Task 5

Source Reduction

Final Report

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Source Reduction Technical Committee

The San Joaquin Valley Drainage Implementation Program and

The University of California Salinity/Drainage Program

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The San Joaquin Valley Drainage Implementation Program was established in 1991 as a cooperative effort of the United States Bureau of Reclamation, United States Fish and Wildlife Service, United States Geological Survey, United States Department of Agriculture-Natural Resources Conservation Service, California Water Resources Control Board, California Department of Fish and Game, California Department of Food and Agriculture, and the California Department of Water Resources.

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San Joaquin Valley Drainage Implementation Program

Report from the Technical Committee on Source Reduction

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Source Reduction: Report of the Task 5 Technical Committee

I. Introduction

About 1,000,000 acres are affected by shallow, saline groundwater in the San Joaquin Valley. Depth to the water table generally is less than 5 to 10 feet in these areas. The water table is shallowest in early spring caused by winter rainfall and preplant irrigations. In many areas, depth to the water table increases with time during the growing season due to reduced percolation from irrigation caused by decreasing infiltration rates, increased soil moisture storage, increased shallow groundwater use by crops, and natural drainage.

Relatively high levels of soil salinity in the root zone occur in the drainage problem areas due to upward flow of groundwater. The soil salinity reflects the salinity of both the irrigation water and the groundwater. Salinity near the surface reflects that of the irrigation water, while at the deeper depth, soil salinity reflects that of the groundwater. Higher levels of soil salinity generally occur in the fall compared with spring levels.

Salinity management is necessary to prevent crop yield reductions due to excessive levels of soil salinity. The traditional approach to salinity control in the presence of saline shallow groundwater is to install subsurface drains. The drains lower the water table depth, thus reducing upward flow, while removing the drainage water needed to leach salts from the root zone. However, disposal of the drainage water is necessary for the drains to operate.

Currently, limited drainage water disposal is permitted into the San Joaquin River from areas in the northern part of the SJV and to evaporation ponds in the Tulare/Kern subarea. Many options such as deep-well injection, desalination, water treatment to remove selenium have been investigated, but were found to be either technically, environmentally, and/or economically unsatisfactory. Presently limited disposal options for subsurface drainage means that drainage systems are not now viable for many areas of the Valley. While some disposal options (water treatment, drain water reuse) continue to be investigated, reducing the amount of subsurface drainage water through source reduction will play a major role in dealing with problems caused by the shallow, saline groundwater.

II. Source Reduction

Source reduction involves reducing the amount of subsurface drainage water from a field. Options recommended by the San Joaquin Valley Drainage Program (1990) are:

- Water conservation:
  - Improve existing irrigation practices and/or adopt new irrigation methods
  - Improve irrigation scheduling.
  - Improve management of irrigation systems.
  - Manage the water table to increase its contribution to crop evapotranspiration.

- Change in land use - cease irrigation of lands that have high salinity and selenium concentrations in underlying shallow groundwater and that are difficult to drain.

This paper addresses source reduction through water conservation. Recommended target reductions of subsurface drainage by the year 2000 are listed in Table 1.

Table 1. Recommended targets for reduction in subsurface drainage in 2000.

Subarea	Target Reduction (acre-feet/acre)
Northern	0.0
Grasslands	0.35
Westlands	0.35
Tulare	0.20
Kern	0.35

III. Improved Irrigation

Uniformity and irrigation efficiency describe the performance of an irrigation system. Uniformity refers to the evenness of the depth of water applied or infiltrated throughout the field and depends on system design and maintenance. An index commonly used to describe uniformity is the distribution uniformity (emissions uniformity sometimes is used for micorirrigation). Irrigation efficiency refers to the amount of water needed for crop production compared with the amount applied to the field and depends on system uniformity and management. Note that sometimes the term “water use efficiency” is used in lieu of irrigation efficiency, which is incorrect. Water use efficiency is not irrigation efficiency. By definition, water use efficiency is the ratio of crop yield to evapotranspiration.

Irrigation practices can be improved by increasing uniformity and efficiency. Improving the uniformity involves upgrading existing irrigation systems or converting to systems with a potential for better uniformity. Improving efficiency involves improving both uniformity and management where management consists of determining when to irrigate and how much to apply. The better the uniformity, the larger the potential for higher irrigation efficiency.

Table 2 lists potential practical maximum irrigation efficiencies, developed from an analysis of nearly 1000 irrigation system evaluations (Hanson, 1995). Practical irrigation efficiencies are ones that are technically and economically feasible. These values assume that the least watered part of the field receives an amount equal to the beneficial use and that surface runoff is beneficially used. Because microirrigation has the potential for the best distribution uniformity, the potential irrigation efficiency is also better.

Table 2. Potential maximum practical irrigation efficiencies.

Irrigation Method	Irrigation Efficiency (percent)
Sprinkler	
Continuous-move	80-90
Periodic-move	70-80
Solid-set	70-80
Microirrigation	80-90
Furrow	70-85
Border	70-85

It is commonly assumed that the uniformity of microirrigation systems, and thus the efficiency, is much higher than that of other irrigation methods. The analysis of nearly 1000 irrigation system evaluations indicates otherwise (Hanson et al, 1995). A conclusion from this analysis is that the field-wide uniformity of microirrigation systems is likely to be similar to those of other irrigation methods. The study also concluded that microirrigation has the potential for higher uniformity, and thus higher efficiency if systems are properly designed, managed, and maintained. Unfortunately, little correlation between age of the system and field-wide uniformity was found indicating that new systems were not designed to realize the potential of microirrigation.

Evapotranspiration, Applied Water, Crop Yield, and Drainage

Strategies for source reduction though improved irrigation practices must consider the effect of the improvement not only on the subsurface drainage, but also on crop yield and farm profits. It is possible to greatly reduce subsurface drainage by deficit irrigation. However, this approach can reduce crop yield, and thus profitability, to a level such that farming is not economical.

Possible interactions between applied water, uniformity, crop yield, and subsurface drainage are illustrated in Figure 1, which shows relationships between alfalfa yield and applied water and between subsurface drainage and applied water for various levels of uniformity. The distributions of applied water used for the different levels of uniformity were developed from sprinkler catch-can data. The alfalfa yield - evapotranspiration relationship (Grimes, et al, 1992) showed the maximum evapotranspiration to be 39.4 inches and maximum yield to be 11.7 tons ac^{-1}.

For a DU equal to 91 percent, maximum yield occurred at about 45 inches, slightly more than the maximum evapotranspiration (Figure 1a). However, as the uniformity decreased, larger and larger applications were required for maximum yield. For a DU equal to 64 percent, nearly 77 inches of water was required for maximum yield. In reality, irrigating for maximum yield is not practical for an irrigation system with a very poor uniformity because large amounts of applied water are needed.

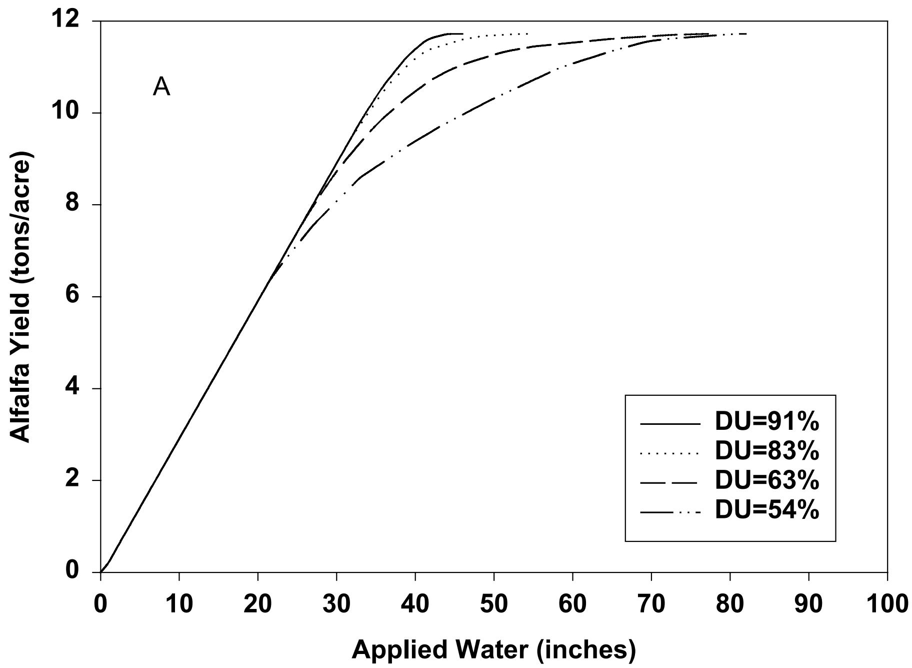
The effect of both uniformity and applied water on the drainage is shown in Figure 1b. For the highest uniformity, no drainage below the root zone occurred until the amount of applied water nearly equaled the maximum evapotranspiration. Drainage amounts were small. As the uniformity decreased, drainage occurred at smaller and smaller amounts of applied water, the result of some parts of the field receiving more water than other parts. For the smallest uniformity, drainage below the root zone started occurring at 22 inches of the applied water. Thus, for a given amount of applied water, the amount of drainage increased as the uniformity of the applied water decreased.

These results show that for high uniformity and proper management, maximum yields can be obtained with minimal little drainage. This translates into high irrigation efficiency. However, the scenarios used for Figure 1 assume proper management of the irrigation water, i.e. the least-watered part of the field received an amount equal to the beneficial use. Lack of proper management can aggravate the situation by applying water in excess of the beneficial use in the least-watered part of the field, resulting in severe overirrigation throughout most of the field.

Improving Irrigation Management

Irrigation management involves irrigation scheduling or determining when to irrigate and how much irrigation water to apply. The water balance method commonly used for irrigation scheduling uses data from the California Irrigation Management Information System (CIMIS) network to calculate crop evapotranspiration. A basic assumption in this method is that changes in soil moisture between irrigations equals crop evapotranspiration between irrigations.

Where shallow groundwater exists, this assumption is invalid. Upward flow of groundwater into the root zone means that changes in soil moisture between irrigations will be less than crop evapotranspiration. Thus, using CIMIS data to estimate changes in soil moisture will result in more water being applied to the soil than is need for soil moisture replenishment, which will increase subsurface drainage.



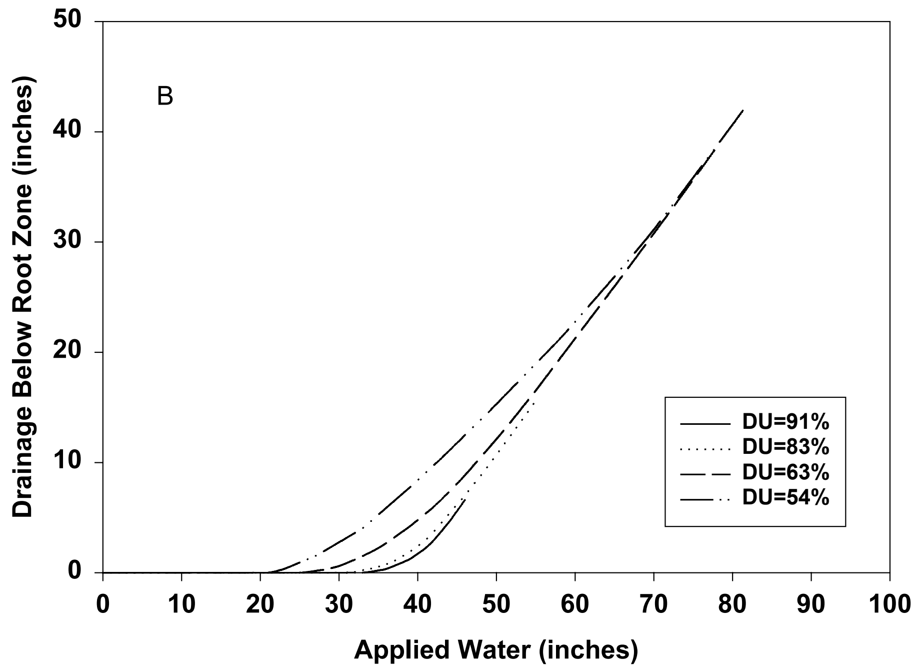


Figure 1. Relationships between (A) yield and applied water and (B) drainage below the root zone and applied water.

Several approaches have been investigated for irrigation scheduling in the presence of saline, shallow groundwater. One approach appropriate for cotton is the pressure chamber, a device that can be used for measuring water and salinity stress in a plant. Grimes and El Zik (1982) developed guidelines for this approach. They related pressure chamber readings just before an irrigation to cotton yield. Hanson and Kite (1984) used this method in a field with a shallow water table and reduced the number of irrigations by one compared with the grower's normal practice. Crop yield increased by about 16 percent using the pressure chamber method. While this method can be used to determine when to irrigate, measurements of soil moisture are still needed to know how much to apply. This method is appropriate for crops that can tolerate some stress from insufficient soil moisture and/or salinity. Unfortunately, relationships between pressure chamber reading just before irrigation and crop yield are not available for crops other than cotton.

Crop evapotranspiration using CIMIS data is determined by multiplying the CIMIS reference crop evapotranspiration by a crop coefficient, which depends on crop type and stage of growth. Ayars and Hutmacher (1994) developed crop coefficients for cotton that account for the upward flow of shallow groundwater. These coefficients depend on stage of growth, depth to the water table, and salinity of the shallow groundwater. The product of these crop coefficients and reference crop evapotranspiration is the soil moisture depletion, not the crop evapotranspiration. Both timing and depth of application of the irrigation can be established using these modified crop coefficients.

Measurements of soil moisture content can also be used for irrigation scheduling. Many methods exist for monitoring or measuring soil moisture content. Devices such as tensiometers and electrical resistance blocks measure soil moisture tension. However, resistance blocks may not be suited for salty soil because the soil water salinity can affect their readings.

Many consultants use neutron moisture meters to measure soil moisture content. These devices are easy to install and operate, and when properly calibrated, provide reasonable accurate measurements. Because they use a radioactive material, registration and training of operators is required.

Recently, dielectric soil moisture sensors are being marketed for measuring soil moisture content. These devices measure the dielectric constant of soil, which largely depends on soil moisture content. Calibration equations relate dielectric constant to soil moisture content. These instruments generally are classified as time-domain-reflectometry (TDR) and frequency-domain-reflectometry (capacitance) devices although other types of instruments exist.

Many different configurations of dielectric sensors are available. Detailed evaluations of some of these devices revealed uncertainty in their performance. Some instruments provided reasonable accurate measurements of soil moisture content in fine-textured soils of the westside of the SJV, while others did not. In some cases, the dielectric instrument would not operate would not operate in these soils. Thus, caution is recommended in using these devices, some of which are expensive.

Improving Irrigation System Uniformity

Uniformity can be improved by upgrading existing irrigation systems or by converting from systems with an inherently low uniformity to ones with a potential for high distribution uniformity. Methods for upgrading existing irrigation systems are discussed below. If implementing these methods fail to substantially improve the distribution uniformity, then conversion to a system with the potential for a higher uniformity is necessary.

Furrow irrigation, the most common irrigation method in the drainage problem areas, is relatively difficult to upgrade and manage efficiently compared to other irrigation methods. The primary problem is that its performance largely depends on the water infiltration rate, which varies during irrigation, varies with time during the irrigation season, and is strongly affected by soil texture variation throughout a field and by cultural practices. Measuring the infiltration rate is not practical for irrigators making the management of furrow irrigation systems somewhat of a trial-and-error procedure. Strategies for improving uniformity include decreasing the water advance time to the end of the field and reducing the infiltration rate. Measures commonly recommended for improving the uniformity of surface irrigation are as follows:

1. Reducing the field length is the most effective measure for improving the uniformity and for reducing drainage below the root zone for field lengths exceeding about 1000 feet (Hanson, 1989). Decreasing the field length by one-half can reduce subsurface drainage by at least 50 percent and increase the DU by 10 to 15 percentage points compared with the initial field length. This measure will be effective only if the irrigation set time is reduced because the advance time to the end of the shortened field can be 30 to 40 percent of the advance time to the end of the initial field length. The reduction in irrigation set time is equal to the difference between the initial advance time and the new advance time. Failure to reduce the set time will greatly increase both subsurface drainage and surface runoff.

   A major problem with this measure is the potential for increased surface runoff. A potential exists for 2 to 4 times more runoff compared with the initial field length. Cutback irrigation can alleviate this problem provided that the irrigation district will allow a decrease in the field inflow rate. Cablegation has proved to be an effective method for providing cutback irrigation and minimizing surface runoff (Kemper et al, 1981). Other measures for coping with this problem using tailwater recovery systems to recirculate the water back to the head of the field or using the runoff on lower-lying fields. Reservoir storage is needed for both scenarios.

2. Increasing the unit inflow rate, a commonly recommended measure, reduces the advance time to the end of the field, thus decreasing variability in infiltration opportunity times along the field length. However, field evaluations coupled with computer modeling of furrow irrigation systems revealed that this measure may have little effect on both the uniformity and the drainage (Hanson, 1989). The higher furrow inflow rates increased the depth of flow in the furrow, which in turn increased the wetted area for infiltration. Thus, the higher inflow rates caused higher infiltration rates, which offset the effect of the smaller advance time to the end of the field.

3. Converting to surge irrigation can reduce drainage below the root zone by decreasing the infiltration rate to a value smaller than would occur under conventional furrow irrigation. Field evaluations have shown that the amount of water needed to reach the end of the field under surge irrigation is about 30 to 40 percent less than that needed under continuous-flow irrigation (Hanson et al, 1994). Surging also appears to reduce the effect of soil variability on infiltration uniformity. At one site, surge irrigation not only reduced the average depth infiltrated by 31 percent, but also reduced infiltration differences caused by soil texture variation by 37 percent (Pukey and Wallender, 1989). Others (Bishop, et al, 1991; Iyuno et al, 1985) found surge irrigation to reduce differences in infiltration rates between wheel and nonwheel furrows and to reduce seasonal differences in infiltration rates.

   Surge irrigation is most appropriate for furrow irrigation systems using gated pipe. Solar powered surge valves are available to control the surge times. Surge irrigation is difficult to apply to furrow irrigation systems using siphons and also to border or basin irrigation systems using alfalfa valves, sliding gates in ditches, and so forth.

4. Other measures for improving the uniformity of infiltrated water include improving the slope uniformity through better land grading, and compacting the furrow surface using torpedoes (cylinder-shaped weights pulled in the bottom of the furrow) or tractor wheels. Field evaluations have shown these measures may have a minor effect on system performance (Schwankl et al, 1992).

Uniformity of sprinkler and microirrigation systems (microsprinklers, drip emitters, drip tape) depends on hydraulic losses throughout the systems and maintenance. Upgrading these systems involves better maintenance and reducing these hydraulic losses. Methods for reducing these losses include proper selection of lateral lengths and pipeline diameters, appropriate pressure regulation throughout the irrigation system, and/or use of flow-control sprinklers or pressure-compensating emitters. Maintenance consists of repairing malfunctioning sprinklers or emitters and preventing clogging of orifices. For the hand-move sprinklers commonly used in the drainage problems areas, proper sprinkler spacing is important for achieving potential uniformities.

Under some circumstances, improving the uniformity or efficiency of a furrow irrigation system may not be feasible or practical. For example, Hanson et al, (1998) found that in one cracking clay soil, reducing the run length, increasing the furrow flow rate, or converting to surge irrigation had little effect of system performance because water flow into the cracks dominated the infiltration process. Also, the uniformity of periodic-move sprinklers (hand-move, wheel-line) may be limited by the interaction of wind and lateral spacing. Under the best of conditions, distribution uniformity of periodic-move systems may range between 70 and 80 percent. Thus, improving uniformity may require converting to an irrigation system with the potential for high DU compared with the existing system.

Options for conversions include changing from furrow systems to hand-move sprinklers, linear-move machines (sprinklers, low energy precise application (LEPA)), or micorirrigation. The potential distribution uniformity of linear-move sprinkler machines and microirrigation systems is at least 80 percent.

Opportunities for Improvement

Data obtained from field evaluations by mobile irrigation laboratories located throughout the state provide information on opportunities for improving irrigation. For microirrigation systems of permanent crops, the evaluation data showed that 66 percent of these systems had a distribution uniformity less than 80 percent, the recommended minimum uniformity level for these irrigation systems. Nearly 38 percent had a DU of less than 70 percent. No relationship was found between DU and system age, indicating that many new systems had an unacceptable DU. About 44 percent of the systems were deficit-irrigated, while 16 percent were overirrigated. These results suggest that much opportunity exist for improving design, maintenance, and management of these systems.

It is hypothesized that the performance of microirrigation systems is more likely to be better than others. Thus, more opportunity for improvement may exist for other irrigation methods.

Field Demonstrations

Goldhamer and Peterson (1984) compared a linear-move sprinkler machine and a furrow irrigation system on a sandy loam soil. Alternate furrow irrigation was used with a field length of about 1250 feet. Results, in Table 3, showed slightly higher cotton yields for the linear-move machine. Infiltrated water was about the same for both systems, however, more deep percolation occurred under the furrow system. Both annual revenue and annual costs were higher for the linear move machine. Net returns (returns to land and management) were slightly higher for the furrow system.

The potential for drainage reduction by reducing furrow length by one-half and set time was assessed using field evaluation data and computer-simulation modeling (Hanson and Fulton, 1994). Results showed that subsurface drainage of the preplant irrigation could be reduced from 7.1 inches to about 2.6 inches. The cost of the improved furrow system resulted in smaller net returns compared with the normal furrow system. No yield increase due to the improvement was assumed in this analysis.

Table 3. Comparison of linear-move sprinkler machine and furrow irrigation systems.

Irrigation method	Cotton yield (lb/ac)	Applied water (inches)	Net returns ($/ac)
Linear-move sprinkler	1,274	29.5	299
Historic furrow	1,176	29.2	308
Improved furrow	1,176	29.5	296

A buried drip irrigation system, an upgraded furrow system, and a surge irrigation system were compared to the traditional furrow system on a clay loam soil (Fulton et al. 1991). The traditional furrow length was 2,362 feet. A 1,180 feet furrow length was used for the preplant irrigation for both the improved and surge systems; a 2,360-foot length was used thereafter. Drip tubing was buried about 18 inches deep with a lateral spacing of about 3.33 ft. Lateral lengths were about 600 feet.

Table 4 shows cotton yield to be about 12 percent higher for the drip system compared with the furrow system. No differences in yield occurred among the furrow systems. About 2.2 inches more water was applied by the improved furrow, 2.6 inches by the surge system, and 4.1 inches by the traditional furrow system compared with the drip system. Surface runoff was assumed to be beneficially used.

Net returns were the largest for the traditional furrow, followed by the improved furrow and surge systems. Net returns for the drip system were about one-half of those of the furrow systems.

Table 4. Comparison of buried drip, improved furrow, surge irrigation, and historic furrow irrigation systems.

Irrigation method	Cotton yield (lb/ac)	Applied water (inches)	Net returns ($/ac)
Drip	1,421	21.9	204
Improved furrow	1,274	24.1	401
Surge	1,274	24.5	401
Historic furrow	1,274	26.0	413

Another field demonstration compared a buried drip system, a LEPA system, and a furrow system on a clay loam soil (Boyle Engineering Corp. 1994) from 1989 to 1993. No improvements were made to the 1989 furrow system, which had a field length of about 1,190 feet. In 1990, an improved furrow system with a field length of 595 feet was used as well as the conventional system. Drip tubing was buried

18 inches deep with a lateral spacing of 80 inches. Hand-move sprinklers were used for stand establishment of the drip system.

Results in Table 5 showed average cotton lint yields of the drip system to be about 16 percent higher compared with the furrow yields. The LEPA system had the smallest average yields, mainly due to management problems. Less water was used by the drip system compared with the furrow systems, and average net returns were higher for the drip system for the project duration.

Table 5. Comparison of buried drip, LEPA, improved furrow, and historic furrow irrigation methods. Values are averages over the duration of the project.

Irrigation method	Cotton yield (lb/ac)	Applied water (inches)	Net return ($/ac)
Drip	1,458	22.1	266
LEPA	987	20.7	27
Improve furrow	1,255	23.5	205
Historic furrow	1,251	25.9	239

Improved furrow irrigation and hand-sprinklers were compared at two locations along the westside of the valley (Dellavalle Laboratory, Inc., 1995). The improved furrow systems consisted of surge irrigation and reduced furrow lengths. In some cases, sprinklers were used for the preplant irrigation only, while, at other times, they were used through the entire irrigation season.

Results, in Table 6, showed that it was not possible to conclude from these comparisons that one irrigation method was better than another. For example, at the Red Rock site, more water was applied during the 1991 preplant irrigation with the hand-move sprinkler system (9.4 inches) than with the furrow system (5.0 inches). The following year, much less water was applied with the sprinkler system (2.3 inches) compared to the furrow system (4.8 inches). These results, however, illustrate the importance of management in source reduction to prevent any overirrigation, regardless of the irrigation method.

Panoche Water and Drainage District Study

A study (Ayars and Schrale, 1990; Ayars, 1995) was conducted to determine if selenium (Se) and other toxic discharge associated with drainage water from irrigated agriculture could be reduced by improved on-farm irrigation practices and drainage management within an irrigation district boundary. The study was conducted within the Panoche Water and Drainage District (PWDD) using District records of applied water, cropping patterns, and drainage flow. Additional sites were located on 6 fields within the district.

The PWDD is located on the west side of the SJV and is comprised of approximately 38,000 acres of irrigated land. It extends from the eastern foot of the coastal range to the west side plain of the San Joaquin River. The soil permeability grades from high to low from west to east and the Se distribution comes from low to high when moving west to east. This means the higher concentrations of Se in the soil profile are found in areas with low permeabilities. Irrigation is primarily by gravity methods followed by sprinkler. These data reflect the time prior to 1989. Surface and subsurface drainage flows were combined prior to and during the investigation. This has changed since the time of the investigation and the subsurface and surface flows are no longer commingled. Principal corps grown in the District include cotton, processing tomato, sugar beet, melons, wheat, and alfalfa.

Table 6. Comparison of historic furrow, surge, and hand-move sprinkler irrigation methods.

Davis Site

Irrigation	1989 Cotton		1990 Cotton		1992 Cotton		1993 Cotton	
	West	East	West	East	West	East	West	East
Applied Water (inches)								
	Surge	Historic	Hist.	Surge	HM	HM	Surge	Historic
Preplant	8.0	6.6	9.8	9.8	5.1	5.1	0.0	0.0
Crop Irrigation.	12.2	11.5	16.5	16.2	17.7	18.9	18.1	21.1
Total	20.2	18.1	26.3	26.0	22.8	24.0	18.1	21.1
Drainage Below Root Zone (inches)								
Preplant	2.1	0.8	1.3	2.4	0.7	0.6	0.0	0.0
Crop Irrigation	1.7	0.9	4.9	4.0	3.4	5.1	3.6	6.6

Red Rock Site

Irrigation	1991 Cotton		1992 Cotton		!993 Cotton	
	West	East	West	East	West	East
Applied Water (inches)						
Preplant	HM 9.4	Fur(880) 5.0	HM 4.8	HM 2.3	NA	NA
Crop Irrigation	Fur (880) 16.4	Fur (880) 16.4	Fur (640) 21.0	Fur (640) 21.0	SS 18.1	Fur (880) 19.4
Total	25.8	21.4	25.8	23.3	18.1	19.4
Drainage Below Root Zone (inches)						
Preplant	1.5	1.5	0.1	0.0	0.0	0.0
Crop Irrigation	7.2	6.9	10.2	9.2	5.8	9.6

HM = hand-move sprinklers
Fur (880) = furrow with length of 880 feet
Fur (640) = furrow with length of 640 feet
SS = solid set sprinklers
West = west half of field
East = east half of field

The irrigation efficiency was characterized at four different levels. The first was on individual fields and landholders, the second was by tailwater groups, the third was drained versus non-drained areas, and the forth was the District as a whole. The irrigation efficiency was calculated as being equal to the crop Et plus the required leaching requirement divided by the applied water. It was characterized on an annual basis by including evaporation from fallow areas and effective rainfall. The non-cropped area was taken into consideration when calculating efficiency. Results of the analysis are given in Table 7.

Table 7. Irrigation efficiency for different units.

Area	Irrigation Efficiency (percent)	
	1987	1988
Farming units	25 to 150	25 to 1220
Tailwater units	50 to 120	31 to 175
Upslope Area (no drains)	65	67
Downslope Area (with drains)	79	89
NW drained portion	72	87
SE drained portion	86	92
Entire District	72	78

These data show that in general the efficiency was higher in areas requiring drainage and in the downslope areas as compared to the upslope areas. Irrigation efficiency for the district improved from 1987 to 1988 probably due to limited water supplies. There was also a difference in the irrigation efficiency in the drained areas. Irrigation efficiencies in excess of 100 percent are due to one or more of the following reasons: (1) the data are incorrect; (2) shallow groundwater contributes significantly to the crop water requirement; (3) the irrigation supplies are mixed with water pumped from a drain, which means more water is being applied than is being measured.

The irrigation efficiency is given in Table 8 for tomato, cotton, and alfalfa in 1987.

Table 8. Irrigation efficiency for different crops.

Crop	Percent of Total Crop Area in District	Number of fields investigated	Irrigation Efficiency percent
Tomato	15	8	52
Cotton	45	8	87
Alfalfa	16	4	103*

*Not fully irrigated during 1987 irrigation season.

The cotton and alfalfa had higher irrigation efficiencies than did the tomato. In part because the cotton and alfalfa are tap rooted crops and less water stress sensitive than the tomato and these crops are irrigated less frequently than tomato. There was also a trend for decreasing efficiency with increases in permeability regardless of the crop being grown.

The drain flow data were characterized using the tailwater groupings in each year. Drainage was measured at each of the sumps and at the outlet from the district using either meters or weirs or estimating flows and durations. There was a reasonable correlation between the estimated drain flows and the measured drain flows. The data also indicated that fluctuations in the drain discharge corresponded to changes in irrigation delivery. Drain flow increased when irrigation began and decreased at the end of irrigation. When the drain flow was analyzed as a function of the delivery the data indicated that the fall and spring had the worst ratios. This is due in part to pre-plant irrigation.

On four intensively monitored field sites, two fields had less drainage than predicted, as a result of either incorrect calculations or deep percolation bypassing the drains. One site had a good correlation between calculated drain flow and measured flow and the remaining site had drain flow equal to the applied water when a crop was present. This is probably a good indication of lateral flow into the field. When a district water balance was calculated it was estimated that probably less than 20 percent of the drainage originated from outside of the district. There are specific instances in the district that are adversely impacted by lateral flow from outside the district. The drainage yield in the district ranged from 0.3 to 2.6 ac ft./ac per yr.

The following conclusions were developed as a result of this study.

1. Lateral flow into the district is not a major source of the drainage flow in the district but originates on the ranches in the district.

2. Source control by improved irrigation management will significantly reduce drainage flows resulting from deep percolation.

3. Use of tailwater return systems to eliminated surface runoff will reduce drainage flow significantly.

4. Improved irrigation management should be directed to water stress sensitive crops such as tomato and melon.

5. Improved irrigation management should be focused initially on upslope undrained areas.

6. Pre-plant irrigation is a major source of deep percolation and improved irrigation practices for this irrigation will result in significant reductions of deep percolation.

Potential for Adoption and Needed Action

We believe that a high potential exists for improving surface irrigation. While progress had been made in some areas, substantial progress has yet to be made in others. Some areas still use ½ -mile furrow lengths. While this furrow length is convenient for growers, it is believed to be a major contributor to subsurface drainage because of excessive percolation below the root zone. This is particularly the case for preplant irrigations. Growers in those areas need to be “encouraged” to reduce their field lengths by at least one-half.

Along with reducing the field length, efforts need to be made to reduce the depth of application during pre-plant irrigation. This irrigation has been identified as the principal source of deep percolation contributing to the drainage problem. Irrigation management needs to be directed to modifying practices during this irrigation. These might include reducing depth of application or switching to sprinklers instead of furrow systems.

Surge irrigation has a potential for reducing percolation below the root zone, particularly in sandy soil. However, this irrigation method has not been accepted along the westside of the SJV. One possible contributor to its lack of acceptance is the complicated surge valves initially used in the late 1980s. However, valves currently used are relatively simple to operate. Adoption of this method is cost effective for growers already using gate pipe. Further effort is need to understand the lack of acceptance of this irrigation method and to encourage its use. Note, however, that surge irrigation may not be effective in soils that are severely cracked just prior to irrigation.

Much uncertainty exists in converting from surface irrigation to irrigation methods such as drip irrigation and linear-move sprinkler/LEPA systems. The economic benefits of this measure are difficult to predict, and thus growers may be reluctant to invest in these relatively expensive systems. Better information is needed on the conditions most likely to be appropriate for converting to these systems.

IV. Water Table Management

In humid areas of the United States, shallow groundwater management is practiced extensively as either subsurface drainage or subirrigation and the management objectives are either to prevent waterlogging or use shallow groundwater as a supplemental water source.

The combined use of a subsurface drainage system for drainage and subirrigation is possible in humid areas because the traditional drainage system design results in closely spaced drain laterals, a shallow installation depth, and installation in areas with a nearly level soil surface. The combination of drain installation and topography makes it possible to effectively control the water table at the same depth under nearly the entire field.

In arid areas, drainage systems are installed at nearly twice the depth and with lateral spacings 4 to 5 times greater than found in humid areas. Generally, fields in arid areas have been graded to a fixed slope to accommodate surface irrigation and as a result have greater slopes than found in humid areas. When these factors are considered it becomes apparent that subsurface drainage systems in arid irrigated areas have limited possibilities for shallow groundwater management or as sub-irrigation systems because the water table can be regulated at a uniform depth under only a small part of the field. Current drainage design practice in arid areas controls the water table depth to depths greater than four feet to prevent waterlogging and salinization, which also limits effective use of shallow groundwater.

Besides the physical limitations the drainage system imposes, managing salinity in the soil profile is potentially a problem for shallow groundwater management. In-situ use of groundwater by a crop moves dissolved ions up into the soil profile where deposition occurs. Continued transport of salt into the root zone will result in increasing salinity levels that have the potential to restrict plant growth and development, and reduce yield. Periodic leaching will be required to control root zone salinity if a crop makes extensive use of saline groundwater.

Field Studies

Wallender et al., (1979) found the contribution of saline, shallow groundwater to cotton evapotranspiration to be about 60 percent. A comprehensive study by Grimes et al., 1984 revealed shallow groundwater contributions to cotton and alfalfa evapotranspiration ranging between 19 and 60 percent, depending on depth to groundwater and its salinity. They developed the following relationship between water table depth, groundwater salinity, and groundwater contribution:

$$WT = 43.3 + 46.93D - 18.56D^2 - 7.542EC + 0.128EC^2$$

where WT is the water table contribution, D is the depth to the water table in meters, and EC is the electrical conductivity of the shallow groundwater (dS m^{-1}). This equation is appropriate for mature cotton and alfalfa growing in fine-textured soil.

Several field studies have been conducted investigating the potential for increased crop utilization of the shallow groundwater through either changing irrigation water management or water table manipulation. Ayars et al. 1996 investigated the use of modified irrigation scheduling of furrow and drip irrigation on cotton and tomatoes. The study objective was to develop irrigation management criteria to maximize the use of shallow groundwater during the growing season while minimizing agricultural drainage pollutant load and impacts on crop yield.

Conclusions were:

1. Using sprinkler irrigation for germination of tomatoes and the first seasonal irrigation eliminated deep percolation losses and effectively controlled soil salinity in the root zone. Surface irrigation can be used on deep-rooted crops such as cotton after the first irrigation.

2. Subsurface drip irrigation (SDI) was effective in reducing deep percolation losses under tomatoes and cotton on the silty clay loam soils in this study area when used to apply small, frequent irrigation amounts which did not exceed the available soil water storage capacity. The net returns were higher for SDI than furrow irrigation in the tomato-cotton rotation in this study but the return on the investment for the two systems was approximately the same. In the crop rotation and practices normally used at the study site the SDI system could replace the furrow irrigation system during the growing season.

3. Maximum use of shallow groundwater by the crop in areas without drainage systems was achieved by improved irrigation scheduling using either leaf water potential (LWP) or crop coefficients which accounted for crop water used from the shallow groundwater. The LWP potential data were used to establish the timing for irrigation of the cotton crop. After the first seasonal irrigation the cracking nature of the soil determined the depth of irrigation. This was generally in the range of 4 to 6 inches. At this time there was adequate soil water storage in the soil profile and very little water was lost to deep percolation.

4. Scheduling irrigations of cotton using the modified crop coefficients (Ayars and Hutmacher, 1994) maximized cotton water use from shallow groundwater when irrigated with a SDI system. Use of the modified crop coefficients accounted for the crop water use from the shallow groundwater and from the stored soil water and established both the timing and depth of application.

Ayars, 1996 conducted another study on water table manipulation. Study objective was to develop subsurface drainage design and management criteria to maximize the use of shallow groundwater during the growing season while minimizing agricultural drainage pollutant load and impacts on crop yield. Conclusions were:

1. In an area with an operational subsurface drain, maintaining the water table within 4 feet of the soil surface resulted in increased use of shallow groundwater by both cotton and tomato. Nearly 17 percent of the cotton water requirement was met from the shallow groundwater and applied irrigation was reduced by 3.9 inches on a tomato crop when the water table was maintained at a depth of 3.9 feet below the soil surface.

2. Through improved irrigation management and reduced deep percolation losses drain spacings calculated using the proposed new design criteria (mid-point water table depth = 3 ft., drain depth = 5 ft.) will be comparable to existing drain spacings calculated using the transient design methodology of the U.S. Bureau of Reclamation. Computer modeling demonstrated that reducing the drain installation depth to 5 feet and the mid-lateral water table depth to 2.9 feet significantly reduced the drain discharge and the pollutant load.

Other Studies

Grismer and Gates (1988) developed a relationship between groundwater contribution and depth to water table for several soil textures. Medium-textured soils were found to have the greatest potential for upward flow of the shallow groundwater into the root zone. They could not find any salinity effects on the upward flow. Hutmacher and Ayars (1991) found with lysimeter studies that tomatoes, cotton, and wheat can use shallow groundwater at salinity levels far in excess of irrigation water salinity levlels normally recommended. They also found that the higher the salinity of the shallow groundwater, the less the crop's use of the groundwater.

In an effort to better understand interactions between crop water use, irrigation water management, leaching, and upward flow from the groundwater, Bradford et al, (1991) simulated cotton and alfalfa production under various irrigation water management schemes with an initial water table depth of 5 feet and a salinity of 9 dS m^{-1}. Scenarios of no within-field lateral flow and within-field lateral flow were included in the study. Results showed that crops irrigated with amounts equal to 60 percent of the potential evapotranspiration had the highest yields when associated with 13 inches of preplant irrigation instead of 7 inches. Initially, lateral flow from areas of the field receiving adequate irrigation to areas under deficit irrigation mitigated the effect of the deficits on crop yield. Over time, however, salt accumulation from the upward flow of the saline groundwater in the deficit-irrigated areas caused long-term yield reductions.

Bradford and Letey (1992) used a multi-seasonal simulation model to evaluate the effect of 3 or 4 seasonal irrigations of cotton with both free-drainage and water table conditions. Higher yields were obtained by using less water during the crop irrigation season and more during the preplant irrigation for salt leaching. They also found that high cotton yields could be achieved for several years even if the water table is saline and no drainage occurs if the irrigation water is low in salt.

Potential for Adoption and Needed Actions

Water table management has potential for reducing subsurface drainage by encouraging crop use of the shallow groundwater. Adjusting the irrigation schedule using the pressure chamber method or modified crop coefficients is practical for cotton irrigation. Data on irrigation scheduling using these techniques are needed for other crops.

Realizing the potential for maximum use of shallow ground water by crops will require adoption of new design criteria for subsurface drains and the development of procedures for managing subsurface drainage systems in coordination with irrigation. Proposed changes in drainage system design criteria include reducing the depth of the mid-point water table depth from 4 to 3 feet and installing drain lines at depths less than 8 feet. These changes have to be developed in conjunction with improved irrigation management. Changing the layout of the drainage laterals to be nearly perpendicular to the surface ground slope is necessary for the implementation of control of the water table. Use of control structures such as valves on the laterals and depth control structures at the outlet and along the sub main collection system is effective when the water table is controlled over large areas of a field. Changing the lateral configuration with respect to the field surface slope makes this possible. These recommendations are applicable for newly installed systems and some existing systems. Additional work is needed to evaluate possible modifications of existing subsurface drainage systems to implement control.

V. Economic Incentives for Implementing Source Reduction

Which irrigation method is the best? The best irrigation method depends on one's perspective. For farmers, the best irrigation method maximizes profits. For regulators and environmentalists, the best method minimizes subsurface drainage. An irrigation method that maximizes profit and minimizes subsurface drainage is the obvious choice.

The problem is that the economic benefits of improving irrigation practices cannot be predicted with a high degree of confidence. Table 9 lists yield and applied water from various field-scale comparisons of furrow and drip irrigation, some of which have been discussed. Crops produced were cotton, tomatoes, and lettuce. These data show a broad range of results indicating that it is difficult to predict the effect on crop yield and applied water due to converting from furrow irrigation to drip irrigation. In some cases, drip irrigation produced higher yields with less water compared with furrow irrigation. Other cases showed similar yields but less applied water under drip irrigation. Still other cases showed similar yields but less applied water under furrow irrigation.

This range of responses reflect site-specific factors such as land quality (soil texture and variability), water quality, level of management of both irrigation methods, and factors such as nutrient levels and disease control. Some of these factors can be measured. Others such as the uniformity of infiltrated water as affected by soil variability and redistribution after irrigation cannot be measured with any reasonable degree of accuracy.

The economics for cotton of these various studies is shown in Table 9. Production costs were not available for the lettuce and tomato crops. No tax or assessment on drainage was applied. As with crop yield, no trend clearly exists showing drip irrigation to be more profitable than furrow irrigation. For the lettuce and tomato crops, little difference in revenue would occur because of the similar yields between the furrow and drip systems. Less water was applied by the drip systems; however, the savings in water costs at that site were insufficient to offset the cost of the drip systems.

Several studies evaluated conditions that encourage the adoption of higher technology irrigation methods over surface irrigation. Conditions such as high water costs, marginal land quality, marginal weather conditions, and higher cash value crops were found to encourage converting from surface irrigation to sprinkler or drip irrigation (Caswell and Zilberman, 1985; Caswell and Zilberman, 1986). Limited water supplies will also encourage the adoption of more efficient irrigation methods. However, irrigation water not continuously available will tend to discourage any conversions to micoirrigation systems.

Irrigators of lower cash-value crops face a dilemma. Regardless of water costs, water supplies, land quality, and so forth, adoption of sprinkler and drip irrigation may be uneconomical. An option for these irrigators is to convert to higher cash-valued crops if possible.

Table 9. Comparison of furrow and drip irrigation.

Reference	Crop	Yield (lb ac^{-1})		Water (inches)		Profit (\$ ac^{-1})	
		Drip	Furrow	Drip	Furrow	Drip	Furrow
Fulton et al, 1991	Cotton	1,409	1,264	21.9	24.1	204	401
Mateos et al, 1991	Cotton	1,552	1,361	20.5	27.6	495	470
Constable et al, 1990	Cotton	1,617	1,572	21.0	17.7	543	673
Boyle, 1994							
1989	Cotton	1,527	1,081	23.0	29.5	465	247
1990	Cotton	1,291	1,275	24.0	19.7	279	437
1992	Cotton	1,566	1,365	23.6	19.7	493	507
1993	Cotton	1,465	1,295	17.9	25.3	440	429
Detar et al, 1992							
1990 (Good)	Cotton	1,704	1,738	24.1	41.8	596	684
1991 (Good)	Cotton	1,613	1,608	26.3	38.5	516	614
1990 (Poor)	Cotton	1,637	1,445	22.9	45.9	550	458
1991 (Poor)	Cotton	1,517	1,325	25.7	41.0	445	386
Hanson et al, 1997							
1991	Lettuce	18.6	19.6	4.4	10.3	-	-
1992	Lettuce	18.2	18.3	9.0	13.2	-	-
Fulton, 1995							
Variety 1	Tomato	51.1	50.2	27.0	38.2	-	-
Variety 2	Tomato	45.3	43.6	27.0	38.2	-	-

For those site-specific conditions that result in higher profit and less applied water under drip irrigation compared with furrow irrigation, drip irrigation should be used instead of furrow irrigation. For conditions where the profit is larger under furrow irrigation, then policies may be needed to encourage drainage reduction.

Several studies investigated the effect of various policy strategies for source reduction. Dinar et al, 1989 analyzed the policies of no regulation, direct fees on drainage discharges, and irrigation water pricing. The water pricing included flat fees on irrigation water use and a tiered pricing consisting of a base price until water use exceeded a chosen value, after which the water price increased. Results showed the unregulated policy to have a substantial cost to society for drainage water disposal. For the drainage fee policy, society net benefits were higher than for the unregulated case, however, net benefits decreased as the drainage fee increased. Most of the drainage reduction occurred for a fee increase from $37/acre-foot to $98/acre-foot. Further fee increases had a small effect of drainage reduction. Under this policy strategy, net benefits increased as the uniformity of the infiltrated water increased.

Under the policy of a flat fee on irrigation water, drainage disposal costs to growers were zero, but an additional charge was placed on the irrigation water. Results showed that substantial increases in irrigation water price were required to induce economically efficient water applications, which caused revenues to exceed drainage disposal costs. Under tiered water pricing, revenues were found to be less than the disposal costs.

Knapp et al, (1990) investigated four policy strategies consisting of nonpoint incentives (tax of the estimated drainage discharges), nonpoint standards (specified maximum level of drainage discharge), management practice incentives (increased water price to induce source reduction), and management practice standards (specified level of irrigation water applications). For each policy strategy, the objective was to achieve economic efficiency. Results showed grower profits to decrease as either the price of irrigation water or drainage fees increased. Profits were significantly higher under the standards policies compared with the incentive policies. The incentive policies required substantially more transfer of information between regulators and growers compared with the standard policies.

Two other studies (Posnikoff and Knapp, 1997; Knapp, 1997) focused on drainage fees as a policy for inducing drainage reduction. They assumed that source reduction would occur due to changes in production practices (irrigation system, acreage allocation, and water applications) as drainage fees increased. Results showed the following:

1. Changes in irrigation systems occurred as drainage fees increased to maintain economic efficiency. The higher the cash value of a crop, the smaller the drainage fees at which a switch in irrigation system occurred.

2. Drainage fees could be increased up to a critical level with a minimal impact on net returns. Increases beyond that level greatly reduced net returns. While the studies reported different critical levels depending on the assumptions and methodology used for the economic models, they indicated that source reduction might be relatively easy in terms of costs and impact on net returns up to the critical level. Beyond that level, source reduction becomes relatively difficult.

<u>Field Study</u>

Broadview Water District implemented a tiered water pricing program to provide an economic incentive to farmers to reduce subsurface drainage (Broadview Water District, 1994). Water deliveries between 1986-89 were used to determine a baseline amount of water. While the district’s average amount of delivery during that time period was not excessive, considerable variation existed in deliveries to individual farms. Thus, an objective of the program was to reduce this variability.

The program, started in 1990, consisted of developing a base price of 16/acre-foot, which was the water price for amounts less than 90 percent of the 1986-89 average. For water deliveries exceeding the base amount, the price increased to $40/acre-foot.

Results clearly showed reduced water deliveries and reduced subsurface drainage during 1990-93 compared to 1986-89. However, it is not possible to separate the effects of the tiered pricing program and reduced water deliveries to the district because of the drought that occurred between 1990-93. Thus, the effect of the pricing program is uncertain at this time.

A considerable shift in irrigation practices has occurred in the district since 1990. Prior to the program, siphon furrow irrigation was used with ½-mile furrow lengths. Now, most cotton irrigators use ¼-mile lengths, while many tomato and melon irrigators use 1/6-mile furrow lengths. In addition, use of gated pipe instead of siphons has increased, thus reducing seepage from earthen head ditches. Sprinkler systems are also being used more and more, particularly for preplant irrigations and early crop irrigations.

The economic impact of this shift is uncertain. Cost data on cotton and tomato irrigation in the Broadview Water District were collected on three irrigation strategies (Wichelns et al, 1997). One strategy used furrow irrigation for the preplant irrigation and seasonal irrigations, while a second approach used sprinklers for the preplant irrigation and early seasonal irrigations. Sprinklers were used for all irrigations for the third strategy. Results showed that fixed irrigation system costs were the smallest for the furrow only (siphons, land leveling) approach, while the combination of sprinklers and furrow irrigation caused the highest fixed costs. Preplant irrigation variable costs (water, labor, and energy) were similar for sprinkler and furrow systems. However, for the seasonal irrigation, sprinkler variable costs were 1.77 and 1.33 times larger for the sprinkler system compared with the furrow systems for cotton and tomatoes, respectively. Recovery of these increased costs must come from improved crop yields. However, uncertainty exists on the effect of improvements on crop yield, thus on revenue. Little data exists showing higher yields under sprinkler irrigation compared with furrow irrigation. Thus, converting from furrow to sprinkler irrigation would reduce net returns to growers under these circumstances.

Potential for Adoption and Needed Actions

The best incentive for implementing source control measures to reduce subsurface drainage is increased farm profits as a result of the improvement in irrigation and drainage water management. Unfortunately, this is not always the case as seen In Table 7. Thus, the effect of some improved irrigation practices on profit is uncertain, and a risk exists in adapting measures such as converting to drip irrigation or linear-move systems.

Some of the studies on policy incentives suggest that a moderate drainage fee could have a large effect on drainage reduction. Fees greater than some critical value, however, would have little effect on further decreases in drainage. This critical value needs to be carefully determined using data that are realistic for the conditions along the westside of the SJV. Critical values obtained in these studies depend on the assumptions used in the economic models. Incorrect assumptions may lead to incorrect results. For example, in one study, the optimal amount of irrigation water applied for processing tomato was greater than 50 inches. Actual amounts used by growers are less than about 30 inches. According to some growers, applying 50 inches of water would cause root disease problems and reduce yield.

VI. Salinity Considerations

Salinity control consists of infiltrating an amount of water in excess of the soil moisture depletion to leach or transport salts below the root zone. This excess water is the leaching requirement and depends on the salinity of the water used to irrigate the crop and the crop's tolerance to salinity. The need for salinity control means that there is a lower limit on the amount of drainage reduction without incurring a yield decrease due to soil salination.

The preplant irrigation plays a major role in controlling soil salinity in the drainage problem areas. Infiltration rates during preplant irrigations generally are high, thus allowing sufficient water to flow through the root zone to leach salts. During the seasonal irrigations, infiltration rates become small, and as a result little or no leaching occurs during those irrigations.

The effect of preplant irrigation (or lack of) on soil salinity was shown by Grimes et al, 1984 for a two year period. Because of salt accumulation in the root zone during the growing season, soil salinity levels in fall were higher than in spring. The preplant irrigation reduced the fall levels down to the spring levels each year. However, where no preplant irrigation occurred, soil salinity levels in spring remained high. Based on studies of seasonal salt accumulation, it is estimated that about 3.3 inches of leaching water for 3.3 feet of soil depth is needed to reduce fall salinity levels to spring levels (Hanson et al, 1993).

<u>Potential for Adoption and Needed Actions</u>

Managing salinity in the soil profile and in the drainage water needs to be considered in the implementation of water table management. The effective use of propellant irrigation for salinity control needs to be emphasized. Since pre-plant irrigation is the single largest contributor to deep percolation and drainage, methods and management alternatives which reduce the volume applied and maintain soil salinity need to be evaluated. Implementation of the proposed changes in drainage system design will result in reduced loads of salt as well as reductions in total flow. Additional field studies are needed to confirm this.

VII. Overall Conclusions

Source reduction is an essential component in dealing with the subsurface drainage problem of the SJV. The potential exists to substantially reduce subsurface drainage by shortening ½-mile long furrow lengths by one-half and then applying proper management to the modified system. Converting to drip irrigation, linear-move machines, etc. has the potential of greatly reducing subsurface drainage although uncertainty exists concerning farm-level economic benefits of these changes. An important component of any system improvement is proper irrigation scheduling to prevent overirrigation.

Water table management also has potential for drainage reduction by adjusting the irrigation schedule to encourage crop use of shallow groundwater or by manipulating water table levels through the design and management of drainage systems.

Salinity will be a limiting factor on the amount of source reduction. Some minimum amount of leaching must occur to prevent adverse levels of soil salinity from accumulating in the root zone.

The best incentive for encouraging source reduction is economic benefits that exceed costs of the improvement. Uncertainty exists, however, in the farm level benefits resulting from any improvements. A policy incentive that may be particularly feasible to encourage source reduction is a fee on drainage discharges. Regardless of the approach used, a systems approach is recommended that considers technical, environmental, and economic aspects at the farm level and at the regional level.

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