worldwide irrigation expansion since the 1970s, barely averaging 1%, and attributed this to declining international lending and the long lead time for new projects. In addition, escalating costs for irrigation projects have made such investments difficult to justify. **Figure 2** illustrates the world-wide irrigated area increase and increases in selected

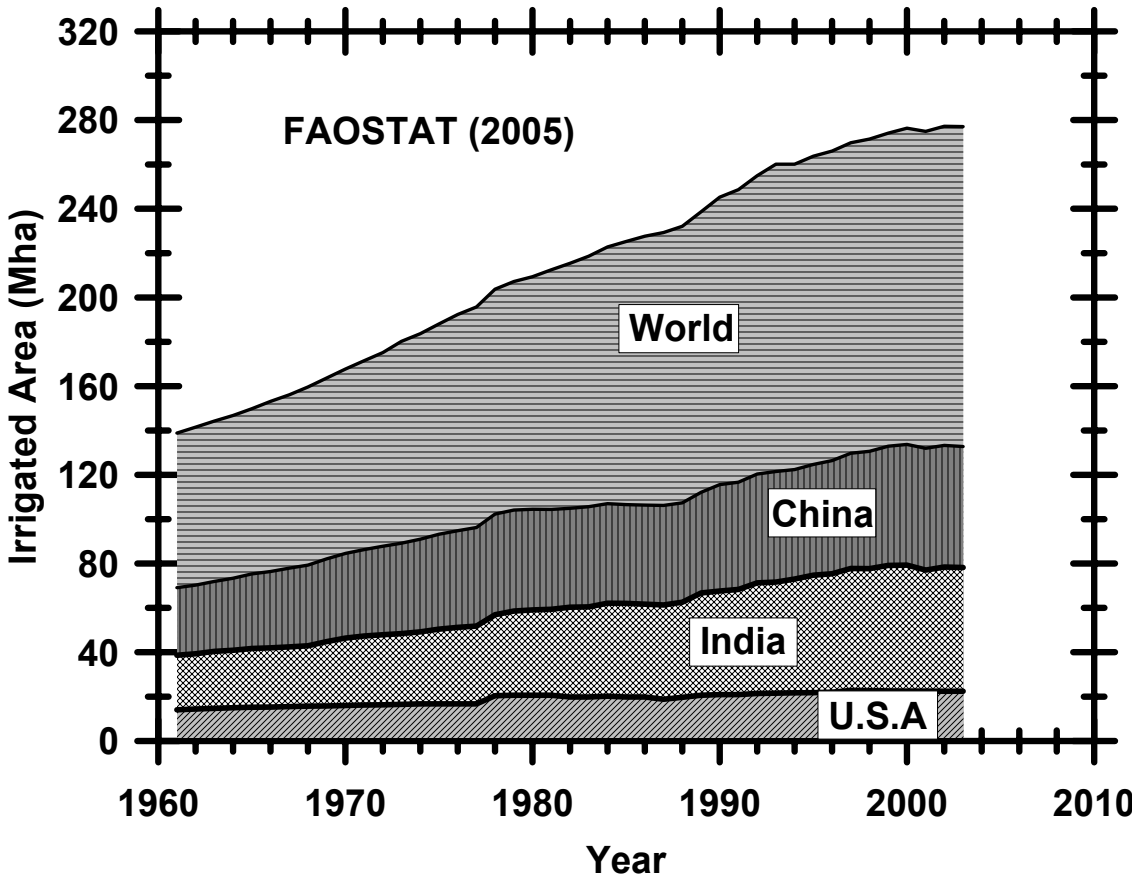

Figure 2. Irrigated area increase since 1961 based on FAOSTAT (2005) data.

countries. The rate of change (slope) in irrigated land exceeded the worldwide population growth rate until the mid 1990s (**Figure 1**), and overall irrigated area growth appears to have nearly stopped after 2000. Also, environmental concerns caused by irrigation raise serious questions and pose difficult problems in many parts of the world, with regards to irrigation sustainability (Rhoades, 1997). Rhoades (1977) quoted Ghassemi et al. (1995) and others who estimated around 40 to 50 Mha of irrigated lands may be already degraded by waterlogging, salinization, and sodication. Postel (2001) noted the historical beginnings of irrigation in Sumeria (present day Iraq) from the Euphrates River over 2000 years ago and the civilization's demise from salinization.

ENHANCING FIELD WATER USE EFFICIENCY IN IRRIGATED AGRICULTURE

These irrigation statistics demonstrate the important role that irrigated agriculture has worldwide and the need to enhance WUE in irrigated agriculture. Although the crop species and even the genotype together with available energy from sunlight are vitally important to WUE (primarily through the CO_2 pathway), water often is the critically important element in agriculture. Water is important in rainfed agriculture, critically important in semiarid dryland agriculture, and explicitly important in irrigated agriculture. Wallace and Batchelor (1997) offered four options for enhancing WUE in irrigated agriculture (**Table 1**). They point out that focusing on only one category will likely be unsuccessful.

WUE is generally defined in agronomy (Viets, 1962) as

$$WUE = \frac{\textit{Crop yield (usually the economic yield)}}{\textit{Water used to produce the yield}} \qquad ...1$$

If the crop yield is expressed in g m^{-2} and the water use is expressed in mm, then WUE has units of kg m^{-3} on a unit water volume basis or g kg^{-1} when expressed on a unit water mass basis. Although useful in many analyses, WUE doesn't take into account the role of irrigation. Bos (1980 and 1985) developed expressions that can, perhaps, more consistently discriminate the role that irrigation has in WUE. His expressions can be written for the ET water use efficiency (ET_{WUE}) and irrigation water use efficiency (I_{WUE}) as

$$ET_{WUE} = \frac{(Y_i - Y_d)}{(ET_i - ET_d)} \qquad ...2$$

$$I_{WUE} = \frac{(Y_i - Y_d)}{I_i} \qquad ...3$$

where Y_i is the yield and ET_i is the ET for irrigation level "i," Y_d is the yield and ET_d is the ET for an "equivalent" dryland or rainfed only plot, and I_i is the amount of irrigation applied for irrigation level "i." Of course in most arid areas, Y_d would be zero or small; however, ET_d could be much greater than zero and variable depending on the agronomic practices. In semiarid dryland and or sub-humid to humid rainfed areas, Y_d could be determined several ways. In the strictest sense, it would be the yield under exactly the same management as the "i" treatment or system, but without irrigation. A

better characterization might be the yields from “comparable” dryland/rainfed plots. Often however, agronomic practices differ substantially between dryland and/or rainfed and irrigated practices (variety, sowing date, fertility management, pest management, sowing density, planting geometry, etc.). Thus, quite different results might be obtained for Y_d and ET_d based upon differences in management.

The water use in **Equation (1)** is difficult to determine precisely. So, in some situations, a “benchmark” WUE (WUE_b) is used by many irrigation practitioners. It can be defined as

$$WUE_b = \frac{\textit{Yield (usually the economic yield)}}{(P_e + I + SW)} \qquad ...4$$

where P_e is “effective” rainfall, I is irrigation applied, and SW is soil water depletion from the root zone during the growing season. The denominator of **Equation (4)** is a surrogate estimate for the water used to produce the crop neglecting percolation, ground water use, and surface runoff. Experienced practitioners can use **Equation (4)** for a specific region and to identify differences between irrigation methods and/or irrigation management.

Howell et al. (1990) presented an expression for field WUE based on Cooper et al. (1987) and Gregory (1990) as

$$WUE = \frac{(HI\ DM)}{\left\{T\,(1 - WC)\left[1 + \frac{E}{(P + I + SW - D - Q - E)}\right]\right\}} \qquad ...5$$

Table 1. Examples of options available for improving irrigation efficiency at a field level adapted from Wallace and Batchelor (1997).

Improvement Category	Options
Agronomic	crop management to enhance precipitation capture or that reduces water evaporation (crop residues, conservation till, plant spacing, etc.) ; improved varieties; advanced cropping strategies that maximize cropped area during periods of lower water demands and/or periods when rainfall may have greater likelihood of occurrence
Engineering	irrigation systems that reduce application losses and/or improve distribution uniformity; cropping systems that can enhance rainfall capture (crop residues, deep chiseling or paratilling, furrow diking, dammer-diker pitting, etc.)
Management	demand-based irrigation scheduling; slight to moderate deficit irrigation to promote deeper soil water extraction; avoiding root zone salinity yield thresholds; preventive equipment maintenance to reduce unexpected equipment failures
Institutional	user participation in an irrigation district (or scheme) operation and maintenance; water pricing and legal incentives to reduce water use and penalties for inefficient use; training and educational opportunities for learning newer, advanced techniques

where HI is the harvest index (dry yield per unit dry matter), DM is dry matter in g m^{-2} (it has to be the same as the DM component used to calculate HI whether aboveground DM or total DM including roots), T is transpiration in mm, WC is the standard water content used to express the economic yield (in a fraction; i.e., 0.15 to 0.155 is common for corn and 0.14 for other cereals), E is soil water evaporation in mm, P is precipitation in mm, I is irrigation in mm, SW is soil water depletion from the root zone in mm, D is deep percolation below the root zone in mm, and Q is surface runoff in mm. In some cases, other water balance components, like interception or runon or upward flow from groundwater into the root zone, may need to be considered. **Equations (1, 4,** and **5)** illustrate the common problems encountered in accurately assessing WUE from field measurements. Both P and I may contribute water to surface runoff, Q, making estimates of effective precipitation, P_e, difficult to determine in some cases. Likewise, both P and I may contribute or cause water to move past the crop root zone resulting in difficulties in characterizing D. Profile soil water depletion can be measured, but it typically can only be determined at a few discrete points in a plot or field. The stochastic distribution of P across a plot or field is often ignored together with the distribution of I, which is known to be more predictable, but still probabilistic. All of these spatial variations impact ET and soil water depletion, SW. In order to obtain reproducible and reliable estimates for P, I, Q, D, and SW to estimate ET in **Equations 1** or **2**, extreme measures like plot leveling and bordering may be required. These techniques, although widely used in arid and semi-arid experiments, may be impractical in many situations or induce undesired effects on ET_d or Y_d, particularly in higher rainfall regions, and even affect D in those cases both by changing the profile soil water balance and by leaching crop nutrients from the root zone affecting Y_i.

Equation (5) represents all of the agronomic and engineering mechanisms offered by Wallace and Batchelor (1997) to enhance WUE. These are 1) increasing the harvest index through crop breeding or management; 2) reducing the transpiration ratio (T/DM_{ag}) by improved species selection, variety selection, or crop breeding; 3) maximizing the dry matter yield through enhanced fertility, disease and pest control, and optimum planting; and/or 4) increasing the transpiration (T) component relative to the other water balance components. In particular, element 4 might be obtained by reducing E by increasing residues, shallow mulch tillage, alternate furrow irrigation, or narrow row planting; reducing D by avoiding overfilling the root zone and minimizing leaching to the absolute minimum for salinity control; and reducing Q by using furrow diking, dammer diking, crop residues, or avoiding soil compaction and hardpan problems while increasing soil water depletion from the profile by gradually imposing soil water deficits, deeper soil wetting, or using deeper rooted varieties. Although both elements 1 and 2 are biologically controlled and difficult to manipulate, some diversity and variability may exist in the field that can be controlled. Element 3 is the focus of much current precision agriculture research to enhance yields relative to needed inputs at the correct time and location in the field. Element 4 is the basis of almost all current water conservation technologies to enhance rainfall capture and to improve irrigation technologies to avoid or minimize application losses.

Engineers have long characterized irrigation performance using various “efficiency” and “uniformity” terms (Burt et al., 1997). Wang et al. (1996) offered a new efficiency term, called the “general” efficiency, E_g, based on the ratio of transpiration to the sum of the volume of applied water and the volume of the deficit expressed as

$$E_g = \frac{\alpha \; E_a E_s}{\left(E_a + E_s - E_a E_s\right)} \qquad ...6$$

where E_g is the "general" irrigation efficiency fraction, α is the transpiration fraction of ET (T/ET), E_a is the application efficiency fraction (volume of water stored in the root zone per unit water volume delivered to the field), and E_s is the storage efficiency fraction (volume of water stored in the root zone per unit water volume needed in the crop root zone). **Equation (6)** is related to **Equation (5)** without the yield parameters that have become integral in WUE. It clearly emphasizes, like Wallace and Batchelor (1997), the need to maximize transpiration while minimizing application losses and meeting the crop water needs. Wang et al. (1996) believed that E_g would be more closely associated with crop yield than the individual "efficiency" terms since it could simultaneously consider both deep percolation losses and irrigation deficits while excluding the soil water evaporation loss that may not directly contribute to crop yield. **Equation (6)** can be applied to differing irrigation scales from plots to watersheds, although like all efficiency characterizations (Burt et al., 1997), the various water components remain challenging to measure in the field.

Example:

The WUE, ET_{WUE}, and I_{WUE} values for corn at Bushland, TX varied dramatically between irrigation application methods and water management treatments (**Table 2**; see Howell, 2001 for reference sources). Several items from these data are evident: 1) I_{WUE} is typically much greater than just WUE; 2) both WUE and I_{WUE} do not differ greatly among irrigation methods when operated to avoid and/or minimize application losses; 3) I_{WUE} generally tends to increase with a decline in irrigation if that water deficit does not occur at a single growth period [i.e., see the surface data with specific period deficits (likely attributed to reducing the transpiration component in relation to total water use)]; 4) both WUE and I_{WUE} for corn at Bushland, TX, are maximized with a small water deficit (likely attributed to reducing unnecessary soil water evaporation while not reducing transpiration) while ET_{WUE}, generally, is highest with less irrigation implying full use of the applied water and perhaps a tendency to promote deeper soil water extraction to make better use of both the stored soil water and growing season rainfall. Tanner and Sinclair (1983) presented data that supported their concept of greater WUE of corn in more humid environments. Their mean WUE was 1.8 kg m^{-3} for several western sites while it averaged more than 2.5 kg m^{-3} in more humid sites. The WUE values for corn at Bushland, TX, are lower than values in Tanner and Sinclair (1983; their Table 5) reflecting the greater vapor pressure deficit and greater evaporative demand in the Southern High Plains for corn. However, this region has some of the nation's highest mean county corn yields (TASS, 1999; NASS, 1999). For example, Dallam County in Texas averaged 12.8 Mg ha^{-1} over more than 61,100 ha in 1998, which was a drought year, (TASS, 1999) compared with the best county in Iowa in 1998, Scott County, which averaged 10.6 Mg ha^{-1} over more than 47,100 ha (NASS, 1999). Interestingly, the higher Bushland I_{WUE} values approached the 2.5 kg m^{-3} values for WUE in the more humid sites indicating the greater effectiveness of the applied irrigation component of the total water balance. The mean ET_{WUE} from these experiments was 2.49 kg m^{-3}, which was essentially the same as the humid site WUE value of 2.5 kg m^{-3} from Tanner and Sinclair (1983). The higher ET_{WUE} values compared with the I_{WUE} values at near maximum ET or I, indicated either the lack of use of the extra water by the crop or the ineffectiveness of the rainfall combined with the irrigation. In almost every case, a slight under irrigation (about 0.75 to 0.8 of full irrigation or withholding early vegetative irrigations) maximized WUE, ET_{WUE}, and I_{WUE}.

Table 2. Example WUE†, ET_{WUE}, and I_{WUE}†† values for corn irrigated by surface (level basins), LEPA (low energy, precision application) and drip/microirrigation (subsurface drip and surface drip). The data were averaged for two years. See Howell (2001) for specific reference sources.

Irrigation Method	Irrigation Fraction	WUE†	ET_{WUE}	I_{WUE}††
		kg m^{-3}	kg m^{-3}	kg m^{-3}
Surface	Full	1.35	2.66	2.41
(level basins)	Vegetative Deficit	1.23	3.01	2.53
1976 & 1977	Pollination Deficit	0.91	1.97	1.98
	Grain-Filling Deficit	1.11	1.96	2.06
	0.00	0.00	----	-----
LEPA	1.00	1.35	2.13	1.73
1992 & 1993	0.80	1.45	2.56	2.07
	0.60	1.38	2.59	2.01
	0.40	1.38	3.06	2.36
	0.20	1.28	3.85	2.10
	0.00	0.93	----	----
Subsurface	1.00	1.42	1.42	1.79
Drip	0.67	1.53	1.53	2.35
1993 & 1994	0.33	1.21	1.21	2.28
	0.00	0.43	0.43	----
Surface Drip	1.00	1.39	1.95	1.78
1993 & 1994	0.67	1.52	2.37	2.28
	0.33	1.23	2.42	2.35
	0.00	0.43	----	----

† Yields based on 15.5% grain water content.
†† Preplant irrigations were excluded.

The main exception was the high ET_{WUE} and I_{WUE} values for the low energy, precision application (LEPA) irrigated corn for the lower irrigation fractions. This may be attributed to the effects of the furrow dikes used with LEPA to reduce plot surface water redistribution or surface runoff despite that the drip and surface plots were leveled and bordered, too. A large ET_{WUE} or I_{WUE} or even WUE may not insure a profitable yield (production) level.

Many reports can be cited like Postel (2001) that imply improved irrigation technology alone by converting to drip or LEPA can reduce irrigation requirements from 20 to 70% while increasing crop yields by 20 to 90% compared with surface irrigation. But in most situations without unduly poor irrigation management, irrigation requirement reductions and crop yield increases with advanced irrigation technologies are modest, at best. Generally, irrigation management (scheduling, etc.) is equally important, if not more so, as exhibited by data shown in **Table 1**. Howell (2001) presented two examples – 1) a closed groundwater basin (Texas High Plains) and 2) an open basin (Southern Idaho) where irrigation efficiency improvements on-farm could reduce overall basin irrigation efficiency (and thereby WUE) unless changes in institutions or regulations (laws) were enacted.

SUMMARY

Irrigation remains vitally important worldwide as a means to enhance production and increase WUE and meet the growing food/feed demands from an increasing population. Irrigation water supplies will remain the principle target for urban water resources. Many agronomic, engineering, and management technologies can reduce non-productive water use in irrigated agriculture. However, in some cases increasing irrigation efficiencies may not simply achieve "new" water for allocation unless the consumptive use part of the diverted water is actually reduced. Seckler (1996) summarized these opportunities as:

- Increasing output per unit of evapotranspiration (essentially WUE)
- Reducing losses of usable water to sinks
- Reducing water pollution (from sediments, salinity, nutrients, and other agrochemicals)
- Reallocating water from lower valued to higher valued uses

The latter opportunity can be "positive" or "negative" to agriculture depending on how secondary and tertiary interest holders are addressed. Irrigated agriculture needs to be proactive to educate the urban public, and especially government agencies, on the critical role irrigation must take in meeting future food/feed security issues. Irrigated agriculture can be a positive environmental factor if water management becomes a higher and more dominate influence worldwide.

REFERENCES

Bos, M.G. 1985. Summary of ICID definitions of irrigation efficiency. ICID Bulletin 34:28-31.

Bos, M.G. 1980. Irrigation efficiencies at crop production level. ICID Bulletin 29(2):18-25, 60.

Brown, L.R. 1999. Feeding nine billion. pp. 115-132. In L. Starke (ed.) State of the World 1999, W.W. Norton & Co., New York, NY.

Burt, C.M., A. J. Clemmens, T.S. Strelkoff, K.H. Solomon, R.D. Bliesner, L. Hardy, T.A. Howell, A., and D.E. Eisenhauer. 1997. Irrigation performance measures: Efficiency and uniformity. J. of Irrig. and Drain. Engr. (ASCE) 123(6):423-442.

Clothier, B.E. 1983. Research imperatives for irrigation science. J. of Irrig. and Drain. Engr. (ASCE) 115(3):421-448.

Clothier, B.E., and S.R. Green. 1994. Rootzone processes and the efficient use of irrigation water. Agric. Water Manage. 15:1-12.

Cooper, P.J.M., P.J. Gregory, D. Tulley, and H,G. Harris. 1987. Improving water use efficiency of annual crops in rainfed farming systems of West Africa and North Africa. Exp. Agric. 213:113-158.

FAO. 1988. World agriculture toward 2000: An FAO study. N. Alexandratos (ed.). Bellhaven Press, London.

FAOSTAT. 2005. FAO statastical database. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy. http://faostat.fao.org/faostat/collections?subset=agriculture [accessed on 15 March 2006].

Ghassemi, F., A.J. Jakeman, and H.A. Nix. 1995. Salinization of land and water resources, human causes, extent, management, and case studies, CAB Int.

Gregory, P.J. 1990. Plant management factors affecting the water use efficiency of dryland crops. pp. 171- 175. In P.W. Unger, T.V. Sneed, W.R. Jordan, and R. Jensen (eds.). Challenges in Dryland Agriculture, A Global Perspective, Texas A&M University, College Station.

Howell, T.A., R.H. Cuenca, and K.H. Solomon. 1990. Crop yield response. pp. 93-122. In G.J. Hoffman, T.A. Howell, and K.H. Solomon (eds.) Management of Farm Irrigation Systems. ASAE Mono., Am. Soc. of Agric. Engr., St. Joseph, MI.

Howell, T.A. 2001. Enhancing water use efficiency in irrigated agriculture. Agron. J. 93(2):281-289.

Karasov, C.G. 1982. Irrigation, efficiency in water delivery. Technology 2(2):62-74.

NASS, 1999. U.S. Department of Agriculture, National Statistical Service. http://www.usda.gov/nass/graphics/county98/cryld.htm, Washington, D.C.

Pereira, L.S., J.R. Gilley, and M.E. Jensen. 1996. Research agenda on sustainability of irrigated agriculture. J. of Irrig. and Drain. Engr. (ASCE) 122(3):172-177.

Postel, S. 2001. Growing more food with less water. Sci. American 259(2):46-51.

Postel, S. 1993. Water and agriculture. Chapter 5. Pp. 56-66. *In* Gleick, P.H. (ed.). Water in crisis: A guide to the World's Fresh Water Resources. Oxford Univ. Press, New York, NY.

Rhoades, J.D. 1997. Sustainability of irrigation: An overview of salinity problems and control strategies. pp. 1-42. *In* CWRA 1997 Annual Conf. "Footprints of Humanity: Reflections on Fifty Years of Water Resource Developments," Lethbridge, Alberta, Canada, June 3-6, 1997.

Seckler, D. 1996. The new era of water resources management from "dry" to "wet" water savings. IIMI Research Report. No. 5, Int. Irrig. Mange. Inst., Columbo, Sri Lanka.

Seckler, D., U. Amarasinghe, D. Molden, R. de Silva, and R. Barker. 1998. World water demand and supply, 1990 to 2025: Scenarios and issues. IIMI Research Report. No. 19, Int. Irrig. Mange. Inst., Columbo, Sri Lanka.

Sinclair, T.R., C.B. Tanner, and J.M. Bennett. 1984. Water-use efficiency in crop production. Bioscience 34:36-40.

Tanner, C.B., and T.R. Sinclair. 1983. Efficient water use in crop production: Research or re-search? pp. 1-27. In H.M. Taylor, W.R. Jordan, and T.R. Sinclair (eds.) Limitations to Efficient Water Use in Crop Production, Am. Soc. of Agron., Crop Sci. Soc. of Am., Soil Sci. Soc. of Am., Madison, WI.

TASS. 1999. 1998 Texas agricultural statistics. Texas Agricultural Statistical Service, U.S. Dept. of Agric. and Tex. Dept. of Agric., Austin, TX.

Unger, P.W., and T.A. Howell. 1999. Agricultural water conservation — A global perspective. J. Crop Production 2:1-36.

Viets, F.G., Jr. 1962. Fertilizers and the efficient use of water. Adv. Agron. 14:223-264.

Wallace, J.S., and C.H. Batchelor. 1997. Managing water resources for crop production. Phil. Trans. Roy. Soc. London B 352:937-947.

Wang, Z., D. Zerihum, and J. Feyen. 1996. General irrigation efficiency for field water management. Agric. Water Manage. 30:123-132.