

IMPROVING WATER MANAGEMENT IN IRRIGATED AGRICULTURE

James E. Ayars¹

ABSTRACT

Increasing demand for food, fiber, and clean water resulting from the increase in world population is putting significant stress on irrigated agriculture. Currently, irrigated agriculture supplies nearly 40% of the world food products and is expected to contribute more in the future with less water and the same cultivated land area. Analysis of the global water supply and existing irrigation management reveals many alternatives for irrigated agriculture to meet the production challenges with the same water supply while minimizing the environmental impact of irrigated agriculture. These alternatives include: improving existing water management practices for surface irrigation, switching to alternative irrigation systems, improved management to include fertilizer management and the use of alternative water supplies including saline drainage water and treated effluent. In addition to water application, sustaining irrigated agriculture depends on managing the salt in the soil profile and the salt load emanating from the irrigated area. This can be accomplished by improving drainage system management and changing the drainage design criteria. Data from the U.S. and Australia will be used to demonstrate the effect of changes in irrigation system management on water use efficiency and drainage system design and management on the salt load from irrigated agriculture.

INTRODUCTION

Competition for water between urban, industrial, environmental, and agricultural interests will become more intense in the future. Recent studies project that the world population will increase to 9 billion people by 2050 from a current population of approximately 6 billion (UN, 2004). This increase will bring additional demands for food, clean water for drinking, water for the environment, and production of consumer goods. Currently, irrigation uses approximately 80% of the developed water supply worldwide, and this water will be a logical source for meeting other demands associated with population growth. Irrigation currently supplies approximately 40% of the world food supply on less than 20% of the arable land and has a significant future role in meeting the projected world food demand (Postel, 1999). The impact of irrigated agriculture on the total food supply is demonstrated by the fact that irrigated agriculture in California produces 55% of all the fruits, nuts, and vegetables in the United States on 3% of the total US farmland.

¹ Agricultural Engineer, USDA-ARS, 9611 S. Riverbend Ave., Parlier, CA 93648

Most of the land suitable for irrigation in the United States has been developed and the lack of water supplies is now the limiting factor in continued development. The alternative to new irrigation development will be to increase yields on existing agricultural areas through improved irrigation technology, improved crops, and improving productivity of lands impacted by high water tables and salinity.

The environmental consequences of irrigation may be significant if the system is poorly designed and operated. Poor irrigation practices may result in pollution of surface water with soil sediments, pesticides, salts, fertilizers, and agro-chemicals while ground water may be contaminated with agro-chemicals, soluble fertilizers (e.g., nitrate), and salts transported by deep percolation from irrigation. There will always be some salt transport associated with irrigated agriculture resulting from the need to leach salt deposited by the irrigation water from the root zone. The impact on the environment could be lessened by improved management of irrigation and drainage systems resulting in the lowest practical levels of salt transport needed to sustain production.

Integrated management of irrigation and drainage systems will be required for irrigated agriculture to be sustainable, which will require the use of new and advanced management techniques and equipment. However, the first step prior to the adoption of new technologies or management practices is to insure that existing technology and methodology have been implemented properly and to the fullest extent possible. Improved water management should help to minimize the loss of water by evaporation, transpiration, surface runoff, and deep percolation. If existing practices are not adequate to achieve the desired conservation goals then new technology and practices will need to be adopted. This paper will highlight some existing and proposed management practices that result in improved water use efficiencies and thus increased food production with the existing water supply.

IRRIGATION WATER MANAGEMENT ALTERNATIVES

A goal of improving the irrigation and drainage water management is to improve the water use efficiency (WUE) of irrigated agriculture. Water use efficiency has been defined as "the production of marketable unit of crop yield per unit of water consumed by evapotranspiration", Jensen et al. (1990). This does not imply that the maximum yield will be obtained for a given crop. One way of achieving maximum WUE is to maintain yields while reducing the applied water. This can be done by improving the efficiency of the irrigation system or reducing the total seasonal application when the irrigation system is already being operated efficiently. Three methods that result in a reduction of applied water are regulated deficit irrigation (RDI), microirrigation, and irrigation scheduling. Each of these methods is discussed in the following paragraphs.

Regulated Deficit Irrigation

Regulated deficit irrigation has the largest potential impact on perennial crops that continue to transpire after the harvestable yield has been removed and has been applied successfully to tree crops such as pears, peaches (Mitchell et al, 1986; Chalmers et al, 1986; Chalmers et al, 1981), and plums (Johnson et al, 1994). Chalmers et al. (1986) found with Bartlett pears that there were two time periods that could be used as part of an RDI scheme. The first period occurred prior to fruit expansion and the second occurred after harvest. This resulted in significant water savings without a reduction in yield. Application of the process requires an understanding of plant physiology such that water is applied during critical growth stages that insure development of the fruit and withheld during non-critical growth stages. The non critical stages will vary depending on the fruit.

In a three year study on May harvested plum, Johnson et al. (1994) found that water could be withheld from plums after the harvest was completed and not affect yield. The plums were irrigated at 100% ET until harvest after which the stress treatments were applied. One treatment (T1) received 50% of the water applied to the control at the same frequency as the control, while the second treatment (T2) was subjected to cyclic stress that varied from year to year. The second treatment (T2) received the same amount of water as T1 in a different sequence. The imposed irrigation treatments resulted in a savings of 300 mm of water over the season compared to the control without a loss in yield or quality. A total of 889 mm of water were applied to the control treatment so the stress treatments resulted in a 33% water savings. The study was done using a low volume irrigation system having 2 emitters per tree each with a discharge rate of 19L/hr on a sandy loam soil with an underlying hard pan.

Microirrigation

One of the first suggestions for improving irrigation efficiency or water use efficiency is to change the irrigation system being used. If furrow or surface irrigation is being used, the recommendation will be to switch to either sprinkler or some form of microirrigation (drip, microsprays, bubblers). This switch makes it possible to improve the distribution of water over the field and match the application rate to the infiltration rate. These systems are also capable of automated control enabling higher frequency irrigation and a better match of supply and demand. This reduces the plant stress and also deep percolation losses if properly operated.

Studies done over a 6 year period in the San Joaquin Valley using both surface and subsurface drip demonstrate the effect of irrigation frequency, drip lateral location, and fertigation on yield and WUE. An overview of the materials and

methods used in the study are provided here, and the complete details of the studies can be found in Ayars, et al. (1999).

A progression of water management and fertilization experiments was conducted at the University of California West Side Research and Extension Center using a subsurface drip irrigation system (SDI), a surface drip system (SD), and a weighing lysimeter. The cropping pattern was processing tomatoes in 1984, 1985, 1987, and 1990, cantaloupe in 1986, cotton in 1988, and sweet corn in 1989. The design was a randomized block consisting of 3 treatments with 4 replications. This was modified in 1987 with the blocks being subdivided into two sub-plots. The initial installation was completed in 1984. The plots were 91 m long and contained 10 beds spaced 1.63 m from center to center.

Filtration was by nested screen with 180 mesh being the finest. The headworks consisted of 3 sections each with a computer lysimeter feedback control backed up by a time clock, electric valve, water meter, pressure regulator, and pressure gage leading to a 7.6 cm diameter polyvinyl chloride (PVC) mainline. At each plot a 2.5 cm diameter PVC manifold was connected by a 5.1 cm diameter PVC riser assembly to the mainlines. The riser assembly and plot manifold were made portable for the surface microirrigation plots. The microirrigation laterals had in-line turbulent flow emitters with flow rates of 4 L h^{-1} spaced 0.91 m apart along the lateral. The SDI laterals were in the center of the bed at a depth of 0.45 m. The surface laterals were installed after planting and removed before harvest each year. The soil is a Panoche clay loam (Typic Torriorthents).

A large weighing lysimeter was used in feedback mode to schedule irrigation automatically in the SDI and SD treatments after 1 mm of crop ET_c had measured by the lysimeter. An irrigation of 25 mm was applied to the low frequency SD after 25 mm of ET_c was measured by the lysimeter. The lysimeter was irrigated using SDI and corresponded to the high frequency irrigation treatment.

Irrigation frequency: In this study irrigation was initiated on the high frequency plots when approximately 1 mm of ET_c had occurred resulting in up to 8 irrigations a day. The low frequency was 25 mm applied approximately once every 3 days during the heat of the summer. In either case the soil water depletion was not nearly equal to that expected when furrow irrigating. The data in Table 1 are for a tomato crop that was fertilized solely with nitrogen at the recommended rates. There was higher evapotranspiration with the low frequency surface drip (LFSD) than with either of the high frequency treatments. The data in Table 1 show that there was not a statistical difference in the yields (Y_T), but when crop water use was considered there was a statistical difference in the WUE with the high frequency surface drip irrigation (HFSD) having a larger WUE than the LFSD.

Table 1. Water use efficiency red tomatoes grown with drip irrigation in 1984.

Irrigation Treatment	E_t (mm)	Y_r (Mg/ha)	WUE (kg/m^3)
SDI	659	121a ^a	18a
HFSD	650	126a	19a
LFSD	690	114a	16b

^a Columns followed by the same letter are not significantly different at the 95% confidence level, as determined by the Duncan test on separation of means. Y_r , yield of large red tomatoes, E_t crop evapotranspiration, WUE water use efficiency.

High frequency automated control of the drip system was possible because of the weighing lysimeter which would not generally be available for commercial agriculture. However, there are new control technologies that enable automated control of irrigation systems with a frequency comparable to the low frequency irrigation in this study (Charlesworth, 2000; Clark and Phene, 1992; Phene et al., 1992; Phene, 1996). A frequency of application that meets the crop water requirement once every one to three days will result in less plant stress than a system that applies water once every 2 weeks. This reduced stress will have a significant impact on yield in a water stress sensitive crop like tomato.

Fertilization: The results in Table 1 demonstrate the potential effect of irrigation frequency and meeting the crop water requirement on a nearly daily basis. Similar studies were done in 1985 and 1987 using the same scheduling methodology with fertilization treatments. These data are summarized in Table 2. In 1985 phosphorus (P) was added with the nitrogen, and in 1987 both P and potassium (K) were added with the nitrogen.

Table 2. Yield of large red tomatoes and WUE for water and fertilization treatments in 1985 and 1987.

Irrigation treatments	1985 (N+P)			1987 (N+P+K)		
	E_t (mm)	Y_r (Mg ha^{-1})	WUE (kg m^{-3})	E_t (mm)	Y_r (Mg ha^{-1})	WUE (kg m^{-3})
SDI	751	168a ^a	22a	708	220a	31a
HFSD	741	152b	20b	695	201b	29b
LFSD	724	130c	18c	709	187c	26c

^a Column means followed by the same letters are not significantly different at the 95% confidence level, as determined by the Duncan test on separation of means. Y_r , yield of large red tomatoes, E_t crop evapotranspiration. WUE water use efficiency.

The data in Table 2 show a significant difference in the WUE and yield as additional fertilizer components are added to the irrigation water supply. The difference in E_t will be in part due to seasonal variability in climate across years.

When the WUE is compared between treatments there is a steady increase as fertilizer is added. The SDI treatment is consistently the largest producer. The addition of phosphorous and potassium to the nitrogen in 1987 nearly doubled the yields from 1984 in the high frequency irrigation treatments with a nominal increase in the applied water. Similar responses were seen with cantaloupe and sweet corn.

Irrigation scheduling

Irrigation scheduling should be an important part of water management, but it is often given very little consideration. The basic concept is to determine when to irrigate and how much to irrigate. This can be done using a water balance technique that provides both answers. However, the actual crop water use needs to be calculated and the storage capacity of the soil needs to be known. Both of these can be determined. The advent of computer control of irrigation systems and the potential for feedback control of an irrigation system based on changes in measured soil water content has provided additional irrigation scheduling opportunities. In feedback control mode a threshold water content is set and the irrigation system applies a fixed water volume each time the threshold is met. This may result in a high frequency irrigation that matches the crop water use and minimizes deep percolation losses.

Crop coefficient: One problem in the water balance method is the calculation of the crop water use. This is typically done by modifying the reference evapotranspiration (ET_0) by a crop coefficient (K_c). The ET_0 is available in many states from regional climate station networks. The K_c values are often difficult to find and are cumbersome to use, so there is a need to provide simplified methods to develop the coefficients and to update existing coefficients to reflect new varieties. In the past, the K_c has been developed using lysimeters to measure the crop water use as a function of plant age or development. As an alternative, Grattan et al. (1998) used the Bowen Ratio method to estimate crop water use and correlated it to canopy cover. This was done for a wide variety of vegetable crop grown in the Central Valley of California. Application of the technique only requires the grower to make a simple measurement of ground cover to estimate the crop coefficient. It has the advantage of incorporating climatic impact on plant development that might not be accounted for in a system that is simply time based.

Shallow groundwater: One component of the water balance equation is the water loss or gain from the shallow ground water. When scheduling irrigation this term is routinely set to zero, which can lead to significant over irrigation in areas with shallow ground water. Including the shallow ground water contribution to the crop water use extends the irrigation interval and reduces the total irrigation demand. Ayars and Hutmacher (1994) developed crop coefficients for cotton that accounted for crop water use from shallow ground water as a function of ground

water quality and depth. Similar studies need to be done for other crops. In-situ use of ground water in the range of 15 to 60% of the crop water requirement has been documented for alfalfa, cotton, peaches, pears, string bean, sugar cane, corn, and tomato. By managing this resource the WUE will also be improved because less water will be used for production.

DRAINAGE WATER MANAGEMENT ALTERNATIVES

Drainage water comes from two sources in irrigated agriculture: from surface runoff occurring naturally as part of surface irrigation, or from subsurface drains installed to control waterlogging. Surface drainage often contains silt, sediment, and a minimal amount of salt and chemicals adsorbed to the soil. It generally is suitable for reuse on an adjoining field after the sediment is removed. The subsurface drainage water will often contain salt and fertilizer. The concentration of salt will depend on the existing soil salinity levels and the depth of placement of the drains. In the past, subsurface drainage was discharged to surface water bodies without regard to the environmental consequences of this procedure. However, unregulated release of subsurface drainage and disposal of saline drainage water are major problems confronting irrigated agriculture. Several alternatives are being evaluated to solve this problem. Reuse of drainage water to supplement irrigation water supplies has been investigated (Ayars et al, 1993; Rhoades et al, 1989; Rhoades, 1989) and found to be a part of the solution. The suitability of this water for reuse depends on the crop salt tolerance, and the salinity of the water. Reuse of drainage water should be one of the last steps in the disposal process because of the potential negative impacts on the soil environment with the accumulation of salt and toxic elements. The first step should be reduction of the total drainage water volume (source control) which will minimize the volume of water requiring disposal. This was the recommendation of the San Joaquin Valley Drainage Program study (1990). This means that the irrigation efficiency should be improved to the maximum extent possible prior to implementing any drainage water reuse programs.

In addition to improving irrigation efficiency, steps should be taken to actively manage the subsurface drainage system. This is a significant departure from current practice. In the past, drainage systems were designed to draw the water table down to at least 1.2 m below the soil surface at the mid-point between the drains and to run continuously. This can result in over-drainage of the soil (Doering et al. 1982) and significant load of salt being discharged. Christen and Ayars (2001) developed a set of best management practices for the design and operation of subsurface drainage systems. They recommended initially improving the irrigation system efficiency and then installing control structures on the outlet of the drainage system. These structures maintain the water level at a fixed depth below the ground surface, prevent excess drainage, and insure that water is available for in-situ use by crops.

Outlet controls: Controlling the water table at the outlet not only maintains the water table closer to the surface but it modifies the flow path to the drains. Wider drain spacings have deeper flow paths, and in areas where salt concentrations increase with depth more salt will be discharged to the surface. When controls are placed on these systems the flow path depth is reduced and less salt is discharged. In a study in Australia, Christen and Skehan (2001) demonstrated the impact of managing subsurface drainage on salt load. The study evaluated the salt discharge from an area with deep drains (2.1 m deep), deep drains with an outlet control, and shallow drains (0.9 m deep). The results are given in Table 3.

Table 3. Salt load from subsurface drainage systems.

Treatment	Drainage Depth (mm/ha)	Average Salinity (dS/m)	Salt Load (kg/ha)
Unmanaged deep drains	70	11	5867
Managed deep drains	47	7 - 8	2978
Shallow drains	15	1 - 3	319

These data demonstrate how the electrical conductivity (EC) of the drainage water was reduced by managing the drains to create a water table depth of 1.2 m at the outlet. A further reduction in EC was achieved by using shallow drains. Controlling the drains also significantly reduced the total discharge as did using shallow drain placement. The combination of reduced flow and reduced EC resulted in significant reductions in salt load. Depending on the configuration of the drainage system, alternative designs can be developed to control individual laterals or parts of the entire system (Ayars, 1996).

CONCLUSION

There exists an extensive body of knowledge on how to manage on-farm irrigation and district operations and the challenge for the future is to implement this knowledge. The water management challenge in the 21st century will be to shift from a technology based to an information intensive system (Postel, 1999) that implements intensive management of irrigation systems. The goal will be to improve water use efficiency and get more crop for drop of water. This paper described alternatives for improved management of pressurized irrigation systems that will improve water use efficiency. The need for integrated management of irrigation and drainage was also discussed and areas for future research to improve water management in irrigated agriculture were also highlighted. There will be consequences on a watershed level associated with improved on-farm water management that will have to be considered. Less surface runoff and deep percolation from inefficient irrigation might affect the return flow to the river and impact the downstream water supply later in the irrigation season. There is no

simple answer as to the total water savings that will result from the implementation of any of these practices.

REFERENCES

- Ayars, J.E. 1996. Managing irrigation and drainage systems in arid areas in the presence of shallow groundwater: case studies. *Irrigation and Drainage Systems*, 10:227-244.
- Ayars, J.E., and Hutnacher, R.B. 1994. Crop coefficients for irrigating cotton in the presence of groundwater. *Irrigation Science*, 15(1):45-52.
- Ayars, J.E., Hutnacher, R.B., Schoneman, R.A., Vail, S.S., and Pflaum, T. 1993. Long term use of saline water for irrigation. *Irrigation Science*, 14:27-34.
- Ayars, J.E., Phene, C.J., Hutnacher, R.B., Davis, K.R., Schoneman, R.A., Vail, S.S., and Mead, R.M. 1999. Subsurface drip irrigation of row crops: A review of 15 years of research at the Water Management Research Laboratory. *Agricultural Water management*, 42:1-27.
- Chalmers, D.J., Mitchell, P.D., and van Heek, L. 1981. Control of peach tree growth and productivity by regulated water supply, tree density, and summer pruning. *Journal of American Society for Horticultural Science*, 106:307-312.
- Chalmers, D.J., Burge, G., Jerie, P.H., and Mitchell, P.D. 1986. The mechanism of regulation of "Bartlett" pear fruit and vegetative growth by irrigation withholding and regulated deficit irrigation. *Journal of American Society for Horticultural Science*, 111:904-907.
- Charlesworth, P., 2000, *Soil Water Monitoring*, Irrigation Insights, Number One, Land and Water Australia, 96 pgs.
- Christen, E.W., and Ayars, J.E., 2001, *Subsurface drainage system design and management in irrigated agriculture: Best management practices for reducing drainage volume and salt load*, Technical Report 38-01, CSIRO Land and Water, Griffith, NSW, Australia, 129 pg.
- Christen, E.W. and Skehan, D. 2001. Design and management of subsurface horizontal drainage to reduce salt loads. *ASCE J. of Irrigation and Drainage* 127(3):148-155.
- Clark, D.A., and Phene, C.J., 1992, *Automated centralized data acquisition and control of irrigation management systems*.
- Doering, E.J., Benz, L.C., and Reichmann, G.A. 1982. Shallow-water-table concept for drainage design in semiarid and subhumid regions. In *American Society of Agricultural Engineers (ed), Advances in Drainage, Proceedings of the Fourth*

National Drainage Symposium, Vol. ASAE Publication 12-82, ASAE St. Josephs, MI, pg 34-41.

Grattan, S.R., Bowers, W., Dong, A., Snyder, R.L., and Carroll, J.J. 1998. New crop coefficients estimate water use of vegetables, row crops. *California Agriculture*, 52:16-21.

Jensen, M.E., Rangeley, W.R., and Dieleman, P.J. 1990. Irrigation trends in world agriculture. p. 1218 *IN* B.A. Stewart and D.R. Nielsen (ed.) *Irrigation of agricultural lands*. ASA-CSSA-SSSA, Madison, WI.

Johnson, R.S., Handley, D.E., and Day, K.R. 1994. Postharvest water stress of an early maturing plum. *Journal of Horticultural Science*, 69:1035-1041.

Mitchell, P.D., Chalmers, D.J., Jerie, P.H., and Burge, G. 1986. The use of initial withholding of irrigation and tree spacing to enhance the effect of regulated deficit irrigation on pear trees. *Journal of American Society for Horticultural Science*, 111:858-861.

Phene, C.J., DeTar, W.R., and Clark, D.A. 1992. Real-Time irrigation scheduling of cotton with an automated pan evaporation system. *Applied Engineering in Agriculture*, 8:787-793.

Phene, R.C., 1996, Real-time irrigation scheduling with automated evaporation pan systems, *Proc. of Evapotranspiration and Irrigation Scheduling Conference*, San Antonio, Texas, Nov. 3-6, American Society of Agricultural Engineers, St. Joseph, MI, pg 1093-1098.

Postel, S. 1999. *Pillar of sand: Can the Irrigation Miracle Last?* : New York, W.W. Norton & Company.

Rhoades, J.D. 1989. Intercepting, isolating and reusing drainage waters for irrigation to conserve water and protect water quality. *Agricultural Water Management*, 16:37-52.

Rhoades, J.D., Bingham, F.T., Letey, J., Hoffman, G.J., Dedrick, A.R., Pinter, P.J., and Replogle, J.A. 1989. Use of saline drainage water for irrigation: Imperial Valley study. *Agricultural Water Management*, 16:25-36.

San Joaquin Valley Drainage Program. 1990. The problem. p. 183 *IN* U.S. Department of Interior and California Resources Agency (ed.) *A Management Plan for Agricultural Subsurface Drainage and Related Problems on the westside San Joaquin Valley*. California Department of Water Resources, Sacramento, California.

United Nations Secretariat. 2004. Department of Economic and Social Affairs, Population Division, *World Population Prospects: The 2002 Revision and World Urbanization Prospects: The 2001 Revision.*, <http://esa.un.org/unpp>.