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**An ASABE Conference
Presentation**

Paper Number: IRR10-8339

Drip Irrigation Can Reduce California's Water Application by 2.4×10^6 ac-ft. per Year Without Yield Reduction

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**Written for presentation at the
5th National Decennial Irrigation Conference
Sponsored jointly by ASABE and the Irrigation Association
Phoenix Convention Center
Phoenix, Arizona
December 5 - 8, 2010**

Abstract. *The California Department of Water Resources has predicted that California's population, now 38×10^6 , may exceed 48×10^6 by 2030. In 2008, California irrigated agriculture generated a gross income of $\$39 \times 10^9$ by irrigating about 9.6×10^6 ac of land with 34.2×10^6 ac-ft of water (average 3.56 ac-ft/ac). About 50% of the irrigated agriculture still relies on furrow and flood irrigation and, based on research and demonstration, this acreage could be converted to drip and subsurface drip irrigation (DI and SDI) with a yearly reduction in applied water of 0.5 ac-ft/ac.*

Maximizing efficiency of irrigation systems depends mostly on the irrigation manager's ability to: 1. Reduce or eliminate runoff (R)--adequately designed, installed and managed DI and SDI systems did not generate R when pressure compensated emitters were used; 2. Reduce deep percolation below the root zone (D)--soil physics theory and research indicated that to avoid D the soil water must not be allowed to reach saturation or near-saturation, except in a small soil volume surrounding the source of water; 3. Overcome the infiltration variability of the soil surface--measurements of water distribution uniformity and statistical uniformity with a two-year old, thin wall drip system were respectively 0.91 and 97.4% and in the acceptable range; 4. Optimize irrigation scheduling—when using high frequency irrigation scheduling, soil evaporation (E) decreased significantly with depth of SDI installation and, although not fully eliminated at depths of 6 and 12 in., it became insignificant at installation depths of 18 in., and 5. Reducing crop evapotranspiration (ET_c) of Thompson seedless grapes by 20% did not reduce yields and/or soluble solids. This paper will demonstrate that with well-designed, installed and managed DI and SDI systems, these factors can be satisfied and that in California, a conservative estimate of reduced water application of 2.4×10^6 ac-ft/Year (7.02%/year) without yield reduction is achievable.

Keywords. Population growth, agricultural sustainability, water management, irrigation, microirrigation, subsurface drip irrigation, low pressure irrigation, water use efficiency, irrigation scheduling, soil-water balance.

Introduction

In 2007, Governor Arnold Schwarzenegger proposed construction of new water storing facilities in California to accommodate the increasing population needs for water and competing agricultural and environmental water demands. Data in Figure 1 report and predict the State population growth between 1960 and 2005 (actual growth) and between 2005 and 2030 (Schwarzenegger et al., 2005). Figure 1 also provides the straight-line growth regression for comparison. The past and present population growths support the Governor's concern and vision for the need of additional water storage infrastructures and water conservation measures.

More than ever, all Californians must learn to balance water use efficiently to sustain maximum utility by urban, agricultural and environmental users. The Department of Water Resource (DWR) plan calls for less water to be pumped out of the Sacramento delta to meet the requirements of the Endangered Species Act.

In a 2007 reply to the DWR plan, farmers' attorneys warned of "devastating impacts for agriculture." Water contractors say that if California suffers another dry year, growers on the San Joaquin Valley's west side could lose all federal irrigation water". Economists hired by California farmers say agricultural losses could range from \$111 million to \$484 million in 2009 under the environmentalists' plan (private communication). This is just one example of the continuous water war faced by Californians, especially when the State incurs recurring severe drought conditions.

In 2005, DWR published a comprehensive five-volume updated edition of the California Water Plan. This plan clearly outlines the vision, the initiatives to ensure reliable water supplies and the needed foundational actions to ensure future sustainable water uses.

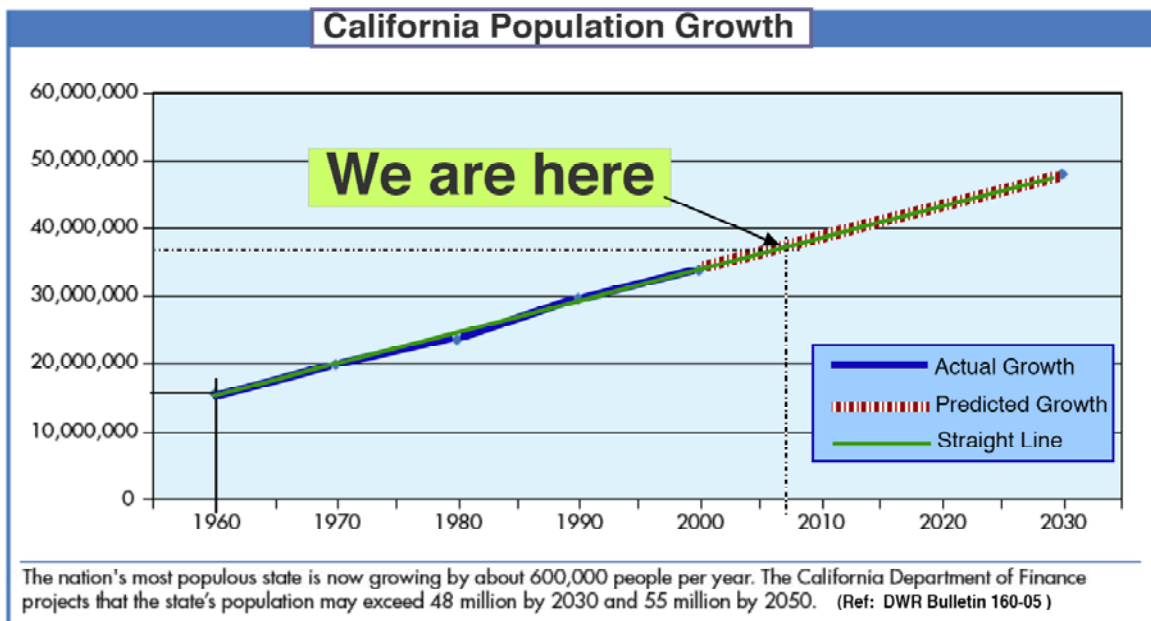


Figure 1. Predicted State population growth between 1960 and 2005 (actual growth) and between 2005 and 2030 (predicted growth) and the regression growth line for comparison (Adapted from Schwarzenegger et al., 2005).

Current Water Use and Potential Use Reduction with Drip Irrigation Technology

The objective of this treatise is to focus on actions to improve sustainability and efficient agricultural water use, as outlined in DWR Bulletin 160-05, Chapter 3 of Volume 2 (Schwarzenegger et al., 2005), (Figure 3, bottom row, left hand block); specifically to demonstrate that in California, drip irrigation technology can conserve an average of 6 ac.-in./ac./year.

Data in Figure 2 (Schwarzenegger et al., 2005) present a detailed example of the effects of drought on the California Water Balance. The 31.4% decrease in water availability in 2001, compared to the 1998 wet year is dramatic. As shown in Table 1, the present drought period (2006-2007) is well below the long-term average and below the other two drought periods in (1975-1977) and (1986-1992) (Schwarzenegger et al., 2005). Coupled with an ever-increasing population, the need for improved and balanced water management is critical to sustain the present standard of living.

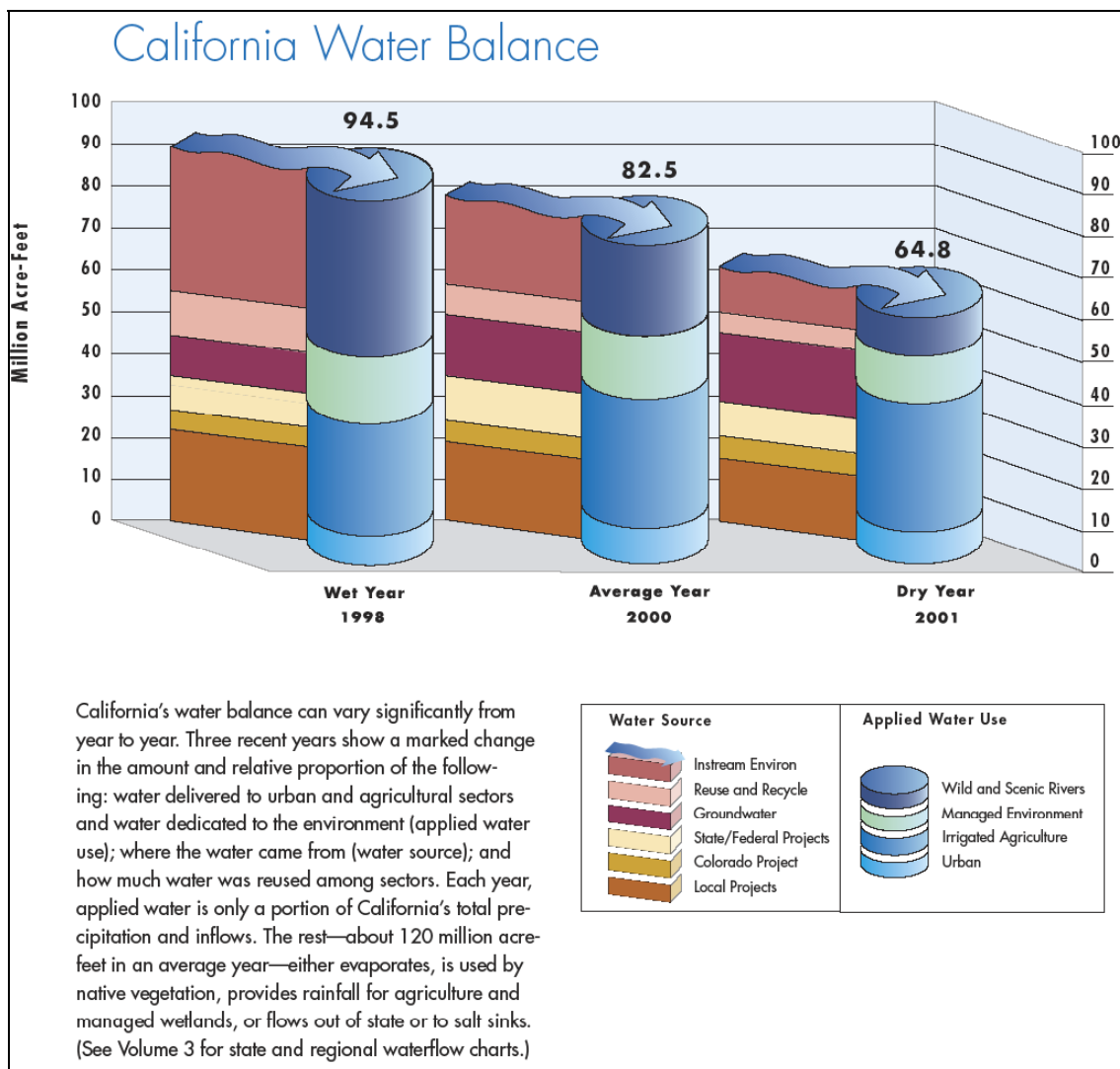


Figure 2. The effects of drought on the California Water Balance (Schwarzenegger et al., 2005).

In 2008, California agriculture generated a gross income of $\$39 \times 10^9$ by irrigating approximately $9.0\text{--}9.6 \times 10^6$ ac. of agricultural land (9.6×10^6 ac. in year 2000) with 34.2×10^6 ac-ft of water for an average 3.56 ac-ft/ac (Schwarzenegger et al., 2005, and USDA-ERS, 2008). This is a large amount of applied water; however, this is a significant improvement considering that between 1980 and 2000 the increase in water use efficiency (WUE) of 32 important California crops was 38% (WUE = Yield/ac-ft.) and the inflation-adjusted gross crop revenue per unit of applied water ($\$/\text{ac-ft}$) increased by 11%. Undoubtedly, these increases were the result of changing irrigation methods (see Table 2) and improving management techniques such as irrigation scheduling (temporal and spatial water application, i.e.: when and how much water is needed). In the early 1980's, the implementation of the California Irrigation Management Information System (CIMIS) provided statewide weather information necessary to develop and improve irrigation scheduling methods (Fulton et al., 1990).

Bulletin -160-05 (Schwarzenegger et al., 2005) and associated research indicates that improving agricultural WUE can primarily occur from three equally important areas of activities:

- Hardware – On-farm irrigation and water supplier delivery systems
- Water management – Improving management of on-farm irrigation and water Supplier delivery systems
- Crop water consumption – Reducing non-beneficial evapotranspiration (ET_c)

With respect to **Hardware** and **Water management**, this paper will restrict its discussion to the “on-farm” portion of these activities. With respect to **Crop water consumption**, it will only be concerned with ET_c reduction without loss of yield.

On-Farm Hardware, Water management and Water Use Efficiency

Is there still a potential for further improving agricultural water use efficiency in California without reducing productivity and if so, how could this be implemented?

In California, approximately 50% of the irrigated agriculture (4.8×10^6 ac.) still relies on furrow and flood irrigation and, based on years of research and demonstrations, this acreage could be converted to drip irrigation with potential yearly water saving (PYWS) of 0.5 ac-ft/ac (1 acre-foot = 325,900 gallons):

$$PYWS = 4.8 \times 10^6 \text{ ac.} \times 0.5 \text{ ac-ft/ac} = 2.4 \times 10^6 \text{ ac-ft of water}$$

This 2.4×10^6 ac-ft represents the amount of water that will be needed in the near future to satisfy the present agricultural needs and the increase in urban and environmental demands. The average on-farm costs involved in the conversion of furrow to drip/subsurface drip irrigation at an average cost of $\$1200/\text{ac}$ for fully automated systems using CIMIS for irrigation scheduling the total conversion cost would be:

$$\text{Cost to convert } 4.8 \times 10^6 \text{ gravity-irrigated acres to drip} = 4.8 \times 10^6 \text{ ac} \times \$1,200/\text{ac} = \$5.76 \times 10^9.$$

This cost of $\$1200/\text{ac}$. is averaged for crops ranging from vegetable crops with narrow lateral spacing and short-life drip systems to tree and vine crops with wide lateral spacing and long-life, pressure compensated emitter systems. Variable types of monetary and tax incentives could be provided by State and Federal agencies in amounts proportional to the conversion costs. This systematic approach could be implemented quickly to provide relief while the new storage reservoirs are being engineered, approved and constructed.

Table 1. Yearly precipitation (top, in.) and runoff (bottom, 10⁶ ac-ft.) for the long-term averages and droughts in 1975-1977, 1986-1992 and 2006-2007 (Schwarzenegger et al., 2005).

Precipitation (inches)		July 1 to June 30 Precipitation Totals												
City	Average	06-07	75-76	76-77	86-87	87-88	88-89	89-90	90-91	91-92	98-99	99-00	00-01	01-02
Eureka	39.55	36.52	33.55	17.56	27.93	32.31	34.88	26.83	25.11	21.92	49.99	36.44	22.84	40.66
Redding	37.00	22.73	22.90	20.97	21.48	30.22	33.53	29.93	22.07	28.42	30.87	34.28	30.15	28.86
San Francisco	20.26	11.66	7.73	11.05	10.74	14.34	13.77	11.87	13.47	18.21	16.91	20.69	16.24	19.32
Sacramento	18.20	12.22	7.25	7.53	12.81	15.37	15.13	19.40	14.73	16.68	15.27	23.74	17.31	17.08
Fresno	10.95	6.06	8.18	7.61	9.32	8.07	8.73	9.45	9.77	11.05	7.01	12.91	10.56	7.03
Santa Barbara	16.32	7.24	7.83	15.90	10.91	14.06	8.76	5.76	16.74	18.33	12.04	25.10	23.68	9.07
Bakersfield	6.23	3.06	4.37	4.19	5.58	5.55	3.74	3.30	5.95	7.00	6.96	5.15	5.77	3.59
Long Beach	12.11	2.12	4.98	8.78	7.59	8.25	6.09	6.39	9.99	13.76	8.47	6.60	10.90	2.21
Los Angeles (Civic Ctr)	14.89	3.21	7.22	12.31	7.66	12.48	8.08	7.35	11.47	21.00	9.09	11.57	17.94	4.42
San Diego	10.21	3.83	9.11	8.08	9.61	13.18	5.65	7.84	11.79	12.93	6.71	5.76	8.58	2.99
Riverside	10.09	1.70	7.89	8.70	6.65	9.27	6.94	5.80	10.53	11.18	5.86	5.19	7.35	3.30
Redlands	13.37	3.93	9.68	12.45	10.51	12.92	8.28	7.79	14.07	15.72	7.76	7.86	10.31	3.58
Death Valley	2.28	1.83	3.44	2.74	1.96	5.78	0.68	0.57	1.77	2.59	1.24	1.23	2.70	0.46

Runoff (MAF)		Water Year Totals (October 1 to September 30)												
Index	Average	06-07	75-76	76-77	86-87	87-88	88-89	89-90	90-91	91-92	98-99	99-00	00-01	01-02
Sacramento Valley Index	8.33	6.2*	5.29	3.11	5.86	4.65	6.13	4.81	4.21	4.06	9.80	8.94	5.76	6.35
San Joaquin Valley Index	3.29	2.0*	1.57	0.84	1.86	1.48	1.96	1.51	1.96	1.56	3.59	3.38	2.20	2.34

*Estimates

The American Society of Agricultural and Biological Engineers (ASABE) in Standard S526.1 “Soil and Water Terminology” defined drip irrigation (DI) and subsurface drip irrigation (SDI) (ASAE Standards, 1996); SDI is defined as the frequent applications of water, at least 50 mm below the soil surface, through emitters, with discharge rates, generally in the same range as DI.

Comprehensive historic research and application reviews of DI and SDI have been performed in the past 36 years (Goldberg and Shmueli, 1970; Howell et al., 1981; Bucks et al; 1982; Hall, 1985; Bucks and Davis, 1986; Phene. 1995; Camp, 1998; Reinders, 2000, Lamm and Camp, 2007). In most of these reviews and surveys, crop yield and water use efficiency advantages of these methods over conventional irrigation methods were established. Because of these advantages, the worldwide uses of DI and SDI have increased significantly during the last 20 years (Table 2). Data in Figure 3 shows the estimated United States growth of land irrigated by microirrigation, by state, from 1970 to 2000 (Ayars et al., 2007). This graph indicates that California has more than 50% of the total land irrigated by microirrigation in the USA.

Data in Table 3 compares the California irrigated acreage by irrigation methods for the years 1990 and 2000 and gives the percentage change in irrigation methods during this period. During this ten-year period, the use of gravity irrigation declined by 16 % and the use of sprinkler and microirrigation increased by 5 and 11 %, respectively. This relatively large change in irrigation methods was mostly caused by the 1986-1992 prolonged droughts (see Table 1), the associated increase in water prices and the publication of drip irrigation research results.

Table 2. The growth of microirrigation in the world since 1981 (from Reinders, 2000).

Countries	1981 (ac)	1986 (ac)	1991 (ac)	2000 (ac)
United States	457876	968,632	1,497,426	2,594,550
India	49	0	135,905	642,460
Australia	49544	145,191	363,264	637,518
Spain	0	277,988	395,360	568,330
South Africa	108724	252,660	355,824	543,620
Israel	201881	313,348	257,730	397,831
France	54362	0	125,905	345,940
Mexico	4942	31,342	148,260	259,455
Egypt	0	169,140	169,140	256,984
Japan	0	3,459	141,089	247,100
Italy	25451	53,621	194,221	197,680
Thailand	0	9,044	111,566	177,912
Colombia	0	0	72,895	128,492
Jordan	2520	29,652	29,652	94,639
Brazil	4942	49,791	49,791	86,485
China	19867	24,710	46,949	84,014
Cyprus	14826	24,710	61,775	61,775
Portugal	0	58,229	58,229	61,775
Chinese Taipei	0	24,722	24,722	44,478
Morocco	8896	14,394	24,132	42,007
Other	124934	95,927	248,921	437,367
World	1078814	2,546,558	4,512,755	7,910,412

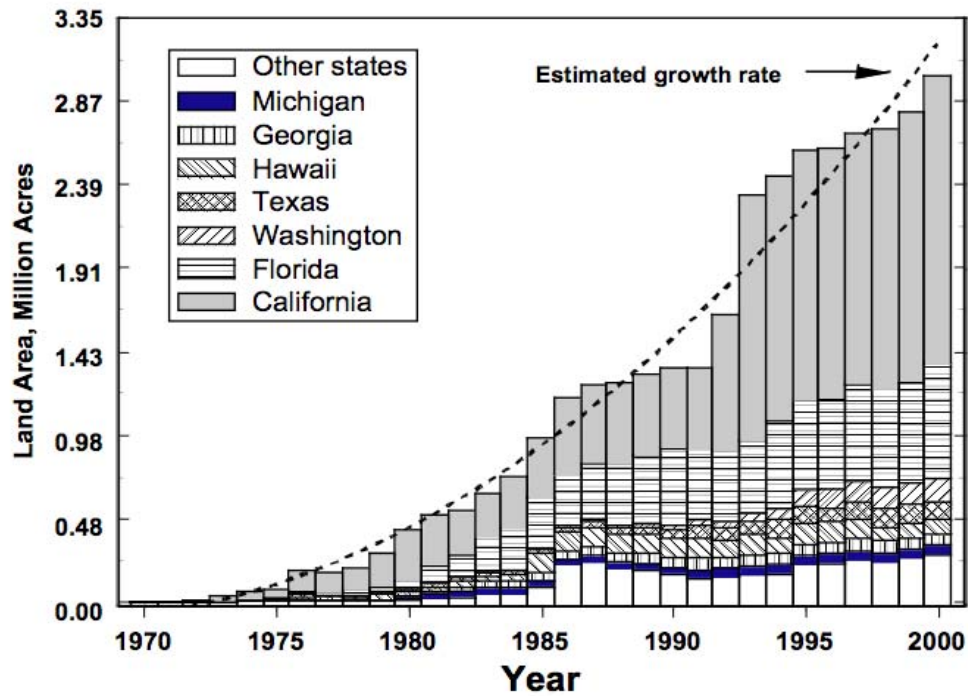


Figure 3. Estimated United States growth of land irrigated by microirrigation, by state, from 1970 to 2000 (adapted from Ayars et al., 2007).

Table 3. Trends in California irrigated acreage (ac.x10⁶) by irrigation methods for the years 1990 and 2000 and % change in irrigation methods. (Schwarzenegger et al., 2005).

Irrigation Methods	1990 Area (ac.x10 ⁶)	1990 % of Total	2000 Area (ac.x10 ⁶)	2000 % of Total	Change 1990-2000 % change in acreage
Flood, furrow	6.5	67	4.9	51	-16
Sprinkler	2.3	24	2.8	29	5
Drip/Micro	0.8	9	1.9	20	11
Total	9.6	100	9.6	100	

Does the irrigation/crop water requirement theory indicate that there is a potential for improving irrigation efficiency and reducing applied water?

Emission uniformity and irrigation efficiency determine the performance of an irrigation system. The emission uniformity (EU) is a measurement of the evenness of the applied water or infiltrated water. Irrigation efficiency is the ratio of evapotranspiration to the water applied to the field. The theoretical factors that predict the potential for increasing the irrigation efficiency (Ie) will be presented along with research and demonstration results that support the feasibility for reducing average water application statewide by 6 ac-in./ac/year.

The uses of DI and SDI do not guarantee the potential, advertised, or expected water conservation because system design, installation, maintenance and management are integral components necessary to achieve their highest potential. Assuming that the system's material, design, installation and maintenance are adequate, then management, irrigation scheduling in particular, and adequate fertigation (plant nutrient injection with irrigation water) (Phene et al., 1988) will be essential factors in achieving water conservation and improved water use efficiency (WUE is usually defined as the ratio yield/evapotranspiration; however because crop evapotranspiration (ETc) is difficult to measure, DWR uses the ratio yield/units of applied water). Howell et al., (1981) have shown that maximizing efficiency of irrigation systems depends mostly on the irrigation manager's ability to: 1. Reduce or eliminate runoff, 2. Reduce deep percolation below the root zone, 3. Overcome the infiltration variability of the soil surface and 4. Optimize irrigation scheduling.

With well-designed and managed DI and SDI systems, runoff at the end of the field is eliminated. The use of SDI systems can further eliminate infiltration variability at the soil surface and minimize soil surface evaporation. Irrigation scheduling of DI and SDI systems can be optimized and managed to minimize deep percolation (Phene et al., 1989). Camp (1998) reported that in the last twenty years more than 25 projects have compared the performance of DI and SDI with a variety of crops while obtaining different results depending on crops, soil types, environments and management methods. Results have also shown that DI and SDI technologies are sustainable (Lamm et al., 2009), economical and capable of minimizing environmental soil and water pollution from soluble fertilizers (Phene and Ruskin, 1995).

The process of well-managed irrigation is defined as "one that optimizes the spatial and temporal distribution of water so as to promote crop growth and yield and to enhance the economic efficiency of crop production" (Hillel, 1982). Hillel further defines the field water balance as:

$$(\Delta S + \Delta V) = (P + I + U) - (R + D + E + T) \quad (1)$$

Where $(\Delta S + \Delta V)$ represents the changes in soil ΔS and plant ΔV water content, P is the precipitation, I is the irrigation water applied and U is the upward water movement from the capillary fringe of a shallow water table; these three variables, $(P + I + U)$ represent the water inputs into the system. The four variables $(R + D + E + T)$ represent the outputs from the system where R is the runoff from the field, D is the deep percolation below the root zone, E is the evaporation at the soil and plant surfaces and T is the plant transpiration. Figure 4 is a schematic representation of this extremely dynamic and complicated process.

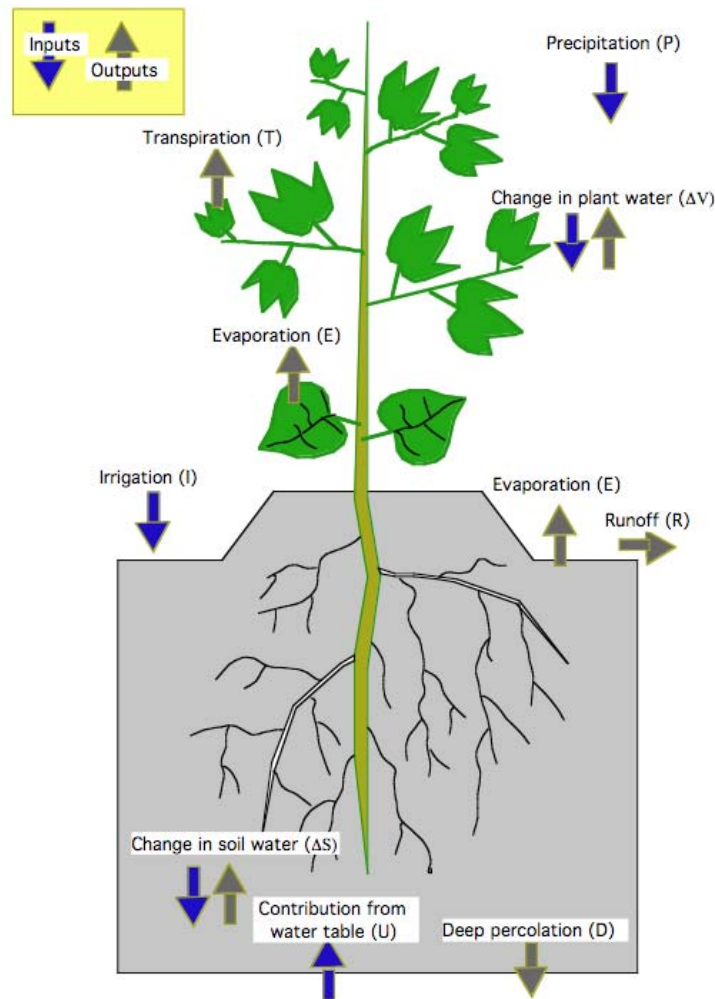


Figure 4. Schematic representation of the dynamic soil/plant water balance.

With DI and SDI, ΔV is negligible and so is U if the water table is deep or the soil is stratified. It has also been found that $E+T$ is relatively constant, that is if E decreases, T increases almost proportionally so that the two terms can be combined into plant evapotranspiration (ET_c). Equation 1 can now be reduced to:

$$\Delta S = (P+I)-(R+D+ET_c) \quad (2)$$

On a field scale, it has been demonstrated that, when properly managed, there is no runoff with drip irrigation so that $R=0$; and deep percolation D can be negligible, except for the leaching requirement (LR) (Ayars & Phene, 2007).

In arid and semi-arid zones LR will be a function of the salinity of the irrigation water and the amount of yearly precipitation. Because in most cases LR is relatively small, the leaching is most efficiently applied once a year rather than continuously. Hence with drip (DI) and more so with Low Pressure Systems (LPS) and Subsurface Drip Irrigation (SDI), equation 1 can be further reduced to:

$$\Delta S = (P+I)-ET_c \quad (3)$$

At this point, based on published USDA-ARS lysimetric research conducted with several field crops in the California San Joaquin Valley (Phene et al, 1993), while maintaining ΔS nearly constant ($\Delta S \approx 0$), DI and SDI results averaged over several years have shown that slightly under-irrigated crops can potentially conserve significant water without decreasing yields and the D component can be nearly eliminated, except during precipitation events (see Table 4). Hence,

$$ET_c = P + I \quad (4)$$

If a CIMIS or a commercial weather station is available nearby then ET_o , and P can be downloaded and ET_c can be calculated in real time by equation (5):

$$ET_c = K_c \times ET_o \quad (5)$$

Where K_c is the crop coefficient for the specific crop and sometimes a specific location. If the K_c is not well defined, it may be necessary to measure the soil water and/or the plant water potential and, in a feedback mode, adjust the K_c accordingly. In any case, if the goal of irrigation scheduling is to achieve Irrigation efficiency (I_e) = $ET_c/(P + I) \geq 0.95$, then accurate measurements of inputs (P and I) and output calculations (ET_c) must be performed for each irrigation. This is why it is critical to have accurate K_c 's and using an automated irrigation system is advantageous for applying the correct amount of water at the right time (Ayars & Phene, 2007).

Applied depth of Irrigation water (I) is calculated by multiplying ET_c [adjusted by the irrigation efficiency factor (I_e) and, when needed, the leaching fraction (LF)] so that:

$$I = (ET_c/I_e)(1+LF) \quad (6)$$

LF calculations are available in the literature (Hoffman et al., 1990). With drip irrigation and especially SDI, LF values are lower than under conventional irrigation because if irrigated adequately, the soil does not dry up and the soil solution salts do not concentrate.

In summary, in order to decrease I without yield reduction, we must reduce the outputs from the system (R+D+E+T) while improving the irrigation efficiency (I_e) and the emission uniformity (EU) of the drip system.

Results of Drip and Subsurface Drip Irrigation Studies Demonstrating the Validity of Above Theoretical Claims

The following results were obtained by the USDA-ARS, WMRL staff in cooperation with the University of California at the West Side REC, Kearney REC and Brawley REC. Results were obtained over a decade (1984-1993) from several statistically designed research experiments using precision weighing lysimeters (Phene et al., 1989, Ayars et al., 1999). High frequency soil water concepts for DI and SDI reviewed by Warrick and Or (2007) were used to design and managed this research effort. One of the objectives of this research was to determine if the yield and WUE of several field and forage crops could be improved with drip irrigation (DI) and SDI while decreasing the amount of applied water. Table 4 summarizes some of these results.

- Runoff (R)—Typically, adequately designed, installed and managed DI and SDI systems will not generate runoff (Howell and Meron, 2007). On sloping lands, R can be avoided with adequate design and/or by using pressure compensated non-leak emitters.
- Drainage (D)—Drainage is a more complicated issue, first because it cannot be determined visually, second because in arid areas, some salt leaching is required when normal P is low and when P occurs in significant amounts, some drainage will occur naturally. In this case,

it is therefore necessary to go back and look at the soil water factors generating drainage. Warrick and Or (2007) provide an extensive review of the soil water concepts. Equation 7 is the mathematical vector representation of Darcy's Law (Adapted from Richards, 1931).

$$\partial\theta/\partial t = -\nabla \bullet (K(\Psi)\nabla\Psi) + \partial K/\partial Z \quad (7)$$

This equation defines the rate of change of the soil water content with respect to time ($\partial\theta/\partial t$). The value $\partial\theta/\partial t$ is a function of the sum of the three-dimensional capillary force field, $\{-\nabla \bullet (K(\Psi)\nabla\Psi)\}$ and the gravitational downward force field, $\partial K/\partial Z$ (Z positive downward), where the unsaturated hydraulic conductivity, $K(\Psi)$ is function of water potential, Ψ multiplied by the three-dimensional water potential $\nabla\Psi$ and K is the saturated hydraulic conductivity. As the soil water potential (Ψ) approaches saturation (zero), the three-dimensional capillary force field approaches zero and the gravitational downward force field ($\partial K/\partial Z$) remains constant, thus allowing a downward flux of water and the occurrence of undesirable drainage. Assuming a bare soil, the basic implication is that in order to eliminate or reduce deep drainage, the absolute value of the capillary force field, $|\nabla \bullet (K(\Psi)\nabla\Psi)|$ must equal or exceed the constant downward gravitational force field, $\partial K/\partial Z$.

$$|\nabla \bullet (K(\Psi)\nabla\Psi)| \geq \partial K/\partial Z \quad (8)$$

In other words, the soil water must not be allowed to reach saturation or near-saturation, except in a small soil volume surrounding the source of water (Phene et al., 1989). The increasing availability of soil water and ET measurement techniques (Phene et al., 1990a) has facilitated the use of high frequency irrigation (several short irrigations per day, typically 1-2 mm at a time). The recent availability of very low discharge rate emitters (as low as 0.07 gph) is also more able to match the infiltration rate of most soils and the ETc requirement of the crop and thus can be operated almost continuously at very low pressure.

Phene et al. (1989) used a weighing lysimeter to directly measure evapotranspiration of a SDI irrigated tomato crop. In this experiment, the water application rate (I) was equal to the sum of soil evaporation (E), plant transpiration (T) and deep percolation (D) less precipitation (P) and water was applied as often as 1.0 mm/hour as measured by the mass change of the weighing lysimeter (2 x 2 m area and 2.35-m deep). Electronic soil matric potential sensors (SMP, Ψ_m) (Phene et al., 1971) were installed at depths of 0.15, 0.30, 0.45, 0.70, 1.00, 1.55, 2.00 m below the soil surface. A shallow water table was also maintained at a 2.35-m depth. These conditions caused a slight upward hydraulic gradient from the water table. The Ψ_m of the Panoche clay loam soil was measured hourly at above-mentioned depths. The crop lysimeter was irrigated by a SDI system with the drip lateral installed 0.45-m deep. Mean daily Ψ_m measurements (calculated from 24 hourly measurements) for a period of 30 days indicated that the SDI system maintained a nearly constant daily and seasonal Ψ_m profile and a net upward hydraulic gradient ($\Delta H/\Delta Z$), where $\Delta H/\Delta Z = (H_2 - H_1)/(Z_2 - Z_1)$ is the vertical hydraulic gradient, $H = \Psi_m - Z$, Ψ_m is the soil matric potential, ΔZ is the vertical distance between two measurement points and Z is the soil depth measured downward from the soil surface. Figure 5 shows the Ψ_m profile and the direction of $\Delta H/\Delta Z$. These data indicate that except directly below the drip lateral, between soil depths of 0.45 and 0.70 m, $\Delta H/\Delta Z$ is upward everywhere else. Therefore the net flux of water is upward and deep drainage losses can either be prevented or controlled. By using this high frequency SDI management approach with salt-tolerant crops we can also force the plant to utilize a significant volume of water from the shallow water table and thus help temporarily and locally control the water table level with minimum or no drainage outflow.

Ben-Asher and Phene (1993) have used a 2-dimensional simulation model (SUTRA, Voss, 1984) to show that for a given discharge rate of water: (1) the spherical volume of a wetted clay loam soil is approximately 46% larger for the SDI system than the hemispherical volume wetted

with a similar DI system; (2) the corresponding wetted surface area available for root uptake is 62% larger in the SDI system than in the DI system (excluding the soil surface in the surface drip pattern, if included, the difference is 8.0%); and (3) the wetted radius is 10% shorter in the SDI than in the DI system (Figure 6).

The implications are that under similar irrigation conditions: (1) the wetted soil volume in the SDI system will be at a lower water content than that in the DI system and the drainage potential will be lowered, (2) the surface area of soil available for root uptake of water and nutrients will be increased in the SDI system and (3) the shorter wetted radius in the SDI system will allow closer emitter spacing than in the DI system, resulting in potentially improved wetted uniformity. Model outputs were validated in the field as shown in Figures 7a (for SDI) and 7b (for DI).

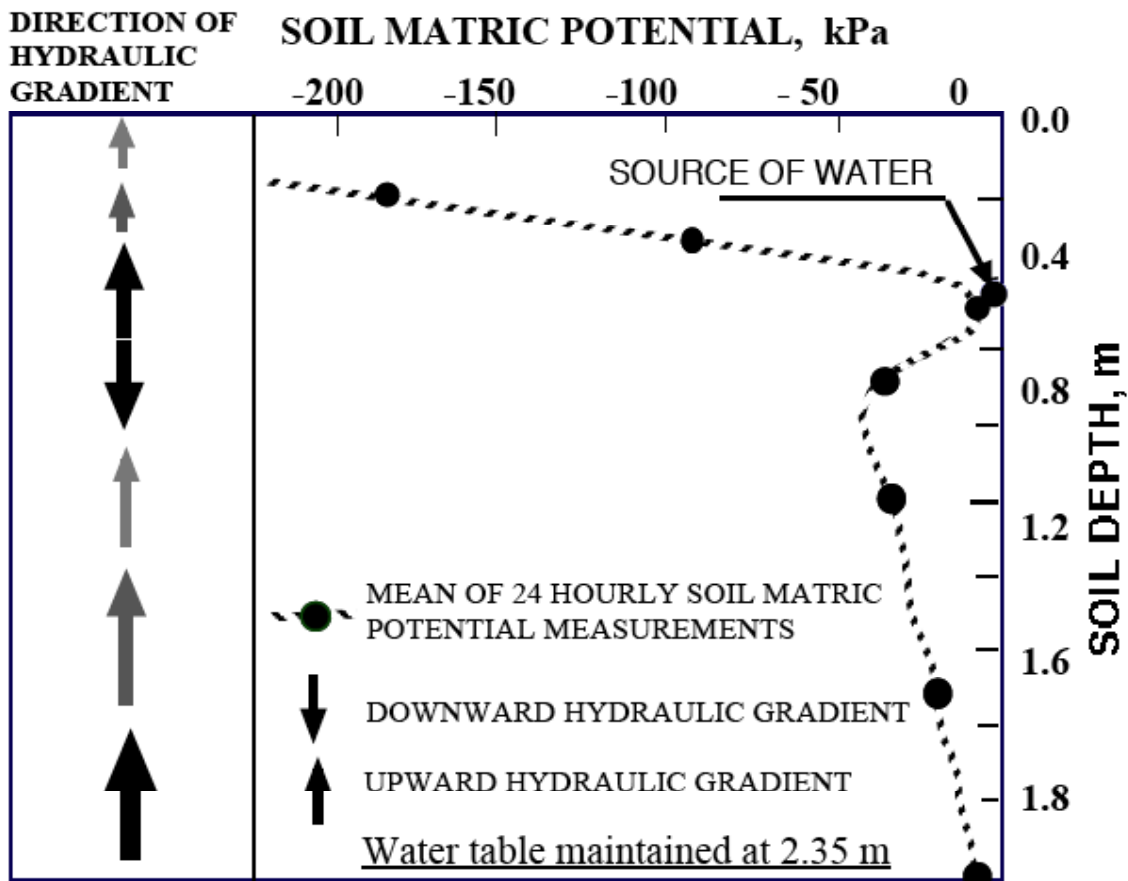


Figure 5. The SMP (Ψ_m) profile and the direction of the hydraulic gradient ($\Delta H/\Delta Z$) for day 195 of 1987 are shown in the presence of a water table at 2.35 m (Phene et al., 1989).

Steady state wetted patterns created in a dry Panoche clay loam soil by a SDI (Fig. 7a) and by a DI system (Fig. 7b) validated the model simulations. The wetted patterns extended similarly, vertically and laterally in Figures 7a and 7b, indicating that the gravitational force field was not exceeding the capillary force field and thus no significant drainage was occurring. Phene et al., (1990) showed that with sweet corn, root extended well below the wetted zone. As will be further demonstrated next, the lack of surface water in the SDI example (Fig. 7a) will reduce surface evaporation when the canopy does not fully cover the exposed soil area between the two crop rows (60 in. apart).

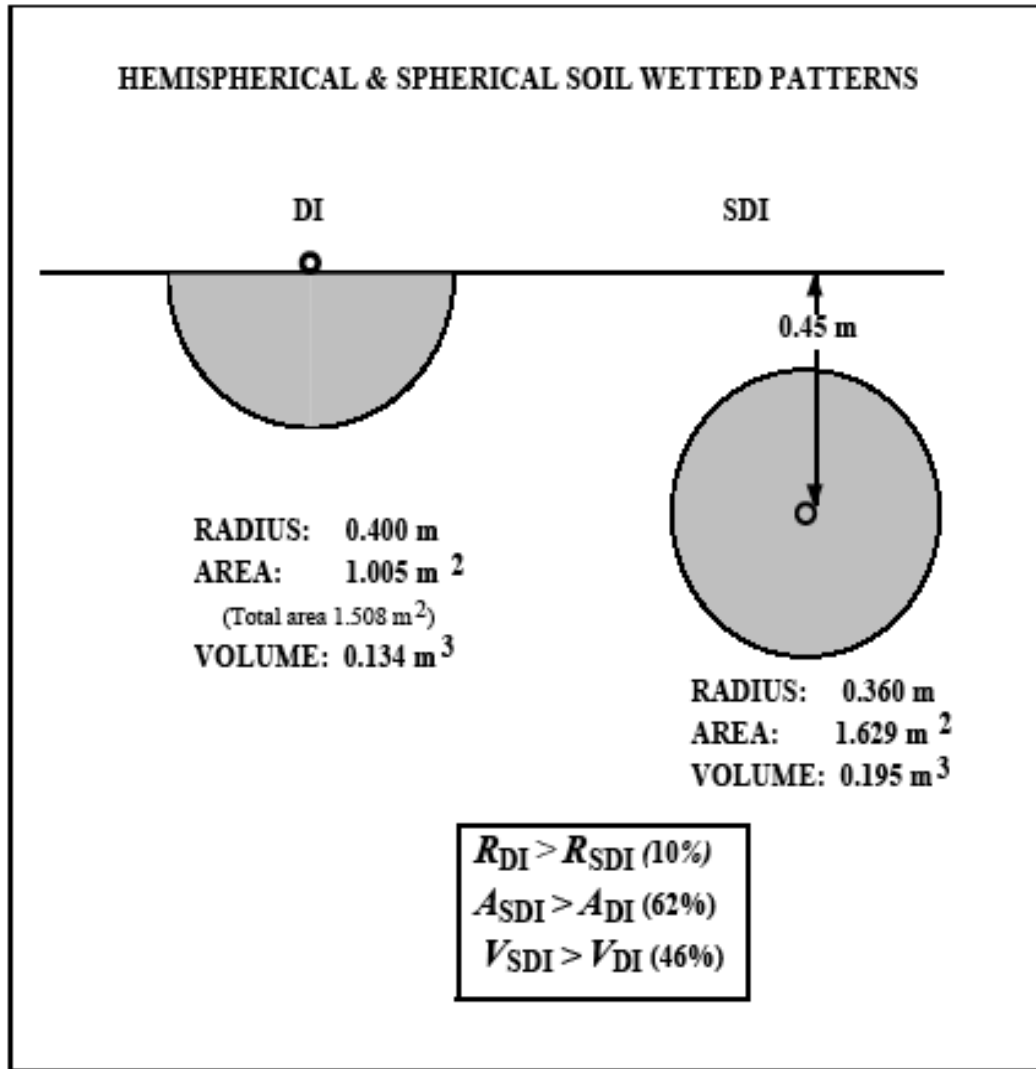


Figure 6. Simulated wetted patterns created in a dry Panoche clay loam soil by a DI and a SDI system with discharge rate of 2 l/h and a 3-h irrigation period (from Ben Asher & Phene, 1993).



Figure 7a. Wetted patterns created in a dry Panoche clay loam soil using a SDI system with discharge rate of 2 l/h and a high frequency (1-hour) irrigation period.

- Evaporation (E)--Properly designed, installed and managed DI minimize evaporation whereas SDI systems nearly eliminate evaporation of water at the soil surface (non-beneficial use of water) and minimizes salt accumulation and crusting resulting from water evaporation.

Phene et al., (1989) measured bare soil evaporation under high frequency irrigation with DI and SDI, using two precision weighing lysimeters (Figure 8). A one-mm irrigation was applied when the mass loss of the lysimeter was equivalent to a one-mm loss of water. Reference evapotranspiration of grass (ET_o) was measured by a similar weighing lysimeter planted to



Figure 7b. Wetted patterns created in a dry Panoche clay loam soil using a DI system with discharge rate of 2 l/h and a high frequency (1-hour) irrigation period.

short cool season grass, located 100 m south. The ratio of lysimeter-measured evaporation from bare soil (E_{bs}) to lysimeter-measured evapotranspiration of the cool season grass, E_{To} (E_{bs}/E_{To}) was calculated hourly when the bare Panoche Clay Loam soil (Typic Torriorthents) was irrigated by DI and SDI; E_{bs}/E_{To} ratios for DI and SDI are shown in Figure 8. The mean E_{bs}/E_{To} for SDI was nearly constant at 0.06 and required three irrigations to maintain constant soil moisture for 28 days, whereas the mean E_{bs}/E_{To} for DI was 0.12, varying between 0.08 and 0.20 in response to irrigation, and it required six irrigations for the same time period. Based on these results, in bare soil irrigated by SDI, evaporation was nearly negligible (Phene, 1995a).

Evelt et al., (2000) compared evaporation (E) in a corn canopy from surface drip, SDI at 15-cm depth and SDI at 30-cm depth from emergence to fully mature canopy (114 days). They showed that soil evaporation was reduced by 51 mm (2 in.) with SDI installed at 15 cm and 81

mm (3.2 in.) with the SDI system installed at 30-cm depth. As the results in Figure 8 and in the Evett study point out, soil evaporation decreases significantly with depth of SDI installation and although not fully eliminated at depths of 0.15 and 0.30 m, it becomes insignificant at installation depth of 0.45 m.

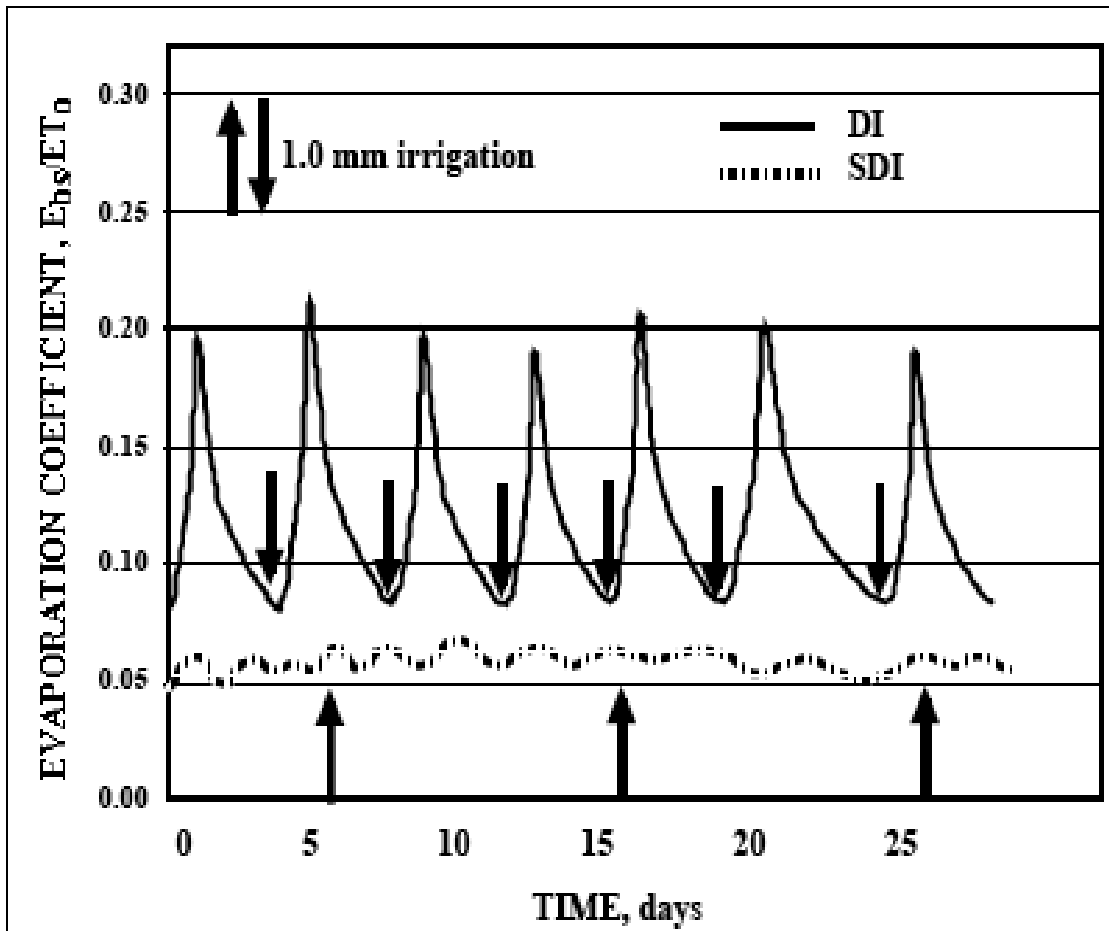


Figure 8. Comparison of bare soil evaporation coefficients under high frequency irrigation with DI and SDI (1 mm/h), as measured by two precision weighing lysimeters on Panoche Clay Loam soils (*Typic Torriorthents*) (Phene, 1995a).

- Reducing non-beneficial E_{Tc}, without loss of yield.

In another study using a large weighing lysimeter at UC Kearney REC (4 x 2 x 2.3 m) as the basal 100% E_{Tc}, Williams et al., (1992) showed that there was no yield decrease for Thompson Seedless (*Vitis vinifera* L. cv. Thompson Seedless) grown on a single wire and 1.2- m trellis and irrigated by drip irrigation at a rate of 80% of the vines grown in the lysimeter (100% E_{Tc}) (Figure 9). Furthermore, maximum WUE was obtained for the irrigation treatment using 60% of the lysimeter (100% E_{Tc}); considering that this irrigation regime did not reduce the soluble solids (°Brix) compared to that of the lysimeter, this represents another great potential water saving. Reducing E_{Tc} of Thompson seedless grapes by 20% did not reduce yield, soluble solids and WUE.

- Emission Uniformity--The design emission uniformity (EU) is an estimate of the percentage of the average depth of application required by a system to irrigate adequately the least watered plants.

The EU can be computed by equation 9:

$$EU = 100(1.01 - (1.27/\sqrt{e})CV)(q_n/q_a) \quad (9)$$

Where: EU = design emission uniformity, %; e = number of emitters per plant (>1); CV = manufacturer's coefficient of variation; q_n = minimum emitter discharge computed with the minimum pressure using the nominal relationship between emitter discharge and pressure head, gph; and q_a = average emitter discharge (of all the emitters under consideration), gph.

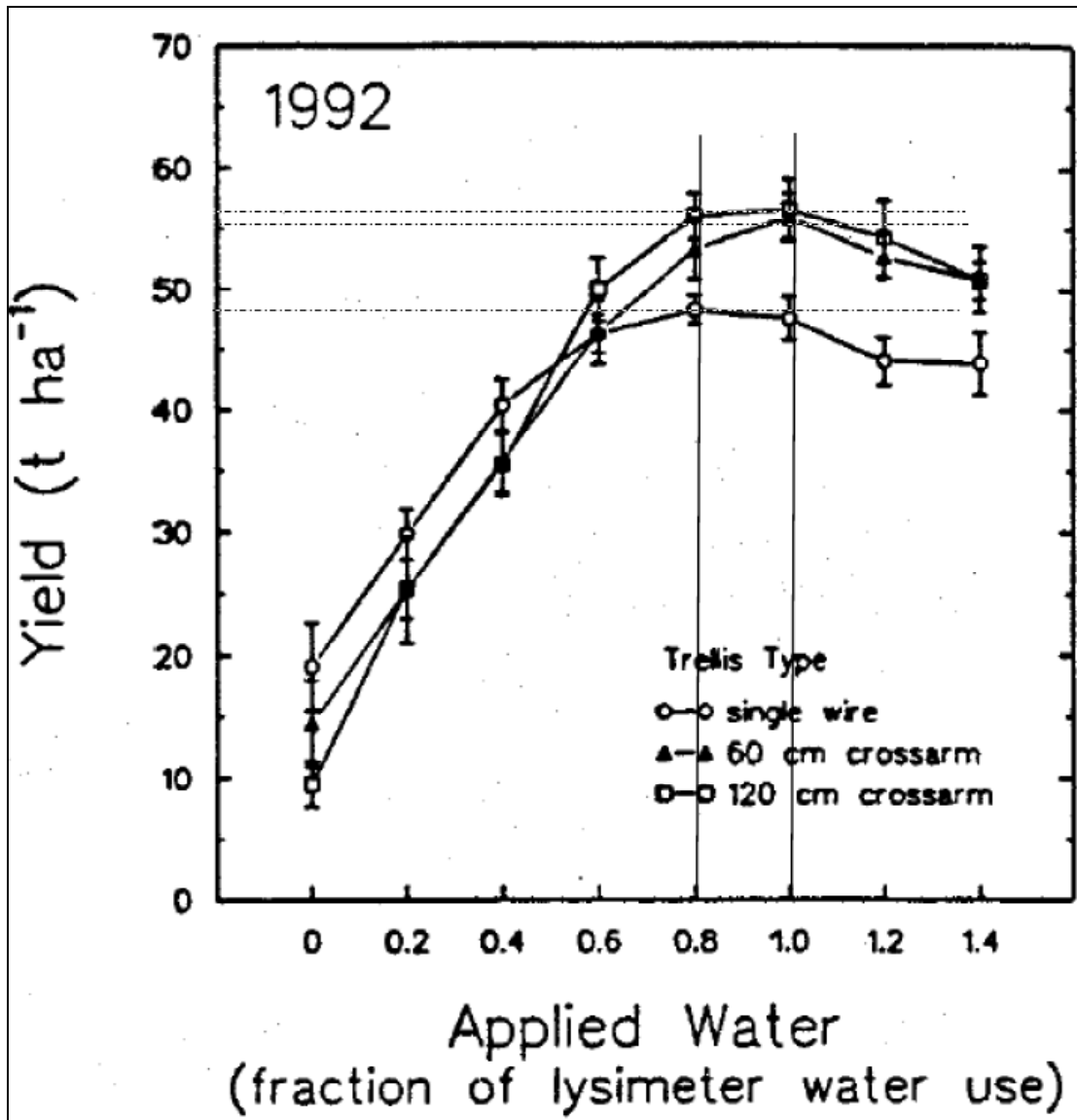


Figure 9. Effect applied water as a fraction of lysimeter water use (100%) and various trellis types. Applied water of 1 = 100% of water evapotranspired by the vines in the lysimeter (Williams et al., 1993).

Equation 9 implies that in order to keep the Irrigation efficiency (*i_e*) as high as possible, the CV must be as small as possible and the ratio (*q_n/q_a*) must be as close to 1 as possible in order to keep the EU \geq 90%. Visual examples of DI, SDI and LPS system uniformity are shown in Figures 10, 11 and 12. Wetted patterns in Figure 10 show an example of high uniformity soil

wetting generated by a two-year old single DI lateral on a 60-in. bed before planting at the UC West Side REC in April 1982. The soil there is a deep Panoche clay loam that has been rototilled prior to the test.



Figure 10. An example of high uniformity soil wetted pattern generated by a two-year old single Drip System (DI) lateral on a 60-in. bed before planting at the UC West Side REC in April 1982.

The aerial photo in Figure 11 shows an example of surface salinity-induced infiltration variability on cotton canopy uniformity differences between 10 ac. irrigated by a SDI system (left hand side), 10 ac. irrigated by a surge flow furrow irrigation system during an irrigation event (middle) and 10 ac. irrigated by a conventional furrow system (right hand side) on July 27, 1987 near Strathmore, CA. Regardless of the dramatic effect caused by the irrigation water in the surge flow furrow irrigation system, the canopy variability on the 10 ac. irrigated by a conventional furrow system (right hand side) is also visible. The SDI lateral installed 18 in below the soil surface by-passed the surface problem and eliminated the infiltration problem created by the soil surface variability.

An example of high uniformity soil wetted patterns generated by single Low Pressure Drip System (LPS) lateral on a 60-in. bed planted to cotton at UC Shafter REC in April 2004 is shown in Figure 12. Here the low cost LPS laterals are installed at a 3-4 in. depth, in the middle of a 60-in. sandy loam bed and irrigated continuously for several hours a day at a discharge rate of 0.16 gph. The duration of water application is determined daily by calculating plant water requirements based on CIMIS ETo and a crop coefficient. The discharge uniformity (DU) and statistical uniformity (Us) of this system were measured in 2005 and 2006 and the 2006 results are shown in Table 5.

Treatment #1 (top line) is the results for a LPS system similar to the one shown in Figure 12. The end of season DU and Us are respectively 0.91 and 97.4 %.



Figure 11. A commercial example of cotton canopy uniformity differences between 10 ac. Irrigated by a SDI system (left hand side), a surge flow irrigation system being irrigated (middle) and a conventional furrow system (right hand side) on July 27, 1987 (Photo courtesy of USDA-ARS, WMRL 1987).

- Fertigation and Water use efficiency--Feddes et al., (1978) and Van Ootegem et al., (1982) have shown that harvestable dry matter and often crop yields increase linearly with T but that E is generally non-beneficial. Since we have shown above that deep SDI systems essentially eliminate E from the soil surface, the use of SDI systems should maximize WUE. However, it is recognized that besides water management, fertility management is the next most limiting factor in maximizing yields and WUE (Bar-Yosef et al., 1989; Bar-Yosef, 1999).

Phene et al. (1988) showed that tomato yields increased significantly with accurate fertigation without increasing ETC. Water use efficiency of tomato from four years of research with DI and SDI were presented in Table 4 and Figure 13. The significant increases in yield and WUE were achieved by adequately matching crop requirements for N, P and K without requiring additional water (values in mm below the yield points in Figure 13 are the amount of applied water given in Table 4 for 1984, 1985 and 1987). The top three yields are given to show the effect of three phosphorus fertigation rates (P_2O_5) on yields of marketable tomato. Considering that all other variables were constant (N, K, applied water, weather, etc...), these results clearly demonstrate the importance of P-fertigation with SDI; however, too much P (272 lb/ac P_2O_5) did not increase yields beyond 136 lb/ac. P_2O_5 . The mean water applied for the three years given in Table 4 was 28.1 in. (714 mm), which is approximately 6 in. less than typically applied with good furrow irrigation. The mean WUE was 2.8 kg/m³ or at least twice what is normally achieved with good

furrow irrigation. *With SDI, fertigation increases yields and WUE without increasing water application.*



Figure 12. An example of high uniformity soil wetted patterns generated by a single Low Pressure Drip System (LPS) lateral on a 60-in. bed planted to cotton at UC Shafter REC in April 2004.

Table 4. Yearly values (12 months) of grass reference ET (ET_o) and crop evapotranspiration (ET_c), precipitation, irrigation application, drainage from the crop lysimeter, and water use efficiency (WUE) for DI and SDI systems for several crops grown by the USDA-ARS, Water Management Research Laboratory from 1984-1993 at the UC West Side REC, Five Points, California.

CROP	YEAR	ET_o	CROP ET_c & SOIL E	PRECIP. mm	IRRIGATION APPLICATION	DRAINAGE	WUE*	
							DI	SDI
							kg/m ³	
TOMATO	1984	1,823	959	104	692	0	2.25	2.20
TOMATO	1985	1,720	855	127	792	59	2.22	2.41
CANTALOUPE	1986	1,701	863	167	552	90	1.68	1.81
TOMATO	1987	1,657	793	187	658	36	3.49	3.88
COTTON	1988	1,583	979	205	694	83	2.78	3.13
SWEET CORN	1989	1,514	693	86	667	2	2.90	2.92
TOMATO	1990	1,618	875	145	773	38	2.53	2.65
FALLOWED**	1991	1,589	304**	184	0**	21**	N/A	N/A**
WINTER WHEAT**	1992	1,542	385**	198	350**	7**	N/A	N/A**
COTTON	1993	1,527	803	313	550	62	N/A	N/A**
MEANS	1984-93	1,627	853	172	672	46	2.55	2.72

* WUE defined as total aboveground dry matter yield / irrigation water applied.
 ** ET_c , Irrigation Application, Drainage and WUE data not included in calculation of means.

Table 5. Differences in LPS discharge and statistical uniformities between measurements obtained on 6/28/06 and 8/16/06.

Treatments	DU 6/28	U_s 6/28	DU 8/16	U_s 8/16	% change in DU	% change in U_s
Treatment #1	0.9323	98.07	0.9095	97.43	-2.45	-0.66
Treatment #2	0.8776	96.39	0.8857	96.63	+0.92	+0.25
Treatment #3	0.9482	98.35	0.8898	96.49	-6.56	-1.89

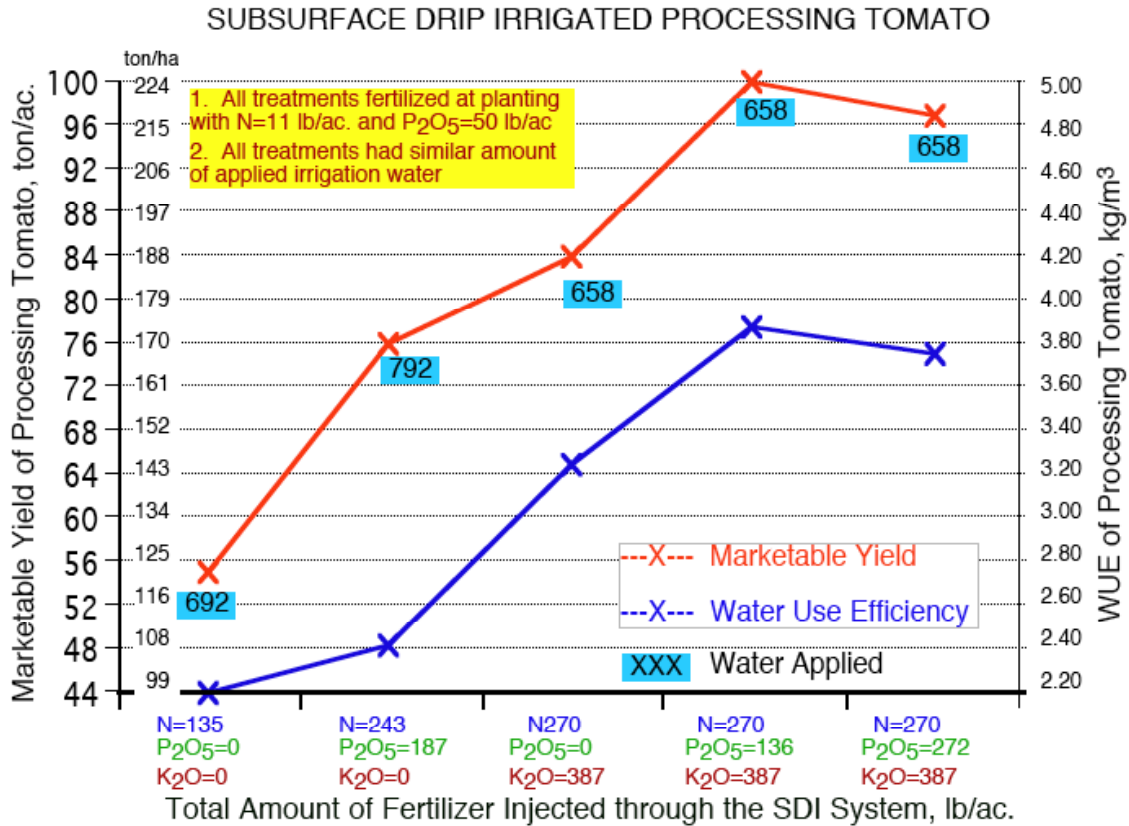


Figure 13. Fertilization with N-P-K affected yields and WUE of tomato at UC West Side REC for the period 1984-1987 (Phene et al., 1988).

An on-farm demonstration with SDI, LEPA, Conventional and Improved Furrow Irrigation

Since the 1980's several on-farm demonstration projects have been conducted to compare SDI with other irrigation methods. In 1989-1993, four 40-ac. blocks of cotton (except in 1991) were irrigated using subsurface drip irrigation (SDI), low-energy precision application (LEPA), scheduled furrow and existing conventional furrow irrigation systems on a SJV West Side farm. This project was funded by the California DWR and conducted by Boyle Engineering Corporation in cooperation with the UC Cooperative Extension and the USDA-ARS-WMRL (Smith et al., 1991). Four-year averaged results indicated that SDI significantly increased cotton yields, water conservation, net return and WUE over the other 3 irrigation methods. For example, WUE (kg lint cotton/m³ of applied water) of SDI-irrigated cotton increased by 36.4, 20 and 30.4 % over that of cotton irrigated by LEPA, improved furrow and conventional furrow systems (Hart, 1996). Assuming \$1,350/ac. system cost for the SDI system (10 year recovery cost at 10% interest) versus \$155/ac./yr for the furrow systems, the net revenue increases for the SDI system were 110 % (Scheduled Furrow) and 107% (Existing Furrow). Some people will question the 10-year recovery cost applied to the SDI system. However, with adequate design and management, research, demonstration and commercial experiences have shown that the 20-year recovery is achievable and even can be exceeded (Lamm et al, 2009). *These results suggest that SDI can be used commercially to irrigate cotton, conserve water and simultaneously provide some significant net income to the growers.*

Approximately one half of the California processing tomato acreage (approximately 130,000 ac) is now irrigated by SDI, producing yields ranging from 60 to 80 t/ac with water application ranging from 30 to 34 ac-in of water. Tomatoes are planted on two rows per 60- to 80-in bed with a single lateral SDI system installed at 12-14-in. depth in the middle of the beds. Figure 14 shows an example of a typical processing tomato crop. The yield (80 t/ac) and WUE (2.5 t/ac-in) shown in Fig. 14 are approaching the research values shown in Table 4, line 4 obtained for the research project conducted in 1987 (Phene et al., 1992).



Figure 14. Processing tomatoes were grown commercially in 2009 on a West Side of the California San Joaquin Valley 80-ac field irrigated by a SDI system. This photo was taken about one week before harvest. Commercial yield on this field was about 80 t/ac using 32 ac-in of applied water (Courtesy of Brock Taylor, 2009).

Conclusion

In order to decrease irrigation water application (I), the outputs from the system must be reduced: Runoff (R), Drainage (D), Evaporation from soil and plant surfaces (E) and Transpiration (T) while improving the emission uniformity (EU) of the irrigation system. It has been demonstrated that this is achieved by using adequate design and management of drip and subsurface drip irrigation systems. The advent of new and improved drip systems (pressure compensated, non-leak, low pressure systems, etc...) and other technologies such as GPS (installation and location of SDI laterals) and automated controls and measurement techniques (irrigation scheduling and system monitoring via phone, wireless and internet) are helping

irrigated agriculture to conserve water. Forty years of research and demonstration results have shown that DI and SDI can reduce the application of water per unit of crop produced that could alleviate water restrictions during drought periods.

- **Runoff (R)**-- Adequately designed, installed and managed DI and SDI systems do not generate runoff. On sloping lands, R can be avoided with adequate design and/or by using pressure compensated non-leak emitters.
- **Drainage (D)**--The soil physics theory indicates that the soil water must not be allowed to reach saturation or near-saturation, except in a small soil volume surrounding the source of water. Research has demonstrated that the net flux of water can be maintained upward and deep drainage losses can either be prevented or controlled. By using the high frequency SDI management technique with salt-tolerant crops, plants can also be forced to utilize a significant volume of water from the shallow water table and thus help temporarily and locally control the water table level with minimum or no drainage outflow.
- **Evaporation (E)**—Lysimetric research as shown that soil evaporation decreases significantly with depth of SDI installation and although not fully eliminated at depths of 0.15 and 0.30 m, it becomes insignificant at installation depth of 0.45 m or deeper.
- **Evapotranspiration (ET_c)**--Reducing ET_c of crops such as Thompson seedless grapes by 20% did not reduce yield, soluble solids and can increase WUE.
- **Emission Uniformity (EU)**—In a dramatic aerial photo of a cotton field, SDI by-passed the surface infiltration problem created by the soil surface variability. Emission uniformity (DU) and statistical uniformity (U_s) measurements in a two-year old, low cost thin wall drip system (LPS) were respectively 0.91 and 97.4% and in the acceptable range.
- **Fertigation and WUE**--With tomato irrigated by SDI, fertigation increased yields and WUE without requiring an increase in water application.
- **An on-farm demonstration with SDI, LEPA, conventional and improved furrow irrigation**--Using the 4-year averaged results from this demonstration project, SDI increased cotton yields, water conservation, net return and WUE over furrow irrigation methods.

Theoretically, California agriculture could conserve 6 ac.-in./ac./yr (approximately 2.4×10^6 ac-ft./year). Between 1990 and 2000, the use of drip/microirrigation has increased by 11% and comprised 20% of all California irrigated agriculture. Since 2000, many tomato growers on the West Side of the San Joaquin Valley have converted to drip and SDI and are doing economically well with the SDI technology. Orchards and vineyards are also being converted in large numbers to the drip/microirrigation technology. Tax and monetary incentives, demonstrations and training should be provided to the growers to convert from furrow and flood irrigation to the drip technology. With the full conversion of flood and furrow irrigation to the drip/microirrigation technologies, at least 2.4×10^6 ac-ft./year of applied water could potentially be conserved, especially during droughts.

Acknowledgements

Most of the research results were obtained by the USDA-ARS, WMRL staff in cooperation with the University of California at the West Side REC, Kearney REC and Shafter REC. The support received from the California DWR, growers and the irrigation Industry is also acknowledged.

References

- American Society of Agricultural and Biological Engineers (ASABE). 1996. Standard S526.1 "Soil and Water Terminology"
- Ayars, J. E., D. A. Bucks, F. R. Lamm and F. S. Nakayama. 2007. Introduction. In *Developments in Agricultural Engineering 13, Microirrigation for Crop Production*. 1-26.
- Ayars, J. E., and C. J. Phene. 2007. Automation. In *Developments in Agricultural Engineering 13, Microirrigation for Crop Production*. 259-284.
- Ayars, J. E., C.J. Phene, R.B. Hutmacher, et al. 1999. Subsurface Drip Irrigation of Row Crops: A Review of 15 years of Research at the Water Management Research Laboratory. *Agricultural Water Management* 42, 1-27.
- Bar-Yosef, b., B. Sagiv and T. Markovitch. 1989. Sweet corn response to surface and subsurface trickle phosphorous fertigation. *Agron. J.* 81:443-447.
- Bar-Yosef, B. 1999. Advances in fertigation. *Adv. Agron.* 65:1-77.
- Ben-Asher, J. and C.J. Phene. 1993. The effect of surface drip irrigation on soil water regime evaporation and transpiration. In *Proc 6th Int. Conf. on Irrigation*, 35-42.
- Bucks, D. A. and S. Davis. 1986. Historical development. In *Trickle Irrigation for Crop Production*, 1-26, New York, N.Y.: Elsevier.
- Bucks, D. A. F. S. Nakayama and A.W. Warrick. 1982. Principles, practices and potentialities of trickle (drip) irrigation. In *Advances in Irrigation*, 219-299, New York, N.Y.: Academic Press.
- Camp, C. A. 1998. Subsurface drip irrigation: A review. *Trans. ASAE* 41(5): 1353-1367.
- Evelt, S. R., T.A. Howell and A.D. Schneider. (2000). Energy and water balances for surface and subsurface drip irrigated corn. *International Water and Irrigation Journal*, Vol.20, No. 4, 18-22.
- Feddes, R. A., P. Kowalik and H. Zaradny. 1978. Simulation of field water use and crop yield. Pudoc, Wageningen. Simulation Monograph.
- Fulton, A. E., R. H. Beede and R. C. Phene. 1990. Implementing CIMIS at the farm level: A grower's experience in walnuts. In *Proc Third National Irrigation Symp.*, ASAE 270-274.
- Goldberg, D. and M. Schmueli. 1970. Drip Irrigation—A method used under arid and desert conditions of high water and soil salinity. *Trans. ASAE* 13(1): 38-41.
- Hall, B. J. 1985. History of drip/trickle irrigation. In *Proc Third Int'l Drip/Trickle Irrigation Congress*, 1-7. St. Joseph, MI.: ASAE.
- Hart, R. D. 1996. Results of eight Demonstration & Study Projects in the San Joaquin Valley to Reduce Agricultural drainage. Calif. Dept. of Water Resources, Aug. 1996; 1-8.
- Hillel, D. 1982. *Introduction to Soil Physics*. Academic Press, Inc., New York, NY 304-320.
- Hoffman, G. J., J.D. Rhoades, J. Letey, and F. Sheng. 1990. Salinity Management. In *Management of farm irrigation systems monograph*. 664-715.
- Howell, T. A., D. A. Bucks and J. L. Chesness. 1981. Advances in trickle irrigation. In *Proc Second National Irrigation Symp.*, ASAE, St Joseph, MI. 69-94.
- Howell, T.A. et al. 1981. Design and Operation of Trickle (Drip) Systems. In *Design and Operation of Farm Irrigation Systems*. ASAE Monograph 3, 663-717.
- Howell, T. A. and M. Meron. 2007. Irrigation Scheduling. In *Microirrigation for Crop Production, Design, Operation and Management*, Elsevier Publications. 61-130.
- Irrigation Journal. 2001. 2000 Annual Irrigation Survey. *Irrigation J.* 51(1):12-41.

- Lamm, F.R., J. E. Ayars, and F.S. Nakayama (Eds). 2007. *Microirrigation for Crop Production, Design, Operation and Management*, Elsevier Publications. 608
- Lamm, F. R. and C.R. Camp. 2007. Subsurface Drip Irrigation. In *Microirrigation for Crop Production, Design, Operation and Management*, Elsevier Publications. 473-551.
- Lamm, F.R., D.H. Rogers, M. Alam, D.M. O'Brien and T.P. Trooien. 2009. Twenty years of progress with SDI in Kansas. *ASABE Presentation*, Paper #095923.
- Phene, C.J., G.J. Hoffman and S.L. Rawlins. 1971. Measuring soil matric potential *in situ* by sensing heat dissipation within a porous body: I. Theory and sensor construction. In *Proceedings, Soil Science Society of America* 35(1):27-33
- Phene, C. J., K.R. Davis, R.L. McCormick, R.B. Hutmacher and D.W. Meek. 1988. Water and fertility management of drip irrigated tomatoes. In *Proc 4th Int'l Micro-irrigation Congress*, 10B-1-10B-6.
- Phene, C. J., R.L. McCormick, K.R. Davis, J. Piero, and D.W. Meek. 1989. A lysimeter feedback system for precise evapotranspiration measurement and irrigation control. *Trans. ASAE* 32(2):477-484.
- Phene, C. J., K.R. Davis, R.B. Hutmacher, B. Bar-Yosef, D.W. Meek. 1990. Effect of high frequency surface and subsurface drip irrigation on root distribution of sweet corn. *Irr. Sci.*, 12:135-140.
- Phene, C. J., R.J. Reginato, B. Itier and B.R. Tanner. 1990a. Sensing irrigation needs. In *Management of Farm Irrigation Systems*, 205-261.
- Phene, C. J., R.B. Hutmacher and K.R. Davis. 1992. Two hundred tons per hectare of processing tomatoes - can we reach it? *Hort Tech. J.* 2(1):16-22.
- Phene, C. J., D. A. Bucks, R. B. Hutmacher and J. E. Ayars. 1993. Research successes, applications and needs of subsurface drip irrigation. In *Proc. Water Management in the 21st Century*. Trans., 15th Cong. on Irrig. and Drainage, 249-267.
- Phene, C. J. Research trends in microirrigation. 1995. *Proc. 5th Int'l Microirrigation Congress*, 6-24. St. Joseph, MI.: ASAE.
- Phene, C. J. 1995a. The sustainability and potential of subsurface drip irrigation. *Proc. 5th Int'l Microirrigation Congress*, 359-367. St. Joseph, MI.: ASAE.
- Phene, C. J. and R. Ruskin. 1995. Potential of subsurface drip irrigation for management of nitrate in wastewater. *Proc. ASAE 5th Int'l Microirrigation Congress.*, 155-167.
- Smith, R. B., J.D. Oster and C.J. Phene. 1991. Subsurface Drip produced highest net return in Westlands area study. *California Agriculture*, Vol. 45, #2, 8-10.
- Reinders, F. S. 2000. Microirrigation: A World overview. In *Proc Sixth Int'l Microirrigation Congress*, Paper No. P9.5. 4
- Richards, L. A. 1931. Capillary conduction of liquids in porous mediums. *Physics* 1, 318-333.
- Schwarzenegger, A., M. Chrisman, L. A. Snow. 2005. California Department of Water Resources DWR. *California Water Plan Update 2005*; Vol. 1-5.
- United States Department of Agriculture (USDA-ARS). 2008. Value added to the U.S. economy by the agricultural sector via the production of goods and services, 2000-2007. Economic Research Service
- Van Ootegem, E., J. Feyen, M. Badji and L. Basstani. 1982. Optimization of water consumption by a tomato crop in semiarid climate. *Agronomie* 2(1): 31-6 (in French).
- Voss, C. J. 1984. A finite element simulation model for saturated and unsaturated fluid density-dependent ground water flow with energy transport or chemically reactive single species

- solute transport. U.S.G.S. Water Investigation Report 84-4369, Open File Service Selection Western Distribution Branch, Box 25425, Federal Center, Denver, CO.
- Warrick, A. W. and D. Or. 2007. Soil Water Concepts. In *Developments in Agricultural Engineering 13, Microirrigation for Crop Production*, 27-59.
- Williams, L. E., D. Williams and C.J. Phene. 1992. Modeling grapevine water use. In Proc *Eighth Australian Wine Industry Technical Conference*, 29-33.