Irrigation and Drainage Systems **10:** 227–244, 1996.

Managing irrigation and drainage systems in arid areas in the presence of shallow groundwater: case studies

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Accepted 28 September 1995

Abstract. Two field studies were conducted on the west side of the San Joaquin Valley of California to demonstrate the potential for integrated management of irrigation and drainage systems. The first study used a modified cotton crop coefficient to calculate the irrigation schedule controlling the operation of a subsurface drip system irrigating cotton in an area with saline groundwater at a depth of 1.5 m. Use of the coefficient resulted in 40% of the crop water requirement coming from the groundwater without a loss in lint yield. The second study evaluated the impact of the installation of controls on a subsurface drainage system installed on a 65 hectare field. As a result of the drainage controls, 140 mm less water was applied to the tomato crop without a yield loss. A smaller relative weight of tomatoes classified as limited use, was found in the areas with the water table closest to the soil surface.

Key words: Irrigation, drainage, groundwater uptake management, salinity, shallow groundwater, integrated management

Introduction

In the past, irrigation and drainage systems have been designed and managed as separate entities (U.S. Bureau of Reclamation 1993). The irrigation system was designed and the system management was established based on the climate, soils, cropping pattern, and water quality. The irrigation system design and management are used to estimate deep percolation values which are provided to the drainage engineer for the design of the subsurface drainage system.

In arid areas, subsurface drainage design is based on the concept of "dynamic equilibrium" which assumes that the range of the cyclic annual water table fluctuation is constant. In general, the mid-point water table height reaches the maximum height above the drains at the same time each year, generally by the end of the irrigation season. No interactive management is assumed to occur between the drainage and irrigation systems. In fact, the irrigation management assumes that deep percolation is removed from the

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field by the drainage system, and the crop is not using water from the shallow groundwater.

Several factors have developed which have changed the thinking regarding the management of irrigation and drainage systems. As water supplies become scarce, all available water supplies are evaluated as potential sources of irrigation water. Recent research has indicated that most crops have higher salt tolerance values than previously thought (Rhoades et al. 1989) which means that many drainage waters are suitable for supplemental irrigation purposes. Discharge of drainage water is becoming increasingly more difficult because of the limitations on discharge of salt and trace elements into surface water, so there is a need to reduce drainage volumes.

Many researchers (Namken et al. 1969; Kruse et al. 1985; Ayars & Schoneman 1986) have shown in field and lysimeter studies that crops will extract significant quantities of water from the shallow groundwater. The limitation has been using these data to manage an irrigation system to insure the groundwater use by a crop (Ayars & Schoneman 1984). Ayars and Hutmacher (1994) developed a modification for a cotton crop coefficient to explicitly account for shallow groundwater use by the crop. This modification provides a positive means of developing the passive groundwater management potential in a given irrigation system.

The interaction between crop water use from shallow groundwater and irrigation water management has been used to demonstrate the potential impact on drainage design. Doering et al. (1982) proposed a shallow drain concept which would be effective in increasing crop water use from shallow groundwater. They proposed reducing the spacing and depth of drains in semi-arid areas with good quality shallow groundwater. These changes will maintain a shallow depth (< 2 m) to the water table and promote extraction by plants. Research by Benz et al. (1987) demonstrated that a shallow drain installation depth would reduce irrigation requirements and maintain yields. Garcia et al. (1994) demonstrated a design concept which treats the interaction between irrigation management and drainage design. Ayars & McWhorter (1985) demonstrated a drainage design methodology which incorporated crop water use in the drainage design. Use of this procedure will significantly increase the drain spacing when compared to designs which do not account for the loss to a crop or through seepage.

There has been very little research done in arid areas to actively manage a drainage system. The techniques for active drain water management have been developed primarily in humid areas (Fouss et al. 1990) where managing salinity both in the soil and the groundwater is not a problem. Lord (1987) attempted to control groundwater in an arid irrigated area with only limited success. He provided in-line controls on several drainage laterals in a 60 ha field which resulted in localized increases in the height of the water table above the drains at the controls, but increased depth above the drains was not measured on a field basis.

This paper will present the results of two experiments which are part of the on-going shallow groundwater management research program at the Water Management Research Laboratory, Fresno, CA. The first experiment demonstrated the use of a modified cotton crop coefficient in scheduling irrigation by a subsurface drip irrigation system in an area with shallow saline groundwater. The second experiment demonstrated the impact of controlling flow in a subsurface drain system on irrigation management and crop response in a field using surface irrigation.

Materials and methods

Scheduling subsurface drip irrigation in the presence of shallow groundwater

The modified cotton crop coefficient was used to schedule the operation of a subsurface drip irrigation system (SDI) installed in a cotton field on the west side of the San Joaquin Valley (Fig. 1). Two drip plots, each approximately 2.4 ha in size, were used in the field studies. The drip lateral spacing was 2.0 m which corresponded to placing the drip tubing below every other furrow in cotton with a 1 m row spacing. The laterals were installed approximately 0.45 ± 0.05 m below the soil surface. The soil is classified as Oxalis silty clay.

Lateral lengths were 396 m and 198 m in plot A and plot B, respectively. The pressure was maintained by pressure reducing valves installed on each treatment and the operating pressures were 69 and 104 kPa in plots A and B, respectively. The tubing discharge rate was 0.57 and 0.76 L/min for each 30 m of lateral in plot A and B, respectively.

The drip system operation was controlled and monitored on-site and remotely from the Water Management Research Laboratory using a cellular phone (Cellular One, Model CPTE 1)[1] [1] interfaced to the logger/controller located on-site. A micrologger/controller (Campbell Scientific Inc., Model CR-10, Logan, UT)[1] was used to start and stop the pump, to control the irrigation valve opening and closing, to monitor the water level in the evaporation pan (BCP Electronics, Model MN 2B, Clovis, CA)[1] and to monitor water flow and pressure in each treatment according to methods described

[1] Mention of trade names is provided for the benefit of the reader and does not imply endorsement by the U.S. Department of Agriculture.

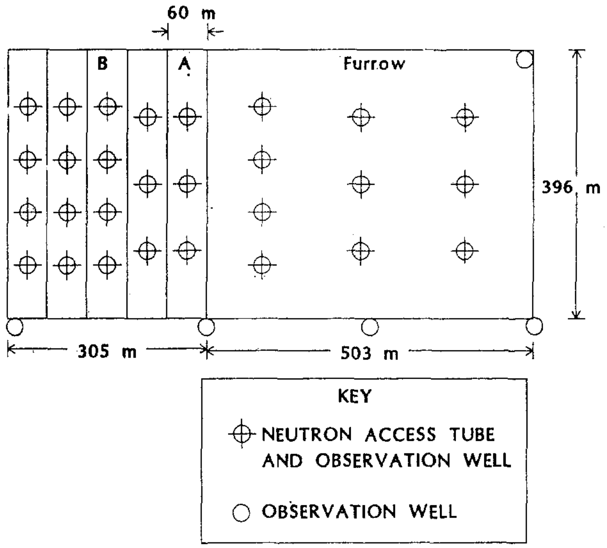

Figure 1. Schematic layout of the subsurface drip irrigated plots (A and B) and furrow irrigated plot with location of observation well and neutron access tube locations.

by Phene et al. (1992). Crop evapotranspiration (ET_{ca}) was calculated by multiplying the evaporation from an on-site evaporation pan (E_{pan}) by a pan coefficient (k_p) and a crop coefficient (k_{cbgw}). The resulting expression for crop evapotranspiration adjusted for groundwater contribution

$$ET_{ca} = k^*_{cbgw} k^*_p E_{pan} \tag{1}$$

The crop coefficient (K_{cbgw}) had been modified to incorporate the groundwater contribution to crop water use (Ayars & Hutmacher 1994). The groundwater contribution was incorporated in the crop coefficient as a function of depth to the water table and salinity of the groundwater. The crop coefficient used in the study was for shallow groundwater at a depth of 2 m with an electrical conductivity of 7.7 dS m^{-1}. The polynomial expression for this crop coefficient is

$$\begin{aligned} k_{cbgw} &= 7.124 \times 10^{-3} - 7.28 \times 10^{-4} GDD + 3.40 \times 10^{-6} GDD^2 \\ &\quad - 2.34 \times 10^{-9} GDD^3 + 3.58 \times 10^{-13} GDD^4 \end{aligned} \tag{2}$$

where GDD is the accumulated growing degree days (GDD) since planting using a base temperature of 13° C.

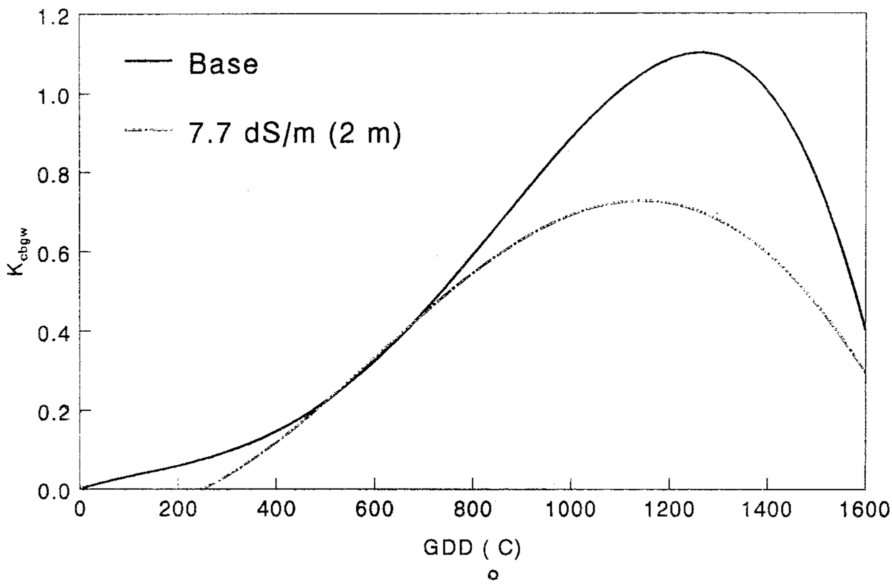

Figure 2. Cotton crop coefficients used for scheduling subsurface drip irrigation of cotton in the presence of shallow saline groundwater. The base coefficient is used with no groundwater present and the 7.7 dS/m (2 m) is used in the presence of 7 dS/m groundwater at a depth of 2 m.

The initial water table depth in the field under the plots ranged from 1.2 to 1.4 m and the EC of the groundwater ranged from 4 to 5 dS m^{-1}. The crop coefficient (7.7 dS m^{-1}, 2 m) used in this experiment was conservative. The K_{cbgw} used in this experiment and the base coefficient (no groundwater contribution) are shown in Fig. 2. The difference between the base coefficient (Base) and the modified coefficient represents the water extracted from groundwater by the crop. The curves were developed previously by Ayars & Hutmacher (1994) using data from lysimeter studies.

An automated weather station operated by the California Irrigation Management Information System (CIMIS) provided the climate data needed to calculate reference ET_0 using the Penman-Monteith equation and growing degree days (GDD) using a base of 13°. The evaporation pan coefficient (K_p) was determined by comparing the measured pan evaporation to calculated ET_0.

A furrow irrigated plot adjacent to the SDI plots was used for plant response and yield comparisons. The furrow lengths were 396 m and irrigation water was supplied to alternate furrows using gated pipe. Irrigation scheduling of the furrow plot was the responsibility of the cooperator.

Pre-plant irrigation of 210 mm was applied to both the drip and furrow plots by furrow irrigation on day of the day (DOY) 1. Cotton (*Gossypium hirusutum* L. var. MAXXA) was planted on DOY 103, drip irrigation began on DOY 162 and ended on DOY 237. Irrigation of the drip plots was scheduled after 4 mm of ET_{ca} had accumulated, based on the modified crop coefficient, K_{cbgw}. A total of approximately 4 mm was applied during each irrigation. Furrow irrigation occurred on DOY 164, 217, and 233 with 140, 140 and 56 mm being applied respectively.

Observation wells made of 38 mm diameter PVC tubing were installed in a grid and used to monitor the groundwater depth and quality in all plots (Fig. 1). The depth to the water table was measured every two weeks and the shallow groundwater was sampled at the time of measurement of water depth.

Leaf water potential (LWP) was measured three times a week in each plot using a pressure chamber. In the San Joaquin Valley, a LWP value of –1.8 MPa is considered a level requiring irrigation of cotton (Grimes & Yamada 1982). The most recently fully expanded leaf was covered with a polyethylene bag, excised from the plant, and stored in a moist dark container prior to measurement. Four leaves were measured in each plot. All measurements were made within 30 minutes of excision of the leaves.

Biomass was determined on DOY 253. All cotton plants in 6.1 m row length, in three replications, were cut level with the soil surface and weighed to determine the fresh weight. A total dry matter to fresh weight ratio was used to determine the average total dry matter. Cotton yield was determined by machine harvesting from each plot until a module was filled. The harvested area was measured and used with the gin records for lint weight for each module to determine the lint yield per ha. An independent estimate of ET_c was made using the plant biomass data collected on DOY 253. Using the equation $TDM = -2.94 + 0.03^*ET_c$, with TDM equal to total dry matter in T ha^{-1} and ET_c in mm (Davis 1983).

Drain system control

The subsurface drain system used for this research, was made of corrugated plastic tubing, and was installed several years prior to this project on 65 ha of land located in the Broadview Water District. The soil at this site is classified as Panoche silty clay. The drainage system was designed to remove deep percolation and maintain a mid-point water table depth of at least 1.2 m. At the time of design and installation, no consideration was given to regulating the flow from the laterals and submain. This project was initiated to evaluate

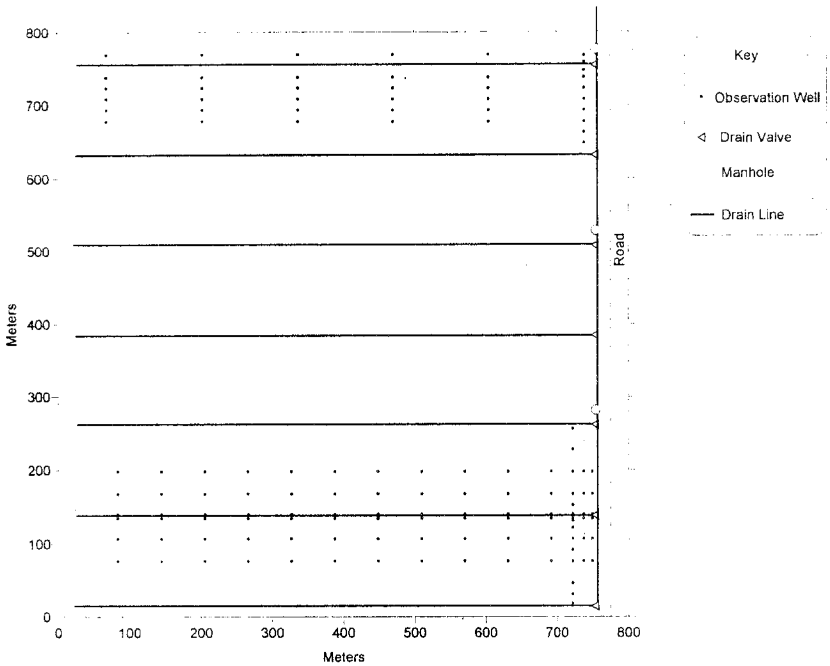

Figure 3. Schematic layout of drain experiment showing location of drain lateral control structures and observation wells in the Broadview Shallow Groundwater Management.

possible drain system modifications to regulate flow and water table position on a significant area of the field. The system is laid out in a gridiron pattern with a total of seven laterals spaced approximately 123 m apart. The drain lateral were installed on a 0.15% grade from west to east with the outlet on the east side of the field. The laterals are 12.7 cm in diameter and 670 m long with installation depth of 2.4 m. Butterfly valves were installed to restrict flow from individual lateral lines and manholes with weir structures were installed at three locations along the main collector (Fig. 3). Schematic drawings of the control structures are shown in Fig. 4.

The installation of the control system was completed on April 7, 1994 and the valves were closed on April 29, 1995. 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, each having a run length of 200 m.

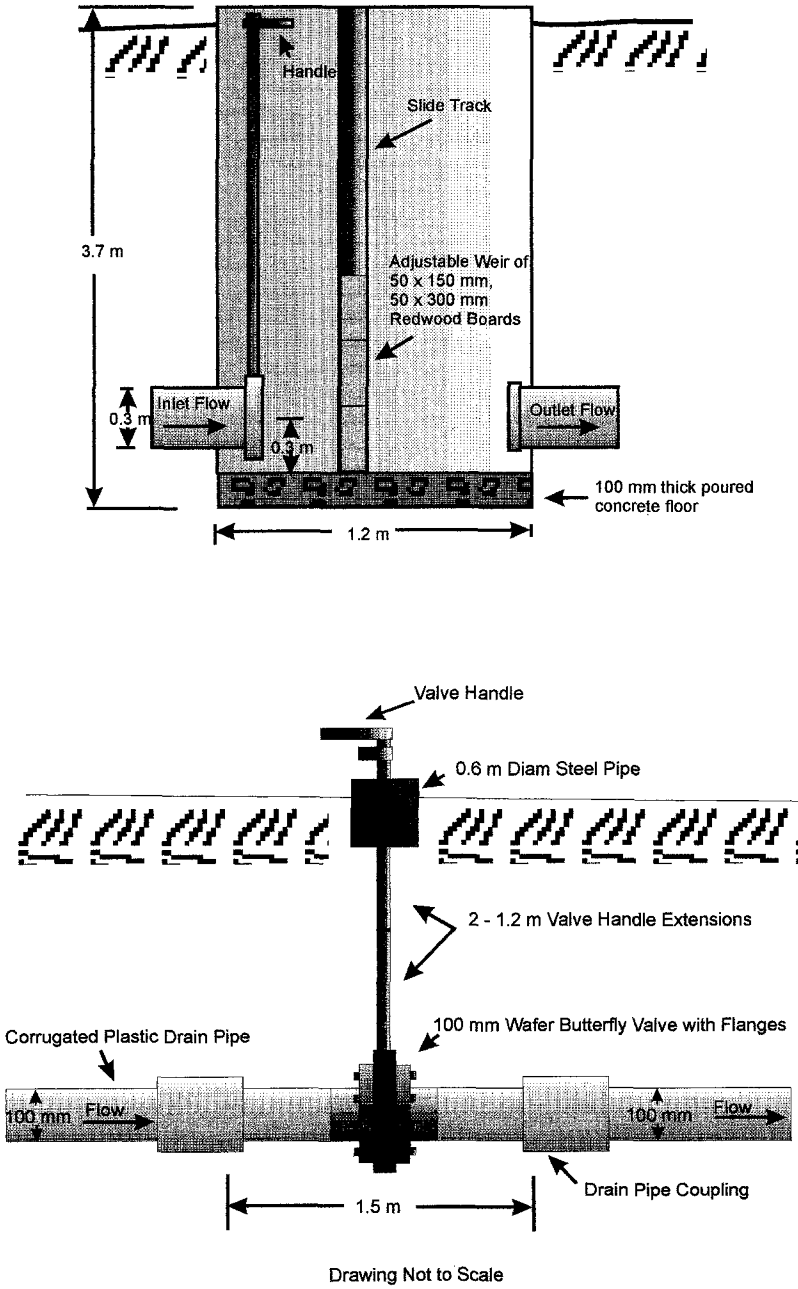

Figure 4. (A) Schematic drawing of valve installation on drain laterals and (B) weir installation on main line of subsurface drainage system in the Broadview Shallow Groundwater Management Project.

Observation wells constructed of three m long 38 mm diameter PVC pipe, which had slits cut into the bottom meter, were installed at each valve installation and across the field between several laterals (Fig. 3). The depth to the water table was measured weekly and used to plot water surface elevations and responses to the valve and weir operation.

Three areas in the field were selected based on initial depth to water tables to characterize the vegetative response to the presence of shallow groundwater. These were labelled shallow (S), medium (M), and deep (D). The tomato rows were planted in a north-south orientation, perpendicular to the drain laterals. LWP was determined two to three times a week at each of these sites using previously described procedures. LWP values of −1.1 MPa are considered non-stress for tomatoes grown in the San Joaquin Valley. These sites were also used when determining crop yield.

Yields were determined both by hand harvest and machine harvest. The hand harvest on August 9, 1994 consisted of cutting a 6.1 m length of row and separating the fruit into large and small red and green tomatoes and limited use tomatoes. Machine harvest was done on August 12–22, 1994 by determining the area required to fill a set of tomato trailers and using the harvested area and the net trailer weight to determine the yield per ha. Machine harvest was possible only on the shallow and deep plot areas.

Results and discussion

Scheduling subsurface drip irrigation

The cumulative ET_c, calculated using the base crop coefficient (no groundwater contribution), is given in Fig. 5 along with the cumulative ET_{ca} calculated using the crop coefficient for groundwater contribution from a water table at a depth of 2 m and salinity of 7.7 dS m^{-1}. The cumulative applied water for plots A and B is also shown in Fig. 5.

The management of the drip irrigation plot was designed to apply a depth of water equal to the cumulative ET_{ca} calculated using the modified crop coefficient. The cumulative applied irrigation data for plots A and B in Fig. 5 show that both plots were under-irrigated compared to ET_{ca} until about DOY 185. At this time, both plots were irrigated until the cumulative applied water roughly equaled the accumulated ET_{ca}, after which the original schedule of the accumulating 4 mm of ET_{ca} was used to initiate irrigation.

After the "catch-up" period, the irrigation applications in plot B were roughly equal to the daily ET_{ca}. However, due to irrigation equipment problems, plot A was consistently under-irrigated for the remainder of the season and no effort was made to adjust the applied water.

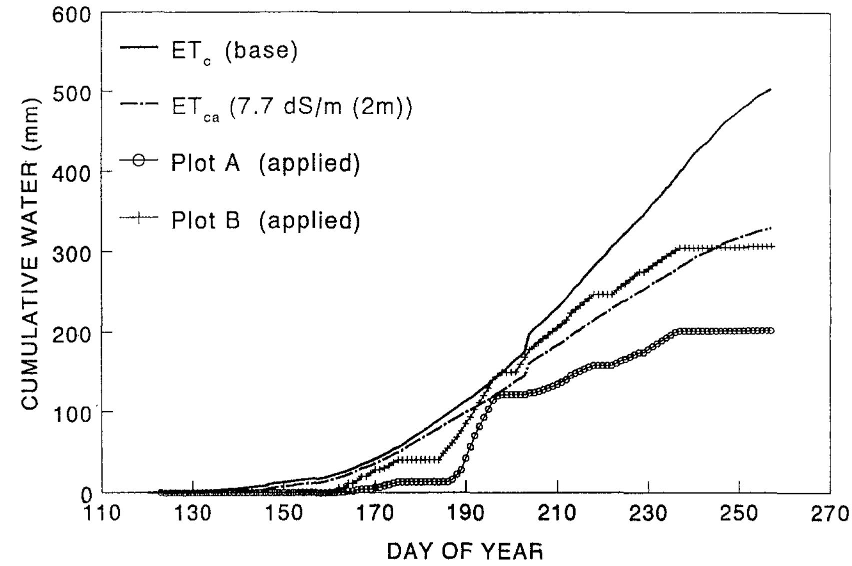

Figure 5. Cumulative evapotranspiration (mm) calculated using base and modified crop coefficient and cumulative applied water in subsurface drip irrigated plots A and B.

From planting to the end of irrigation (DOY 235), the ET_c calculated with the base coefficient (no groundwater contribution) was 400 mm, while the ET_{ca} calculated with the modified coefficient was 275 mm. The cumulative irrigation in plot B was 307 mm for this same time period. Over the interval DOY 120 to DOY 235, approximately 25% of the crop water use is estimated to have been taken from shallow groundwater. This demonstrates that the modified coefficient (K_{cbgw}) purposely underestimated ET_c in order to induce shallow groundwater use by delaying irrigation. The ET_c for the entire growing period, including the period after terminating irrigation, calculated using the base coefficient was 510 mm and 330 mm using the modified coefficient. The ET_c estimated from planting to DOY 253 was 600 mm using the biomass data.

The LWP data or plots A and B and the furrow irrigated comparison plot are given in Fig. 6. The furrow plot was slightly more stressed than the drip plots but none of the plots had excessive stress. None of the plots exceeded −1.8 MPa until after the irrigation season was completed indicating that both the furrow and drip plots were well-watered throughout the growing season.

The lint cotton yield was 2300 kg ha^{-1} in plot A, 1800 kg ha^{-1} in plot B and 1500 kg ha^{-1} in the furrow plot. While the yield in both drip plots exceeded the yield in the furrow irrigated plots, the yields in all plots were acceptable when compared to the average lint cotton yield of approximately 1500 kg ha^{-1} for this area. While plot A was consistently under-irrigated, the LWP data showed that it was well-watered and not suffering any stress. Since 5 dS m^{-1} shallow groundwater was the only other source of water available to the crop, the LWP and yield data indicate that the cotton crop was probably using this source.

The water table response is shown in Fig. 7 for the area under the drip plots and under the furrow plot. There was very little water table fluctuation until approximately DOY 190 when the water table rose across all treatments. This corresponded to the time the drip systems were operated to bring the applied water equal to the accumulated ET_{ca}. Deep percolation from the drip system would explain the rise in plots A and B but not the furrow plot which was irrigated on DOY 164 and 217. After this increase, the water began to recede in all treatments. The water table decline in the furrow plot was halted for several days following the furrow irrigation on DOY 217, indicating some deep percolation. After the rise on DOY 190, there was nearly a one meter decline in the water table under each of the plots. The depth to water was shallow enough that the crop could easily take advantage of the groundwater to meet part of its water requirements since cotton has a rooting depth of up to 3 m.

Drainage system control

The results in the previous section demonstrated a shallow groundwater management alternative for a "passive" system (one that does not have drains installed). The results in this section will demonstrate the effect of active management of a drainage system on shallow groundwater response and the effect it has on the irrigation management of a tomato crop.

The water table response to closing the valves on the laterals is shown in Fig. 8 for the period between the irrigation on 4/17/94 and 5/25/94. The control structures are located at 670 m on the x-axis with the soil surface being shown as the upper surface grid and the water table as the lower surface grid. After the valves were closed on each lateral, the water table rose to within a meter of the soil surface on the side of the field adjacent to the valves and to within 1.5 m on the opposite side of the field. There was one area between drains 2 and 3 where the water was within 0.8 m of the surface. The valves were opened on 5/2/94 and the water level receded to greater than 2 m below the soil surface by 5/13/94 (Fig. 8). The valves were opened because the ranch manager was concerned about drying the soil profile in preparation for tomato harvest.

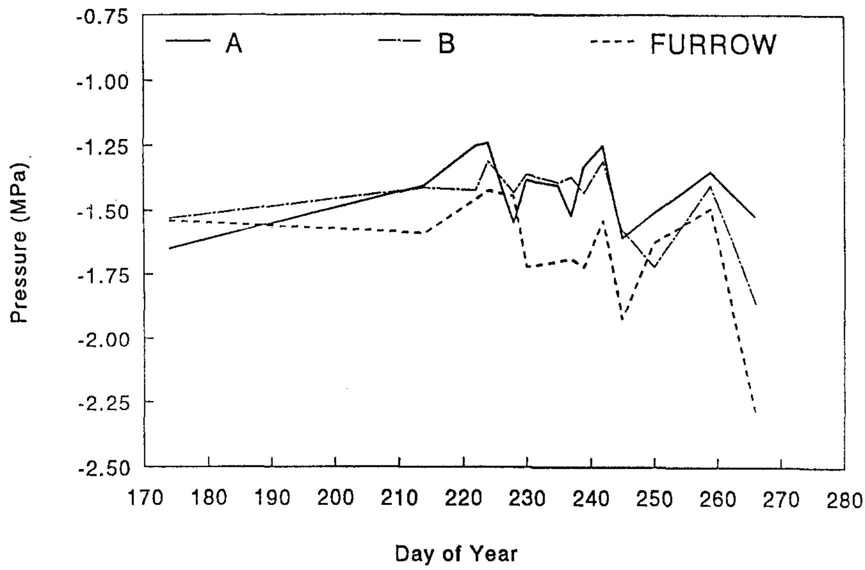

Figure 6. Leaf water potential (MPa) in cotton grown in subsurface drip irrigated (A, B) and furrow irrigated plots in the presence of shallow saline groundwater.

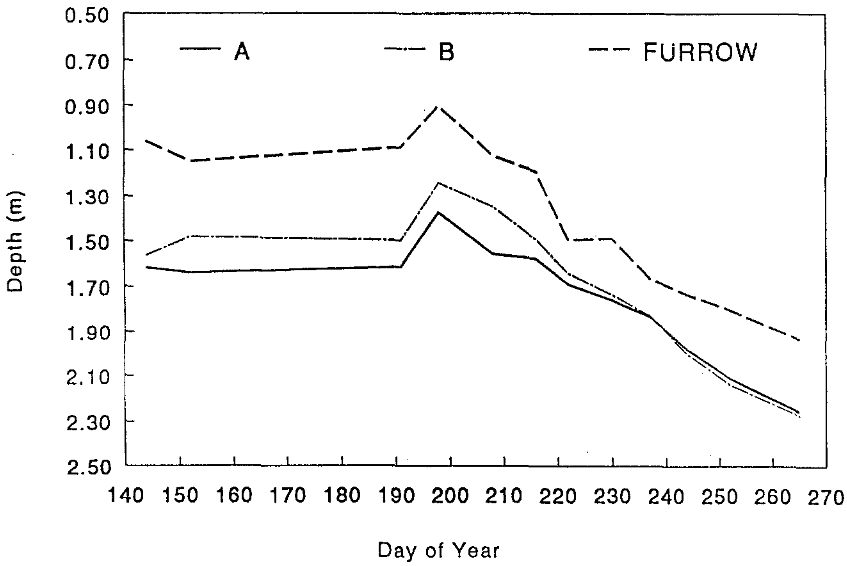

Figure 7. Change in depth (m) to water table below subsurface drip irrigated plots (A, B) and furrow irrigated plots.

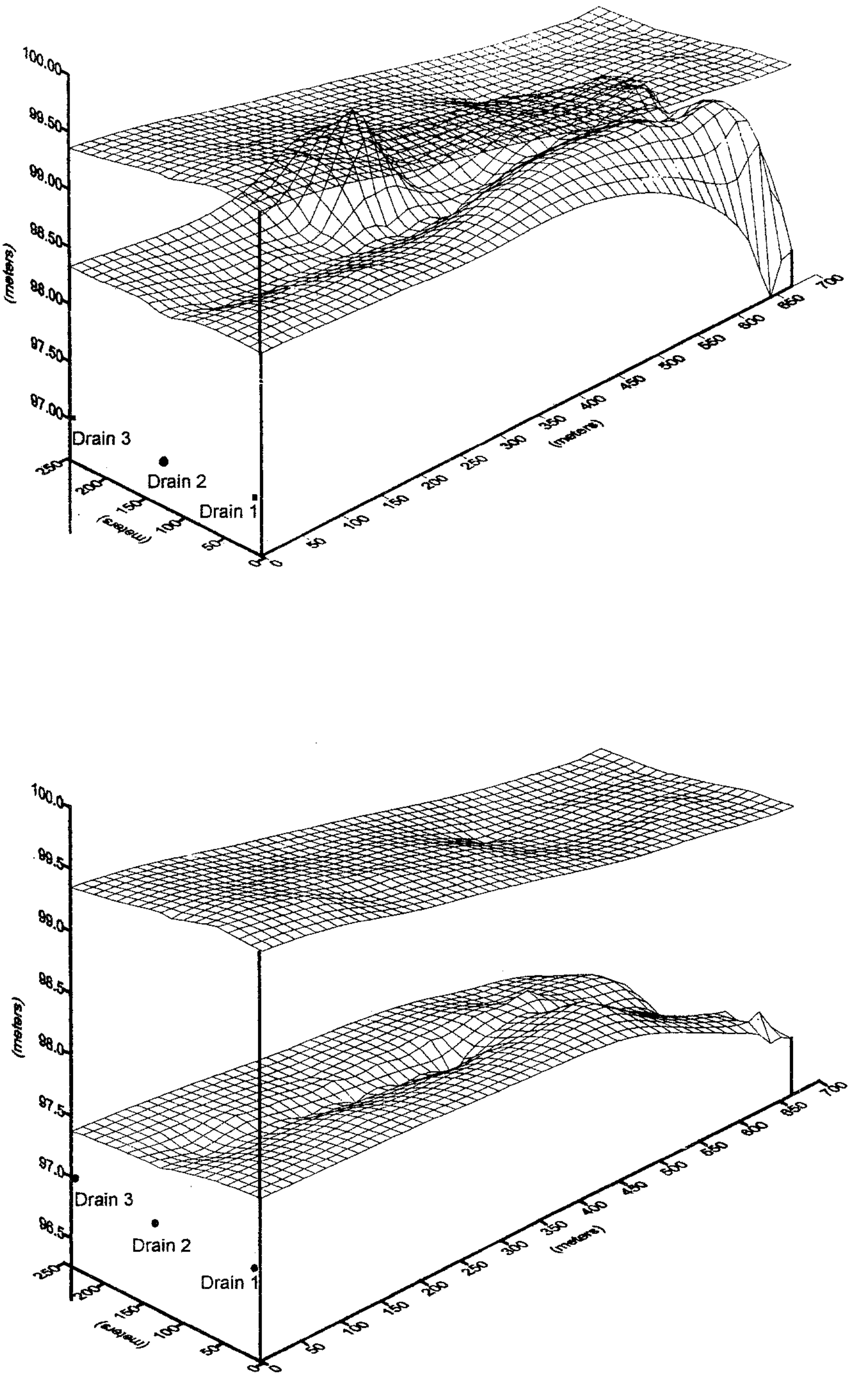

Figure 8. (A) Water table surface in relation to soil surface on May 2, 1994, in Broadview Shallow Groundwater Management Project and (B) water table surface in relation to soil surface on May 13, 1994 in Broadview Shallow Groundwater Management Project.

The shallow (S) area close to the control structures had an initial water table depth of 1.5 m below the soil surface which increased to 2.2 m at the end of the season. The medium (M) depth area had a water table depth of 1.8 m and final depth of 2.6 m while the deep (D) area had an initial and final water table depths of 2.2 to 2.6 m, respectively.

The LWP is given in Fig. 9 for plants growing in each of the three experimental areas. A LWP of –0.9 to –1.1 MPa is considered a minimal stress level for tomatoes. The data show that the plants in the deep area had higher initial stress (approximately –1.45 MPa) than in the other two areas and this level persisted throughout the growing season. LWP greater than –1.1 MPa was not exceeded in the shallow water table area and was only slightly exceeded in the medium water table depth area during the period of measurement.

The hand harvest yields and the component breakdown are shown in Fig. 10 for each experimental area. The total yields in the shallow and medium areas were approximately 10 to 20 T/ha larger than in the deep area. The fresh weight for the biomass was the lowest in the D area, which might explain part of the yield difference. The largest yield component difference was the large red fruit. In the deep areas, approximately 40% of the yield was classified limited use compared to 4% in the other areas. It was noted that after the final irrigation, the vines in the deep area did not hold up as well as the vines in the other areas which probably resulted in 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 EC of the shallow groundwater ranged from 3 to 8 dS m^{-1} 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 dS m^{-1} water when the water table was within 1.2 m of the soil surface. The improved plant vigor, particularly after irrigation terminated, and higher LWP in plants in the shallow and medium depth areas suggested that the crop was using shallow groundwater.

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 to reduce the depth of applied irrigation. The initial furrow irrigations applied 150 mm while the final 3 irrigations applied 50, 75 and 43 mm. The longest irrigation set times were observed in areas with the deepest groundwater. Managing the groundwater on a portion of the field resulted on a net reduction in average applied water.

Maintaining the shallow groundwater reduced the crop irrigation amount by 141 mm. An adjacent tomato field with a water table at the same depth as the experimental field received a total of 829 mm of irrigation while the test field needed only 688 mm. Both fields were managed by the same farmer.

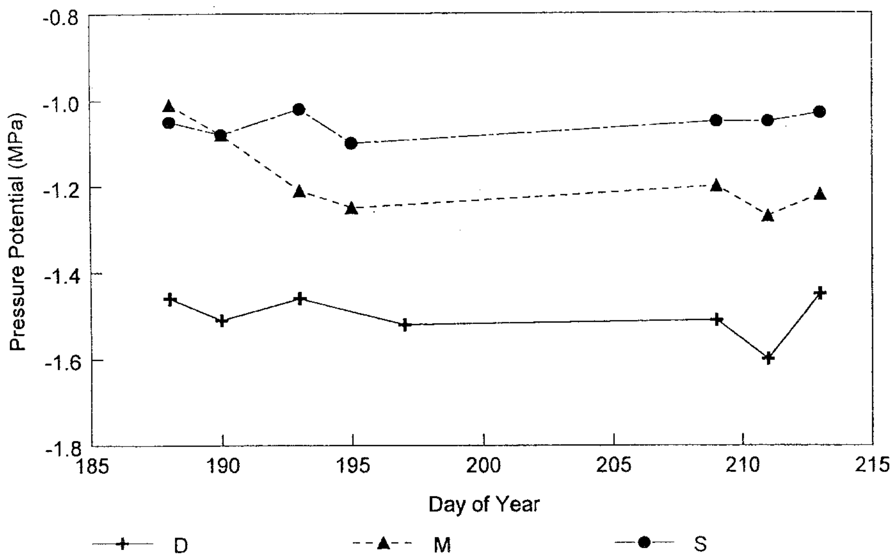

Figure 9. Tomato leaf water potential in shallow (S), medium (M) and deep (D) groundwater areas in the Broadview Shallow Groundwater Management Project.

This resulted in a savings of 6.5×10^5 m^3 of water, which was particularly significant since the water allocation to the district was 35% of the normal supply.

Summary

Results of these field studies demonstrate that it is possible to manage shallow groundwater using either modified irrigation schedules and irrigation management or control structures in existing drainage systems. Passive management was achieved by using a crop coefficient which accounted for the depth to groundwater, the salinity of the groundwater and the stage of crop growth when computing the evapotranspiration. This coefficient purposedly underestimates the crop water use which results in fewer irrigations and requires the deficit to be met by extraction from shallow groundwater. High frequency irrigation was used but it is not a requirement of the technique.

During the irrigation period approximately 25% of the crop requirement came from shallow groundwater, while 40% of the crop water requirement was extracted during the entire growing season. These values of shallow

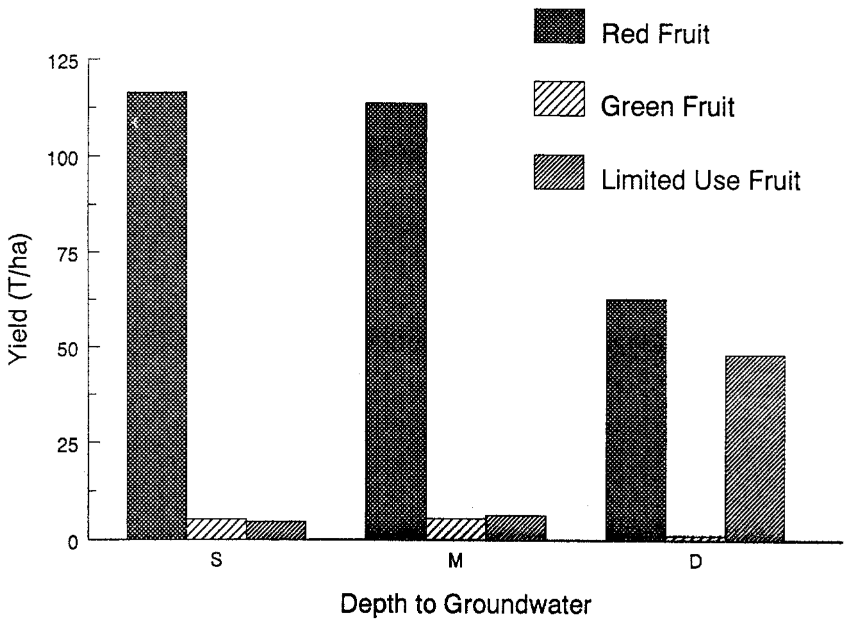

Figure 10. Distribution of tomato fruit yield (T/ha) components in the shallow (S), medium (M) and deep (D) groundwater areas in the Broadview Shallow Groundwater Management Project.

groundwater use by cotton are Ayars & Schoneman (1986) consistent with results reported by and Wallender et al. (1979).

The applied water and yield data in plot A demonstrated that the crop had to be using another source of water besides irrigation, and shallow groundwater was the only other source available. This plot had the highest yields of the three and the least water applied. The LWP data indicated that stress was not developing, so there was not a gradual decrease in the stored soil water.

In lysimeter studies with cotton and tomatoes, Ayars & Hutmacher (1994), and Hutmacher et al. (1989) demonstrated that these crops will extract saline water at the same rate as non-saline water up to a salinity equal to twice the Maas-Hoffman (1977) threshold for yield reduction, which would be 15 dS m^{-1} for cotton and 5 dS m^{-1} for tomatoes. These salinities are not exceeded in the groundwater in either experimental area.

Borg and Grimes (1986) report rooting depths for cotton from 1.5 to 3.0 m and for tomatoes from 1.4 to 2.6 m and these depths of root development have been measured in well-drained soils in this area. In each case the root system has the potential to grow to the depth of the water table.

Active control of groundwater is possible as demonstrated in the experiment using the controls on a drainage system. The plots of water table response indicated that the depth to water was reduced on large portions of the field which enhanced the opportunity of groundwater uptake. The system was not operated until after the crop was well established which helped in the management (Ayars & Schoneman 1984) by insuring the root system was well developed. Controlling the shallow groundwater reduced the irrigation set times on a portion of the field which reduced the average applied water.

The ability of the crop to make use of the groundwater resulted in less fruit in a limited use category on a portion of the field. The LWP data for each of the sites supports the conclusion that the crop was making use of groundwater throughout the season.

References

Ayars, J.E. & Hutmacher, R.B. 1994. Crop coefficients for irrigating cotton in the presence of groundwater. *Irrigation Science* 15(1): 45–52.

Ayars, J.E. & Schoneman, R.A. 1986. Use of saline water from a shallow water table by cotton. *Transactions of the ASAE* 29: 1674–1678.

Ayars, J.E. & McWhorter, D.B. 1985. Incorporating crop water use in drainage design in arid areas. In: C.G. Keyes & T.J. Ward (Eds) *Proceedings, ASCE Irrigation and Drainage Specialty Conference: Development and Management Aspects of Irrigation and Drainage Systems* (pp. 380–389). American Society of Civil Engineers, New York, NY.

Ayars, J.E. & Schoneman, R.A. 1984. Managing irrigation in areas with a water table. In: J.A. Replogle & K.G. Renard (Eds) *Proceedings, ASCE Irrigation and Drainage Specialty Conference: Water Today and Tomorrow* (pp. 528–536). American Society of Civil Engineers, New York, NY.

Benz, L.C., Doering, E.J. & Reichman, G.A. 1987. Water table management saves water and energy. *Transactions of the ASAE* 24: 995–1001.

Borg, H. & Grimes, D.W. 1986. Depth development of roots with time: An empirical description. *Transactions of the ASAE* 29: 194–197.

Davis, K.R. 1983. Trickle irrigation of cotton in California. *Proceedings, Western Cotton Production Conference* (pp. 34–38). Las Cruces, NM.

Doering, E.J., Benz, L.C. & Reichman, 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 (pp. 34–41). American Society of Agricultural Engineers, St Joseph, MI.

Fouss, J.L., Skaggs, R.W., Ayars, J.E. & Belcher, H.W. 1990. Water table control and shallow groundwater utilization. In: G.J. Hoffman, T.A. Howell & K.H. Solomon (Eds) *Management of Farm Irrigation Systems* (pp. 783–824). American Society of Agricultural Engineers, St. Joseph, MI.

Garcia, L.A., Strzepek, K.M. & Podmore, T.H. 1994. Design of agricultural drainage with adaptive irrigation management. *J. Irrig. Drainage Eng.* 120: 179–194.

Grimes, D.W. & Yamada, H. 1982. Relation of cotton growth and yield to minimum leaf water potential. *Crop Science* 8: 134–139.

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

Shallow Groundwater of Processing Tomatoes. *1989 Annual Report* (pp. 18–19). USDA, ARS, Water Management Research Laboratory, Fresno, CA.

Kruse, E.G., Young, D.A. & Champion, D.F. 1985. Effects of saline water table on corn irrigation. In: C.G. Keyes & T.J. Ward (Eds) *Development and Management Aspects of Irrigation and Drainage Systems* (pp. 444–453). [Proceedings of Specialty Conference ed.]. ASCE, New York, NY.

Lord, J.M. 1987. Study of innovative techniques to reduce subsurface drainage flows: Phase II. Sacramento, CA. *San Joaquin Valley Drainage Program,* US Bureau of Reclamation.

Maas, E.V. & Hoffman, G.J. 1977. Crop salt tolerance-current assessment. *Irrigation and Drainage Division, ASCE* 103: 115–134.

Namken, L.N., Weigand, C.L. & Brown, R.O. 1969. Water use by cotton from low and moderately saline static water tables. *Agronomy Journal* 61: 305–310.

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

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

U.S. Bureau of Reclamation. 1993. *Drainage Manual.* U.S. Department of the Interior, Denver, CO.

Wallender, W.W., Grimes, D.W., Henderson, D.W. & Stromberg, L.K. 1979. Estimating the contribution of a perched water table to the seasonal evapotranspiration of cotton. *Agronomy Journal* 71: 1056–1060.