STRATEGIES FOR UTILIZING SHALLOW GROUND WATER IN ARID AREAS

James E. Ayars[1] Richard A. Schoneman[2]

Richard W. Soppe[3]

ABSTRACT

Shallow ground water in arid irrigated areas has generally been treated as a waste product of irrigation which was to be discharged into an available water course for ultimate disposal in an ocean. This practice is no longer environmentally acceptable and means need to be developed to minimize the environmental impact of uncontrolled discharge of drainage water from irrigated lands. This paper presents the results of field and theoretical studies which demonstrate methods to reduce and minimize the volume of drainage water for disposal. The field studies demonstrated the use of subsurface drip irrigation with modified crop coefficients to increase the water use from shallow ground water, and the use of control structures on drainage systems to control the depth to shallow ground water to improve the water use by the crop from shallow ground water. Application of these techniques resulted in significant use of ground water by cotton and tomato. The theoretical studies demonstrated that using new drainage design criteria will result in less drainage discharge and lower salt loads. Improved irrigation efficiency will have the largest impact on reducing total drainage discharge.

INTRODUCTION

---

[1]Research Agricultural Engineer, USDA-ARS, Water Management Research Lab. 2021 South Peach Avenue, Fresno, CA 93727

[2]Agricultural Engineer, USDA-ARS, Water Management Research Laboratory, 2021 South Peach Avenue, Fresno, CA 93727

[3]Visiting Scientist, USDA-ARS, Water Management Research Laboratory, 2021 South Peach Avenue, Fresno, CA 93727

Shallow ground water in arid irrigated areas is generally considered a problem which is corrected using a subsurface drainage system. The conventional wisdom in irrigation and drainage system design for arid areas is that a drainage system is necessary to prevent water logging and to provide leaching of salt from the soil profile. The salt originates from sources such as the irrigation water, fertilizers, and the parent soil materials (Ayars et al, 1987). Disposal of the drainage water containing salt and other naturally occurring elements is one of the major problems facing irrigated agriculture throughout the world. (Ayars and Meek, 1994).

The San Joaquin Valley Drainage Program report (1990) identified the following methods to manage subsurface drainage water; source control, supplemental irrigation with collected drainage water, in-situ use of shallow ground water by salt tolerant crops, and land retirement.

Source control consists of reducing the deep percolation losses from irrigation by conversion of irrigation systems, improved irrigation scheduling, and improved system management. Conversion of irrigation systems includes using gated pipe instead of siphons, using sprinklers instead of surface irrigation methods, or using micro-irrigation instead of surface or sprinklers. In each case the adoption of a new irrigation method should allow for better control of the applied water and reduced deep percolation.

It also comes with a price. The purchase cost of the new irrigation system is the most obvious, but there is also a price associated with learning to manage a new irrigation system. The techniques for scheduling and controlling the water are different than with the old system. If this is ignored then nothing will be gained. An extreme example would be to manage a drip system in the same fashion as a surface irrigation system. It would be difficult to get the water applied in a timely manner with the drip system, and there would be deep percolation associated with the excess application of water at a point.

Improved irrigation scheduling will result in application of the required amount of water at the appropriate time. This is most effective when implemented in conjunction with improvements in the irrigation system management. Irrigation at the beginning of the growing season is the most difficult time to manage water to reduce deep percolation. It is often the case with annual crops that only 1 to 2 inches of water are needed for the first irrigation. Surface systems such as furrow and flood generally can not apply this small an amount of water and the excess water results in deep percolation. Studies in the San Joaquin Valley have shown that the first irrigation of the season has the poorest efficiency and the largest deep percolation values (Ayars and Schoneman, 1991). It is difficult to use a water balance method to schedule irrigation in the presence of shallow ground water because the ground water contribution is unknown.

Supplemental irrigation of salt tolerant crops has been touted a method to reduce the total volume of drainage water for disposal. Studies by Ayars et al. (1993) and Rhoades et al. (1989) have demonstrated the feasibility of using saline water on salt tolerant crops such as cotton and sugar beet and in a rotation with salt sensitive and moderately tolerant crops (Rhoades et al, 1989). In a five year study Ayars et al. (1993) estimated that nearly 70 inches of saline water were used as supplemental irrigation on salt tolerant crops. However, the use resulted in an increase in the salinity and boron concentrations in the soil profile such that it would require nearly 70 inches of good quality water to return the boron concentration to the previous levels. The negative impact of using saline water is the application of salt and other potentially toxic elements to the soil surface and subsequently to the soil profile.

In-situ use of saline water has the potential to lower the volume of water for disposal while minimizing the environmental impact of accumulation of salt, boron, and other elements in the upper part of the soil profile. This technique is not as effective as the surface application of irrigation water since there is a time lag before the plant has developed a large enough root system to begin extracting water from the shallow ground water. The total extraction from ground water depends on the depth to the water table, the ground water quality, and the crop salt tolerance. Cotton potentially can extract up to 45% of its water requirement from ground water with an electrical conductivity of 7 mmho/cm at a depth of 4 feet. Tomato will extract from 30 to 45% of its water requirement from ground water with an electrical conductivity of 0.3 to 5 mmho/cm at a depth of 4 feet. The challenge is to manage the irrigation system to achieve these levels of use. This compares to supplemental irrigation where nearly all the water requirement after crop emergence can be met with saline irrigation water.

All of these techniques either have been or are currently being investigated as methods to enable irrigated agriculture to survive while long term sustainable solutions are developed. This paper will discuss both field and theoretical studies which have applied new concepts to the integrated design and management of irrigation and drainage systems.

STUDIES

Britz Farms

A field study was conducted in the San Joaquin Valley on 320 acres which are underlain by ground water at a depth of 4 to 8 feet depending on the time of year. The shallowest depth to ground water occurs during the winter and spring following rainfall and pre-plant irrigation which occurs during the winter and early spring in this area. A subsurface drip irrigation system (SDI) was installed on two

30 acre parcels, one on each of the quarter sections used in the research. The SDI system was made up of 5 individual systems each of approximately 6 acres and each containing a different type of drip tubing (Roberts, Ram, Chapin, Typhoon, T-System)[4]. The lateral spacing in one 30 acre block was 80 inches and 66 inches in the second block. All drip tubing was installed at a depth of approximately 15 inches below the soil surface. The crop rotations were tomato, cotton, tomato on the block with the 66 inch spacing , and cotton, cotton, cotton on the block with the 80 inch spacing.

The remainder of each quarter section was irrigated using furrow irrigation from gated aluminum pipe. Sprinkler irrigation was used to germinate the tomato crop each year and was followed by furrow irrigation for the remainder of the season. Irrigation scheduling on the furrow plots was the responsibility of the cooperator and the management of the SDI system was the responsibility of the Water Management Research Laboratory. The drip systems were scheduling using evaporation data from an on-site evaporation pan, a pan coefficient developed using weather data collected from a California Irrigation Management Information System (CIMIS) weather station located approximately 3 miles from the site, and a crop coefficient. The cotton crop coefficient was developed by Ayars and Hutmacher (1994) to account for the use of ground water by cotton. Irrigation was scheduled to be applied when approximately 0.16 inches of evapotranspiration had accumulated. The system was run up to twice a day. A locally developed crop coefficient was used for the tomato crop scheduling.

The water balance data of the Britz site for 1992 and 1993 are given in tables 1 and 2, respectively. The Et_c was estimated using both total dry matter (TDM) (Davis, 1983) and with climate data taken from a CIMIS weather station. In 1992, the total water applied by the furrow system was slightly greater than the crop Et_c and resulted in some deep percolation. In the drip plots the high frequency irrigation coupled with the modified crop coefficient resulted in less total applied water than the furrow irrigated plots and resulted in a ground water contribution to the crop water use. In 1993 both the drip and furrow irrigated plots were under irrigated which resulted in substantial use of shallow ground water by the cotton crop.

The yield data for each of the three years is given in table 3. The data show that the yields were improving in the drip irrigated plots during the three years of the project. The average yields for the drip plots were 1230, 1590 and 1830 lb/ac in 1991, 1992, and 1993, respectively. The yields in the furrow irrigated plot

---

4

Product names are given for the benefit of the reader and do not imply endorsement by the USDA-ARS.

Table 1. Water balance for the Britz Shallow Groundwater Management Demonstration Project (1992) for subsurface drip irrigation (Roberts, Ram, Chapin, Typhoon, T-Systems) and furrow irrigation.

Irrigation system	Soil Water Depletion (in)	Effective Rain (in)	Applied Water (in)	Total Dry Matter (t/ac)	Cotton Et_c TDM (in)	Groundwater contribution (%)
Furrow	1.40	0.12	18.7	4.3	17.2	-17
Roberts	-0.28	0.12	11.8	4.6	17.9	35
Ram	-0.28	0.12	14.8	6.2	22.7	35
Chapin	-0.28	0.12	15.0	5.9	22.3	33
Typhoon	-0.28	0.12	14.9	6.6	24.1	39
T-System	-0.28	0.12	15.3	6.4	21.0	28

Table 2. Water balance for the Britz Shallow Groundwater Management Demonstration Project (1993) for subsurface drip irrigation (Roberts, Ram, Chapin, Typhoon, T-Systems) and furrow irrigation.

	Seasonal					
Irrigation system	Applied Water (mm)	Effective Rain (mm)	Soil Water Depletion (mm)	Et_c CIMIS (mm)	Et_c TDM (mm)	Groundwater Contribution (%)
Furrow	13.2	0.0	0.55	22.7	25.4	40
Roberts	8.31	0.0	0.67	22.7	23.3	61
Ram	13.4	0.0	0.90	22.7	32.4	37
Chapin	14.4	0.0	0.94	22.7	29.5	33
Typhoon	12.1	0.0	0.79	22.7	25.9	43
T-System	11.5	0.0	0.63	22.7	24.8	47

remained constant during this time. The cotton yields in the furrow irrigated plots were typical of the previous production levels on this field.

The highest yield on all plots was obtained in 1993 on the SDI plot receiving the smallest amount of irrigation water during the irrigation season. The furrow plot yield in 1993 was comparable to that of 1991 in a situation with apparent under-irrigation and significant contribution from the ground water.

Table 3. Cotton yield of Britz Shallow Groundwater Management Demonstration Project in 1991, 1992, and 1993 for subsurface drip irrigation (Roberts, Ram, Chapin, Typhoon, T-Systems) and furrow irrigation .

Irrigation system	1991 (lb/ac)	1992 (lb/ac)	1993 (lb/ac)
Roberts	1250	1430	2100
Ram	1160	1520	1700
Chapin	1340	1600	2300
Typhoon	1160	1700	1520
T-Systems	1250	1700	1520
Furrow	1340	1250	1340

Broadview Site

A subsurface drain system of corrugated plastic tubing, which had previously been installed on 160 ac of land located in the Broadview Water District, CA, was modified to test concepts for water table control (1996). The system is laid out in a gridiron pattern with a total of seven laterals spaced approximately 400 ft apart. The lateral length is 2200 ft and the depth of installation is 7.8 ft. Butterfly valves were installed on each lateral at the juncture of the lateral and main collector line. Manholes with weir structures were installed at three locations along the main collector line. Schematic drawings of these control structures are shown in Fig. 1a and 1b and the field layout is shown in Fig. 2.

The installation of the control system was completed in April 1994. The site was sprinkle irrigated on 2/1, 3/1, and 3/14/94 and was planted to processing tomatoes (*Lycopersicon esculentum* var. APEX 1000) on February 14-16, 1994. Subsequent irrigation was by furrows with water delivered by gated pipe on 4/17, 5/25, 6/9, 6/17, and 6/25/94. Water was applied in every furrow which had a run length of 655 ft.

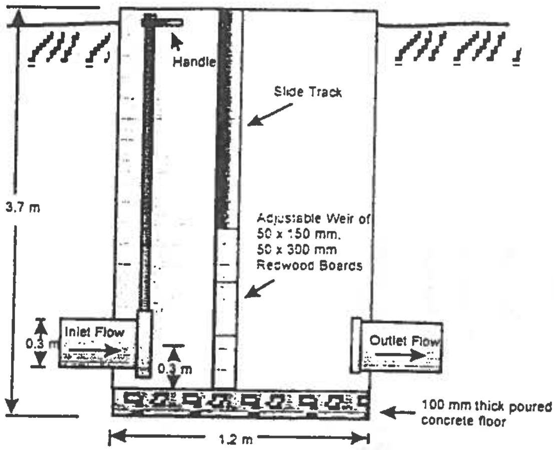

Fig. 1a. Schematic drawing of manhole and weir structure used on Broadview Shallow Ground Water Management Demonstration Project.

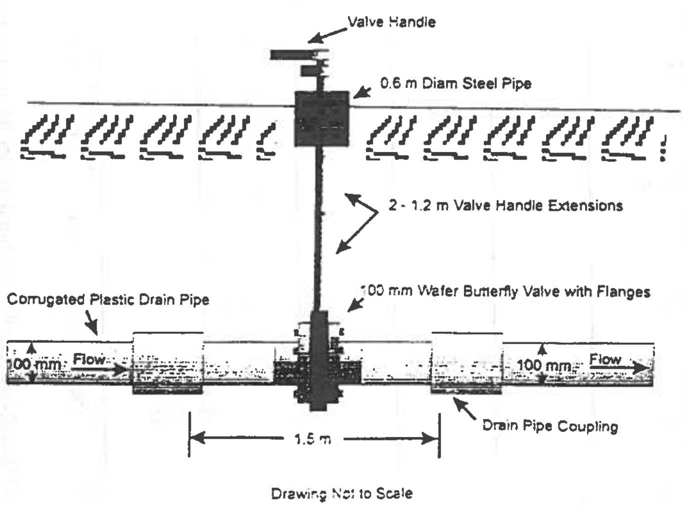

Fig. 1b. Schematic drawing of control valve used on subsurface drainage laterals in Broadview Shallow Ground Water Management Demonstration Project.

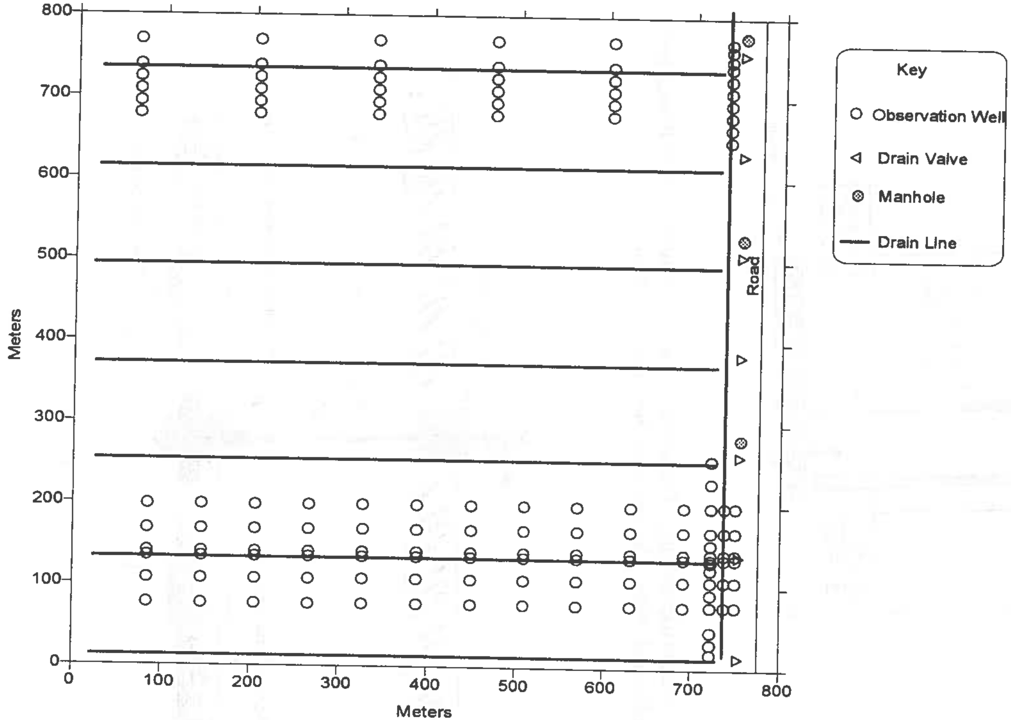

Fig. 2. Layout of Broadview Shallow Ground Water Management Demonstration Project showing the locations of the subsurface drainage laterals, drain control valves, manhole, and observation wells.

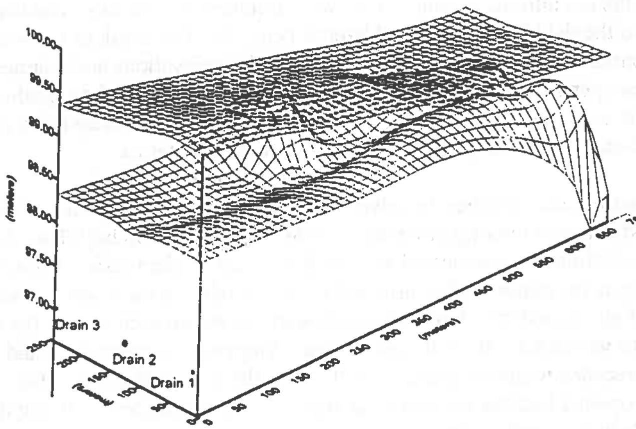

Fig. 3a. Water table position on May 17, 1994 in the Broadview Shallow Ground Water Management Demonstration Project.

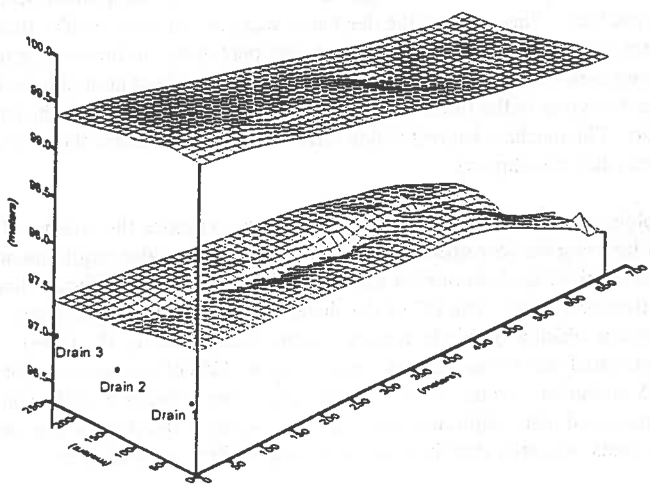

Fig. 3b. Water table position on June 25, 1994 in the Broadview Shallow Ground Water Management Demonstration Project.

Observation wells constructed of 10 ft long 1.5 inch diameter PVC pipe, which had slits cut into the bottom 3 feet, were installed at each valve installation and across the field between several laterals (Fig. 2). The depth to the water table was measured weekly and used to plot water surface elevations and responses to the valves opening and closing. The drain laterals were installed on grade from west to east with the outlet on the east side of the field. The tomato rows were in a north-south orientation, perpendicular to the drain laterals.

The water table response to valve operation is shown in Fig. 3a and 3b for the period between the irrigations on 4/17/94 and 5/25/94. In both Fig. 3a and 3b, the control structures are located at 2200 ft (670 m) on the x-axis. The soil surface is shown as the upper surface grid and the water table as the lower surface grid in both Fig. 3a and 3b. After the valves were closed on each lateral, the water table rose to within a 3.3 ft of the soil surface. The valves were opened and the water level receded to approximately 6.6 ft below the soil surface (Fig. 3b). The valves were opened because the ranch manager was concerned about drying the soil profile in preparation for harvest.

The shallow area close to the control structures had a water table fluctuation from 4.9 to 7.2 ft below the soil surface. The medium depth area had a water table depth of 5.9 to 8.5 ft during the experimental period and the deep area had a water table fluctuation of 7.2 to 8.5 ft. during the experimental period. The hand harvest yields and the component breakdown are shown in Fig. 4 for each of the test areas. The yields in the shallow and medium areas were larger than in the deep area. It appears that the largest difference in yield component occurred in the large red fruit. This value in the deep area was considerably smaller than found in the other two areas. There was also a larger percentage of limited use tomatoes in the deep area than in the other areas; the vines in the deep area did not hold up as well as the vines in the other areas and there was more damage to the fruit from the sun. The machine harvest yields were similar to the values shown for the hand harvest (data not shown).

The objectives of the drain control project were to reduce the volume of drain water by using shallow groundwater to meet the crop water requirement and reduce depth of applications for each irrigation. The results indicate that these objectives were met. The EC of the shallow groundwater ranged from 3 to 8 mmho /cm which is usable by a tomato crop. Hutmacher et al. (1989) demonstrated that tomatoes could extract up to 45% of the water requirement from 5 mmho cm^{-1} water when the water table was within 4 ft of the soil surface. The improved plant vigor and reduced stress levels in the shallow and medium depth areas indicated that the crop was using shallow groundwater.

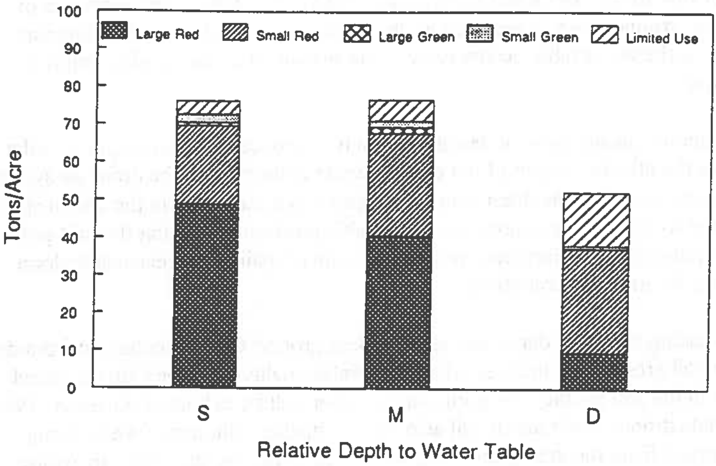

Fig. 4. Tomato yield components from 1994 tomato crop on the Broadview Shallow Ground Water Demonstration Project.

Maintaining the shallow groundwater reduced the crop water requirement by 5.6 in. A companion field which did not have water table control required 32 in of irrigation and the test field needed only 27 in. This resulted in a savings of 73 ac-ft of water. This was significant since the water allocation this year to the district was 35% of the normal supply. In areas with shallow groundwater the irrigation set time was reduced from 12 to 2 hrs.

Subsurface Drainage System Design for Integrated Water Management

Design of drainage systems to integrate irrigation and shallow ground water management will require the adoption of new criteria for the depth and placement of the drains and the depth to water table at the mid-point between the drains (Doering et al, 1982), (Ayars, et al, 1995). Both the drain depth and the allowable mid-point depth need to be reduced from the current recommendation of 8 ft for drain depth and 4ft for mid-point water table depth (U.S. Department of Interior, 1993). Changes in the design which relax current depth and spacing criteria will require additional management criteria to prevent salinization of the soil profile,

The first proposed subsurface drainage design change is to set the recommended mid-point water table depth to approximately 3 ft for all situations. The value of 3 ft was selected as a compromise to permit use of shallower drain depth installation while maintaining a reasonably wide lateral spacing. It was observed in a previous study (Ayars and McWhorter, 1985), that when crop water use of shallow ground water is included in the drainage system design, the minimum depth to the water table occurs early in the season when the rooting depth is shallow.

The second change in drain design criteria is to reduce the drain depth in order to reduce the effective depth of the ground water collection by the drainage system. However, reducing the drain depth also results in a reduction in the lateral spacing in order to adequately control the water table position. Relaxing the mid-point water table depth requirement will compensate to maintain a reasonable drain spacing for irrigated conditions.

By reducing the drain depth and spacing, less ground water is collected from deep in the soil profile, and in cases where the water quality declines with increased depth in the soil profile, less poor quality water will be extracted (Grismer, 1990). The reduction in drain depth will also lead to smaller volumes of water being discharged from the drains and more water being used by the crop. Irrigation scheduling cognizant of salinity stresses at seed germination, and later upward flow from the water table for meeting consumptive use needs of the crop will become part of salinity management in the root zone required in the overall irrigation/drainage management system.

Drainage - No Drainage Cycle

A new concept called drainage - no-drainage was developed as a means to reduce the total drainage flow and induce uptake from shallow ground water (Manguerra and Garcia, 1997) . This proposed operational method starts with a leached profile and then eliminates any drainage flow until the shallow ground water rises to a level which negatively impacts plant growth or the salinity levels in the soil have a negative impact. At this time the drains are opened and a leaching event takes place. The effectiveness of this concept is dependent on the depth of installation of the drains, the configuration of the drain laterals, the salinity of the ground water, the salt tolerance of the crops, and the irrigation efficiency.

The drains should be at least 8 feet deep with the laterals installed perpendicular to the surface grade of the field. This is a configuration similar to that found in the Broadview study. This configuration gives maximum control over the water table over the entire area of the field as was demonstrated in the Broadview Study.

The interaction of the crop salt tolerance and the ground water salinity will determine the potential uptake by the crop. The total ground water utilization will be affected by the age of the crop and the depth to the water table as previously discussed.

As the irrigation efficiency increases the total deep percolation losses will be reduced and the interval between drainage cycles will be increased. This is demonstrated with an example cotton crop with a water requirement of 26 inches, a drain depth of 7 feet, a minimum water table depth of 3 feet, soil porosity of 0.5, and assuming no capillary fringe. The time to store 20 inches of deep percolation was calculated based on percentage uptake by a cotton crop and irrigation efficiency.

Case 1 assumed an irrigation efficiency of .7 and a 20% ground water contribution to the crop water requirement. Case 2 assumed an irrigation efficiency of 0.8 and a ground water contribution of 10%. Case 3 used an irrigation efficiency of 0.7 and a ground water contribution of 10% while case 4 assumed an irrigation efficiency of 0.9 and a ground water contribution of 5%.

The results of this study indicated that there is a 6 year cycle for case 1 with 40 inches of water being extracted from the ground water. Case 2 had a 7 year cycle of operation with only 21 inches of water being extracted from the ground water. Case 3 was the shortest cycle with the estimate being every 2 years with only 9 inches of water coming from ground water. The final example had a 13 year cycle with 13 inches of water coming from ground water. The study demonstrates that the most significant impact will be derived by improving the irrigation efficiency.

SUMMARY

Field and theoretical studies demonstrated new concepts for using and managing shallow ground water in arid irrigated agriculture. The objective of these techniques is to reduce the total volume of drainage water for disposal by maximizing the use of available water supplies. Using subsurface drip irrigation in conjunction with a modified crop coefficient resulted in the maximum uptake of water by cotton from the ground water with the minimum application of water without a yield reduction. Use of controls on a subsurface drainage system resulted in a saving of 5 inches of water applied to a tomato crop without a negative impact on yield. Changing the drainage design criteria for new drainage system design will result in reduced drainage volume and reduce salt load. Adopting a cycle of drainage and no-drainage with improved irrigation efficiency will result reductions of drainage discharge.

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 R.B. Hutmacher. 1994. Crop Coefficients for Irrigation Cotton in the Presence of Groundwater. Irrigation Science, 15(1):45-52.

Ayars, J.E., and D.B. McWhorter. 1985. Incorporating crop water use in drainage design in arid areas. p. 380-389 *IN* C.G. Keyes and T.J. Ward (ed.) Proceedings, Specialty Conference, Development and Management Aspects of Irrigation and Drainage Systems, Irrigation and Drainage Division, ASCE. American Society of Civil Engineers, New York, New York.

Ayars, J.E., and D.W. Meek. 1994. Drainage Load-Flow Relationships in Arid Irrigated Areas. Transactions of the ASAE, 37:431-437.

Ayars, J.E., and R.A. Schoneman, 1991, Interaction of irrigation water and drainage flow, Proceedings, Irrigation and Drainage Division, IR DIV/ASCE, Honolulu, HI, 22-26 July, pp 275-282.

Ayars, J.E., S.H. Patton, and R.A. Schoneman. 1987. Drain water quality from arid irrigated lands. p. 220-230 *IN* American Society of Agricultural Engineers (ed.) Proceedings of Fifth National Drainage Symposium. American Society of Agricultural Engineers, St. Joseph Michigan.

Ayars, J.E., R.B. Hutmacher, R.A. Schoneman, S.S. Vail, and T. Pflaum. 1993. Long Term Use of Saline Water For Irrigation. Irrigation Science, 14:27-34.

Davis, K.R. 1983. Trickle irrigation of cotton in California. Proceedings of Western Cotton Production Conference, Las Cruces, NM, 9-11, August, pp 34-38.

Doering, E.J., L.C. Benz, and G.A. Reichman. 1982. Shallow-water-table concept for drainage design in semiarid and sub-humid regions. p. 34-41 *IN* American Society of Agricultural Engineers (ed.) Advances in Drainage, Proceedings of the Fourth National Drainage Symposium. Vol. ASAE Publication 12-82, American Society of Agricultural Engineers, St Joseph, Mich.

Grismer, M.E. 1990. Subsurface Drainage System Design and Drain Water Quality. Journal of Irrigation and Drainage Engineering, 119:537-543.

Hutmacher, R.B., J.E. Ayars, S.S. Vail, and R.A. Schoneman, 1989, Measurements in Small Weighing Lysimeters: Effects of Groundwater Salinity on

ET Rates and Water Uptake from Shallow Groundwater of Processing Tomatoes. Water Management Research Laboratory Annual Report, page 18 -19.

Manguerra, H.B., and L.A. Garcia. 1997. Field strategy for agricultural drainage and water-quality management. Journal of Irrigation and Drainage Engineering, 123:37-44.

Rhoades, J.D., F.T. Bingham, J. Letey, G.J. Hoffman, A.R. Dedrick, P.J. Pinter, and J.A. Replogle. 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.