Design Considerations for Vegetable Crop Drip Irrigation Systems

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Additional index words. microirrigation, irigation management, water management

Summary. Proper design and installation are essential to provide a drip irrigation system that can be managed with minimal inputs and maximum profit. Because drip irrigation can apply precise amounts of water and chemicals, constraints associated with the plants, soil, water supply, and management must be considered in the design, installation, and management processes.

Procedures that are appropriate in one location or with certain cropping systems may not work as well in other locations or for other crops. As a result, systems and management guidelines vary considerably and generally are customized for each cropping system. Usable water from soil moisture can range from 2% by irrigated volume on very sandy soils to more than 10% on heavier, fine-textured soils. Irrigation schedules based on soil conditions, crop evapotranspiration, tubing discharge characteristics, and other system properties can range from three cycles per day to once every 3 days. Choice of drip tubing may include low-flow, closely spaced emitters or high-flow emitters on greater spacings and should be based on the soil conditions, plant spacing, available water supply, pump capacity, and management practices. Finally, thorough water treatment and the correct filtration system are imperative for the successful operation of all drip irrigation systems.

Evaluations of vegetable crop production under drip irrigation compared with other irrigation methods have demonstrated equal or improved crop yield and quality with reduced water and fertilizer inputs (Clark et al., 1991; Locascio and Myers, 1974; Locascio and Smajstrla, 1989; Locascio et al., 1989; Myers and Locascio, 1972; Pitts and Clark, 1991). Other advantages include multiple cropping options (Stanley et al., 1991) and reduced bed widths to minimize plastic and soil fumigation costs (Clark and Maynard, 1992), both of which provide economic incentives to vegetable growers. However, the typically high conversion costs for irrigation systems (Prevatt et al., 1992) generally have retarded large-scale adoption of drip irrigation when other less costly irrigation systems are in place.

A successful drip irrigation system requires proper design, installation, and operation, which, in turn, require information on the water source, field, and crop. Water source inputs include quality and quantity. Important field inputs include the soil types and their related hydraulic properties, the length and width, the slope(s), and the location of the field with respect to the irrigation pump and water source. Soils with low water-holding capacities have limited wetting patterns from point-source drip emitters (Clark et al., 1993; Victor and Clark, 1991) and require special consideration regarding the placement of drip laterals and emitters (Pitts et al., 1989). The type of crop and planting date(s) strongly influence subsequent management and irrigation scheduling. All of this information is required to properly size the pump, pipe network, drip irrigation laterals, filtration system, and chemical injection system (Fig. 1). Fertigation system design and management (Dangler and Locascio, 1990; Locascio et al., 1989) are other factors that require careful consideration when vegetable crop drip irrigation systems are designed.

Many drip irrigation systems have been installed and are in use. However, poor designs result in poor uniformity of applied water. Furthermore, scheduling does not always consider the relationships between soil properties, crop development, and evaporative demand. Therefore, efforts to compensate for these conditions include liberal management with respect to applications of water and fertilizer, subsequently increasing the operating cost of these systems. The objective of this paper is to provide general design and management considerations for drip irrigation of shallow-rooted vegetable crops.

Soil and plants

Water movement and distribution in the soil from drip emitters is influenced primarily by the hydraulic properties of the soil. Maximum lateral wetting fronts from drip emitters can range from 6 to 12 inches on very sandy soils and from 16 to 32 inches on finer-textured silt and clay soils (Bar-Yosef and Sheikholslami, 1976; Clark et al., 1993; Keller and Bliesner, 1990; Victor and Clark, 1991). The lateral movement of water combined with the depth of the root zone define the soil volume that is wetted by the drip system (Fig. 2). Wetted volumes associated with surface drip irrigation systems on vegetable crops with shallow root systems often can be estimated using the pattern shown in Fig. 3. However, the distribution of water within the wetted soil volume is variable and

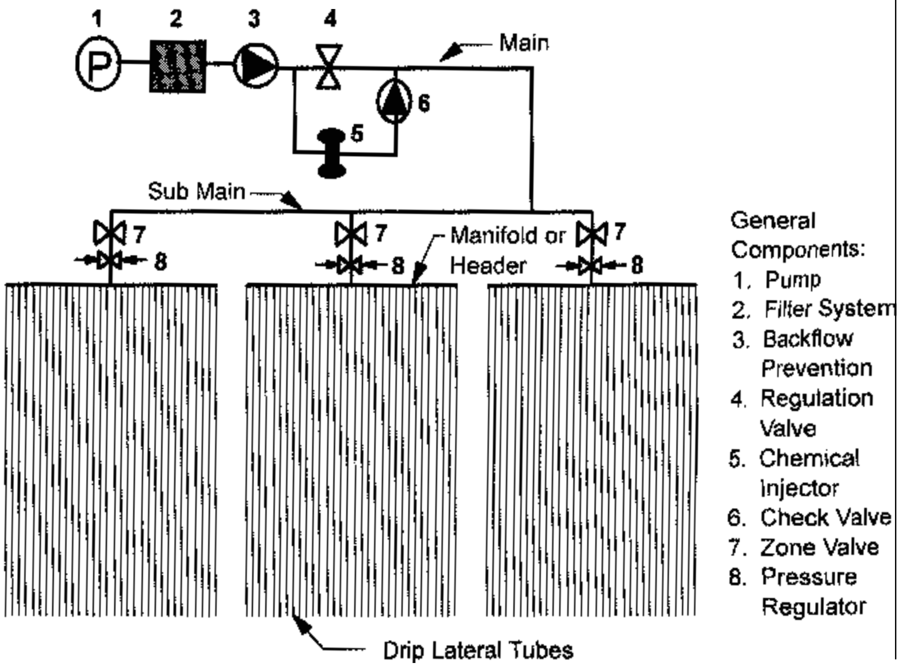

Fig. 1. General components of a vegetable crop drip irrigation system.

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Kansas Agricultural Experiment Station contribution no. 96-290-J.

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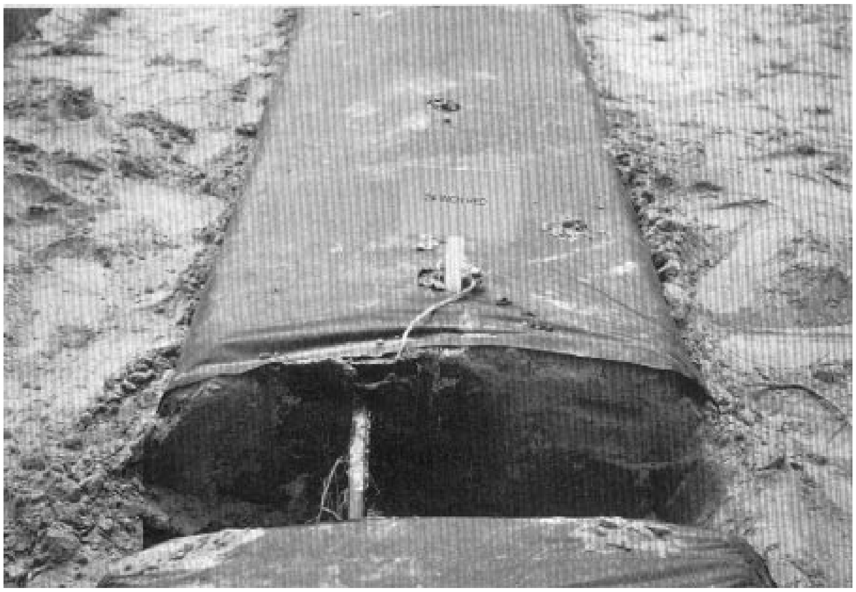
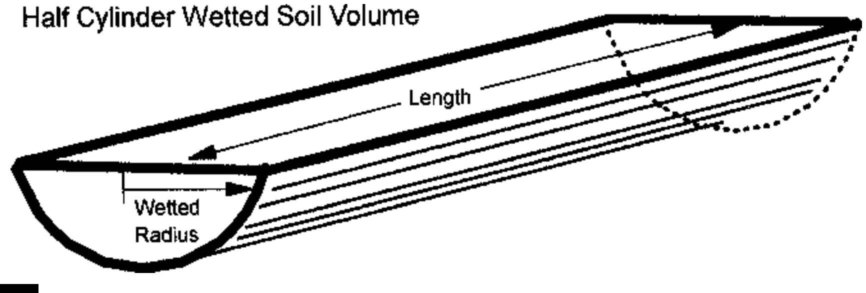


Fig. 2. Cutaway of a drip-irrigated plastic-mulch bed showing the wetting pattern on a sandy soil.

depends on the soil and irrigation management. As a result of soil wetting characteristics, discrete row systems used in vegetable production, and drip tubing discharge characteristics, it is generally easier to discuss irrigation requirements and schedules in volumetric units rather than depth units. For example, Table 1 assumes a uniform water distribution for the pattern defined in Fig. 3 and provides estimates of the volume of available soil water in gallons per 100 feet of row length as a function of wetted radius and available water capacity (%). Table 2 can be used with other wetting patterns based on the cross-sectional area of the specific pattern.

Available water [(AW) the difference between field capacity (FC) and permanent wilting point, (WP)] ranges from 3% to 5% for sandy soils and up to 20% for very fine-textured soils. Because many vegetable crops are sensitive to even short-term water deficits, which can occur rapidly with shallow root systems, the usable water (UW) often is taken as 33% to 50% of AW. As the soil water amount is depleted below the UW level, the remaining water is held more tightly by the soil and it is more difficult for the plants to extract. Thus, the plant may undergo mild stress and cell growth and development may decline.

Fig. 3. Diagram of a half-cylinder wetted soil volume.



From Tables 1 and 2, a sandy soil with a 6% AW holding capacity and a 12-inch wetted radius has 71 gallons AW/100 ft of bed length. This soil would provide only 20 to 35 gallons usable water/100 ft of bed length before the next irrigation. With daily crop water requirements of 60 to 80 gallons/100 ft, this provides only a 2-h reserve of UW during peak evapotranspiration (ET) periods. Conversely, a heavier loamy soil with a 12% AW holding capacity and a 15-inch wetted radius has 220 gallons AW/100 ft of bed length. This soil would provide 70 to 100 gallons/100 ft of UW, sufficient to meet the daily crop water demand.

Average reference evapotranspiration (ET_o) levels during the vegetable cropping seasons in the United States typically range from 0.10 to 0.25 inches/d in humid climates, with peaks reaching 0.35 to 0.45 inches/d in windy, arid climates (Jones et al., 1984; van Bavel, 1966). Because many vegetable production areas are in peak production during the months of high evaporative demand, crop water requirements are often high. Crop water-use coefficients (kc) are defined as the ratios of the crop water requirement (ET_c) to ET_o and are used to estimate ET_c from measured or tabulated historical ET_o values. Tomato, watermelon, and many other vegetable crops have peak kc values near 1.0, resulting in water use rates equal to the ET_o level during those growth periods.

Table 3 can be used to convert from ET_c or desired application depth in inches to volumetric units of gallons per 100 feet of bed length. For example, a daily irrigation need of 0.20 inches on a field with a bed spacing of 5 ft converts to 62 gallons of water/100 ft of bed. However, soils with low water-holding capacity and only 20 to 35 gallons/100 ft of UW may require two or three irrigation cycles per day for crops sensitive to water deficits and having shallow root systems. In addition, because crop ET follows the diurnal flux of solar radiation (Zur and Jones, 1981), 30% to 40% of the daily ET can occur during the 2-h period encompassing solar noon. This pattern of water use can result in short-term crop water stress if irrigations are not scheduled properly to provide sufficient soil moisture during that period for such sensitive systems. In general, when limited root zone and soil water-holding capacities require the scheduling of frequent, short-duration irrigations, sufficient time must be provided between cycles for plants to use applied water and nutrientsto avoid deep percolation and leaching.

Excess water applications also can cause problems. Over-irrigation during any one application potentially can leach soluble plant nutrients, such as N and K, from the root zone, particularly on soils with low cation exchange capacity (CEC). When saline irrigation water sources are used, leaching may be necessary to remove harmful salt accumulations by adding from 5% to 25% extra water to an irrigation cycle. The actual leaching amount depends on the salinity level of the irrigation water and the salt tolerance of the crop (Hoffman et al., 1990; Nakayama and Bucks, 1986; Sanchez and Silvertooth, 1996).

Soil physical and hydraulic characteristics must be considered to determine the optimum placement of drip laterals and emitters and the maximum run time per cycle. Drip emitters should be within 4 to 6 inches of plants and plant rows. Lateral drip lines may be placed on the surface or buried to maintain the tube in the desired location (eliminates surface movement). Buried tubes should be no more than 1 to 2 inches deep on sandy soils. Deeper emitter placement may be used on heavier soils; however, the effective root system and soil hydraulic properties also must be considered. Thus, even on heavier soils, drip tubes generally are not buried deeper than 6 inches for most vegetable crops.

Daily system run times of 20 to 40 min/cycle may be necessary during plant establishment to ensure movement of applied water into immature root systems. Subsequent maximum run times per irrigation cycle should be based on dripper discharge, soil properties including water movement, and plant rooting characteristics. If the extent of water movement from drippers is not known, it can be detected visually by digging a small trench perpendicular to the tube or electronically by using a digital volt-ohm meter with heavy electrical wire or brazing rods used as paired electrodes (Fig. 4). A measure of soil resistance between each pair of electrodes is recorded before irrigation and then followed with successive soil resistance measure-

Table 1. ***Volume of soil water stored in a half-cylinder distribution pattern (Fig. 3) (gallons/100 feet of length).***

Soil water capacity (%)	Wetted radius (inches) 3	6	9	12	15	18
	Soil water vol (gallons/100 ft of length)					
3	2.2	9	20	35	55	79
4	3.0	12	26	47	74	106
5	3.5	15	33	59	92	132
6	4.5	18	40	71	110	159
8	6.0	24	53	94	147	212
10	7.0	29	66	118	184	265
12	9.0	36	80	142	220	318

Table 2. ***Volume of soil water stored (gallons/100 feet of length) for various wetting pattern cross-sectional areas and soil water capacity levels.***

Soil water capacity (%)	Wetted cross-sectional area (inches^2) 25	50	75	100	250	500
	Soil water vol (gallons/100 ft of length)					
3	3.9	7.8	12	16	39	78
4	5.2	10	16	21	52	104
5	6.5	13	20	26	65	130
6	7.8	16	23	31	78	156
8	10	21	31	42	104	208
10	13	26	39	52	130	260
12	16	32	47	62	156	312

ments during irrigation. Soil resistance will drop when the wetting front approaches the electrodes. Thus, the time required for the water to move to certain lateral and vertical positions can be determined for the specific field conditions. For wetted radii and depths of 10 to 12 inches, typical maximum run times can range from 40 min for coarse-textured sands to 80 min for fine-textured sands. System run times per cycle in excess of those on sandy soils typically do not increase lateral wetting distances and can move water and soluble nutrients below the plant root zone. Maximum run times on very heavy soils can be 6 to 8 h, but must be managed to maintain applied water and crop nutrients within the managed crop root zone. This also can be checked with tensiometers, gypsum blocks, a capacitance probe, or some other soil moisture sensor.

Drip tubing

Drip irrigation tubing is available in various wall thicknesses, emitter spacings, and water discharge capacities. Products may be classed as tubes, which typically have inserted or attached emitters, and tapes, which typically have emitters formed from the tubing material during the manufacturing process (Fig. 5). Drip tube products typically are made from polyethylene tubing that is flexible and does not collapse when depressurized. Most drip tape products collapse when not pressurized and have wall thicknesses from 4 mil for light-weight products to 20 or 25 mil for the very heavy-weight products. Vegetable crop production systems generally use drip tapes that are medium weight with wall thicknesses of 8 to 12 mil.

Emitter spacing will affect the cost of tubes or tapes that use emitters that are inserted or attached. Conversely, emitter spacing has little effect on drip tapes with emitters molded into the tubing. Close emitter spacings of 8 to 12 inches are preferred for closely spaced (in-row) vegetable crops. Emitter spacings of 18 to 24 inches may be acceptable for use with crops that have greater plant spacings and on clay or loam soils. Emitter spacings greater than 24 inches rarely are used because wider spacings can result in greater variability in availability of water and injected nutrients for closely spaced vegetable crops.

Drip emitter discharge rates commonly range from 0.15 gallons/h to more than 1.0 gallons/h under operating pressures that typically range from 6 to 15 psi for tapes and 15 to 25 psi for tubes. In addition, the combination of emitter discharge rate, spacing, and field slope will influence the maximum length of run for each lateral line. Typical lengths of runs may range from 250 ft for high-flow, closely spaced products, to 1000 ft or more for low-flow emitters on greater spacings.

A common tape arrangement for vegetable crops uses a 10 psi operating pressure with 0.30 gallon/h drippers on a 12-inch spacing and results in a rated tape discharge of 30 gallons/h (0.5 gallons/min) per 100 ft of length. Using higher flow-rate drippers for vegetables produced on sandy soils may restrict run times to only 30 min/cycle because of the low water-holding capacity of the soil and shallow root zones. As a result, these short operation times would not be sufficient for most chemical injection systems to inject and fully purge chemicals from the pipe network into the soil. Purge cycles can require from 20 to more than 60 min depending on the pipe network, system flow rates, and location of the chemical injector. Therefore, low-flow drip products that can extend the length of the irrigation cycle may be more desirable for those field and crop characteristics.

In general, low-flow drippers may be more suitable for very sandy soils, but may constrain the system to only one or two irrigation zones per pump station based on crop ET, tubing discharge rate, and soil conditions. Some low-flow products discharge 12 to 15 gallons/h per 100 ft of length,

Table 3. ***Conversion from crop water use or irrigation application in depth units (inches) to volume (gallons/100 feet of bed length) for various bed spacing (center to center) arrangements.***

Bed spacing (ft)	Crop water use or irrigation depth (inches) 0.05	0.10	0.15	0.20	0.25	0.30
			Gallons/100 ft of bed length			
3	9	19	28	37	47	56
4	13	25	37	50	62	75
5	16	31	47	62	78	93
6	19	37	56	74	93	112

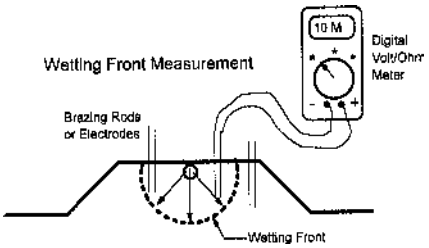


Fig. 4. Wetting front measurement and detection using a digital volt-ohm meter and paired electrodes.

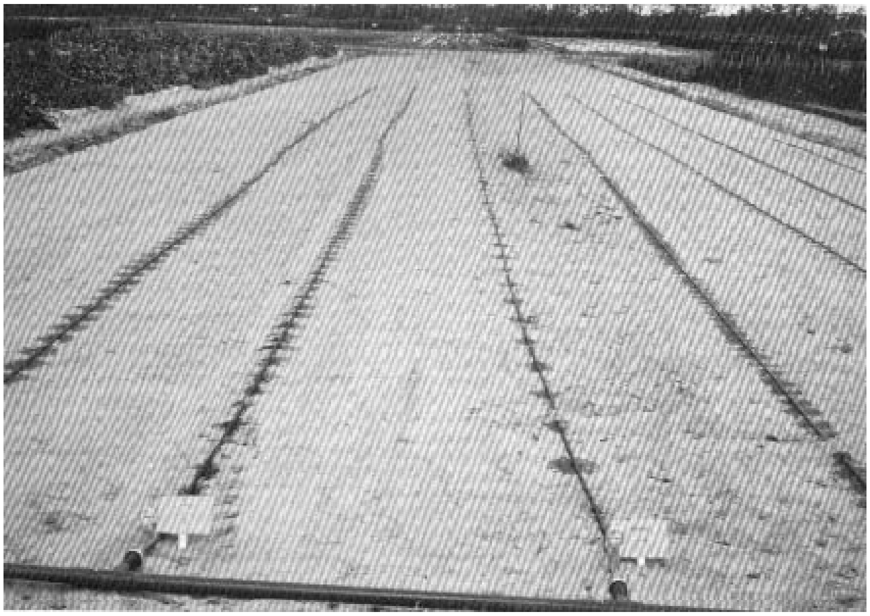


Fig. 5. Drip tapes and emission patterns.

Table 4. ***Conversion from drip emitter spacing and discharge rate to tubing discharge rate (gallons/h per 100 feet).***

Emitter spacing	Drip emitter discharge (gallons/h)					
(inches)	0.15	0.20	0.30	0.50	0.75	1.00
			Gallons/h per 100 feet			
8	23	30	45	75	113	150
12	15	20	30	50	75	100
16	11	15	23	38	56	75
18	10	13	20	33	50	67
24	8	10	15	25	38	50

which closely matches peak ET rates of some vegetable crops. Low-flow drippers also permit greater lateral lengths for given emitter spacings and uniformity allowances. However, because of the small flow paths, these drippers are susceptible to clogging and require high maintenance.

Pump capacity

Required pump capacity may be dictated by the size of each irrigation zone and water discharge rate of the drip system or by the limitations of the water supply. The size of each zone is not as important as the linear feet of tubing per acre or per zone. Table 4 can be used to determine drip tubing discharge rates in gallons/h per 100 feet of tube for different emitter discharge rates and spacing combinations. Then, Table 5 can be used to determine the linear feet of tubing per acre for different bed or tube spacings, and to determine the required pump capacity per acre for different tubing discharge rates.

For example, if a vegetable production field was formed with beds on 5-ft centers and a discharge rate of 20 gallons/h (0.33 gallons/min) per 100 ft tubing were used, the required discharge per acre would be 29 gallons/min (from Table 5). Next, if an existing well and pump system could deliver a peak discharge of 300 gallons/min at the required pressure, a 10.3-acre irrigation zone could be used (300 gallons/min divided by 29 gallons/min per acre from Table 5 = 10.3 acres). If a higher flow rate tube, such as 30 gallons/h (0.5 gallons/min) per 100 ft, were used, then the system would require 44 gallons/min per acre, and the maximum size of the irrigation zone would be limited to 6.8 acres (300 gallons/min/44 gallons/min per acre = 6.8 acres).

Filtration systems

Particulate matter in the irrigation water may clog the tiny orifices in the emitters of drip irrigation systems. Therefore, properly filtered water is essential for the sustained operation of most drip irrigation systems. The choice of filtration system will depend upon the quality and type of water supply (surface or groundwater, and suspended materials) as well as on the type of emitters. Some emitters can pass larger particles than others. In general, most particles larger than 0.003 to 0.006 inches or particles larger than one-tenth of the passage diameter should be removed. Most emitter and/or drip tubing manufacturers provide filtration recommendations and generally will them in terms of a mesh size (such as 200 mesh) for use with their drip irrigation product. Table 6 can be used to convert from screen mesh size to opening size.

If the water source is a surface supply, such as a pond, canal, or river, then media (sand) filters should be used to remove organic matter, such as algae and other suspended materials. Because sand and other particulate matter can escape the media filter through the backwash cycle, a media filter should be followed with a screen or grooved disk filter. When groundwater (i.e., pumped from wells) is used as the water source, a screen or grooved disk filter alone may be adequate. Because most sands are greater than 0.1 mm in size, these particles will be filtered with a 180- to 200-mesh or equivalent screen. However, if excessive sand is being pumped from the well, then a vortex-type sand separator can be required as a primary filter to remove most of the suspended sand prior to a secondary screen or disk filter.

Table 5. ***Conversion from bed spacing to linear feet of tubing per acre and to required pump discharge (gallons/min per acre) for different drip tubing discharge rates.***

Bed spacing	Linear feet	Drip tubing discharge (gallons/h per 100 ft)							
(feet)	per acre	15	20	25	30	35	40	50	75
					Gallons/min per acre				
3	14520	36	48	60	73	85	97	121	182
4	10890	27	36	45	54	64	73	91	136
5	8712	22	29	36	44	51	58	73	109
6	7260	18	24	30	36	42	48	61	91

Table 6. ***Screen mesh numbers and corresponding opening sizes.***

Mesh	Size of opening		
size	inches	mm	µm
40	0.0165	0.42	420
80	0.0071	0.18	180
120	0.0049	0.125	125
150	0.0041	0.105	105
180	0.0035	0.089	89
200	0.0029	0.074	74
270	0.0021	0.053	53

Because pressure of 3 to 10 psi typically is lost across the filters, this loss must be included in the overall system design. The manufacturer of the filtration system should supply this information with the specifications. Pressure loss will increase as the filter begins to clog and this must be considered in design and management. Measurement of pressure drop using pressure gauges placed on either side of the filtration system can indicate when cleaning of filters is necessary. Periodic and routine cleaning will remove the accumulated materials, thus minimizing the associated pressure loss. Cleaning can be performed manually or automatically.

For additional and more detailed information on system design and management the reader is directed to Howell et al. (1980), Nakayama and Bucks (1986), Hoffman et al., (1990), and Keller and Bliesner (1990).

Literature Cited

Bar-Yosef, B. and M. R. Sheikholslami. 1976. Distribution of water and ions in soils irrigated and fertilized from a trickle source. Soil Sci. Soc. Amer. J. 40:575-582.

Clark, G.A., C.D. Stanley, D.N. Maynard, G.J. Hochmuth, E.A. Hanlon, and D.Z. Haman. 1991. Water and fertilizer management of microirrigated fresh market tomatoes. Trans. Amer Soc. Agr. Eng. 34(2):429–435.

Clark, G.A. and D.N. Maynard. 1992. Vegetable production on various bed widths using drip irrigation. Appl. Eng. Agr. 8(1):29–32.

Clark, G.A., C.D. Stanley, and F.S. Zazueta. 1993. Qualitative sensing of water movement from a point-source emitter on a sandy soil. Appl. Eng. Agr. 9(3)299–303.

Dangler, J.M. and S.J. Locascio. 1990. Yield of trickle irrigated tomatoes as affected by time of N and K application. J. Amer. Soc. Hort. Sci. 115:585–589.

Hoffman, G.J., J.D. Rhoades, J. Letey, and F. Sheng. 1990. Salinity management, p. 667–715. In: Hoffman, Howell, and Solomon (eds.). Management of farm irrigation systems. Amer. Soc. Agr. Eng. Monogr., Amer. Soc. Agr. Eng., St. Joseph, Mich.

Howell, T.A., D.S. Stevenson, F.K. Aljibury, H.M. Gitlin, I.P. Wu, A.W. Warrick, and P.A.C. Raats. 1980. Design and operation of trickle (drip) systems, p. 663–720. In: M.E. Jensen (ed.). Design and operation of farm irrigation systems. Amer Soc. Agr. Eng. Monogr. 3. Amer. Soc. Agr. Eng., St. Joseph, Mich.

Jones, J.W., L.H. Allen, S.F. Shih, J.S. Rogers, L.C. Hammond, A.G. Smajstrla, and J.D. Martsolf. 1984. Estimated and measured evapotranspiration for Florida climate, crops, and soils. Fla. Coop. Ext. Ser. Bul. 840.,Gainesville.

Keller, J. and R.D. Bliesner. 1990. Sprinkle and trickle irrigation. Van Nostrand Reinhold, New York.

Locascio, S.J. and J.M. Myers. 1974. Tomato response to plug mix, mulch and irrigation method. Proc. Fla. State Hort. Soc. 87:126–130.

Locascio, S.J., S.M. Olson, and F.M. Rhoads. 1989. Water quantity and time of N and K application for trickle-irrigated tomatoes. J. Amer. Soc. Hort. Sci. 114:265–268.

Locascio, S.J. and A.G. Smajstrla. 1989. Drip irrigated tomato as affected by water quantity and N and K application and timing. Proc. Fla. State Hort. Soc. 102:307–309.

Myers, J.M. and S.J. Locascio. 1972. Efficiency of irrigation methods for strawberries. Proc. Fla. State Hort. Soc. 85:114–117.

Nakayama, F.S. and D.A. Bucks. 1986. Trickle irrigation for crop production. Elsevier Science Publishers, Amsterdam, The Netherlands.

Pitts, D.J. and G.A. Clark. 1991. Comparison of drip irrigation to subirrigation for tomato production in southwest Florida. Appl. Eng. Agr. 7(2):177–184.

Pitts, D.J., C.E. Arnold, and J.M. Grimm. 1989. Influence of lateral tubing location and number on growth and yield of tomatoes with micro irrigation. Proc. Fla. State Hort. Soc. 102:304–307.

Prevatt, J.W., G.A. Clark, and C.D. Stanley. 1992. A comparative cost analysis of vegetable irrigation systems. HortTechnology 2:91–94.

Sanchez, C.A. and J.C. Silvertooth. 1996. Managing saline and sodic soils for producing horticultural crops. HortTechnology 6:99–107.

Stanley C.D., A.A. Csizinszky, G.A. Clark, and J.W. Prevatt. 1991. Sequential cropping for vegetable production using microirrigation on sandy soils in southwestern Florida. HortTechnology 1:72–76.

van Bavel, C.H.M. 1966. Potential evaporation: The combination concept and its experimental verification. Water Res. Res. 2(3)455–467

Victor, P.R. and G.A. Clark. 1991. Uniformity of soil moisture in microirrigated plastic mulched beds. Soil and Crop Sci. Soc. Fla. Proc. 50:9–12.

Zur, B. and J. W. Jones. 1981. A model for the water relations, photosynthesis, and expansive growth of crops. Water Res. Res. 17(2):311–320.