Injecting Chemicals into Drip Irrigation Systems

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Summary. The injection of chemicals into irrigation systems is discussed in terms of injection systems, concentration injections, bulk injections, quantity of chemicals to be injected, injection system calibration, and injection periods. Sufficient clean-water flush time should be scheduled to purge irrigation lines of injected chemicals unless it is desired to leave that particular chemical in the irrigation system for maintenance purposes. Chemical injection rates vary with desired chemical concentration in the irrigation water, concentration of the stock solution, volume of chemical to be injected, and duration of each injection. All injection systems should be calibrated and maintained in proper working order. This information is presented to assist irrigation system designers and operators with chemigation system design, scheduling, and management.

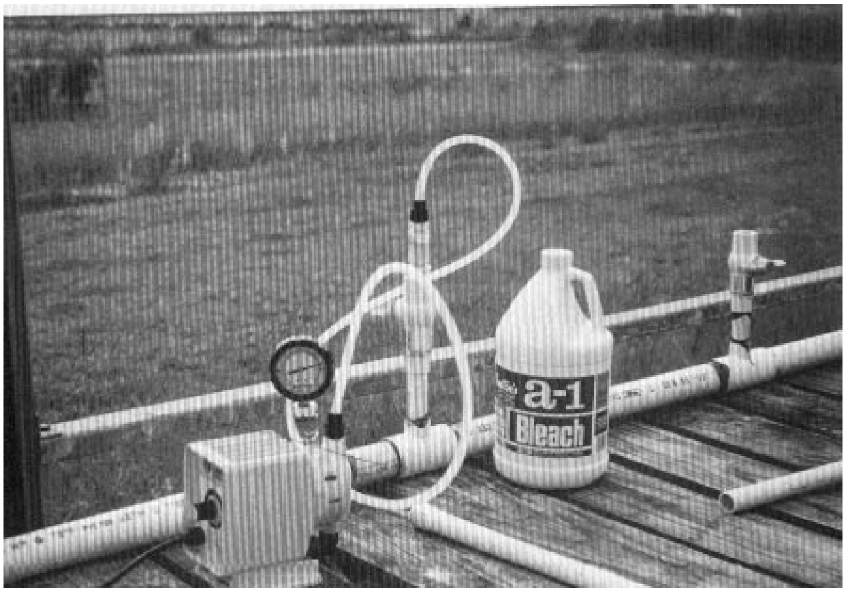


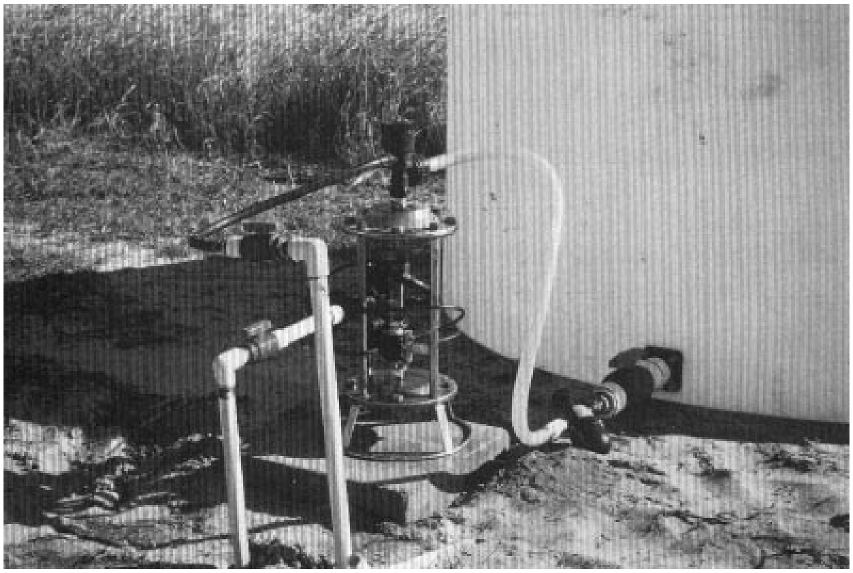
Fig. 1. Positive displacement AC-powered diaphragm injection pump.

Drip irrigation systems can be used to transport soluble chemicals to the soil and crop. Depending on the type of irrigation system, chemicals may be applied to the root zone, the aerial part of the plant, or both. The process of chemical transport using the irrigation system is referred to as chemigation and includes specific terms such as pestigation and fertigation to refer to specialized applications. Irrigation systems designed or adapted for chemigation require specialized equipment for injecting the chemical solution into the irrigation system at a controlled rate. While several injection methods are available (Nakayama and Bucks, 1986), the cost, accuracy, reliability, and longevity of equipment varies greatly among systems and manufacturers.

It is important to select the proper equipment, establish a regular maintenance and calibration program, and properly operate the system to ensure a successful chemigation program. New irrigation system designs should consider which chemicals are to be injected while selecting the system components to ensure compatibility between injected chemicals and other parts of the system. Because uniformity of chemical application cannot exceed that of the irrigation system, it is very important to have a well-designed and well-maintained irrigation system for optimal application uniformity of water and injected chemicals.

When existing irrigation systems are to be adapted for chemigation, they should be examined thoroughly for uniformity of application and compatibility with the chemicals to be injected. Water quality is another factor to consider in the design or adaptation of an irrigation system for chemigation. Some water supplies require chemi-

Fig. 2. Positive displacement, water-pressure-powered diaphragm fertilizer injector pump.



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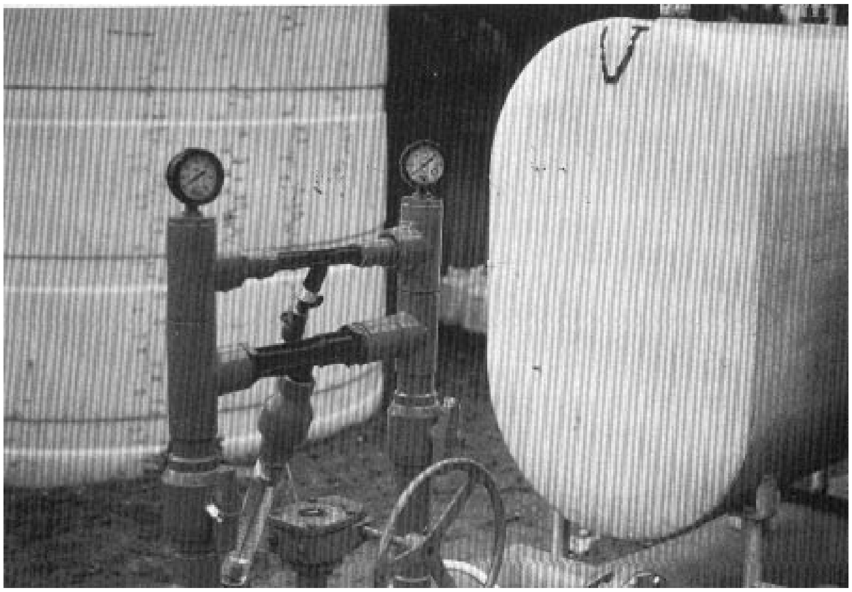
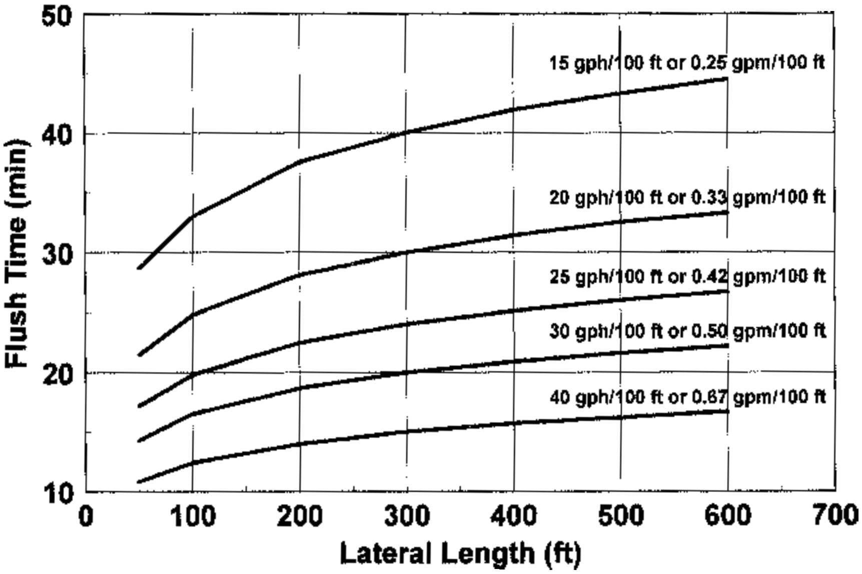


Fig. 3. Venturi injection system using two injectors for different chemicals.

cal amendment to prevent bacterial growth or chemical precipitants from clogging the irrigation system. Chemical reactions may occur between injected chemicals and existing chemicals in the water supply and may produce precipitates that can clog the drip emitters. Therefore, injected chemicals must be checked for complete solubility in the irrigation water supply.

This document discusses the major types of chemical injection systems, management of chemigation systems, and methods for determining amounts and rates of chemicals to be injected.

Fig. 4. Average chemical flush times from drip tape laterals (5/8-inch I.D., 12-inch emitter spacing) for various emitter/tube water discharge rates.



Chemical injection systems

Selecting and sizing a chemical injection pump should be based on the chemicals to be injected, the rate of injection, and any restrictions or requirements on the method of chemical injection. Some chemicals, such as some pesticides or other materials used to amend the water, must be metered precisely to maintain an injection rate that remains proportional to the irrigation rate. This injection mode typically requires positive displacement diaphragm (Fig. 1), piston, or gear-type pumps, which may be powered by electric motors, by water pressure from the irrigation system (Fig. 2), or by a power take-off (PTO) shaft on a tractor.

Venturi injectors (Fig. 3), bladder tanks, and other bulk injection systems generally result in more variable injection rates, which may be acceptable with chemicals that do not need to be injected at precise rates, such as many fertilizers. These injection systems usually operate in response to a pressure differential in the irrigation system. The pressure required by injection systems that operate on the pressure differential principle must be incorporated into the design of the irrigation system, including the sizing of the pump and power unit. Existing irrigation systems must be evaluated to determine if sufficient pressure is available to operate the injection system under consideration properly.

The length or duration of the injection cycle must be consistent with the irrigation cycle and should provide sufficient post-injection flush time to purge irrigation lines of injected chemicals. The purge time required is based on the velocity of the water in the pipelines and the hydraulic distance between the injection location and the mostdistant emitters. Main and submain pipes generally are sized to restrict flow velocities to 5 ft/s or less; however, existing systems should be evaluated to determine actual velocities. Because most irrigation systems will have less than 2500 ft of main and submain pipe from the pump to the drip laterals, most injected chemicals in this portion of the irrigation system will flush within 10 to 20 min after injection has ceased.

Flow velocities within the drip lateral lines are much lower than main and submain pipes and require longer periods of flush time than those pipe sections. Chemical flush times are shown in Fig. 4 for drip laterals of different combinations of lateral length and tubing discharge rate. Emitter discharge rate and emitter spacing combinations should be used to determine the tubing discharge rate in gallons/h per 100 feet. Moderate flow rate tubes of 25 to 30 gallons/h (0.42 to 0.50 gallons/min) per 100 ft may require 20 to 25 min of flush time in addition to the time required to flush mains and submains. Low flow rate drip irrigation products require long flush times. Therefore, 30- to 40-min flush times may be very common for many drip irrigation systems and should be incorporated into the design and management guidelines.

It is very important to have the proper backflow prevention equipment installed on the system when chemical injection systems are used (Smajstrla et al., 1985). Backflow prevention requirements vary with the toxicity class of the injected chemicals)and also vary among states and municipalities. In general, a backflow prevention assembly may consist of a vacuum relief valve, a low pressure drain, and a check valve located between the pump and injection site and in the order shown in Fig. 5. When injected chemicals are classified as toxic or poisonous, double backflow prevention assemblies may be required. The injection line also should have a check valve at the injection site to prevent backflow of water through the pump and into the chemical supply tank, and the injection system should be interlocked with the irrigation system such that chemicals cannot be injected unless the irrigation system is operating.

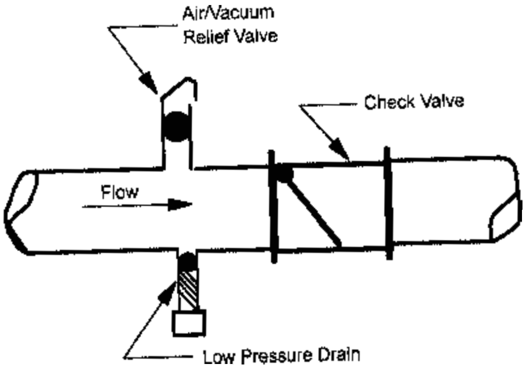


Fig. 5. Components of an irrigation system backflow prevention system.

Chemical mixtures and injections

Some injected chemicals must be maintained at a precisely managed concentration while other chemicals, such as fertilizers, can be injected with possibly varying concentration levels. Injection of precise concentrations, especially low concentrations, normally requires a positive displacement pump. An injection system must be calibrated for the specific irrigation system where it will be used, and the calibration should correspond to the operating conditions that will exist when chemicals are injected. Variations in operating pressure, system flow rate, and sometimes even temperature can influence the calibration of the injection system.

Bulk injection simply involves the injection of a desired volume or amount of chemical into the system. While the injection rate may not need to be precisely controlled, it should not be so large that it damages any part of the system or crop, should not exceed manufacturers' recommended application rates, and should allow the chemical to be applied in a time period that avoids over-irrigation or leaching of previously applied chemicals.

Concentration mixtures of a stock solution. Some chemical applications require the maintenance of a constant concentration level. Concentrations may be expressed in percent (%) or in parts per million (ppm), both of which refer to the ratio of the weight or mass (lb, g, etc.) of the active chemical to the weight or mass of the mixture. A 1% solution is equivalent to a 10,000 ppm concentration. Many chemical injection concentration levels are very low, thus ppm is a convenient unit to use. For stock solutions, the following equation can be used to determine the weight or mass of chemical required to achieve a particular ppm level.

$$\text{lb raw chemical/100 gal} = \text{desired ppm/1205} \qquad [1]$$

Equation [1] provides an estimate of the mass of actual chemical that must be dissolved per 100 gallons of water to achieve a certain desired concentration level. For example, a 200 ppm concentration level of nitrogen as a fertilizer solution will require 200 ppm/1205 = 0.17 lb N/100 gal water.

Many chemicals are supplied as either a percentage by weight of a dry or liquid mixture. Therefore, the required mass of chemical mixture will depend on the concentration of raw chemical in the mixture. Table 1 combines Eq. [1] with the concentration of the chemical in the dry mixture form to determine the mass of chemical mixture (for example fertilizer mix) that must be added to 100 gallons of water to obtain a certain concentration of the desired chemical. As an example, a 20–0–20 soluble, granular fertilizer is to be dissolved to make 100 gallons of liquid fertilizer solution that has a nitrogen concentration of 200 ppm. From Table 1, 0.41 lb of 20–0–20 fertilizer would be needed for a 100 ppm solution, therefore, 0.82 lb should be used for a 200 ppm solution.

When chemicals are supplied in liquid form, it is more convenient to measure volumes rather than masses or weights. This requires the use of the specific density or specific weight (S_x) of the liquid mixture, such as pounds of chemical per gallon of liquid. This information should be provided by the manufacturer or chemical supplier, and it can be used to convert from required lb to required gallons. For example, a liquid fertilizer provided as a 4–0–8 solution has 4% N by weight. However, the amount of N is not known unless the specific weight of the chemical (fertilizer) solution is known. The weight of water is 8.3 lb/gal, however, most fertilizer solutions weigh between 9 and 10 lb/gal. While this weight varies among chemical mixtures it should be listed on the chemical label, and it may be obtained from the chemical supplier or measured by weighing a known volume of the solution.

Concentration injection rates. The previous section described the procedure for mixing particular concentrations of a stock solution. However, many systems require the maintenance of a desired concentration of chemical in the irrigation water. This requires injecting a supply mixture or stock solution at the proper rate to maintain the desired concentration. Equation [2] or Table 2 can be used to determine the necessary injection rateto maintain the desired concentration in ppm of a chemical (X) in the irrigation supply water:

$$Q_i = (\text{ppm}_x)(Q_w)(8.3)/(\%X)(10000)(S_x) \qquad [2]$$

where Q_i = injection rate of the solution in gallons per minute (gpm), Q_w = irrigation system water flow rate (gpm), 8.3 = specific weight of water (lb/gal), ppm_x = desired ppm level of chemical X, %X = concentration percentage of chemical X in the stock solution, and S_x = specific weight of the stock solution mix (lb/gal).

This equation was simplified for concentration levels of 1000 ppm or less. For example, chlorine is to be injected to provide 10 ppm of available chlorine into a microirrigation system that has a system flow rate of 550 gpm. The chlorine stock solution contains 5% available chlorine and has a specific weight of 9.1 lb/gallon. Therefore, Q_w = 550; ppm_x = 10; %X = 5; S_x = 9.1; and Q_i = (10)(550)(8.3)/(5)(10000)(9.1) = 0.10 gallons/min.

Table 1. ***The mass (lb) of chemical mixture (i.e., fertilizer mix) to add to 100 gallons of water for different ppm level solutions.***

Solution	Percent analysis of the mixture							
(ppm)	5	10	15	20	25	30	40	50
			lb/100 gallon					
10	0.17	0.08	0.06	0.04	0.03	0.03	0.02	0.02
20	0.33	0.17	0.11	0.08	0.07	0.06	0.04	0.03
30	0.5	0.25	0.17	0.12	0.1	0.08	0.06	0.05
40	0.66	0.33	0.22	0.17	0.13	0.11	0.08	0.07
50	0.83	0.41	0.28	0.21	0.17	0.14	0.1	0.08
60	1	0.5	0.33	0.25	0.2	0.17	0.12	0.1
70	1.16	0.58	0.39	0.29	0.23	0.19	0.15	0.12
80	1.33	0.66	0.44	0.33	0.27	0.22	0.17	0.13
90	1.49	0.75	0.5	0.37	0.3	0.25	0.19	0.15
100	1.66	0.83	0.55	0.41	0.33	0.28	0.21	0.17

Table 2. ***Chemical injection rate expressed in gph of injection rate per 100 gallons/min of irrigation system flow rate for different desired concentration levels (ppm) and different stock solution concentration levels.***[z]

Solution	Percent analysis of the chemical in the stock solution							
(ppm)	4	8	12	16	20	30	40	50
	gallons/h of injection per 100 gallons/min of irrigation rate							
10	1.5	0.75	0.5	0.38	0.3	0.2	0.15	0.12
20	3	1.5	1	0.75	0.6	0.4	0.3	0.24
30	4.5	2.25	1.5	1.13	0.9	0.6	0.45	0.36
40	6	3	2	1.5	1.2	0.8	0.6	0.48
50	7.5	3.75	2.5	1.88	1.5	1	0.75	0.6
60	9	4.5	3	2.25	1.8	1.2	0.9	0.72
70	10.5	5.25	3.5	2.63	2.1	1.4	1.05	0.84
80	12	6	4	3	2.4	1.6	1.2	0.96
90	13.5	6.75	4.5	3.38	2.7	1.8	1.35	1.08
100	15	7.5	5	3.75	3	2	1.5	1.2

[z] *Caution: these values assume a stock solution specific weight equal to water. For greater accuracy, these numbers may be adjusted by multiplying by the ratio of the specific weight of the chemical solution to the specific weight of water.*

Therefore, the injector should be set to provide 0.10 gallons/min of stock solution into the irrigation system to maintain an injected available chlorine level of 10 ppm. The actual ppm of available chlorine throughout the system will depend on how much chlorine is tied up by organic and mineral elements in the water supply and in the irrigation system.

If the specific weight of the injected chemical solution is close to that of water, Eq. [2] can be simplified as

$$Q_i = (ppm_x)(Q_w)/(\%X)(10000) \qquad [3]$$

where Q_i = injection rate in gallons per minute (gpm), Q_w = water supply flow rate (gallons/min), ppm_x = desired ppm level of chemical X, and %X = concentration percentage of chemical X in the stock solution.

In repeating the above chlorine example, Q_w = 550 gpm; ppm_x = 10; and %X = 5; and Q_i = (10)(550)/ (5)(10000) = 0.11 gallons/min.

This result is about 10% greater than the result from the previous example. In many cases, Eq. [3] may be used. However, if greater accuracy is needed, use Eq. [2].

Some chemical injectors are calibrated on a gallons/h basis. Therefore, the injector rate determined above must be converted by multiplying by 60. For example, a flow rate of 0.10 gallons/min is equal to a flow rate of 6.0 gallons/h.

Some injectors are proportional feed devices. These typically are adjusted according to the mixing ratio. For example, a mixing ratio of 1:250 provides one unit of injected solution for each 250 units of water flow through the injector. The mixing ratio typically is set to provide a certain concentration of the injected chemical, such as 150 ppm of N or 10 ppm of chlorine. If the specific weight of the injected chemical solution is close to that of water, Eq. [3] can be rearranged to determine the mixing ratio as follows:

$$Q_w{:}Q_i = 10000\ (\%X)/\ ppm_x \qquad [4]$$

where $Q_w{:}Q_i$ = the mixing ratio of irrigation system flow rate to injected chemical flow rate. Other terms are as previously defined. For example, it is desired to provide a 200 ppm injected solution of nitrogen fertilizer with a proportional feed injector and a stock solution that has 6% N by weight. The mixing ratio would be $Q_w{:}Q_i = 10000 \times (6)/200 = 300{:}1$

Therefore, the injector should be set for a 300 to 1 (300:1) injection ratio. Using the data from the above chlorine example (Q_w = 550 gallons/min; ppm_x = 10; and %X = 5) results in a mixing ratio of 5000 to 1 (5000:1). If the resultant mixing solution does not match the range of the pump, the injected solution may be diluted to fit within the acceptable range. Diluting the chlorine solution in this example with water to a 0.5% chlorine stock solution results in a 500 to 1 (500:1) mixing ratio.

Injection volumes and periods

Chemical mixtures may be injected directly from the stock supply tank or from an injector feeder tank. Injector feeder tanks are useful for injecting a specific volume, regardless of the injection rate. When the tank is empty, the desired volume of chemical mixture has been injected. This procedure eliminates excess applications of chemicals due to pump or controller failure.

The size of the feeder tank required will depend on the volume of chemical mixture to be

Table 3. ***The mass (lb) of active chemical contained per gallon of stock solution (S_{mx})[z] for different combinations of specific weight and chemical concentration.***

Specific wt	Percent concentration of the active chemical							
(lb/gallon)	4	8	12	16	20	30	40	50
	lb of active chemical/gallon							
8	0.32	0.64	0.96	1.28	1.6	2.4	3.2	4
8.5	0.34	0.68	1.02	1.36	1.7	2.55	3.4	4.25
9	0.36	0.72	1.08	1.44	1.8	2.7	3.6	4.5
9.5	0.38	0.76	1.14	1.52	1.9	2.85	3.8	4.75
10	0.4	0.8	1.2	1.6	2	3	4	5
10.5	0.42	0.84	1.26	1.68	2.1	3.15	4.2	5.25
11	0.44	0.88	1.32	1.76	2.2	3.3	4.4	5.5
11.5	0.46	0.92	1.38	1.84	2.3	3.45	4.6	5.75

[z] *$S_{mx} = (\%X)(S_x)/100$; where S_{mx} =mass of chemical X per gallon of stock solution (lb/gallon), %X = percentage of chemical X in the solution, and S_x = specific weight of the stock solution (lb/gallon).*

injected, which in turn, will depend on either the total amount or volume of chemical to be applied or on the length of the injection period. For example, a pesticide may require that X pounds of a chemical be applied per acre; a vegetable grower may want to apply a certain mass of fertilizer per acre or per 100 bedded feet of plant row; or a citrus or nursery operator may want to supply a certain amount of fertilizer per irrigated plant. In addition to the desired level of fertilization, these situations require knowledge of the irrigated acreage per zone, total feet of bedded production area irrigated per zone, or the number of plants or trees irrigated in each zone.

Injection volumes. To determine the required injection volume for bulk applications, the mass of the desired chemical or compound dissolved per gallon of stock solution must be known. This can be determined by using Table 3. Then the mass of the desired chemical contained per gallon of stock solution can be used to determine the required volume of chemical stock solution from Table 4.

For example, a vegetable grower wishes to apply 4 lb N /1000 bedded feet of plant row each week; the N is to be applied in three applications per week; 20 acres are to be irrigated per set; and the system has 8700 bedded feet per acre. What size feeder tank is necessary for injecting a 4–0–8 fertilizer solution that has a specific weight of 9.5 lb/gallon?

The weekly production requirement of total N is (20 acres)(8700 ft/acre)(4 lb N/1000 feet/week) = 696 lb N/week.

The application requirement of N (3 applications) is (696 lb N per week)/(3 applications/week) = 232 lb N per application.

From Table 3, S_{mx} = 0.38 lb N/gallon of solution (about 0.4 lb/gal). From Table 4, the injection volume per application is about 600 gallons. Therefore, the feeder tank size must be at least 600 gallons to provide storage for this fertilizer application.

Sometimes chemicals are injected on a periodic basis to maintain a certain injected concentration of that chemical during that period. In this case, the required injection volume of stock solution depends on the length of the injection period, and on the injection rate. The required stock solution volume is determined as the multiple of those two values.

For example, a microirrigation system manager desires to inject 10 ppm of chlorine into an irrigation system for a period of 45 min. The irrigation system flow rate is 550 gallons/min, the chlorine stock solution weighs 9.1 lb/gallon and contains 5% free chlorine. From a previous example using Eq. [3], the required injector flow rate was 0.10 gallons/min. Then the required injection volume is V_m = (0.10 gallons/min)(45 min) = 4.5 gallons stock solution.

Therefore, only a small 5-gal feeder tank would be required for this application.

Injection periods and calibration. The length of the injection cycle is important from an irrigation management viewpoint. With respect to the injection period, several criteria may need to be addressed, such as the frequency of chemical application (daily, semi-weekly, weekly, etc.) and the maximum time allocated per irrigation zone. Furthermore, if the injection duration exceeds the maximum allowable duration, resulting in over-irrigation and leaching, then split chemical applications will be necessary.

The injection period generally is determined from the volume of chemical to be applied and the rate of injection. As was previously mentioned, some chemical applications require that a specific concentration be maintained for a particular application or injection period. In this case the injection period is preset. In other cases, the injection rate may be set by the supplier of the chemical injection system. However, whether the injection rate is already available or not, calibration of the injection system (Smajstrla et al., 1992) should be performed on the irrigation system that is to be used with the injection system. Also, because irrigation system operating pressures and flow characteristics may influence injection rates, calibration should be performed while the irrigation system is operating under normal operating conditions.

One calibration procedure involves placing an accurate flowmeter on the injection line and then measuring the volume of chemical injected during a specific time period. A measurement period of 2 to 5 min should suffice, however longer measurement periods increase measurement accuracy. Also, three or more replications of the measurement should be performed to obtain an accurate calibration and to minimize measurement errors or discrepancies. The quality of the flowmeter will influence the quality of the calibration. Therefore, a good quality flowmeter sized to operate in the estimated flow range of the injection system and manufactured for use with the chemicals being injected should be used. Corrosion of the flow meter could alter the injection rate and possibly result in damage to other parts of the irrigation system. Also, the flowmeter should operate under the higher pressures associated with some injectors.

A second calibration procedure involves physical measurement of the injected volume during the measurement period. This procedure can be performed using one of two methods. In each method a container is filled with a known volume of the chemical to be injected. Water or colored water may be substituted for the chemical, but it may not provide accurate results with some injec-

Table 4. ***Required volume (V_m, gallon)^z of chemical stock solution to provide a desired level of an active chemical for different concentrations (lb/gallon) of the chemical in the stock solution from Table 4.***

Mass of chemical desired (lb)	**Mass of chemical (lb) per gallon of stock solution**							
	0.2	**0.4**	**0.6**	**0.8**	**1**	**2**	**3**	**4**
	gallons of stock solution							
20	100	50	33	25	20	10	7	5
40	200	100	67	50	40	20	13	10
60	300	150	100	75	60	30	20	15
80	400	200	133	100	80	40	27	20
100	500	250	167	125	100	50	33	251
50	750	375	250	188	150	75	50	38
200	1000	500	333	250	200	100	67	50
250	1250	625	417	313	250	125	83	63
300	1500	750	500	375	300	150	100	75
350	1750	875	583	438	350	175	117	88
400	2000	1000	667	500	400	200	133	100
450	2250	1125	750	563	450	225	150	113
500	2500	1250	833	625	500	250	167	125

$^z V_m = (M_x)/(S_{mx})$; *where* V_m *= required mixture volume (gallon),* M_x *= mass of chemical required (lb), and* S_{mx} *= mass of chemical per gallon of mixture, (lb/gal; from Table 3).*

tors if the viscosity is very different from that of the chemical. The first method measures the time required to inject all of the known chemical volume. The second method measures the initial volume and the final volume after a specified injection period. The injection period should be at least several minutes, but short enough so that all of the chemical has not been injected. The injection rate is calculated as the injected volume divided by the injection time. If a positive displacement type of pump is used, the injected volume could be determined by counting the number of piston strokes during the measurement period and then multiplying the number of strokes by the displacement volume per stroke. The displacement volume per stroke should be measured periodically to ensure proper operation.

Once the injection rate is known, the injection duration for any chemical volume can be determined. For example, the vegetable grower in the previous fertilizer example has a piston injection pump which was measured to give 75 piston strokes in a 3-min period. Each piston stroke of the pump corresponds to 0.15 gal. Therefore, the injection rate is Q_i = (75 strokes)(0.15 gal/stroke)/3 min = 3.75 gallons/min.

In the previous example the grower needed to apply 600 gal of fertilizer mix three times each week. The required injection period for this volume of fertilizer will be T_i = 600 gal/3.75 gallons/min = 160.

Therefore, the system must be operated for about 160 min on each of the three fertilizer injection days to apply the required level of fertilizer. If the crop is shallow-rooted and the soil has a low water-holding capacity, it may be best to apply the fertilizer in two or three cycles (i.e., morning, midday, and afternoon) to avoid leaching fertilizer out of the root zone of the crop. If this injection schedule is a problem, it may be better to inject fertilizer every day or to upgrade the capacity of the injection system to reduce the duration of each injection.

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Water Management in Drip-irrigated Vegetable Production

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Additional index words. trickle irrigation, irrigation scheduling

Summary. Many factors influence appropriate drip irrigation management, including system design, soil characteristics, crop and growth stage, and environmental conditions. The influences of these factors can be integrated into a practical, efficient scheduling system that determines quantity and timing of drip irrigation. This system combines direct soil moisture measurement with a water budget approach using evapotranspiration estimates and crop coefficients.

Drip (trickle) irrigation offers the potential for precise water management and divorces irrigation from the engineering and cultural constraints that complicate furrow and sprinkler irrigation. It also provides the ideal vehicle to deliver nutrients in a timely and efficient manner. However, achieving high water- and nutrient-use efficiency while maximizing crop productivity requires intensive management. Central to that management is appropriate irrigation scheduling in terms of timing and volume applied. This discussion focuses on the practical aspects of drip irrigation management for commercial vegetable production.

There are two basic approaches to scheduling drip irrigation: soil-moisture-based scheduling and a water-budget-based approach that estimates crop evapotranspiration. There are limitations to both methods, but when used together they are a reliable way to determine quantity and timing of drip irrigation.

Estimating evapotranspiration

The amount of water evaporated from the soil surface and lost through transpiration of the crop is collectively called evapotranspiration (ET). With drip irrigation, evaporation from the soil is minimized, particularly in plastic mulch production systems, leaving crop transpiration as the main component of water loss.

Environmental variables, primarily solar radiation, air temperature, relative humidity, and wind, are the driving forces behind evapotranspiration. There are two widely used systems that integrate the effects of these variables into a daily reference value. Reference evapotranspiration (ET_o), calculated from the aforementioned environmental variables, estimates ET from a well-watered, uniform-height, actively growing turf, alfalfa, or similar crop (Pruitt et al., 1987). Historical mean daily ET_o is available for many locations; for example, California has a network of computerized weather stations that provide real-time daily ET_o (Snyder et al., 1987).

The other common technique used to estimate relative evaporative demand is pan evaporation (Ep), the daily loss of water from a standardized open, water-filled pan. Ep is a common measurement made at many weather stations across the United States, and historical mean daily Ep values are widely available. ET_o and Ep are reported as depth of water lost (inches or mm).

Neither pan evaporation nor ET_o calculated by empirical equations accurately reflects actual crop ET in all climates; these ET estimates commonly require modification based on local conditions (Pruitt et al., 1987; Burman et al., 1980). Although it differs somewhat among climates and pan locations (over bare soil vs. green crop), Ep averages 20% to 30% higher than comparable ET_o estimates (Doorenbos and Pruitt, 1977). For an in-depth discussion of ET estimation see Burman et al. (1980).

Using crop coefficients. Ep or ET_o values estimate relative evaporative demand. The amount of water actually lost from a particular field is mostly a function of crop growth stage; as the crop canopy expands water loss increases. To account for crop growth stage, crop coefficients (K_c) are used to adjust either Ep or ET_o to fit current field conditions. K_c values are available for the common vegetable crops, mostly from regional sources that have compiled local research results or have adapted published information to local conditions.

Several words of caution are appropriate regarding the use of published crop coefficients. They are specific to a particular evapotranspiration estimate (ET_o or Ep). They are also specific to a particular field configuration, because they are based on an assumed maximum degree of crop canopy coverage; the importance of this can be illustrated by a simple example. A K_c system developed for double-row pepper on a 40-inch (1-m)

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