SHALLOW GROUNDWATER USE BY ALFALFA

Dr. James E. Ayars[1], Dr. Peter Shouse, Dr. Scott M. Lesch

ABSTRACT

Disposal of saline drainage water is a significant problem for irrigated agriculture. One proposal is to recycle drainage water to irrigate salt tolerant crops until the volume has been reduced sufficiently to enable final disposal by evaporation. Part of this concept requires in-situ crop water use from shallow groundwater; and data is needed to quantify the potential use of groundwater by alternative crops. A column lysimeter study was initiated to determine the potential crop water use from shallow groundwater by alfalfa as a function of groundwater quality and depth to groundwater. The results demonstrated that up to 50% of the crop water use could be met from shallow groundwater (<1.2 m) with an electrical conductivity less than 4 dS/m, and that the potential crop water use from deeper groundwater (2m) increased over the years. The columns with higher salinity (EC > 4dS/m) in the shallow groundwater experienced increasing salinity in the soil profile with time, resulting in reduced crop water use from shallow groundwater. Periodic leaching will be required for in-situ use to be a sustainable practice. Statistical analysis demonstrated that shallow groundwater, even marginally saline, contributed significantly to crop yield with significant differences occurring between treatments. Trend analysis demonstrated a significant reduction in yield with time for higher salinity groundwater treatments (EC> 4dS/m), and was characterized by a simple inverse relationship of the log transformed groundwater salinity. Comparing yield data from the control treatment to the groundwater treatment suggests that alfalfa yield could be enhanced from the presence of groundwater salinity up to 6 dS/m at least for the first few years.

Keywords: Groundwater, in-situ use, alfalfa, drainage, irrigation management, crop water

INTRODUCTION

Irrigated agriculture faces the challenges of competition for available water supply, and the disposal of saline drainage water. As the world's population increases, there is increasing demand for high-quality water to meet municipal and industrial needs, and to provide for the environment (Postel 1999). Since irrigated agriculture uses approximately 80% of the developed water supply, it will be the primary water source for these competing uses. Thus, irrigated agriculture will have to rely on improved irrigation management and poorer quality water to meet the crop water demands of the future.

---

[1] James E. Ayars, Research Agricultural Engineer, USDA-ARS, 9611 S. Riverbend Ave, Parlier, Ca, 93648, james.ayars@ars.usda.gov. Peter Shouse. Soil Physicist, Soil Physicist, USDA-ARS, George E. Brown, Jr., Salinity Laboratory, 450 W. Big Springs Road, Riverside, CA 92507, pete.shouse@ars.usda.gov. Scott Lesch, Principal Consulting Statistician, Dept. of Environmental Science and Statistical Collaboratory, University of California, Riverside, scott.lesch@ucr.edu. In: Proceedings, 2008 California Alfalfa & Forage Symposium and Western Seed Conference, San Diego, CA 2-4 December 2008. UC Cooperative Extension, Plant Sciences Department, University of California, Davis, CA 95616. (See http://alfalfa.ucdavis.edu for this and other Alfalfa Symposium Proceedings).

It is a given that irrigated agriculture will require some level of drainage to control salinity in the crop root zone. Disposal of saline drainage water is a significant environmental problem throughout the world and will be a necessary practice to sustain irrigation. Options identified for saline drainage water disposal include source control, use of drainage water for supplemental irrigation, and discharge into evaporation ponds (San Joaquin Valley Drainage 1990).

Source control is the reduction of the total volume of deep percolation by improved irrigation management, e.g. improved irrigation scheduling, improved system management, and changing irrigation systems. Modifying the irrigation scheduling to incorporate in-situ crop water use from shallow groundwater is a component of source control (Ayars et al. 2000). Use of drainage water for irrigation is a well developed concept (Rhoades et al. 1989) and has been used extensively in the Central Valley of California (Ayars et al. 1993; Ayars et al. 2000; Ayars et al.1986). A system being developed for disposal of saline drainage water is serial biological concentration (SBC) (Blackwell et al. 2005) which is the successive use of saline drainage water to reduce the volume and increase the salt concentration of the deep percolate prior to disposal. This concept is being implemented in California as integrated on-farm drainage management (IFDM) (Ayars and Basinal 2005). Crop water use from shallow groundwater will be a significant component in the operation of sequential use systems.

Research quantifying crop water use from shallow groundwater has demonstrated the potential for meeting up to 50% of the crop requirement from shallow groundwater (Ayars and Hutmacher 1994; Hutmacher et al. 1996). In-situ use by plants is affected by the depth to water table relative to the rooting depth, groundwater salinity, and crop salt tolerance (Ayars et al. 2006).

Perennial crops such as alfalfa have a larger potential for in-situ use compared to annual crops because of the well developed root system after the first growing season that enables in-situ use early in subsequent growing seasons. One limitation on the potential uptake by alfalfa is its moderate salt tolerance. Alfalfa is a crop with significant economic value, because of its use as animal feed.

The objective of this study was to determine the potential in-situ crop water use and yield of a salt tolerant alfalfa as a function of depth and salinity of shallow groundwater.

MATERIALS AND METHODS

Alfalfa (*Medicago sativa* L. var SW9720) was grown in above ground column lysimeters made of 0.45-m diameter polyvinyl chloride (PVC) pipe, and constructed in two heights: 1.80 m (short column) and 2.60 m (tall column). The basic construction details and support system were as described in Robbins and Willardson (1980). A Marriotte bottle system was used to control the water table depth and to provide a volumetric measure of the amount of water required to maintain a static groundwater level. The columns were closed on the bottom and connected to the Marriotte bottle via flexible PVC tubing. The water table was maintained at depths of 1.2 m and 2.0 m in the short and tall columns, respectively. This covers the range of depths that are normally found on the west side of the San Joaquin Valley. The entire column assembly was set on hydraulic pillows, constructed of 60-cm long by 30-cm diameter, rubberized fabric tubing, that was sealed on both ends (Kruse et al. 1993). The hydraulic pillow manometer system allowed determination of the evapotranspiration (ET_c) based on calculated changes in column weight. The pillows were connected to manometers constructed of plastic tubing and each column was individually calibrated. The columns were located in a field site on the San Joaquin Valley Agricultural Sciences Center, USDA-ARS in Parlier, California.

The columns were packed to a bulk density of 1.4 Mg m^{-3} with a Panoche Clay loam soil (Typic Torriorthents) collected from the surface 30 cm of the soil profile at the University of California West Side Research and Extension Center near Five Points, California. The soil is similar in physical properties to soils in much of the shallow groundwater area of the central San Joaquin Valley (SJV) and has been described in detail by Nielsen et al. (1973). The soil was initially non-saline (EC_e < 1 dS/m) and was leached with approximately 3 times the column water holding capacity to ensure the initial non-saline condition.

Treatments imposed included no groundwater (T1), non-saline groundwater (T2), and groundwater salinity levels corresponding to one, two, three, and four times the threshold salinity values for yield response as identified by Maas and Hoffman (M-H) (1977). The alfalfa threshold is 2 dS/m and the slope of the yield response is 7.3% yield decrease for each unit increase in salinity above the threshold. The specific EC values used in the alfalfa study were "non-saline" at 0.3 dS/m, designated as treatment T2; and saline treatments at 2 (T3), 4 (T4), 6 (T5), and 8 (T6) dS/m for one, two, three, and four times the M-H threshold salinity, respectively, for the short columns. Groundwater EC of 2 and 4 dS/m were used in the tall columns, designated as treatments T3T and T4T, respectively. There were four replications of each treatment in the short and tall columns. An additional set of columns were sealed on both the top and bottom and used in the temperature correction for the manometer water column. The ground water salinity in the SJV is variable but typically is in the range from 4 to 6 dS/m.

Low salt irrigation water (0.3 dS/m) was applied at the soil surface once or twice a week for irrigation based on changes in column weight. The columns in which plants could not or did not use the groundwater required two irrigations per week to avoid moderate to severe water deficits. Those using considerable quantities of shallow groundwater required one irrigation per week. Changes in column weights and volumetric changes in the Marriotte bottles were determined twice a week and used to determine the required irrigation for that interval. The irrigation was equal to the difference between the average ET_c of the control and the average ET_c of the given treatment as measured by lysimeter weight changes. This system was used previously in studies that determined crop water use from shallow groundwater by cotton and tomato (Ayars and Hutmacher 1994; Hutmacher et al. 1996). Climate data collected at the California Irrigation Management Information System (CIMIS) station located approximately 1 km from the lysimeters were used to calculate reference evapotranspiration (ET_o). The experiment was run for a total of 4 years.

The total crop water use was the sum of the applied water (irrigation + rain) and in-situ use of groundwater, whose contribution to the crop water requirement was characterized as a decimal fraction of the measured ET_c for T1. This was equal to the cumulative water from the Marriotte bottle divided by the crop water use from the control treatment. At the experiment's end, soil was sampled in the 0 to 30-cm, 30 to 60-cm, and 60 to 90-cm depth increments in each column; and the electrical conductivity (EC) of 1:1 soil-water extracts was used to determined mean values of soil salinity for each treatment and depth.

Alfalfa was harvested manually every four to six-weeks, weighed and dried; and the dry masses were used to calculate yield (kg m^{-2}) based on the column area and reported as the average of the four replications. The individual column yields were analyzed to determine: (1)if the availability of non-saline (and/or marginally saline) ground-water can boost the long-term alfalfa yield, (2) does the depth of the available ground-water impact the alfalfa yield in any statistically significant manner, and (3) do the yields decrease over time when subjected to a saline ground-water source?

STATISTICAL METHODOLOGY

A standard RM-ANOVA model was first fit to the yield data. The RM model is essentially a two-way ANOVA model with interaction, along with an additional assumption of correlated errors across time (Davies 2002). For yield data associated with the k^{th} replication of the i^{th} treatment level acquired during the j^{th} year, the model is defined to be

$$\begin{aligned} y_{i(k),j} &= \mu + \theta_i + \tau_j + \delta_{ij} + \varepsilon_{i(k),j} \\ Var(\varepsilon_{i(k),j}) &= \sigma^2,\ Cov(\varepsilon_{i(k),j}, \varepsilon_{i(k),j+m}) = \rho^{|m|}\sigma^2 \quad for\ |\rho| < 1. \end{aligned} \tag{1}$$

Note that in Eq. (1), the errors associated with each specific lysimeter are assumed to follow a common Normal distribution and exhibit a first order, temporal auto-regressive (AR1) correlation structure.

The RM-ANOVA analysis was carried out via a restricted maximum likelihood analysis using the MIXED procedure in SAS (SAS Inc. 1999). A standard one-way ANOVA model was used to analyze each years yield data and various multiple mean comparison procedures were employed to differentiate between treatment means (Montgomery, 2001). A Tukey-Kramer mean comparison adjustment technique was used to adjust the computed p-values of all the pair-wise mean contrasts (Kramer, 1956). These adjusted p-values can be used to test any set of pair-wise contrasts of interest, while preserving the overall type I error level.

Linear trend tests were computed for each treatment individually, in order to determine which (if any) treatment yields exhibited decreasing trends over time. For the yield data associated with each treatment, the calculated slope estimate from a simple linear regression model was used to determine the statistical significance of the linear time trend. Eight linear regression models were estimated in all; none of the residual errors in any of these eight models exhibited statistically significant temporal correlation (AR1) parameter estimates.

RESULTS

Crop water use The annual precipitation and reference evapotranspiration (ET_o) from the CIMIS station #39 Parlier, Ca. are given in Table 1. The precipitation occurred in fall through spring when the crop demand was lowest. The reference annual evapotranspiration ranged from 1302 to 1366 mm during the experimental period.

Table 1. Precipitation and reference evapotranspiration at San Joaquin Valley Agricultural Sciences Center, Parlier, California.

Year	Precipitation (mm)	CIMIS (ET_o) mm
2002	167	1366
2003	209	1343
2004	256	1352
2005	338	1302

The total crop water use is summarized in Table 2 for 2002 to 2005. In 2002 and 2003, treatment T6 had approximately the same water use as in T1 which implies a minimal contribution from shallow groundwater. This result was not unexpected since T6 had the most saline groundwater and uptake was expected to be minimal and most crop water use would be from stored irrigation water. In years 2004 and 2005, there was a significant decrease in crop water use in treatment T6 as compared with T1. This may be explained by the salinization of soil in T6 over time. By experiment's end, soil in the T6 columns was more saline than that in any other treatment (Table 3). A similar response was observed in treatments T3 - T5 in 2004 and 2005. In these treatments the rate of decrease was inversely proportional to the salinity of the groundwater e.g. the higher the groundwater salinity, the lower the crop water use. The increased depth to the water table in T3T and T4T moderated this effect.

There was a significant increase in crop water use by treatment T2 compared to T1 for all years. Recall that T2 was the crop with low salinity groundwater at a depth of 1.2 m. There appears to be a significant increase in crop water use with time in treatment T2 compared to treatments T3 and T4, which had higher salinity groundwater than T2 and in which the soil became more saline over time in the 0 -90 cm depth (Table 3). Treatments T3 and T4 have approximately the same crop water use as seen in treatments T3T and T4T even though the depth to the shallow groundwater was greater in T3T and T4T. By 2005 the deeper water table treatment T3T had higher water use than T3. The deeper water table probably resulted in lower salt aaccumulation in the root zone.

Table 2. Total alfalfa crop water use (ET_c) by irrigation treatment for 2002 to 2005.

Year	T1	T2	T3	T4	T5	T6	T3T	T4T
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
2002	1924	2379	2502	2269	2261	1907	2358	2282
2003	1947	2688	2507	2299	2363	1979	2475	2286
2004	2805	3467	2126	1657	1101	784	2368	1425
2005	1236	2403	1384	1074	767	660	1667	1129

Table 3. Electrical conductivity (dS/m) of soil salinity from treatments T1to T6 of the column lysimeters at the end of the experiment based on one-to-one soil water extracts.

	Sample depth			
Treatment	0-30 (cm)	30-60 (cm)	60-90 (cm)	Ave.
	(dS/m)	(dS/m)	(dS/m)	(dS/m)
T1	0 .43	0.68	1.33	0.82
T 2	0.5	0.76	4.96	2.08
T3	0.87	1.53	3.77	2.06
T4	0.61	1.24	5.23	2.36
T5	0.6	3.27	9.51	4.46
T6	0.98	3.94	9.61	4.84

The cumulative water use is for a period from approximately the middle of February to the end of October and includes both irrigation and rainfall. These values are larger than would be anticipated in an agronomic or commercial situation due to the higher frequency irrigation and additional cuttings. Farmers in the Central Valley would typically apply two surface irrigations between cuttings and 4 cuttings per year. The increased frequency of irrigation in this experiment resulted in reduced plant stress and promoted a more vigorous yield response and crop water use.

The crop water use from shallow groundwater was characterized as a fraction of the total crop water use in a particular treatment and as the cumulative relative contribution. Data from 2003 over a 30-week period show considerable variability in the first 15 weeks of growth and irrigation (Fig. 1). This is the time period when not only irrigation but rainfall is occurring, which accounts for some of the variability. There is also at least one harvest during this time. After the first 15 weeks, the crop water use is reasonably uniform, corresponding with the time that only irrigation is occurring, and there is a consistent pattern of crop water use from shallow groundwater. As a result, only the final 15 weeks of irrigation were considered each year to evaluate the variation in crop water uptake from shallow groundwater as a function of time and groundwater quality.

In 2002, the fractional contribution from the groundwater decreased as the electrical conductivity of the groundwater increased from 0.3 to 8 dS/m (Fig. 2). The tall treatments T3Tand T4T lagged behind their counterpart short columns in terms of contribution and at the end of the season were still providing less water to the crop water demands than was found in the short columns (Ayars et al. 2006). In 2002 the good quality groundwater and the 2 dS/m groundwater were providing roughly the same amount of water to the crop. The T4 and T5 treatments had roughly the same contribution, while contribution from groundwater for T6 was less than the other treatments.

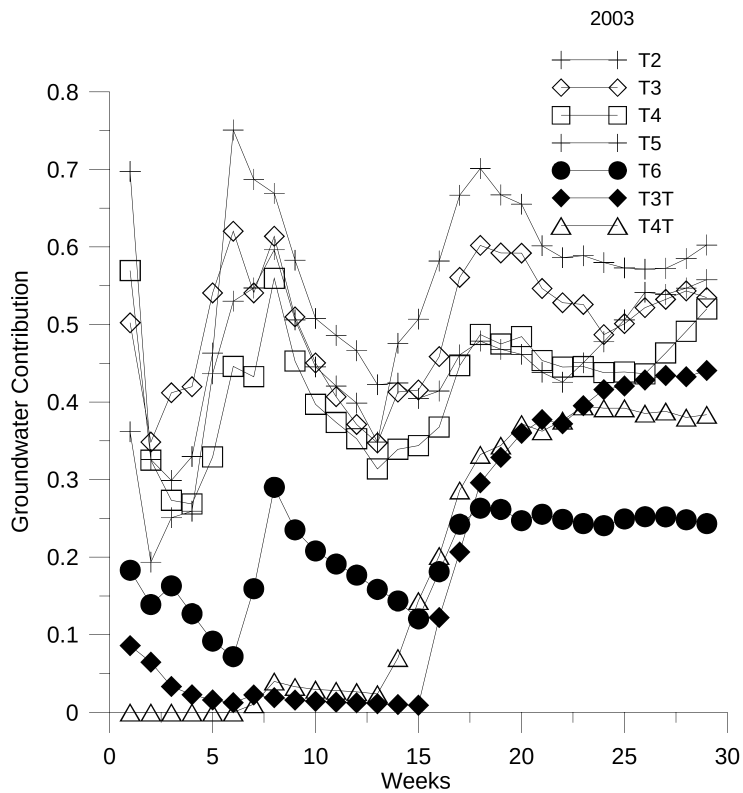

Figure 1. Groundwater contribution as a fraction of crop water use in 2003 in the column lysimeters.

By 2005, there were larger differences in the percentage contributions between each of the treatments (Fig. 3). Recall that in 2002 the T2 (freshwater treatment) was providing approximately 50% of the crop water use from groundwater, but by 2005 this treatment was getting almost 100% of crop water use from shallow groundwater. Groundwater use in treatment T3T (a tall column) went from less than 30% to nearly 62% of total crop water use from 2002 to 2005. The contribution from groundwater for the most saline treatment T6, which initially was roughly 20% of the crop water requirement, had been reduced to less than 10% of the crop water requirement by 2005. It is interesting that the T4 treatment and the tall treatment T4T both provided approximately the same amount of water from groundwater. By contrast, the T3 and T3T treatments showed that the tall column provided more water than the short column.

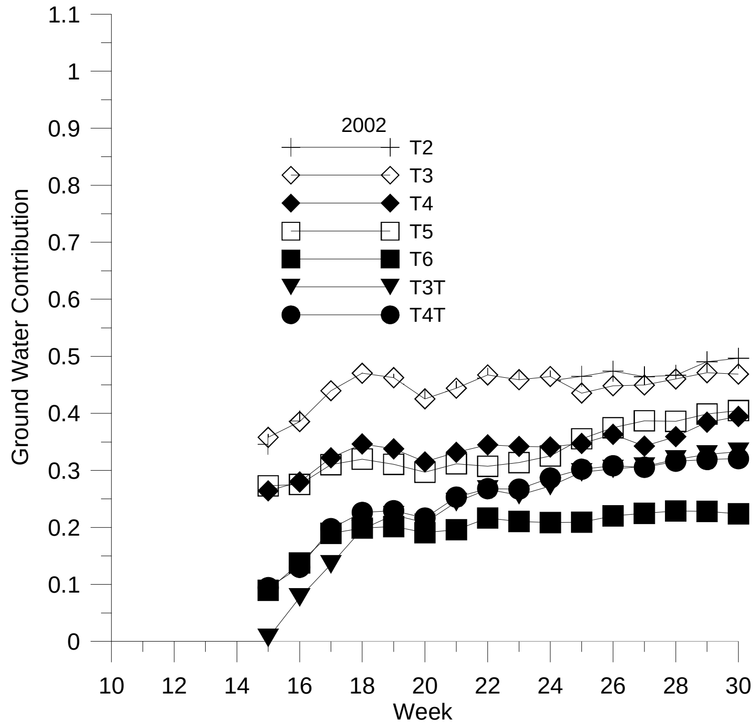

Figure 2. Groundwater contribution as a fraction of crop water use in 2002 in the column lysimeters

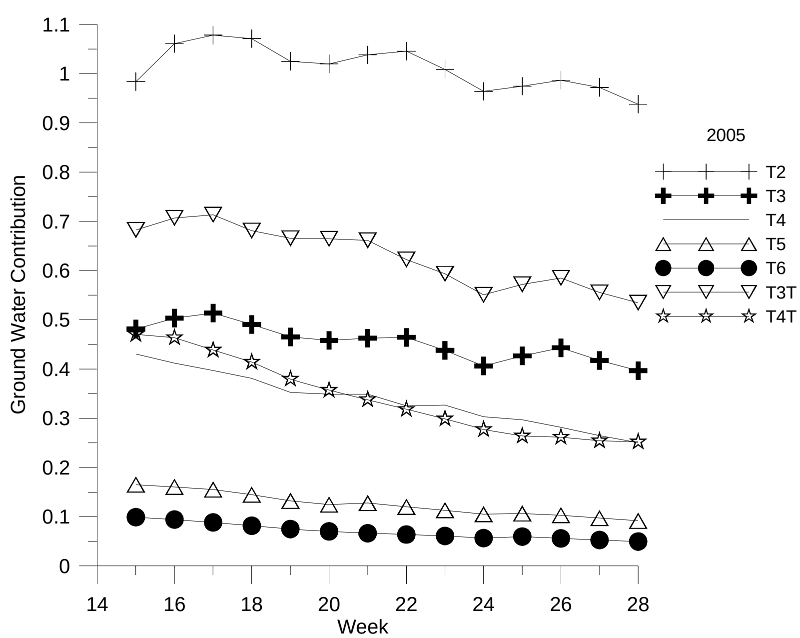

Figure 3. Groundwater contribution as a fraction of crop water use in 2005 in the column lysimeters.

Yield Response. The average yield data are summarized in Table 4 and Table 5. Yields from treatment T2 were much larger than those from T1, which was the control, and were also higher than any of the other treatments (Table 4). This is reflected in the fact that the ET_c for treatment T2 was larger than in any of the other treatments throughout all years, which is consistent with the idea that the crop biomass is directly related to the total crop water use. The average yield for T1 was approximately 3.0 kg m^{-2} compared with the average yield in central California of approximately 2.2 kg m^{-2}, so the control treatment, even though its yield was less than those for the other treatments, still had yield larger than the average for field grown alfalfa.

Table 4. Average alfalfa yield by treatment in kilograms per square meter for 2002 to 2005.

Year	T1	T2	T3	T4	T5	T6	T3T	T4T
	(kg/m^2)	(kg/m^2)	(kg/m^2)	(kg/m^2)	(kg/m^2)	(kg/m^2)	(kg/m^2)	(kg/m^2)
2002	3.3	6.8	5.7	4.8	4.8	4.1	5.1	5.0
2003	2.3	5.5	4.5	3.8	3.6	2.8	4.5	3.6
2004	4.3	9.0	4.9	3.7	2.4	3.2	5.9	3.2
2005	2.3	4.8	2.7	1.7	1.6	1.9	3.1	2.3

In the first two years the yields were similar in a water quality treatment with differences being between the treatments. The yields were similar for the treatments above the M-H crop salinity threshold. There was an unexpected increase in the yield in T1 and T2 between 2003 and 2004 for which there is no apparent explanation. However, the water use data show that additional yield was possible and was in response to the availability of water. After two years there was a yield decrease for the treatments above the crop salt threshold T4 and even T3, which was at the threshold, was impacted in the fourth year. The effect was delayed in the deeper groundwater treatments. This was probably in response to accumulation rates of salt in the root zone.

The data in Table 5 were used to determine the yield response to groundwater salinity and depth. The AR1 correlation coefficient was estimated to be $\hat{\rho} = 0.296$ and was statistically significant ($p = 0.001$) according to a likelihood ratio Chi-square test. The corresponding root mean square error (RMSE) estimate was estimated to be $\hat{\sigma} = 96.5$. The treatment and year main effects, in addition to the treatment $\times$ year interaction effects were all found to be highly statistically significant ($p < 0.0001$) in the fitted model.

The yield associated with the T1 control treatment (no groundwater) is clearly much lower than nearly all the groundwater treatments; note also that these latter yields also tend to decrease as the groundwater salinity level rises. The yields also appear to be trending downwards in most of the groundwater treatments, although the average time trend is rather inconsistent. The various treatment $\times$ year interaction effects also seem to be quite complex, particularly in 2004.

Given the highly significant interaction effects, an analysis of the treatment means on a year by year basis was done. A standard one-way ANOVA model was used to analyze each year of yield data and various multiple mean comparison procedures were employed to differentiate between treatment means (Montgomery, 2001).

Table 5. Average alfalfa yields (gms per column), by treatment and year.

	2002	2003	2004	2005	Average
T1	525.9	359.1	677.0	365.4	481.8
T2	1080.9	877.7	1437.4	757.2	1038.3
T3	908.1	711.1	771.9	432.8	706.0
T3T	817.2	721.6	940.2	488.9	742.0
T4	769.9	599.4	592.4	276.3	559.5
T4T	790.7	576.1	503.8	370.7	560.3
T5	768.8	566.6	383.0	252.4	492.7
T6	652.7	447.7	511.0	309.2	480.2
Average	781.3	599.9	725.6	405.3	

Using the data in Table 5 the RM-ANOVA model calculated standard errors for the treatment and year specific estimates are T1 (49.6), T2 through T6 (55.4). The standard errors for the treatment averages are T1 (30.6), T2 through T6 (34.2), and the standard error for the year averages is 19.4.

A Tukey-Kramer mean comparison adjustment technique was used to adjust the computed p-values of all the pair-wise mean contrasts (Kramer, 1956). The adjusted p-values are shown in Tables 6a through 6d for the 2002 through 2005 modeling results, respectively. These adjusted p-values were used to test any set of pair-wise contrasts of interest, while preserving the overall type I error level.

From Table 6a (year 2002), we can conclude that the control treatment is significantly different from treatments T2, T3, T3T and T4T (at a joint 0.05 significance level). Likewise, T2 is significantly different from T4, T4T, T5 and T6. All other treatment contrasts are not significantly different at a joint 0.05 significance level.

From Table 6b (year 2003), we can conclude that the control treatment is significantly different from treatments T2, T3, T3T and T4. Likewise, T2 is significantly different from T4, T4T, T5 and T6. T3 and T3T are also significantly different from T6. All other treatment contrasts are not significantly different at a joint 0.05 significance level.

From Table 6c (year 2004), we can conclude that treatment T2 is significantly different from all other treatments (note the elevated T2 yield level in Table 2). Additionally, treatment T3T is significantly different from treatments T4, T4T, T5 and T6. All other treatment contrasts are not significantly different at a joint 0.05 significance level.

Finally, from Table 6d (year 2005), we can again conclude that treatment T2 is significantly different from all other treatments. Additionally, treatment T3 is different from T4 and T5, and treatment T3T is different from T4, T5 and T6. No other treatment contrasts are significantly different at a joint 0.05 significance level.

Table 6a. Tukey-Kramer adjusted p-values for all pair-wise mean contrasts, 2002 yield data.

	T1 vs	T2 vs	T3 vs	T3T vs	T4 vs	T4T vs	T5 vs
T2	0.0001						
T3	0.0014	0.4682					
T3T	0.0227	0.0713	0.9552				
T4	0.0837	0.0204	0.7217	0.9991			
T4T	0.0481	0.0359	0.8510	0.9999	0.9999		
T5	0.0862	0.0198	0.7140	0.9989	0.9999	0.9999	
T6	0.7519	0.0007	0.0878	0.5291	0.8521	0.7231	0.8578

Table 6b. Tukey-Kramer adjusted p-values for all pair-wise mean contrasts, 2003 yield data.

	T1 vs	T2 vs	T3 vs	T3T vs	T4 vs	T4T vs	T5 vs
T2	0.0001						
T3	0.0011	0.3818					
T3T	0.0007	0.4618	0.9999				
T4	0.0445	0.0211	0.8116	0.7359			
T4T	0.0889	0.0102	0.6344	0.5471	0.9999		
T5	0.1164	0.0075	0.5552	0.4695	0.9998	0.9999	
T6	0.9129	0.0001	0.0331	0.0240	0.4963	0.6872	0.7610

Table 6c. Tukey-Kramer adjusted p-values for all pair-wise mean contrasts, 2004 yield data.

	T1 vs	T2 vs	T3 vs	T3T vs	T4 vs	T4T vs	T5 vs
T2	0.0001						
T3	0.9725	0.0001					
T3T	0.1596	0.0011	0.7135				
T4	0.9856	0.0001	0.6464	0.0381			
T4T	0.6279	0.0001	0.1889	0.0049	0.9861		
T5	0.0853	0.0001	0.0151	0.0003	0.4652	0.9280	
T6	0.6741	0.0001	0.2143	0.0058	0.9915	0.9999	0.9053

Table 6d. Tukey-Kramer adjusted p-values for all pair-wise mean contrasts, 2005 yield data.

	T1 vs	T2 vs	T3 vs	T3T vs	T4 vs	T4T vs	T5 vs
T2	0.0001						
T3	0.7047	0.0001					
T3T	0.0832	0.0001	0.8832				
T4	0.3791	0.0001	0.0211	0.0008			
T4T	0.9999	0.0001	0.8198	0.1454	0.3735		
T5	0.1393	0.0001	0.0055	0.0002	0.9991	0.1447	
T6	0.8518	0.0001	0.1136	0.0058	0.9930	0.8275	0.8760

Table 7 lists the calculated slope coefficients for the linear trend analysis for each treatment, along with the associated standard errors, t-tests and p-values. As shown by the t-test p-values, treatments T3, T4, T4T, T5 and T6 exhibit significantly decreasing linear trends over time. However, treatments T1, T2 and T3T exhibit non-significant trends. In principle, we would not expect treatments T1 (control) or T2 (groundwater salinity equal to the irrigation water salinity) to exhibit any yield reduction over time. In contrast, the saline ground-water treatments might be expected to exhibit decreasing yields over time. The trend results shown in Table 7 are generally consistent with the above expectations.

Table 5 shows the computed mean yields by treatment and year, along with the average treatment means (across years) and year effects (averaged across treatments). If we set aside the control treatment (T1), the remaining marginal treatment means shown on the right hand side of Table 5 exhibit a clearly decreasing trend. Upon closer inspection, this trend appears to be inversely related to the natural log transformed groundwater salinity level. A formal test for such a trend can be carried out regressing the time-average, marginal treatment means (computed for the 28 distinct replications) against the five log transformed salinity levels. Furthermore, a formal lack-of-fit (LOF) test can also be constructed for this hypothesized model; this LOF test can be used to determine if the postulated relationship describes all of the observed variation in the marginal mean estimates.

Upon fitting a simple linear regression function to these data, we obtained the following fitted equation: Ave total yield = 927.1 – 244.8[ln(EC_{GW})]. Both the intercept and slope estimates were highly significant ($p < 0.0001$) and the model produced an R^2 value of 84.6% and a RMSE estimate of 78.75. Additionally, a LOF F-test produced a non-significant test score of F = 1.68 (p = 0.1835), suggesting that this simple function fully describes the variation in the computed marginal means. Table 8 below lists these predicted mean values for each of the seven treatments, along with the computed marginal means (from Table 5). Note that the agreement between these two sets of mean estimates is quite good.

Table 7. Linear regression model slope coefficients, standard errors, t-tests and p-values.

Treatment	T1	T2	T3	T3T	T4	T4T	T5	T6
Estimate	-16.35	-41.15	-136.49	-76.65	-148.80	-133.24	-173.28	-96.72
Std.error	28.58	68.97	26.71	45.06	18.74	18.11	15.79	40.30
t-test	-0.57	-0.60	-5.11	-1.70	-7.94	-7.36	-10.98	-2.40
p-value	0.5744	0.5603	0.0002	0.1110	0.0001	0.0001	0.0001	0.0309

Table 8. Predicted and observed marginal (time-averaged) means, for treatments T2 through T6.

Treatment	T2	T3	T3T	T4	T4T	T5	T6
Predicted	981.7	757.4	757.4	587.8	587.8	488.6	418.1
Observed	1038.3	706.0	742.0	559.5	560.3	492.7	480.2

DISCUSSION

Previous studies of annual crops (cotton, tomatoes) using these column lysimeters showed that approximately the same amount of water was extracted from the columns with groundwater EC equal to twice the threshold for the Maas Hoffman equation (Ayars and Hutmacher 1994). Cotton is considered a salt tolerant crop while alfalfa is a moderately salt sensitive crop and apparently the differences are reflected in the fractional uptake. The uptake from the T3 treatment, which was at the threshold value for the Maas Hoffman equation, ranges from approximately 40% in 2002 to approximately 50% in 2005. The most interesting response was in the increase in percentage uptake in the tall treatment, T3T with time until the contribution in the tall treatment exceeded that in the short column (T3).

The data for the crop water use in shallow groundwater demonstrate that significant quantities of water can be extracted from shallow groundwater even when EC values are twice the Maas Hoffman threshold. The reduction in crop water use from shallow groundwater over the four-year period of the study with the groundwater treatments having higher salinity suggests that the increased soil salinity has reduced the potential for crop water use. The columns were not leached other than with rainfall over the period of the study and thus there was some accumulation of salt with depth in the soil profile in the shallow groundwater treatments having higher electrical conductivity groundwater. The soil salinity data in T1 is representative of the initial soil salinity in all of the soil columns (Table 3).

The crop water use from a shallow groundwater and the higher salinity groundwater in treatments T3, T4, and T5 resulted in increased concentration of salt in the root zone. Considering that the M-H threshold value for alfalfa is 2 dS/m, the average EC of the soil profile in treatments T5 and T6 would indicate a reduced potential for uptake from shallow groundwater due to the average soil salinity. The data show that water use for treatments T3 and T4 was also restricted because of the increased salinity in the 60 to 90 cm data (Shalhevet and Bernstein 1968).

The RM-ANOVA analysis confirms that there are highly significant differences between the various treatment means ($p < 0.0001$) and year effects ($p < 0.0001$), as well as complex treatment $\times$ year interaction effects. When analyzed on a year-by-year basis, the following three trends emerge: (i) treatment T2 appears to exhibit the consistently highest yields, followed by treatments T3T and T3, (ii) the control treatment (T1) consistently produces yields that are similar to the more saline groundwater treatments, and (iii) treatments T3 and T4 produce yields that are statistically equivalent to treatments T3T and T4T. These trends imply that the non-saline and marginally saline (2 dS/m) ground-water treatments consistently produce the highest yields, that the groundwater deficient treatment produces yields similar to the more saline groundwater treatments, and that the depth to groundwater does not effect the average yield estimates.

Linear trend analyses of the yield showed that treatments T3, T4, T4T, T5 and T6 exhibit significantly decreasing linear trends over time, while treatments T1, T2 and T3T exhibit non-significant trends. These results are generally consistent with the expectation that treatments T1 and T2 should not exhibit any yield reduction over time, while the more saline treatments might be expected to exhibit decreasing yields over time. An analysis of the marginal non-control treatment means suggests that these time averaged estimates exhibit a simple inverse relationship to the log transformed groundwater salinity level. Additionally, the LOF F-test for this fitted relationship is not significant; suggesting that this simple function fully describes the variation in the computed marginal means. Since the time-averaged yield for the control (T1) treatment was 481.8, we can tentatively conclude that an alfalfa crop should experience elevated yields when exposed to ground-water with a salinity level no higher than $\exp[(927.1-481.8)/244.8] = 6.17$ dS/m, at least for the first few years.

CONCLUSIONS

The data from four years of research on crop water use from shallow groundwater by alfalfa demonstrate that significant quantities of water were used from shallow groundwater by alfalfa even when electrical conductivity of the groundwater is in excess of the Maas-Hoffman yield reduction threshold. In-situ crop water use was reduced more rapidly with higher groundwater salinity in the salt sensitive alfalfa than was previously observed in cotton. Also, the potential for increased use from shallow groundwater was demonstrated over the period of time for the water qualities that were greater than the Maas Hoffman threshold in both the shallow and deep groundwater treatments. Finally the two groundwater depths do not produce statistically significant yield differences; i.e., treatments T3 and T4 produce yields that are statistically equivalent to treatments T3T and T4T.

ACKNOWLEDGEMENTS

The authors thank Mr. Richard Schoneman, Mr. Octavio Viveros, and Mr. Xavier Arellano for their operation of the columns and on-going data collection.

REFERENCES

Ayars, J.E., R.B. Hutmacher, R.A. Schoneman, S.S. Vail, and D. Felleke. 1986. Drip irrigation of cotton with saline drainage water. *Transactions of the ASAE* 29:1668-1673.

Ayars, J.E., and G. Schrale. 1989. Irrigation efficiency and regional subsurface drain flow on the west side of the San Joaquin Valley, Report to California Department of Water Resources, Sacramento, Ca.

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.

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

Ayars, J.E., R.B. Hutmacher, R.A. Schoneman, R.W. Soppe, S.S. Vail, and R. Dale. 2000. Realizing the potential of integrated irrigation and drainage water management for meeting crop water requirements in arid and semi-arid areas. *Irrigation and Drainage Systems* 13:321-347.

Ayars, J.E., and L. Basinal. 2005. A Technical Advisor's Manual: Managing Agricultural Irrigation Drainage Water: A guide for developing Integrated On-Farm Drainage Management Systems. Center for Irrigation Technology.

Ayars, J.E., E.W. Christen, R.W.O. Soppe, and W.S. Meyer. 2006. Resource potential of shallow groundwater for crop water use-A review. *Irrigation Science* 24: 147 -160.

Blackwell, J., Jayawardane, N., Biswas, T. and Christen, E.W**.** (2005). Evaluation of a sequential biological concentration system in natural resource management of a saline irrigated area. *Australian Journal of Water Resources*, Vol. 9. No.2: 169- 176.

Davies, C. S. 2002. Statistical methods for the analysis of repeated measurements. Springer-Verlag, New York, N.Y.

Doorenbos, J, and A.H. Kassam. 1979. Yield response to water. *FAO Irrigation and Drainage Paper No. 33* ed. FAO, Rome, Italy.

Hutmacher, R.B., J.E. Ayars, S.S. Vail, A.D. Bravo, D. Dettinger, and R.A. Schoneman. 1996. Uptake of shallow groundwater by cotton:growth stage, groundwater salinity effects in column lysimeters. *Agric. Water Manage.* 31:205-223.

Kramer, C. Y. 1956. Extension of multiple range tests to group means with unequal number of replications. Biometrics, 12: 307-310.

Kruse, E.G., D.F. Champion, D.L. Cuevas, R.L. Yoder, and D. Young. 1993. Crop water use from shallow, saline water tables*. Transactions of the ASAE* 36:696-707.

Maas, E.V., and G.J. Hoffmann. 1977. Crop salt tolerance-current assessment. *J. Irrig. Drainage Div*. ASCE 103:115-134.

Montgomery, D. C. 2001. Design and analysis of experiments, 5th Edition. John Wiley & Sons, New York, N.Y.

Nielsen, D.R., J.W. Biggar, and K.T. Erh. 1973. Spatial variability of field measured soil-water properties. *Hilgardia* 42:215-259.

Postel, S. 1999. Pillar of sand:Can the irrigation miracle last? W.W. Norton & Company, New York.

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.

Robbins, C.W. and L.S. Willardson. 1980. An instrument lysimeter system for monitoring salt and water movement. *Transactions of ASAE* 23:106-111.

San Joaquin Valley Drainage, P. 1990. The problem, p. 183, *In* U. S. D. of. Interior and Department of California Resources, eds. A Management Plan for Agricultural Subsurface Drainage and Related Problems on the westside San Joaquin Valley. California Department of Water Resources, Sacramento, California.

SAS Institute Inc. 1999. SAS/STAT User's Guide, Version 8. SAS Institute Inc., Cary, N.C.

Shalhevet, J., and L. Bernstein. 1968. Effects of Vertically Heterogeneous Soil Salinity on Plant Growth and Water Uptake. *Soil Science* 106:85-93.