MANAGING SALINITY FOR SUSTAINABILITY OF IRRIGATION IN AREAS WITH SHALLOW SALINE GROUND WATER[1]

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ABSTRACT

Irrigation will be required to meet the demands of the world population for food. Water will also be needed to meet the municipal, industrial, and environmental demands of the growing population. As a result irrigation water supplies will be reduced and irrigators will probably be forced into using degraded water as part of the supply and the possibility for increased salinity in the soil profile will occur. Drainage will be required to assist in the management of the water needed for leaching to prevent soil salinisation. Drainage water containing salt and other contaminants creates a water quality problem for the water body receiving the drainage water. The paper presents the results of three cases studies that address the issue of disposal of saline drainage water through reuse for supplemental irrigation, water table control, and changing the design criteria for subsurface drainage as methods to reduce the drainage volume. The first study demonstrated that over 50% of the crop water requirement can be met with saline drainage water and that salinity in the soil profile can be managed to not adversely affect yields. This is not the case if the drainage water contains high levels of boron. The second study demonstrated that the water table can effectively be manipulated if the drainage system is properly installed. The third study showed the reduction in salt load as a result of implementing drainage control on deep drains or installing shallow drains. The results from these studies demonstrate that irrigated agriculture is sustainable in arid and semi-arid areas through improved management of the subsurface drainage system.

Keywords: Shallow ground water, salinity, crop selection, controlled drainage.

1. INTRODUCTION

Irrigation supplies approximately 35% of the world food supply on less than 20% of the arable land and has a significant future role in meeting the projected world food demand. Currently, irrigation uses approximately 80% of the developed water supply worldwide, and this water will be a logical source for meeting other demands for water i.e., municipal, industrial, and environmental. The alternative to new irrigation development will be to increase water use efficiency through improved irrigation technology, improved crops, improved productivity of lands impacted by high water tables and salinity. Surface irrigation is the major form of irrigation throughout the world and as a result the world wide irrigation efficiency is in the range of 30 to 50%. This poor efficiency provides opportunities for improvement that will result in water for other uses without having a negative impact on production. Low irrigation efficiency is also responsible for extensive areas of water logging and shallow ground water in irrigated agriculture that continue to require subsurface drainage. Improvements in irrigation management will reduce water logging and deep percolation. However, there is still a need for deep percolation to manage salinity in the root zone, thus resulting in areas of shallow ground water that have to be managed.

In the past shallow ground water was viewed as a waste product of irrigation that required disposal. Recently, shallow ground water is viewed as a resource to meet crop water demands either through in-situ use or by using drainage water for supplemental irrigation (Ayars and Schoneman, 1986; Ayars et al., 1986, 1993, 1998; Ayars, 1996, 1999). Each of these techniques has been used to supplement irrigation supplies with varying degrees of success depending on the crop, shallow ground water quality, and irrigation management. When drainage water is used for supplemental irrigation or in-situ, it has to be stored for future use. If it is to applied by an irrigation system it must be stored in a surface pond for use during the irrigation season which requires an additional irrigation infrastructure. For in-situ use it must be stored in place in the ground by maintaining the water table position and preventing drainage. In-situ use is a more complicated system because there are limited data on the potential crop water use from shallow ground water and how to achieve the full potential. Even though there has been extensive research on in-situ crop water use by a wide variety of crops over the past 50 years, the full potential of this resource has not been quantified. This lack of quantification is the result of the complexity of the system, the limited equipment, and the wide variety of objectives being met in the research. Subsurface drainage is a necessary component of irrigated agriculture in arid and semi-arid areas of the world. In the past, drainage systems were designed to prevent salt accumulation using criteria that resulted in deep placement of drainage laterals with wide spacings that insured a mid-point water table depth of 1.2 m. Also, drainage systems were not managed but left to run continuously resulting in a maximum drainage flow and disposal of salt, pesticide, and nitrate without consideration of the water quality consequences for the receiving water body. It is no longer acceptable for a drainage system design not to include a consideration of the impact of drainage water on surface water quality (Ayars et al, 1997; Guitjens et al, 1997). Future drainage design will require that a subsurface drainage system be part of a water management system that includes both irrigation and drainage. The drainage system will contain structures that permit active control of the water table position and discharge (Ayars, 1999; Ayars et al, 2000) (Christen and Ayars, 2001).

Active management of subsurface drainage systems is a new concept for arid and semi-arid areas even though it has been a

common practice in humid areas of the world (Fouss et al, 1990). A major limitation in arid areas is the need to manage salinity in soil profile to insure that yield and soil quality are not negatively impacted. The emphasis on drainage management has been for water quality reasons. In humid areas there has been a need to reduce the nitrate level in shallow ground water. In arid areas, salt, toxic elements, and nutrients are the components that affect drainage water quality. In arid and semi-arid areas it is not possible to remove most water quality contaminants through a chemical process so the emphasis has been on methods that reduce the total load delivered to the receiving water body. The approaches taken include source control, the reduction of deep percolation through improved irrigation management, reusing the drainage water for supplemental irrigation, and managing shallow groundwater position for in-situ use by crops. Each of these approaches presents differing opportunities and challenges for managing the salt load in the drainage water and the salt in the soil profile.
The objective of this paper is to use data from case studies in the United States and Australia to discuss the impact of practices and approaches developed to manage the total drainage flow from saline soils in arid and semi-arid areas world on the sustainability of irrigated agriculture.

2. REUSE OF SALINE DRAINAGE WATER

When developing best management practices for subsurface drainage system design, Christen and Ayars (2001) assumed that the irrigation management on a field was developed to the highest practical economic level prior to implementing practices such as reusing drainage water or in-situ use by crops. The first step in solving the drainage water disposal problem in the Central Valley of California (San Joaquin Valley Drainage Program, 1990) was improving irrigation management and was dubbed source control . The next step was reusing saline drainage water for supplemental irrigation, followed by land retirement because there were limited options for discharging water into any surface water supply or evaporation basins. As a result, there were several studies conducted in California to evaluate using saline water for irrigation to reduce the total drainage volume and salt load (Rhoades, 1989; Rhoades et al, 1989) (Ayars et al,
1993). Rhoades et al. 1989 demonstrated cyclic use of saline (3-4 dS/m) and low salinity (1 dS/m) water to alternately grow sensitive and moderately salt sensitive crops with out a loss in crop productivity while maintaining soil salinity at low levels. The study by Ayars et al. (1993) detailed in the following sections used saline water and salt tolerant crops. The essential elements in both studies were the matching of the crop to the water quality and providing leaching at appropriate intervals during the crop rotation.

2.1 Murrieta Farms

This research/demonstration project evaluated irrigation and salinity management on saline soils using either or both low salinity and saline water in the presence of an operating subsurface drainage system. The site was located on the west side of the San Joaquin Valley of California in an area containing naturally occurring saline soils, a product of the weathering of the Coast Range of California. The experiment was conducted for six years (1982 -1987) on a 60 ha field site at Murrieta Farms located near Mendota, California, USA. The soil in the experimental field was classified as an Oxalis silty clay loam (fine, montmorillonitic, thermic Pachic haploxeralls) with a well-developed salinity profile. The salinity development in the profile is typical of many irrigated areas throughout the world with salinity increasing with depth in the profile. This means that deep drain placement will result in high concentrations of salt in the drainage water and high salt loads.The field was underlain by a shallow (1 to 1.9 m deep), saline ground water having an electrical conductivity (ECw) of 7 - 10 dS m^{-1}, high concentrations of boron (B), selenium (Se), sodium (Na), calcium (Ca), sulfate (SO_4), chloride (Cl), and nitrate (NO_3). The entire field was drained by subsurface 100 mm diameter plastic drains installed at depths ranging from 1.5 to 1.7 m with lateral spacings of 80 to 90 m. The field was divided into six experimental plots of approximately 10 ha each, four of which were used in this experiment.
Furrow irrigation (F) was used on two plots and surface drip irrigation (T) was used on the remaining two plots. The drip irrigation treatments T1 and T2 were irrigated with saline drainage water collected from the experimental site and adjacent fields (EC_w = 7 dS m^{-1}, B = 5 mg L^{-1}) and stored in a pond adjacent to the site. A separate pumping system was used to move water from the storage pond to the field and to pressurize the drip irrigation system.

Table 1. Composition of irrigation waters used form 1983 through 1987 - data shown are average values.

Year	Irrigation Treatment	EC_w dS/m	Cl meq/L	B mg/L
1983	T1 and T2[a]	7.2[b]	28.3	5.6
	F1 and F2	0.3	1.2	0.5
1984	T1 and T2	7.4	27.4	4.9
	F1 and F2	0.5	1.1	0.4
1985	T1 and T2	0.6	1.3	0.5
	F1 and F2	0.5	1.3	0.5
1986	T1 and T2	7.9	27.5	6.4
	F2	3.8	14.3	2.6
	F1	0.3	2.3	0.3
1987	T1 and T2	7.7	34.4	6.7
	F2	3.5	15.3	3.1
	F1	0.5	3.0	0.3

a After 7/15 of 1983, this quality water was used in T1/T2 plots, prior to the data water comparable of F1 plot was used.

b Values shown represent the mean of 3 to 7 measurement dates per year at approximately 3 to 5 week intervals.

Two plots furrow irrigated with low salinity, water were used for comparison with plots trickle irrigated with saline water. These plots were adjacent to drip irrigated plots T1 and T2. The treatment F1 was furrow irrigated with low salinity (0.3 to 0.5 dS m^{-1}) water during the 1982 to 1987 period, while treatment F2 received low salinity water from 1982 to 1985 and both saline and low salinity water in 1986 and 1987. The saline water in F2 generally consisted of a 1:1 mix of the saline drainage water (used in treatments T1 and T2) and the low salinity water supplied by the Westlands Water District.

Table 2. Rainfall and applied water (low-salinity water (NS) EC_w = 0.3 to 0.5 dS/m and saline EC_w = 3.5 to 3.8 dS/m in F1 and F2 treatments.

Year	Crop	Rainfall (mm)		Applied water (mm)			
		Between planting and harvest	Total (planting to planting)[a]	Treatment			
				F1		F2	
				NS	S	NS	S
1982	cotton	42	287	276	0	502	0
1983	cotton	64	126	302	0	302	0
1984	cotton	29	128	715	0	725	0
1984/85	wheat	60	64	532	0	535	0
1985/86	sugar beet	245	349	836	0	114	720
1987	cotton	68	68	770	0	270	515
Total - 1982 (planting) through 1987 (harvest)		508	1022	3631	0	2448	1235

a Represents total rainfall received from planting time for the year shown in the column of table to planting time of the subsequent crop (in either the same, or the next calendar year - see table for planting dates). The 1987 data are for period of planting to harvest.

Table 3. Rainfall and applied water (low-salinity water (NS) EC_w = 0.3 to 0.5 dS/m and saline water EC_w = 7.2 to 7.9 dS/m in plots T1 and T2.

Year	Crop	Rainfall (mm)		Applied water (mm)			
		Between planting and harvest	Total (planting to planting)[a]	Treatment			
				T1		T2	
				NS	S	NS	S
1982	cotton	42	287	580	0	580	0
1983	cotton	64	126	175	200	175	200
1984	cotton	29	128	150	336	150	547
1984/85	wheat	60	64	526	0	526	0
1985/86	sugar beet	245	349	114	666	114	973
1987	cotton	68	68	155	573	155	749
Total - 1982 (planting) through 1987 (harvest)		508	1022	1700	1775	1700	2469

[a] Represents total rainfall received from planting time for the year shown in the column of table to planting time of the subsequent crop (in either the same, or the next calendar year - see table for planting dates).The 1987 data are for period of planting to harvest.

Depth of applied water in the furrow irrigated plots was determined by apportioning total applied water measured from the Westlands Water Districts meters based on the plot area, then subtracting tailwater from each area measured using cutthroat flumes equipped with water stage recorders. Depth to shallow ground water was determined in treatments F2, T1, and T2 using shallow wells. Average irrigation water qualities (EC_w, Cl, B) are shown in Table 1. Rainfall and total water applications are shown in Table 2 for the furrow irrigation and Table 3 for the drip irrigation.

The crop rotation used was cotton (Gossypium hirsutum L.), cotton, cotton, wheat (Triticum aestivum), sugar beet (Beta vulgaris), and cotton during the 1982 to 1987 experiment. With the exception of the wheat seed, which was broadcast, all other crops were planted on a 0.76 m row spacing. Pre-plant irrigation with approximately 150 mm of low salinity water was done in a fallow period each year prior to planting. The wheat crop, which was planted approximately 30 days after cotton harvest and was sprinkled with 50 mm of low salinity water for germination. The wheat was irrigated with only low salinity water. After germination, saline water was used exclusively in treatments T1 and T2 to meet crop water requirements for the sugar beet and cotton crops in all years, and after 1986 in treatment F2. Soil sampling for chemical analysis was done in the Spring each year prior to planting but after pre-plant irrigation and in the Fall after harvest but prior to most rainfall and pre-plant irrigation. The soil profile was sampled in 0.3 m increments to a depth of 1.8 m at three to eight locations within each plot using either a machine-driven or 51 mm diameter manual sampling auger. Saturation extracts were made from each sample and a complete analysis of anions and cations was run on the extract. The EC_e, Cl, and B analyses will be used to demonstrate the irrigation management needed for salinity control.

2.1.1 Results

2.1.1.1 Applied water

The total applied water (NS, S) ranged from 3475 mm for treatment T1 to 4196 mm in Treatment T2 (Table 3). In the six crop rotation, 51% and 59% of the total water applied in the T1 and T2 treatments, respectively, was supplied by saline water, while 34% of total applied water was saline in treatment F2. In treatment T1, analysis of the crop water requirements based on ET:crop production functions (Ayars et al, 1986) indicated that crop water use from shallow ground water for the different crops ranged from 15 to 40% of total crop water use. This indicated that most of the applied saline water in T1 was used in evapotranspiration and did not result in net deep percolation losses. This was not true for treatment T2 where applied water in 1986 and 1987 was equal to 1.4 and 1.3 times the estimated Etc. Throughout the experiment the furrow irrigation applications (F1, F2) exceeded the calculated crop water requirement based on Eto and the Etc:crop production functions (Table 2). The shallow ground water was not actively managed during this experiment but there was some passive control on the system that was exerted by the water meters used to measure flow from the individual plots. The water meters were 19 mm residential type water meters that restricted the flow and sustained the water table for a longer period than would normally have been expected with the design. This enabled the cotton and sugar beet to use water from the shallow ground water that would otherwise have been removed by the drainage system.

2.1.1.2 Soil Chemistry

Managing these plots for long term sustainability using saline water of qualities shown in Table 1 requires considering both the short and long term responses of the soil to salinity and specific ion accumulations in response to the application of saline water. The data in Tables 4 and 5 and Figs 1 and 2 will be used to demonstrate the responses and problems associated with using only a good quality water, using degraded quality water, and a combination of degraded and good quality water. By the Fall of 1984 following the cotton crop and the application of 536 mm of saline water in T1 and 747mm in T2, the EC data in Table 4 show that of the salinity in the surface layers of the soil profile in Treatments T1 and T2 had exceeded levels recommended as being safe for germination of moderately or even salt tolerant crops in successive years if leaching did not occur (Maas, 1986). The 1984 cotton crop was followed by wheat, which was irrigated with 526 to 535 mm of low salinity water (Table 2) in addition to 64 mm of rain. the EC_e data for the top meter of the soil profile in the Fall of 1985 indicate that leaching had occurred over the Fall 1984 to Fall 1985 period. By the Spring of 1986 the average salinity in the top 90 cm of the soil in both T1 and T2 had been reduced further by leaching due to rainfall (245 mm) and pre-plant irrigation (114 m) with low salinity water. The Fall 1986 salinity levels in the top meter of the soil profile had increased to about the previous levels of Fall 1984 after irrigating the sugar beets with 666 mm and 973 mm of saline water in T1 and T2, respectively.
In treatment F1, irrigated with low-salinity water, the average salinity levels in the upper 120 cm profile varied between 4.2 dS m^{-1} and 5.6 dS m^{-1} in the period from Fall 1984 to Fall 1986, with ECe in treatment F2, which received 720 mm of saline water (ECw .3.5 dS m^{-1}) in 1986, the average salinity levels in the top 120 cm of soil increased from 6.4 dS m^{-1} by 1984 to 9.3 dS m^{-1} by the Fall of 1986. The salinity data for treatments T1 and T2 show that in the short term (individual seasons) the surface soil salinity levels in the top 60 cm of soil can be controlled by leaching during pre-plant irrigation and rainfall. The EC_e data for the upper 30 cm of the soil profile of the F1 treatment show that the salinity at planting was never at a level which would negatively impact germination and plant growth.

Table 4. Mean electrical conductivity of soil saturation extract (EC_e) as a function of depth, time of season, and irrigation treatment in 1984, 1985, and 1986.

Treatment	Depth in Profile (cm)	EC_e (dS/m)			
		Fall 1984[a]	Fall 1985	Spring 1986	Fall 1986
F1	0 - 30	1.6 (0.2)[b]	1.4 (0.2)	1.4 (0.2)	2.2 (0.2)
	30 - 60	4.7 (0.6)	1.3 (0.2)	3.2 (0.4)	3.4 (0.3)
	60 - 90	7.1 (0.6)	5.3 (0.7)	6.6 (0.7)	6.3 (0.5)
	90 - 120	9.0 (0.5)	8.8 (0.7)	8.8 (0.6)	9.0 (0.6)
F2	0 - 30	1.3 (0.1)	1.5 (0.3)	1.2 (0.1)	5.9 (0.5)
	30 - 60	5.1 (0.3)	4.2 (0.3)	2.1 (0.3)	8.8 (0.6)
	60 - 90	8.0 (0.6)	9.3 (0.6)	7.8 (0.2)	11.2 (1.1)
	90 - 120	11.5 (0.4)	12.8 (0.7)	11.4 (0.7)	11.6 (1.2)
T1	0 - 30	7.6 (0.2)	3.0 (0.4)	3.2 (0.3)	7.8 (0.5)
	30 - 60	9.0 (0.8)	7.7 (0.4)	6.7 (0.6)	10.7 (0.3)
	60 - 90	13.8 (1.3)	14.3 (1.6)	12.1 (0.2)	11.3 (1.3)
	90 - 120	12.9 (0.6)	14.5 (0.5)	14.0 (1.2)	12.7 (0.9)
T2	0 - 30	10.9 (0.6)	3.2 (0.4)	3.1 (0.3)	7.6 (0.8)
	30 - 60	11.8 (0.5)	8.1 (1.0)	6.8 (0.2)	11.4 (0.8)
	60 - 90	11.6 (0.2)	11.6 (1.1)	11.4 (0.9)	13.3 (1.7)
	90 - 120	13.5 (0.9)	13.7 (0.6)	14.2 (1.6)	15.6 (0.9)

[a] Day of year corresponding to Fall (1984), Fall (1985), Spring (1986), and Fall (1986) were 315, 310, 98, and 272, respectively.
[b] Standard error of the mean is given in parenthesis.

The data in Fig. 1 and 2 show the levels of EC_e and Cl at the initiation of the experiment (Spring 1982), the beginning of the final season (Spring 1987, after rainfall and low salinity pre-plant irrigation) and at the end of the final season (Fall 1987), respectively. The Cl data are presented to characterize salt transport and ground water uptake. The shallow ground water represented a potential source of degraded water which could move up in the soil profile due to plant uptake and evaporation. Comparison between Spring 82 and Spring 87 shows that the EC_e levels and Cl concentrations of had increased throughout the profile in treatments (T1 and F2) receiving saline irrigation water (Figs. 1, 2). The amount of the increase was related to the total depth of applied water, with a larger increase occurring in T1 than in F2 in the top 90 cm of the profile. Comparing between the Spring 87, and Fall 87 data show that within a season there were increases in EC_e and Cl concentrations in treatments T1 and F2. In general, pre-plant leaching was adequate to return the profiles to nearly the original condition but the data taken at the end of the experiment indicate that there is still some accumulation of salt occurring within the profile. T2 received the largest amount of saline water, approximately 40% more than T1, during the experiment. In addition, the water was much more saline than that applied to treatment F2 as a result of the differences in total application and salinity amounts, the EC_e and Cl profile responses were quite different between T2, T1, and F2. Below approximately 45 cm the EC_e and Cl concentrations in the T2 profile were reduced between Spring 1982 and Spring 1987 rather than increased as in T1 and F2. This is an indication of a large leaching occurring in T2 and not in T1 and F2.

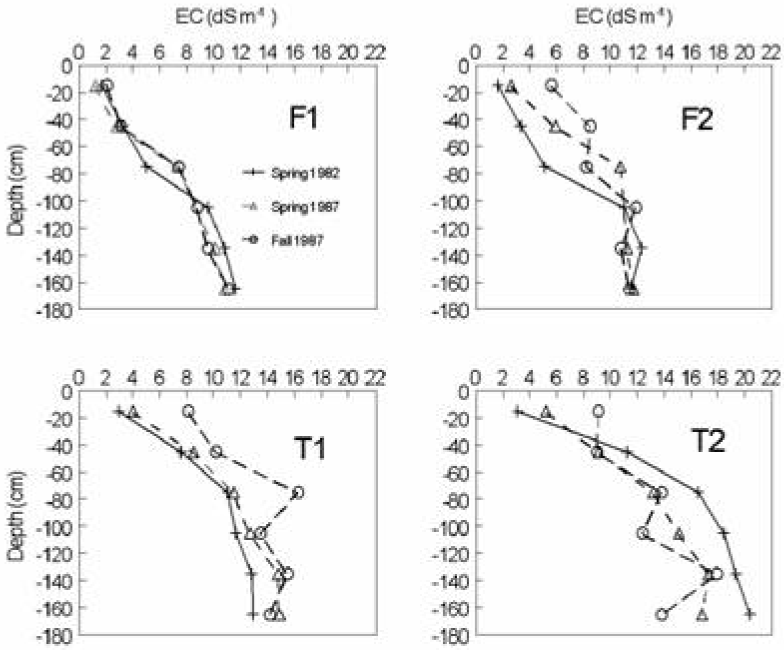


Figure 1. Distribution of electrical conductivity in plots irrigated with low salinity water (F1, F2) and high salinity water (T1, T2).

The boron data in Table 5 and Fig. 3 show a different response than observed in the EC and Cl data. In treatments T1 and T2 (Table 5) there was a gradual increase in the B concentration in the top 90 cm with no observed reductions associated with within year leaching as was observed with the EC_e values. This is particularly evident in the data in Table 6. The B concentrations increased throughout the profile in the drip treatments T1 and T2 and in the furrow treatment F2 which received saline water in 1986, while remaining constant in the furrow irrigation treatment irrigated with only low salinity water (F1). Over the 6 year study, the B concentration in treatment T2 increased from an average of 2.2 mg B kg^{-1} in the top meter of the soil profile to and average of 6.8 mg B kg^{-1}. The increased concentration was due to the application of saline irrigation water with a B concentration which ranged from 4 to 7 mg B L^{-1} during the study.

The data in Figure 3 show the increases in B from the beginning of the experiment. The data in F1 remained constant over the years. In the remaining treatments the B concentrations with depth showed a steady increase with the time which directly related to the depth of applied water. The data in T2 showed the largest increases compared to F2 and T1. It is possible that T2 had reached the maximum concentration of adsorbed B by 1987, since there was no increase in the B concentration with depth as was experienced in T1 and F2.

Table 5. Boron (B) in soil saturation extract as a function of depth, time of season, and irrigation treatment in 1984, 1985, and 1986.

Treatment	Depth in Profile (cm)	B (mg/L)			
		Fall 1984[a]	Fall 1985	Spring 1986	Fall 1986
F1	0 - 30	0.9 (0.2)[b]	1.2 (0.3)	ND[c]	1.5 (0.4)
	30 - 60	2.3 (0.2)	2.4 (0.2)	ND	2.7 (0.2)
	60 - 90	3.6 (0.9)	3.2 (0.1)	ND	3.9 (0.1)
	90 - 120	4.9 (0.5)	5.6 (0.2)	ND	5.6 (0.1)
F2	0 - 30	1.8 (0.2)	1.9 (0.4)	1.8 (0.5)	2.9 (0.4)
	30 - 60	2.5 (0.4)	2.2 (0.2)	2.8 (0.2)	4.4 (0.1)
	60 - 90	4.2 (0.1)	4.6 (0.2)	3.9 (0.1)	5.6 (0.3)
	90 - 120	4.0 (0.3)	4.5 (0.5)	4.1 (0.3)	6.3 (0.2)
T1	0 - 30	2.2 (0.1)	1.9 (0.2)	2.0 (0.4)	3.2 (0.1)
	30 - 60	2.3 (0.4)	2.8 (0.8)	3.2 (0.2)	4.4 (0.3)
	60 - 90	3.6 (0.6)	4.2 (0.1)	4.1 (0.1)	4.7 (0.1)
	90 - 120	3.8 (0.2)	4.3 (0.1)	4.5 (0.3)	6.0 (0.5)
T2	0 - 30	1.6 (0.1)	1.7 (0.4)	1.7 (0.5)	4.0 (0.1)
	30 - 60	3.4 (0.2)	2.8 (0.2)	2.9 (0.6)	5.3 (0.6)
	60 - 90	3.5 (0.1)	4.1 (0.5)	4.1 (0.2)	6.5 (0.4)
	90 - 120	3.2 (0.2)	4.4 (0.3)	4.4 (0.4)	7.0 (0.3)

[a] Day of year corresponding to Fall (1984), Fall (1985), Spring (1986), and Fall (1986) were 315, 310, 98, and 272, respectively.
[b] Standard error of the mean is given in parenthesis.
[c] No data.

Using the reclamation guidelines in Hoffman (1990) it would take approximately 130 to 200 mm of low salinity water to restore the average EC_e profile in the top one meter of T1 to previous levels using intermittent applications of low salinity water. If reclamation were attempted by ponding, it would take almost 600 mm of water. It would take almost 1800 mm of boron free low salinity water to restore the first meter of the soil profile in treatment T1 to the original B levels using intermittent leaching. It is apparent that salinity can be managed in the profile and that large quantities of water can be use without detrimental effects on the soil structure. However, this is not the case if the drainage water contains high concentrations of boron.

2.1.1.3 Yields

The yield data for each treatment and each year are summarized in Table 6. With the exception of the wheat crop grown in 1984/85, the yields were not affected by using saline water to meet part of the crop water requirement during the 6 years of the study. Recall that only low salinity water was used to irrigate the wheat in all the treatments. The yield loss in the wheat crop in T1 and T2 was a result of the use of saline water for irrigation of cotton prior to planting the crop. The residual effects of the salt in the soil profile reduced the yield. The lower lint yields in 1983 in all treatments compared to 1982 and 1984 was a result of a shortened growing season in 1983. The cotton yields were comparable in 1982, 1984 and 1987 for all treatments and across all years and are typical of this area.

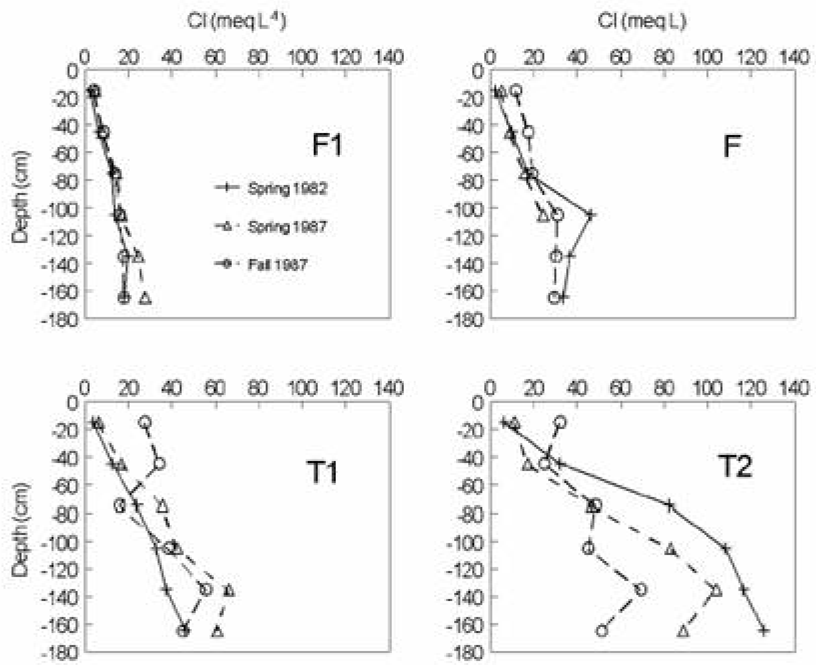


Figure 2. Distribution of chloride under plots irrigated with low salinity water (F1,F2) and high salinity water (T1, T2).

3. CONTROLLING SHALLOW GROUND WATER

In-situ use of shallow ground water as an aid to drainage water disposal is being studied in the Untited States, Australia, Egypt, and Pakistan. For this practice to be effective, the ground water position will have to be controlled during the growing season. Ideally, the water table position will be capable of being controlled at different depths from the soil surface in response to the plant development. The effectiveness of in-situ use will depend on the source of the water, the quality of the ground water, the salt tolerance of the crop, the depth to ground water, and the configuration of the drainage system. If the shallow ground water is solely a result of poor irrigation practice, then improving the irrigation management will result in reduced availability of water for crop use and in the extreme might eliminate the need for drainage. If improved irrigation efficiency doesn't eliminate the need for drainage then drainage control and in-situ use should be considered. If the excess water is due to lateral inflow from regional flows due to climate or poor irrigation management then ground water control should be considered.

Table 6. Yield data for each treatment and crop.

Year	Crop	Commodity	Yields (Mg ha^{-1})			
			Treatments			
			F1	F2	T1	T2
1982	cotton	lint	1.6	1.4	1.6	1.6
1983	cotton	lint	0.9	1.0	1.1	1.1
1984	cotton	lint	1.6	1.6	1.8	1.8
1984/85	wheat	wheat seed	7.0	7.0	5.7	5.2
1985/85	sugar beet	sugar	10.5	10.8	10.8	10.2
1987	cotton	lint	nd[a]	1.5	1.5	1.6

[a] No data

Figure 3. Distribution of boron under plots irrigated with low salinity water (F1,F2) and high salinity water (T1, T2).

Salt tolerance of the crop and ground water quality are a concern when considering the potential for crop water use from the shallow ground water. The Maas-Hoffman (M-H) (Maas, 1986) salt tolerance data and thresholds offer a good starting point for consideration of the potential use from shallow ground water. Previous work (Ayars et al, 1993; Ayars and Hutmacher, 1994; Hutmacher et al, 1996)has shown that crops will use water from the shallow ground water with salinity in excess of twice the M-H threshold value at the same rate as low salinity water. This means that there is considerable potential for crop water use even for salt sensitive crops. A list of crops that have reportedly used water from shallow ground water is given in Table 7.

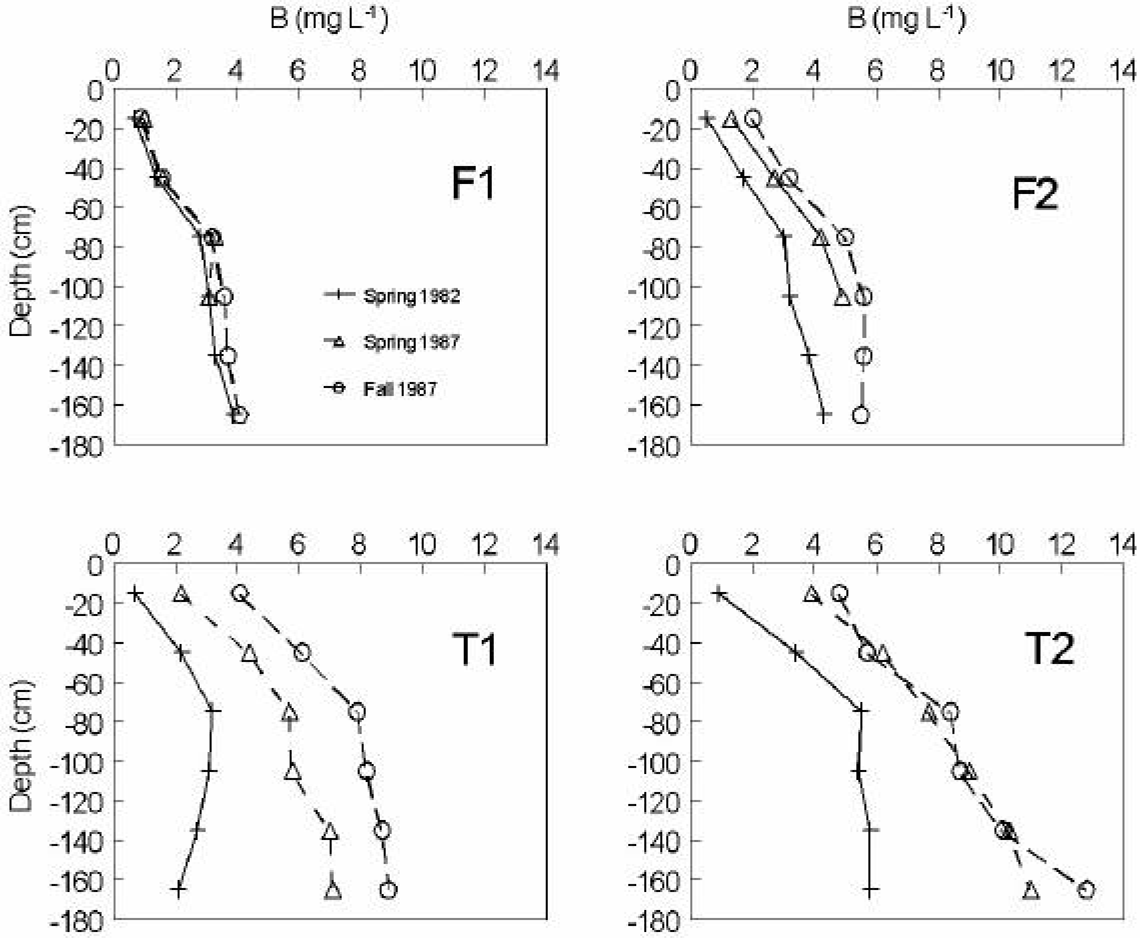


Table 7. Crops reported to have successfully used water from shallow ground water and references.

Crop	Reference
alfalfa	Benz et al., 1983, 1987; Grimes and Henderson, 1984; Kruse et al., 1993; Meyer et al., 1996, Meyer, 1996; Smith et al., 1996; Zhang et al., 1999
carrot	Schmidhalter et al., 1994

corn (maize)	Follett et al., 1974; Benz et al., 1984; Kruse et al., 1985, 1993; Kang et al., 2001; Sepaskhah et al., 2003
cotton	Namken et al., 1969; Williamson and Carreker, 1970; Williamson and Kriz, 1970; Wallender et al., 1979; Grimes and Henderson, 1984; Ayars and Schoneman, 1986; Ayars and Hutmacher, 1994; Cohen et al., 1995; Hutmacher et al., 1996
eucalyptus	Thorburn et al., 1995
pasture	Shih and Snyder, 1984
peach	Boland et al., 1996
sorghum	Mason et al., 1983; Shih, 1984; Robertson et al., 1993; Sepaskhah et al., 2003
soybean	Dugas et al., 1990; Meyer et al., 1990; Meyer, 1996
string bean	Williamson and Carreker, 1970; Williamson and Kriz, 1970
sugar beet	Follett et al., 1974; Benz et al., 1984, 1987
sugar cane	Escolar et al., 1971; Omary and Izuno, 1995; Sweeney et al., 2001
sunflower	Mason et al., 1983
tomato	Hutmacher and Ayars, unpublished data
wheat	Chaudary et al., 1974; Meyer et al., 1987; Kruse et al., 1993; Kang et al., 2001

The depth to ground water has a significant impact on the potential for crop water use as does the soil type. Water use by a plant from the ground water requires that water move through the unsaturated zone of the soil from the water table to the root system. The potential flux is controlled by the unsaturated hydraulic conductivity function which is highly variable across soil types and as the distance increases between the plant and water table the sustainable flux decreases rapidly. The net result is that the water table in a sandy soil has to be considerably closer to the plant than in a loam soil to maintain the same flux. The effect of soil type and depth to water table on average contribution to cotton water use can be seen in Figure 4. The percentage of water use by cotton increased as the depth to water table decreased and as the soil went from a clay to a loam soil. One problem is how to enable the control of shallow ground water without creating problems with waterlogging in a portion of the field. This will be a significant consideration for systems designed with laterals parallel the surface grade of the field. In this case restricting flow at the outlet or on each lateral will result in waterlogging a portion of the field without providing much control on the remainder of the field. Therefore, a design change will be required such that the laterals are installed perpendicular to the surface grade and the submain collector is run parallel to the surface grade. This will enable control along the submain to extend to large portions of the field and will prevent waterlogging at the low end of the field. In cases with extremely low grade on the surface it might be possible to control the water table at only the outlet (Fouss et al, 1990).

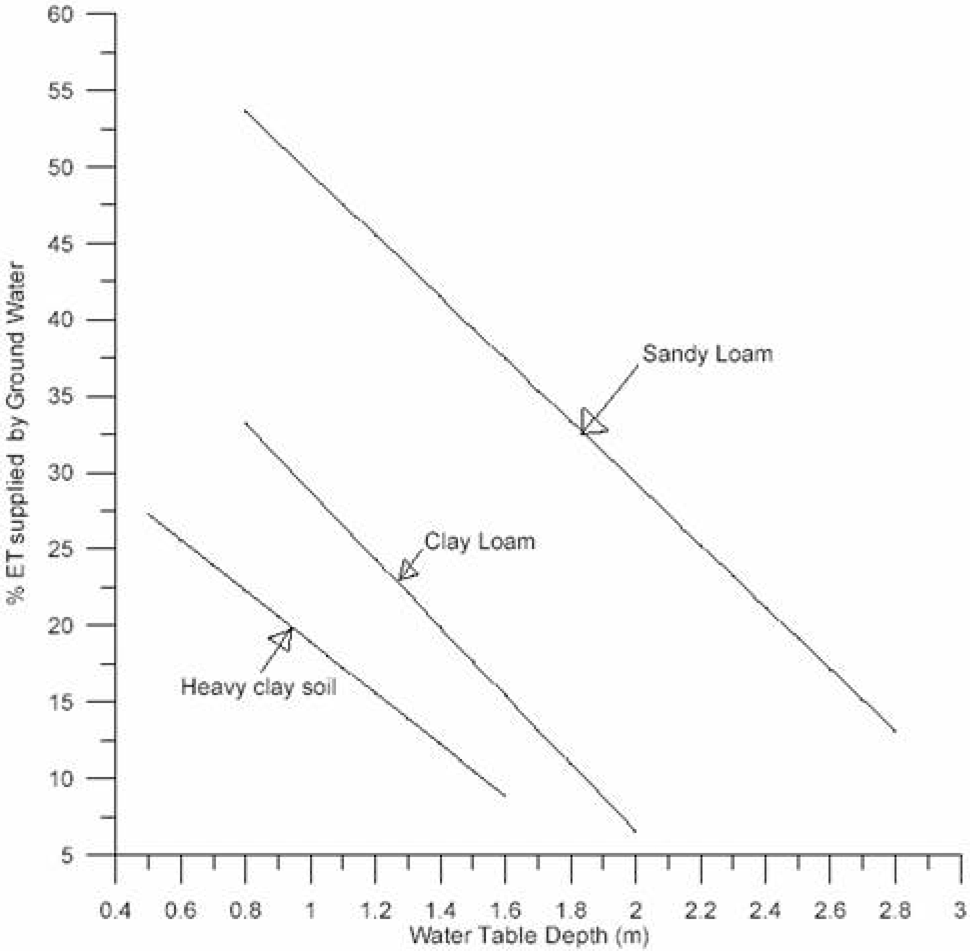


Figure 4. Percentage ground water use by cotton as a function of water table depth and soil type. After Grismer and Gates (1988).

The following sections describe a drainage control system tested in the San Joaquin Valley of California (Ayars, 1996).

3.1 Cilker Farms

A subsurface drain system of corrugated plastic tubing, which had previously been installed on 65 ha of land located in the Broadview Water District, was used for this research. The system is laid out in a gridiron pattern with a total of seven laterals spaced approximately 123 m apart. The lateral length is 670 m and the depth of installation is 2.4 m. 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. Figure 5 gives a schematic of the site showing the subsurface drain laterals, the location of the manholes, lateral valves, and observation wells. 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. Furrow irrigation using gated pipe occurred on 4/17, 5/25, 6/9, 6/17, and 6/25/94. 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 (Figure 5). The depth to the water table was measured weekly and used to plot water surface elevations and
responses to the valves opening and closing. Three areas in the field were identified to characterize the vegetative response to the water table depth. These were labeled shallow (S), medium (M), and deep (D). The drain laterals were installed on grade from west to east with the outlet on the east side of the field. The shallow area close to the control structures had a water table fluctuation from 1.5 to 2.2 m below the soil surface. The medium depth area had a water table depth of 1.8 to 2.6 m during the experimental period and the deep area had a water table
depth of 2.2 to 2.6 m during the project. The tomato rows were in a north-south orientation, perpendicular to the drain laterals. The individual sites were located such that the shallow site was on the east side of the field with the deep site on the west side and the medium site located between the two. LWP was determined two to three times a week at each of these sites. These sites were also used to determine crop yield. Yields were determined both by hand harvest and machine harvest.

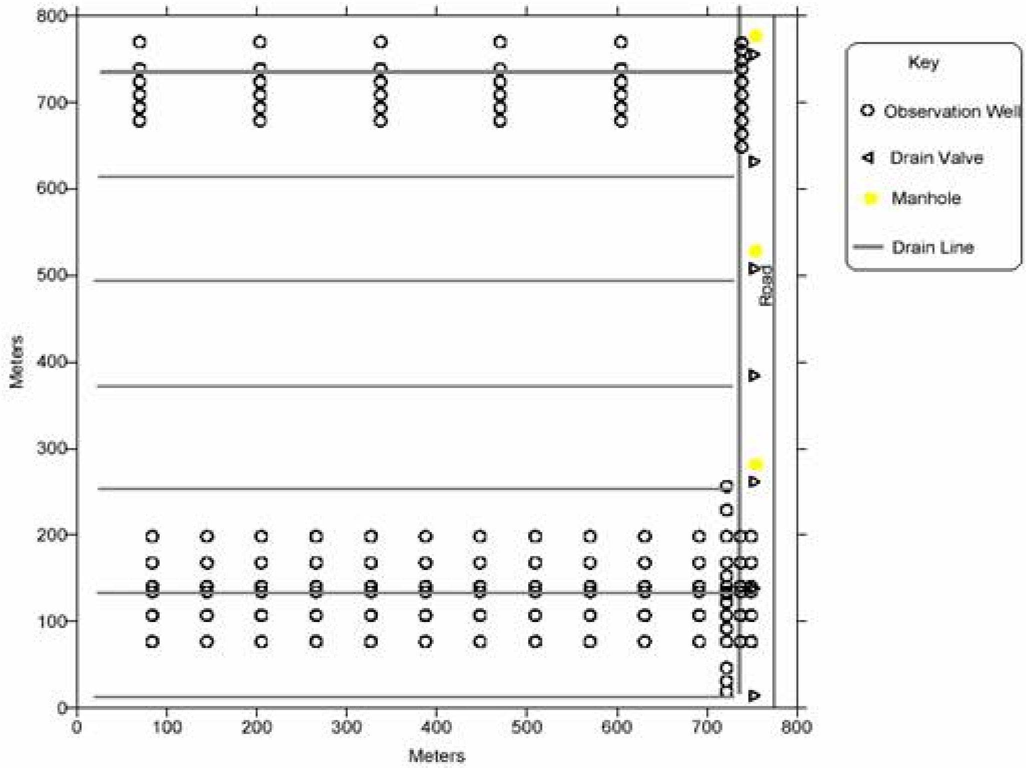
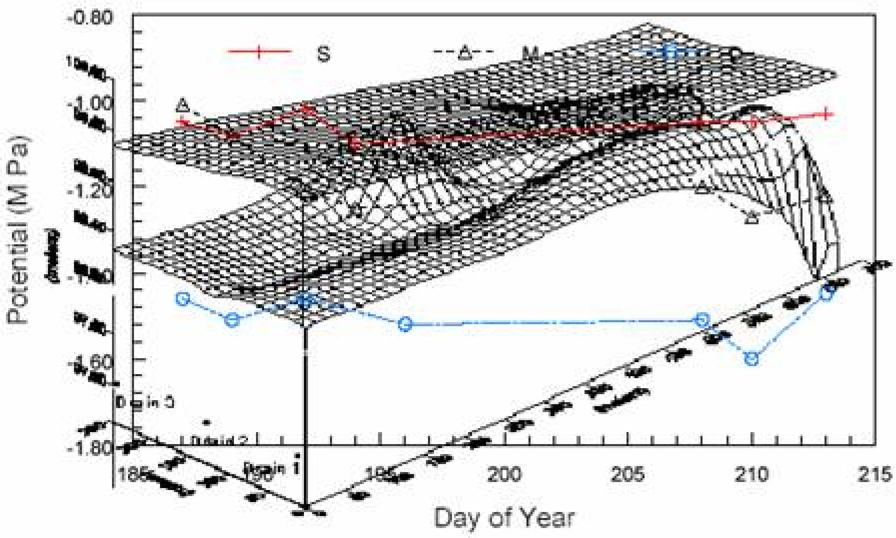


Figure 5. Schematic of field layout of drainage control system on Cilker farms.

3.1.1 Results

The water table response to valve operation is shown in Figure 6 for the period between the irrigations on 4/17/94 and 5/25/94. In Figure 6, the control structures are located at 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 Figure 6. After the valves were closed on each lateral, the water table rose to within a meter of the soil surface. The valves were opened and the water level receded to approximately 2 m below the soil surface (Figure 6). The valves were opened because the ranch manager was concerned about drying the soil profile in preparation for harvest.



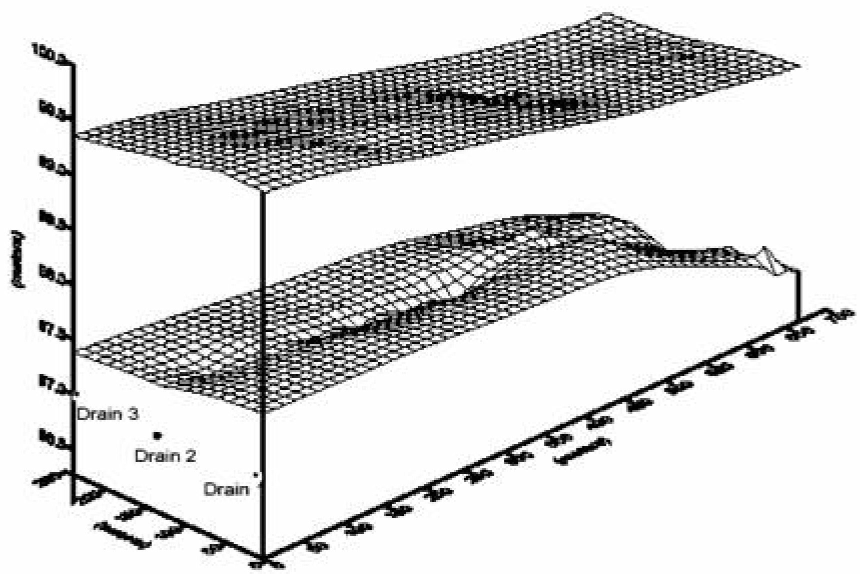


Figure 6. Water table position for the period between 4/17/94 and 5/25/94 in field with drainage system control.
Figure 7. Leaf water potential in tomato crop grow on field with water table control and three depths towater table, shallow (S), medium (M), and deep (D).

The plant response was measured in three areas in the field. The LWP is given in Figure 7 for plants growing in each experimental area. The data show that the plants were progressively more stressed as the initial depth to the water table increased. A potential of -0.9 to -1.1 MPa is considered a stress level for tomatoes that will not negatively impact yield. This level of stress was not attained in the shallow water table area and was only slightly exceeded in the medium water table depth areas. During the entire time of measurement, the plants in the deep water table area were stressed at a much higher level than in the other areas.

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, to reduce depth of each irrigation application, and determine if it was possible to control the water table. The results indicate that these objectives were met. 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 and reduced stress levels in the shallow and medium depth areas indicated that the crop was using shallow groundwater. Maintaining the shallow groundwater reduced the crop water requirement by 141 mm. A companion field which did not have water table control required 829 mm of irrigation and the

test field needed only 688 mm.
This resulted in a savings of 6.5 x 105 m_3 of water.

4. DESIGN CRITERIA

Another method to reduce drainage flow is to install the drains at a shallower depth. Doering (1982)proposed a shallow drainage concept to reduce over-drainage of soils. They found that shallow placement of the drains reduced the total flow and increased the amount of water used from the shallow ground water by the crop. Soil and water salinity were not a significant problems in the region where that research was conducted. The effect of shallow drainage placement on the drainage water quality and soil salinity is a significant concern and needs to be evaluated before this type of change can be recommended. Christen and Skehan (2001) reported on a replicated field trial in a vineyard in the Murrumbidgee Irrigation Area (MIA) that evaluated improved drainage design and management strategies. The new strategies were tested against current design and management practice, and a no drainage scenario, and are summarized in Table 8. Measurements were taken over three years from 1996 to the end of the 1998 season, this period included three irrigation seasons. Measurement on individual drainage treatments involved; irrigation and rainfall, run-off, drain flow, drainage salinity, water table depth, and soil salinity.

Table 8. Drainage treatment summary

Treatment name	Deep Drains	Shallow Drains	Managed Deep Drains	Undrained
Drain type	slotted PVC pipe	Unlined soil channel (mole)	slotted PVC pipe	none
Depth (m)	1.8	0.7	1.8	
Diameter (mm)	100	65	100	
Spacing (m)	20	3.65	20	
Length (m)	70	70	70	
Management	unrestricted flow	unrestricted flow	flow only when water table is above 1.2m, and not during irrigation events	

4.1 Results

The different drainage treatments resulted in markedly different drainage volumes and salinities, and hence salt loads, Table 9. The differences in flow resulted from the drain position in the soil profile and the management of the drains. The Deep Drains flowed continuously during the irrigation seasons, a small saline flow being sustained between irrigations and a large flow during and just after irrigation, Figure 8. The Deep Drains continued to flow long after an irrigation had ceased because they were draining a larger soil volume, down to 1.6-1.8 m, and they were influenced by regional groundwater pressures. This was despite the area having no significant shallow aquifer systems and being in a fairly flat area so that hydraulic gradients from neighbouring farms and channels were small. That there were some regional effects was demonstrated by the rise in piezometric levels at the beginning of the irrigation season in the experimental area before any irrigations had been applied. The Managed Deep Drains were less influenced by these regional effects and the Shallow Drains were completely isolated from them.

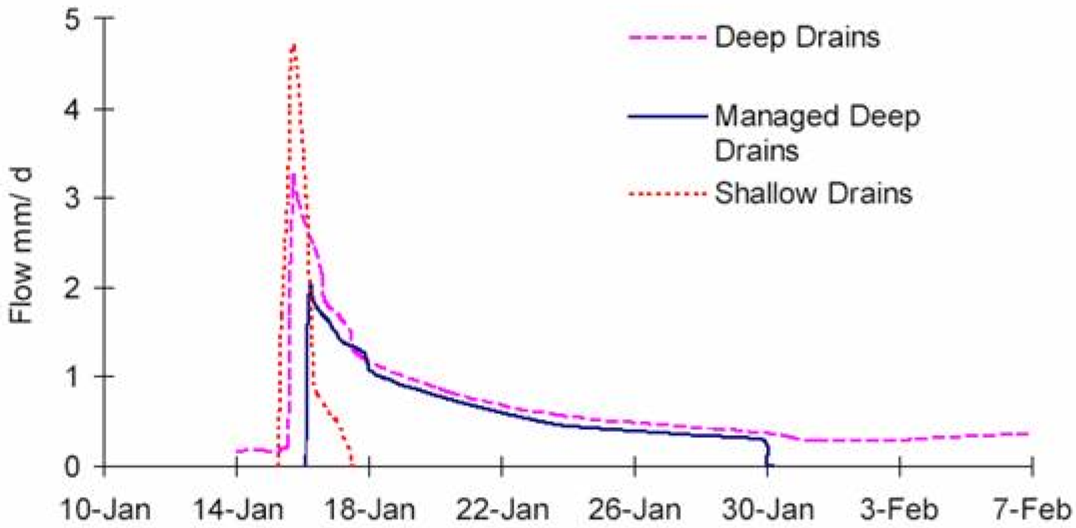


Figure 8. Drainage treatment hydrographs during and after an irrigation

The Deep Drains removed the most water and at the highest salinity, about 11dS/m, and hence had the highest salt load, Table 9. The Managed Deep Drains had 33 % less flow than the Deep Drains and a lower salinity, 7 -8 dS/m, resulting in a 49 % reduction in salt load. The Shallow Drains removed 78 % less water than the Deep Drains at a significantly lower salinity, about 2 dS/m, resulting in a 95 % reduction in salt load. The large amounts of water removed by the Deep Drains leads to reduced overall water use efficiency and increased farm costs in terms of increased pumping and nutrient loss. The extra salt removed by the Deep Drains compared to the Shallow Drains and even the Managed Deep Drains doesn't have a negative impact on the drained area but will adversely affect the receiving waters. If in the future farmers are charged for the amount of salt they export off farm then this extra salt export will have a negative effect upon farm income. Where farms are denied the option of off farm disposal of drainage water, then the use of shallower drains will be advantageous in reducing the overall volume requiring disposal and also the lower salinity of the drainage water will leave more options open for reuse.

Table 9. Drainage treatment volume, salinity and salt load.

Drainage Treatment	Total drainage volume (mm)	Average drainage salinity (dS/m)	Total salt load (kg/ha)
Deep drains	70	11	5867
Managed deep drains	47	7 - 8	2978
Shallow Drains	15	2	319

the three drainage treatments tested only the Shallow Drains came close to a salt balance with the irrigation water, removing 0.7 of the salt applied in the irrigation water. This is actually a small accumulation of salt, but this was in absolute terms a very small amount 170 kg/ ha, and was not accumulated in the root zone. The Deep Drains removed 11 times more salt than was applied, a large net leaching of salt. This leaching was not reflected in the soil salinity in the top 2 m, thus this salt was from below drain depth. The managed treatment exported 5 times more than the salt applied, still a large net export. This shows that drains placed deep in the soil profile will export large quantities of salt over and above that applied in the irrigation water. Assessment of the drainage water salinity with depth of water table confirms this. When the water table was at one meter below the surface the drainage water salinity from the Deep Drains was around 8 dS/ m; as the water table fell to 1.6 m below the surface the salinity increased to around 11 dS/m, Figure 9. This is consistent with the suggestion that deeper drainage intercepts deeper water flow paths that move through much more saline portions of the soil profile.

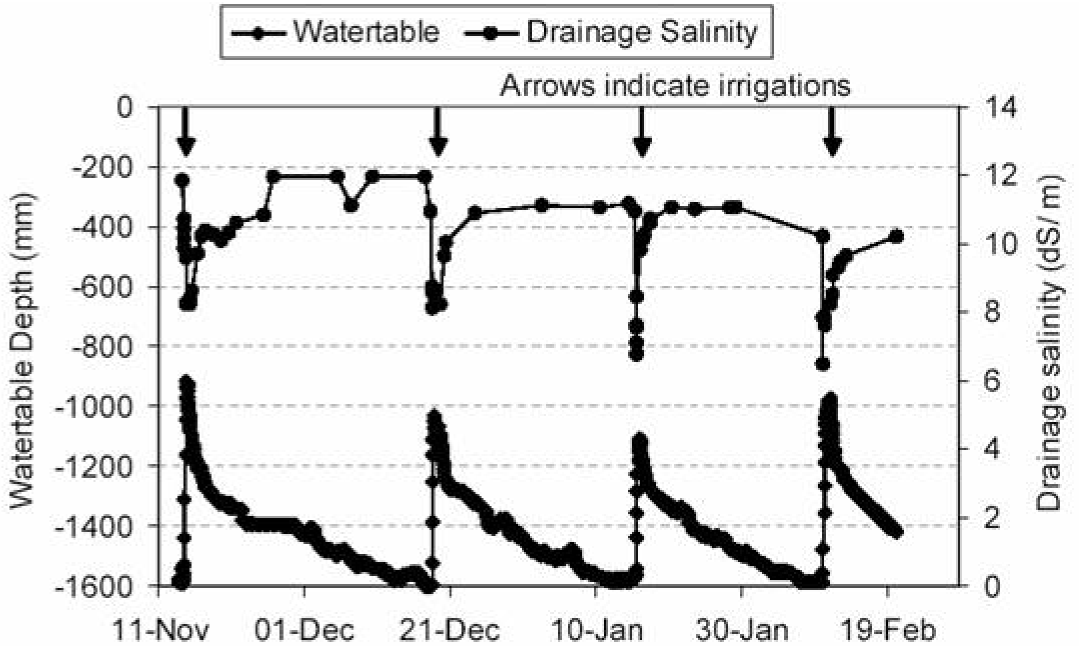


Figure 9. Drainage water salinity and watertable depth between drains

In terms of water table and waterlogging control the Deep Drains were adequate in reducing the periods of high water tables and waterlogging to a negligible amount, Table 10. The management changes used to control water flow from deep drains had only a small effect on waterlogging, about an extra day of waterlogging during the irrigation event itself. This minimal increase in waterlogging is a small trade off for the benefits of less water drained resulting in greater water use efficiency, lower operating costs and improved downstream water quality. At this stage in the development of the vineyard this small increase in waterlogging had no effect on vine leaf chlorides or yield. The Shallow Drains as expected gave the best control of root zone waterlogging, the watertable did build up beneath this treatment but was controlled at mole depth.
These varying water table regimes resulted in some differences in the root zone soil salinity trends over the two seasons monitored, Figure 10 and Figure 11. The Undrained treatment soil salinity remained static, whereas all the drained treatments showed a decrease in salinity after the first season. In both the Shallow Drains and Managed Deep Drains there was a rise after the second season resulting in no net change. For the average salinity down to two metres this picture was similar except the Deep Drains showed a fall in salinity after both the first and second seasons. These results are somewhat unclear in terms of the possible effects of the different treatments on long-term soil salinities especially since the undrained treatment did not show any change in salinity over the experimental period. However, there is an important outcome from this analysis in that, the drainage treatments had only small effects on the root zone salinity, no measurable effect on vine health over the experimental period, but still drained water and salt from the area. So over this particular time the water drained, salt removed, costs incurred and downstream impacts of drainage water resulted in little benefit to the farm. Under these circumstances of small benefit from a drainage system, which can occur due to site factors, dry climatic conditions and plants not highly susceptible to waterlogging, it is even more important that the drainage system incurs the least downstream impacts and least costs to the farmer.

4.2 Discussion

This field trial was conducted in a drier than average year, the relatively low drainage flows and static soil salinities reflect this. During wetter conditions it is likely that the drainage water reduction would be greater than measured here and that there would be more soil leaching due to rainfall, both of which are positive. However, there may be negative effects due to the design and management suggested, such as increased waterlogging. These negative effects are unlikely to be great and with good management could be monitored and controlled. For instance if the water table was remaining high for too long on the Managed Deep Drains then the drainage depth could be increased to provide a greater soil buffer to store rainfall. The main negative effect of a prolonged wet period on the Shallow Drains would be an increased rate of collapse in the mole drains. At this site, the soil was quite stable and as such it is unlikely that the moles would collapse to the point of being ineffective within a single season. Obviously if a shallow pipe system was installed this would not be a concern.

Table 10. Duration of water tables above specified depths

Treatment	Water table depth (mm) 300	500	1000
	Number of hours		
Deep Drains	70	86	156
Managed Deep Drains	26	60	207
Shallow Drains	13	27	64
Undrained	70	168	859
	Percentage of time		
Deep Drains	3	4	8
Managed Deep Drains	1	3	10
Shallow Drains	1	1	3
Undrained	3	8	42

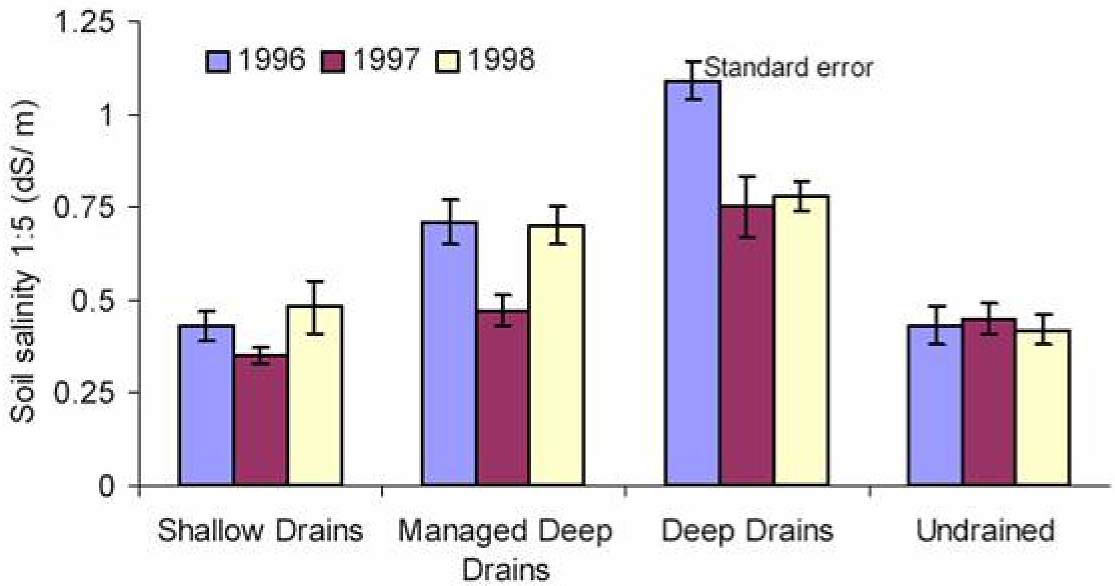


Figure 10. Change in salinity in the top 600 mm of soil

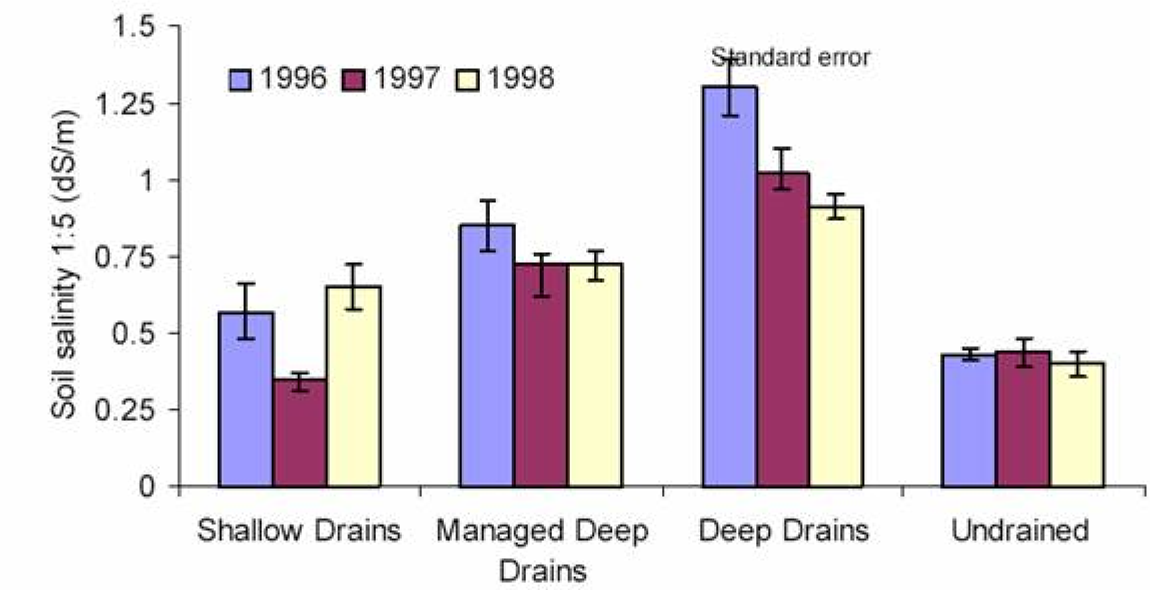


Figure 11. Change in salinity in the top 2000 mm of soil

Predicting the effects of wetter periods on the results of drainage design and management tested here is possible. The likely drain flow under wet conditions can be considered by analysing single high input irrigation events. Figure 12 and Figure 13 show the proportion of water applied that drained through the different drainage treatments at a particular event. During wet periods when the soil has a small storage a lot of the water applied that does not run off will be drained out, similar to irrigations 3 and 4 in Figure12 and the highest ranked drainage events in Figure 13. This gives an indication that under wet conditions it is likely that up to 25 % of water applied may be drained by a deep pipe drainage system, whether managed or not.

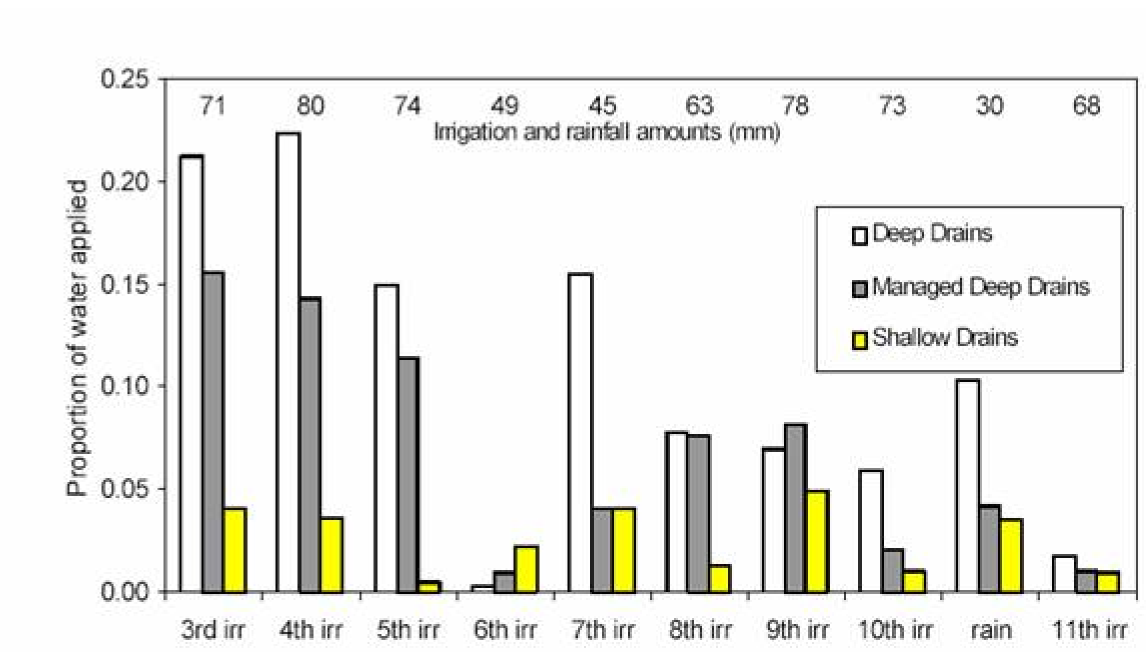


Figure 12. Drainage as a proportion of water applied at each event

The rate of drainage can be predicted by considering the drain hydrographs such as in Figure 8. The peak flow rates shown here are unlikely to be greatly exceeded, but the duration of the peak flows will be prolonged under wet conditions with high inputs of water. The effect of wetter conditions on drain water salinity can be considered using the drainage water salinity as a function of water table depth results. Since water tables are likely to be high during wet conditions the drain water salinity will be lower than dry periods when the water tables are deeper. The height and duration of water tables during wetter periods is harder to predict. Water table depth is a function of the time from the last recharge event, the drainage rate of the system and the combination of deep leakage and plant water use. If recharge events are larger, and at shorter intervals, then watertables will remain higher.

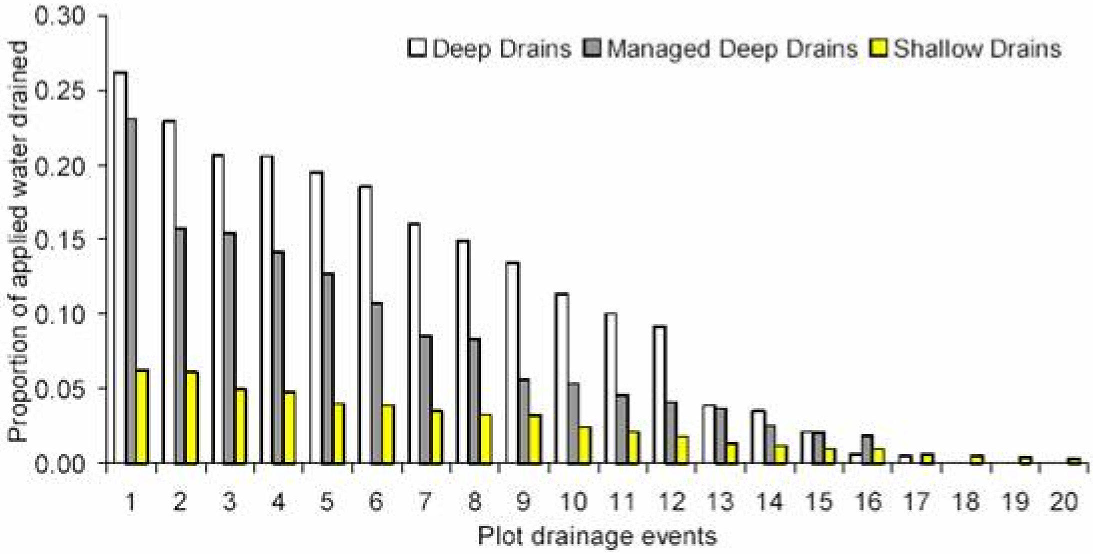


Figure 13. Water application and the proportion of water drained (individual plots)

An indication of the impact of a drainage system on water use efficiency and hence total water costs is shown by the Deep Drains that drained 20 % or more of the water applied in 23 % of plot drainage events and drained 10 % or more in 65 % of plot drainage events. This is a considerable proportion of the water applied that was intended for use by the plant. Management of deep drains cut the proportion of plot drainage events draining more than 10 % of water applied to 37% and events draining more than 20 % to 6 %. This is a significant improvement but does not match the Shallow Drains, which drained less than 5% of the water applied in 90 % of plot drainage events. Drainage systems for irrigated areas on clay soils in south eastern Australia can be designed and managed better than the currently accepted practices, so that detrimental downstream environmental effects due to excessive salt export are reduced, without affecting the productivity of the farm.

CONCLUSIONS

The objective of the study was to evaluate the potential for sustaining irrigated agriculture in arid and semiarid areas that are impacted by salt in the soil and the shallow ground water. Accumulation of salinity in the soil profile, the inability to dispose of saline ground water, and the reduction in the available water supply were considered to be the primary factors affecting the sustainability. Drainage will always be a component in irrigated agriculture and is the system that is needed to manage the salinity in the profile. It is also the system that generates the saline water that has to be managed and requires responsible disposal. The ability to manage the drainage system and the salt load will be central to sustaining irrigated agriculture.

The results from these studies lead to the following conclusions:

Reuse of saline water for supplemental irrigation is a viable alternative for extending existing water supplies, particularly if the area is affected by lateral ground water flows that need to be controlled. Salt in the profile can be managed through the use of rainfall and pre-plant irrigation with good quality water during fallow periods.

Total drainage flow will be reduced when drainage water is used for supplemental irrigation..

Water containing high levels of boron should not be used.

The water table can be controlled over a wide range of depths using either individual control on the laterals or control along the submain collector. Irrigation water requirements are reduced when the water table is controlled.

New configurations of the subsurface drain laterals will be required to effectively manage shallow ground water. Drainage lateral design criteria need to be changed to consider shallow drain lateral placement and control structures.

Shallow drains remove less irrigation water than deep drains, thus reducing irrigation losses.

Compared to deep drains in this trial, shallow drains have low drainage water salinity and remove smaller drainage volumes, thus reducing the salt load, with up to 95 % reduction. Shallow drains control waterlogging better than deep drains.

Managing deep drains by preventing discharge during irrigation and whenever the water table was below 1.2 m deep reduced irrigation water losses compared to unmanaged deep drains.

Managing drains reduces flow and drainage water salinity compared to unmanaged drainage, resulting in a reduction in drainage salt load of 50 % in the third study.

A more rapid decline in drainage water salinity can be achieved by managing deep drains.

In the third study a deep pipe irrigation system, without major groundwater inflow from surrounding areas, only needed to be run for 2 to 7 days after an irrigation to control the water table below the root zone.

Best management practices for subsurface drainage system design and management are needed for drainage systems being constructed and operated in arid and semi-arid areas throughout the world.

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