19 Chemigation

Chemigation is the application of fertilizers and pesticides to agricultural crops with irrigation water. Chemicals are also injected into microirrigation systems in order to prevent microorganisms and calcium carbonate from clogging drip emitters. Microorganisms are killed by injecting chlorine or other disinfectants. Calcium carbonate precipitation is prevented by injecting acid and lowering pH. The potential hazards associated with chemical storage, transport, and injection into irrigation water include precipitation of solids within the irrigation water and clogging of the drip system, production of poison gas, explosions, contamination of the environment, and burning or loss of eyesight from chemical splashing. This chapter describes acid injection for prevention of calcium carbonate deposition, chlorine injection for control of fungal and bacterial growth, and the application of fertilizer and non-fertilizer materials into microirrigation systems.

Use of chemicals should always be supervised by people with knowledge of the chemistry and potential reactions. The chemical supplier will have information about the chemical compatibilities of their products and should be consulted before new chemicals or formulations are injected. Water quality should always be evaluated before injecting a chemical into irrigation water because chemicals may act differently in different waters. Concentration limits for hazardous chemicals in irrigation water are dependent on label requirements, toxicity to the crop, or on corrosivity in the irrigation system. In some cases, increased salinity due to fertilizer addition can be harmful to the crop.

Injection of two or more chemicals at the same time may cause chemical reactions and the resulting precipitation of the reactants may clog microirrigation laterals or emitters. In order to pre-test for chemical precipitation, mix the chemicals and irrigation water in a transparent inert jar. These "jar tests" should be conducted at the same pH, temperature, and other conditions under which the chemicals will be applied. Safety glasses and protective clothing should always be worn when conducting jar tests.

Preventing Calcium Carbonate Deposition with Acid Injection

Calcium (Ca^{++}) and carbonate (CO_3^{-2}) tend to precipitate (form a solid) out of solution and onto the surface of drip emitters. The deposition of calcium carbonate eventually clogs the emitters and reduces flow rate. Because calcium and carbonate do not normally precipitate out of solution in the range of 6.5 pH, microirrigation managers normally lower pH to 6.5 by injecting acid into irrigation water.

Carbonate is the major species that controls pH (acidity) in water. It is a buffer against pH change because hydrogen ions in acid combine with carbonate ions (CO_3^{2-}) and form bicarbonate (HCO_3^-) and eventually carbonic acid (H_2CO_3). Thus, the amount of acid that is required to lower pH to 6.5 depends on the concentration of carbonate in the water.

The critical pH at which carbonate precipitation takes place decreases as water temperature increases. This effect is a problem in surface microirrigation systems where the water becomes warmer during the daytime as it moves through the black plastic tubing. Acid injection rates may need to be increased to compensate for heating.

Because the reaction is a function of the number of positive (H^+) and negative (CO_3^{2-} and HCO_3^-) charges, it is convenient to use units of normality (meq/L) rather than molarity. Each carbonate ion (CO_3^{-2}) has a charge of negative two, thus, the normality (number of charges) is twice the molarity (number of ions).

The pH is a measure of the acidity or alkalinity of water; it is the log of one over the hydrogen ion molarity. The brackets [ ] represent concentration in moles/L.

$$pH = \log\frac{1}{[H^+]} = -\log[H^+] \tag{19.1}$$

Hydronium ions (hydrogen), hydroxide (OH^-), and water are in equilibrium within "water". The reaction is:

P. Waller, M. Yitayew, *Irrigation and Drainage Engineering*, DOI 10.1007/978-3-319-05699-9_19

$$H_2O \leftrightarrow H^+ + OH^- \quad (19.2)$$

The product of the concentration (molarity) of hydrogen $[H^+]$ and hydroxide $[OH^-]$ ions equals a constant, the dissociation constant (also called ionization constant) for water

$$K_w = [H^+]\ [OH^-] \quad (19.3)$$

The ionization constant for water, $[H^+]\ [OH^-] = 10^{-14}$. Thus, the product of hydrogen and hydroxide concentrations is always equal to 10^{-14}.

In-class Exercise 19.1 If the molarity of hydronium ions is 10^{-6}, then what is the pH?

If the molarity of hydroxide ions is 10^{-6}, then what is the pH?

Water that is neither acidic nor alkaline has the same number of hydronium and hydroxide ions. When pH is lower than seven, water is acidic, and when pH is higher than 7, it is alkaline

In-class Exercise 19.2 The dissociation constant for water $K_w = 10^{-14}$. What is the molarity of hydronium ions that is neither acidic nor alkaline (neutral).

Acids and bases dissolved in water ionize and/or hydrolyze. A strong acid, such as sulfuric acid, will completely dissociate in water and all hydronium ions are available to combine with carbonate in order to lower pH. However, the reaction is similar to the water reaction in Eq. 19.2 for a weak acid, with the reaction proceeding in both directions.

$$HA \leftrightarrow H^+ + A^- \quad (19.4)$$

The ionization constant, K_I, for a weak acid is equal to the product of hydrogen and anion concentration divided by the unionized acid. Ionization constants for various acids are found in the CRC Handbook of Chemistry and Physics.

$$\frac{[H^+][A^-]}{[HA]} = K_I \quad (19.5)$$

where

$[H]$ = hydrogen ion concentration (moles/L)
$[A^-]$ = anion concentration (moles/L)
K_I = dissociation constant for the weak acid

When both materials are in the same solution, i.e. acetic acid dissolved in water, both equilibria (water and acid) need to be satisfied.

Example 19.1 Calculate the pH for a volume of acetic acid ($H\text{-}CH_2COOH$) dissolved in pure water such that its concentration is equal to 0.01 moles/L. K_I for acetic acid is $1.85 * 10^{-5}$.

If X is the concentration of H^+ then A^- (CH_2COOH) will also be X. The reason $A^- = H^+$ is that the concentration of H^+ added by the acid is several orders of magnitude greater than the concentration of H^+ in pure water. From Eq. 19.5 we can calculate:

$$X^2/0.01 = 1.85 \times 10^{-5} \rightarrow [H^+] = X = 4.3 \times 10^{-4}$$

We can now calculate the pH and OH^- concentration in this solution.

$$[OH^-] = 10^{-14}/4.3 \times 10^{-4} = 2.3 \times 10^{-11} \quad pH = 3.36$$

If the pH of water is known, then the concentration of HA and A^- can be calculated based on the concentration of acid added to water. Let C_T be the total concentration of a weak acid added to the solution: C_T is the sum of the nonionized acid, HA, and the ionized acid, A^-.

$$C_T = [HA] + [A^-] \quad (19.6)$$

Combining Eqs. 19.5 and 19.6, concentrations of HA and A^- as a function of final pH are:

$$[HA] = \frac{C_T[H^+]}{K_I + [H^+]} \quad (19.7)$$

$$[A^-] = \frac{C_T K_I}{K_I + [H^+]} \quad (19.8)$$

where

C_T = sum of molarities of concentration of HA and A^- in water.

Using Eqs. 19.7 and 19.8, the log of concentration of HA and A^- vs. pH for 0.01 molar acetic acid (Example 19.1) is plotted in Fig. 19.1.

In open waters, the carbonate equilibrium is more complex than that shown in Fig. 19.1 because there are five species: gaseous carbon dioxide $[(CO_2)_g]$, aqueous carbon dioxide $[(CO_2)_{aq}]$, carbonic acid (H_2CO_3), bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}). In addition, Henry's Law is used to calculate the diffusion of carbon dioxide from air to water; however, water in drip irrigation tubes is not in contact with the atmosphere. Carbonic acid and aqueous CO_2 are indistinguishable in water; thus, only three species are required in the model: H_2CO_3, HCO_3^-, and CO_3^{2-}.

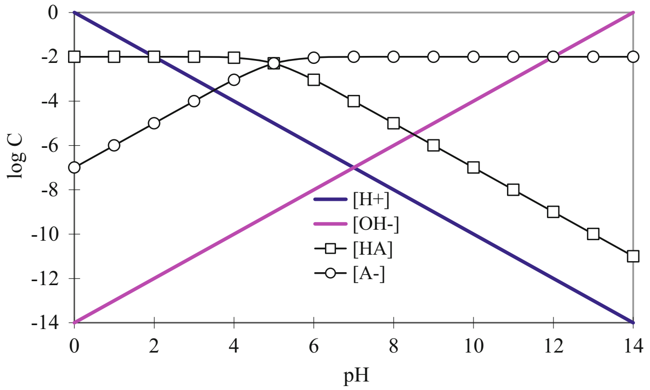


Fig. 19.1 Acetic acid concentrations vs. pH with 0.01 molar added to solution

Carbonic acid, H_2CO_3, ionizes in 2 stages so there are 2 ionization constants:

$$H_2CO_3 \leftrightarrow H^+ + HCO_3{}^- \tag{19.9}$$

$$\frac{[H^+][HCO_3^-]}{[H_2CO_3]} = K_1 \tag{19.10}$$

$$HCO_3^- \leftrightarrow H^+ + CO_3^{-2} \tag{19.11}$$

$$\frac{[H^+][CO_3^{-2}]}{[HCO_3^-]} = K_2 \tag{19.12}$$

Where

K_1 = dissociation constant for carbonic acid, $4.47 * 10^{-7}$
K_2 = dissociation constant for bicarbonate, $4.68 * 10^{-11}$

The 2 constants are multiplied to obtain the ionization constant for the complete dissociation of carbonic acid; $K_1 \times K_2 = 2.5 \times 10^{-17}$

$$\frac{[H^+][HCO_3{}^-]}{[H_2CO_3]}\ \frac{[H^+][CO_3{}^{-2}]}{[HCO_3{}^-]} = \frac{[H^+]^2[CO_3^{-2}]}{[H_2CO_3]} = K_1K_2 \tag{19.13}$$

Equations 19.9, 19.10, 19.11, 19.12, and 19.13 are used to derive the following equations that express the concentrations of the different carbonate species as a function of pH.

$$[H_2CO_3] = \frac{[C][H^+]^2}{[H^+]([H^+]+K_1)+K_1K_2} \tag{19.14}$$

$$[HCO_3{}^-] = \frac{[C][K_1][H^+]}{[H^+]([H^+]+K_1)+K_1K_2} \tag{19.15}$$

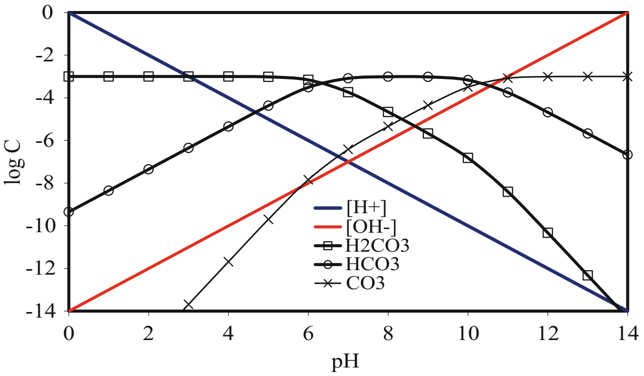


Fig. 19.2 Carbonate concentration versus pH for total concentration = 0.001 moles/L

$$[CO_3{}^{-2}] = \frac{[C][K_1][K_2]}{[H^+]([H^+]+K_1)+K_1K_2} \tag{19.16}$$

where

C = molarity of all carbonate species.

The carbonate species concentrations vs. pH for C_T = 0.001 moles/L (10^{-3}) are shown in Fig. 19.2.

The term, alkalinity, refers to the capacity of negative ions (hydroxide, carbonate and bicarbonate anions) in water to combine with protons (H^+) from the acid. Typically, water analysis reports specify alkalinity, the amount of carbonate in water, as mg/L of calcium carbonate ($CaCO_3$). There are 60 mg $CO_3{}^{2-}$ for every 100 mg of $CaCO_3$. The concentration units for alkalinity in Eq. 19.17 are meq/L (normality), which is the product of molarity and valence.

$$\sum \left(HCO_3^- + CO_3^{2-} + OH^-\right) \tag{19.17}$$

Normally, strong acids are injected into irrigation water because they are more effective at lowering pH and because they may be less expensive. The strong acids are HCl, HBr, HI, HNO_3, H_2SO_4, and $HClO_4$. Nearly all other acids are weak acids. Strong acids are acids for which the reaction in Eq. 19.4 only proceeds to the right. For example, the equation for sulfuric acid ionization in water is

$$H_2SO_4 \rightarrow 2H^+ + SO_4^{2-} \tag{19.18}$$

Sulfuric acid is made by compressing sulfur trioxide gas and water vapor. It is typically sold as 98 % sulfuric acid, which is 18.78 mol/L sulfuric acid.

With irrigation system injection, the acid charge flow rate (meq/s) should equal the neutralized alkalinity charge flow rate (meq/s). The charge flow rate is the product of water flow rate and normality, QC = (L/s)(meq/L) = meq/s: Q_aC_a

$= Q_w C_w$, where a is acid and w is water alkalinity. The equation can be rearranged and solved for acid flow rate, Q_a.

Example 19.2 Calculate the injection rate of 98 % sulfuric acid required to drop the pH to 6.5 for Colorado River water:

pH = 8.3
Carbonate alkalinity as $CaCO_3$ is 100 mg/L,
Irrigation system flow rate, Q_w, is 1,000 L/s

Carbonate concentration as $CaCO_3$ equal to 100 mg/L is equal to 60 mg/L CO_3^{-2} because the molecular mass of carbonate (CO_3^{-2}) is 60 g/mole, and the molecular mass of calcium carbonate ($CaCO_3^{-2}$) is 100 g/mole; thus, carbonate molarity is calculated as follows:

$$\left(\frac{100\ mg\ CaCO_3}{L\ water}\right)\left(\frac{0.6\ mg\ CO_3{}^{-2}}{1\ mg\ CaCO_3}\right)\left(\frac{g\ \ CO_3{}^{-2}}{1{,}000\ mg\ CO_3{}^{-2}}\right)\left(\frac{1\ mole\ CO_3{}^{-2}}{60\ g\ CO_3{}^{-2}}\right) = 0.001\ mole/L$$

The next step is to calculate the total alkalinity at pH = 8.3. Second, calculate the total alkalinity at pH = 6.5. Finally, calculate the change in alkalinity between 8.3 and 6.5.

Calculate hydroxide ion molarity at pH(8.3) : $[OH^-] = 10^{-(14-8.3)} = 2{*}10^{-6}$mole/L.

Calculate initial HCO_3^- molarity at pH(8.3).

$$\begin{aligned}[HCO_3{}^-] &= \frac{[C][K_1][H^+]}{[H^+]([H^+]+K_1)+K_1K_2}\\ &= \frac{[0.001]\left[4.47{*}10^{-7}\right]\left[5.01{*}10^{-9}\right]}{\left[5.01{*}10^{-9}\right]\left(\left[5.01{*}10^{-9}\right]+4.47{*}10^{-7}\right)+4.47{*}10^{-7}{*}4.68{*}10^{-11}} = 9.8{*}10^{-4}\ \ mol/L\end{aligned}$$

Calculate the initial CO_3^{-2} molarity at pH(8.3)

$$\begin{aligned}\left[CO_3{}^{-2}\right] &= \frac{[C][K_1][K_2]}{[H^+]([H^+]+K_1)+K_1K_2}\\ &= \frac{[0.001]\left[4.47{*}10^{-7}\right]\left[4.68{*}10^{-11}\right]}{\left[5.01{*}10^{-9}\right]\left(\left[5.01{*}10^{-9}\right]+4.47{*}10^{-7}\right)+4.47{*}10^{-7}{*}4.68{*}10^{-11}} = 9.8{*}10^{-4}\ \ mol/L\end{aligned}$$

Add up the total alkalinity at pH = 8.3 (multiply CO_3^{2-} molarity by 2).

$$\sum\left(HCO_3^- + CO_3^{2-} + OH^-\right) = 9.80{*}10^{-4} + 2{*}9.15{*}10^{-6} + 2{*}10^{-6} = 0.00100\ \ eq/L$$

Hydroxide ion concentration at pH(6.5) = $10^{-(14\ -\ 6.5)} = 3.2 * 10^{-8}$ mole/L.

Calculate HCO_3^- molarity at pH(6.5).
Calculate the alkalinity at the final pH(6.5).

$$\begin{aligned}\left[HCO_3{}^{-2}\right] &= \frac{[C][K_1][H^+]}{[H^+]([H^+]+K_1)+K_1K_2}\\ &= \frac{[0.001]\left[4.47{*}10^{-7}\right]\left[3.16{*}10^{-7}\right]}{\left[3.16{*}10^{-7}\right]\left(\left[3.16{*}10^{-7}\right]+4.47{*}10^{-7}\right)+4.47{*}10^{-7}{*}4.68{*}10^{-11}} = 5.86{*}10^{-4}\ \ mol/L\end{aligned}$$

Calculate CO_3^{-2} molarity at pH(6.5)

$$[CO_3^{-2}] = \frac{[C][K_1][K_2]}{[H^+]([H^+]+K_1)+K_1K_2} =$$
$$= \frac{[0.001]\left[4.47*10^{-7}\right]\left[4.68*10^{-11}\right]}{\left[3.16*10^{-7}\right]\left(\left[3.16*10^{-7}\right]+4.47*10^{-7}\right)+4.47*10^{-7}*4.68*10^{-11}} = 8.67*10^{-8}\ mol/L$$

Calculate total alkalinity at pH(6.5).

$$\sum\left(HCO_3^- + CO_3^{2-} + OH^-\right) = 5.86*10^{-4} + 2*8.67*10^{-8} + 3.2*10^{-8} = 0.000586\ \text{eq/L}$$

Change in alkalinity = initial alkalinity – final alkalinity

$$0.001\ \text{eq/L} - 0.000586\ \text{eq/L} = 4.14*10^{-4}\text{eq/L} = 0.414\ \text{meq/L}$$

Calculate acid injection rate

$$Q_aC_a = Q_wC_w \rightarrow Q_a*37{,}560\ \text{meq/L} = 1{,}000\ \text{L/S}*0.414\ \text{meq/L}$$
$$Q_a = 0.414*1{,}000\ \text{L/S}/37{,}560 = 0.011\ \text{L/s} = 40\ \text{L/hr}$$

The same calculations are made in the *Acid injection rate* worksheet (Fig. 19.3).

Strong acids are effective, but they can corrode injection pumps, are unsafe, may have high concentrations of heavy metals, or may be unavailable at low cost. One alternative is organic acids. Most organic acids used in agriculture are forms of dicarboxylic acid. In theory, organic acids can remove salts from drip emitters even when pH remains high: organic polyacids combine with cations to form soluble salts and thus dissolve precipitated calcium and magnesium; however, weak acids are generally not as effective at preventing calcium carbonate deposition as strong acids and rarely used.

Although farmers typically lower water pH to 6.5 in order to prevent calcium carbonate precipitation, the threshold pH for precipitation may not be 6.5. The tendency of calcium carbonate to precipitate is a function of many factors: calcium and magnesium concentration, pH, bicarbonate concentration, temperature and TDS (total dissolved solids). The Langelier Saturation Index (LSI) calculates the tendency of calcium carbonate to precipitate. If the LSI is less than 0, then it is likely that no precipitation will occur.

$$\text{LSI} = \text{pH}_m - \text{pH}_c \qquad (19.19)$$

An LSI less than zero means that the calculated equilibrium pH_c of the water is greater than the measured pH_m. This means that the carbonate will come out of solution. The following method for calculating LSI is taken from the "Corrosion Doctors" website.

$$\text{pH}_c = (9.3 + \text{A} + \text{B}) - (\text{C} + \text{D})\ \text{where :} \qquad (19.20)$$

where

A = $(\text{Log}_{10}[\text{TDS as ppm}] - 1)/10$
B = $-13.12 \times \text{Log10}(°\text{C} + 273) + 34.55$
C = $\text{Log}_{10}[\text{Ca}^{2+}\ \text{as}\ \text{CaCO}_3\ (\text{mg/L})] - 0.4$
D = $\text{Log}_{10}[\text{alkalinity as}\ \text{CaCO}_3\ (\text{mg/L})]$
pH_c = calculated pH.
pH_m = measured pH

Example 19.3 Calculate LSI for the following Colorado River water sample at 25 °C and 35 °C.

Measured pH_m	7.96.
Alkalinityas CaCO_3	131 mg/L
Calciumas CaCO_3	72 mg/L
TDS	610 mg/L

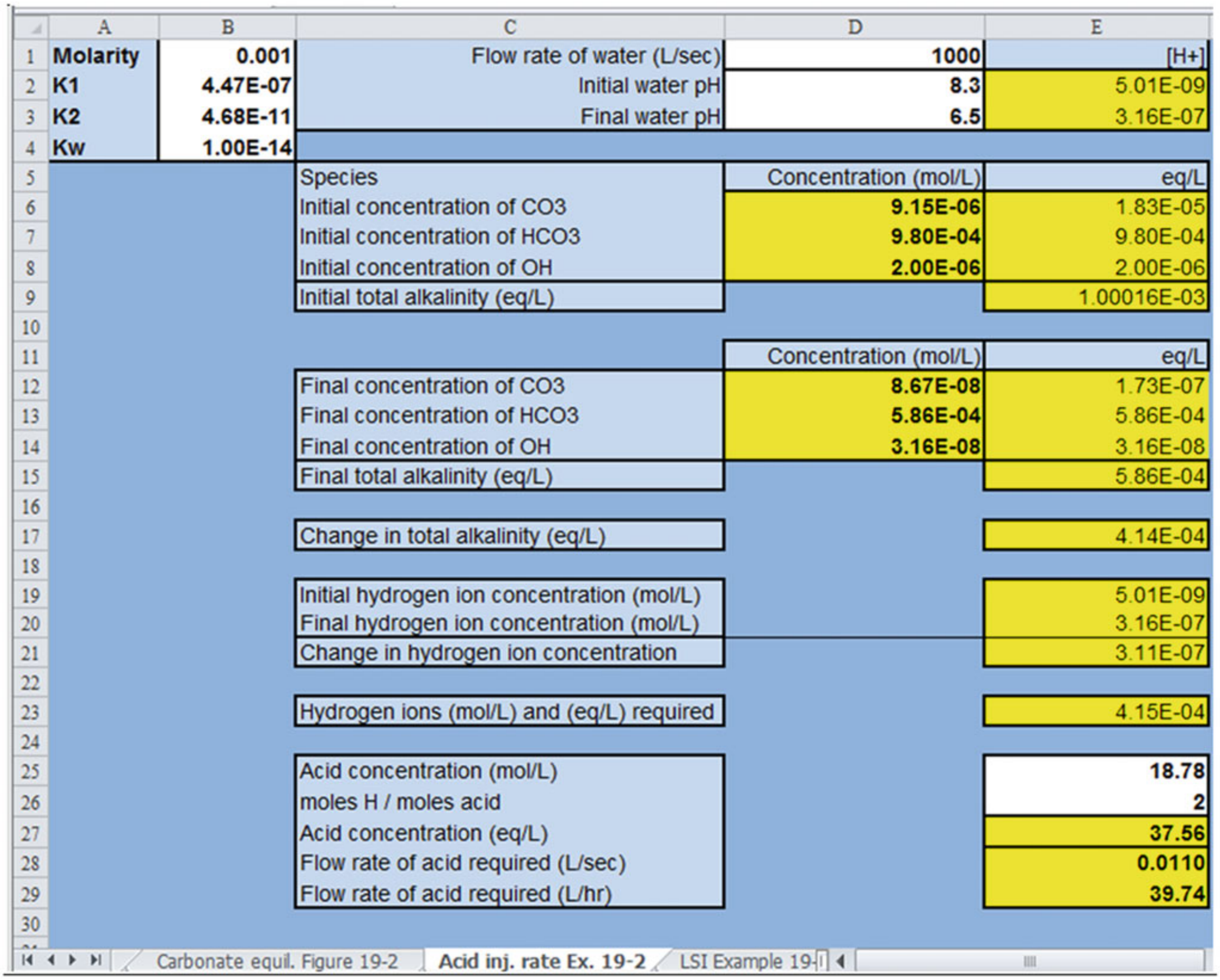
Calculate the LSI at 25 °C

$$A = (Log_{10}[610] - 1)/10 = 0.1785$$
$$B = -13.12 \times Log10\left(25^0C + 273\right) + 34.55 = 2.088$$
$$C = Log_{10}[72] - 0.4 = 1.457$$
$$D = Log_{10}[131] = 2.117$$
$$pH_c = (9.3 + 0.1785 + 2.088) - (1.457 + 2.117) = 7.99$$
$$LSI = pH_m - pH_c = 7.96 - 7.99 = -0.03$$

Because the LSI is close to zero and parameters fluctuate, there might be precipitation at 25 °C. In addition, there are several other factors that may change the tendency of the water to precipitate, such as the high sulfate concentration in Colorado River water (200 mg/L). To be safe, add acid. The calculations are also made in the *LSI* worksheet (Fig. 19.4).

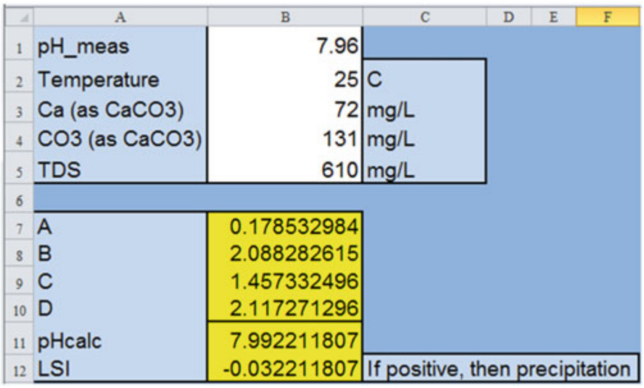
Recalculate for 35 °C

$$B = -13.12 \times Log10(35^oC + 273) + 34.55 = 1.90$$
$$pH_c = (9.3 + 0.1785 + 1.90) - (1.457 + 2.117) = 7.80$$
$$LSI = pH_m - pH_c = 7.96 - 7.80 = 0.16$$



	A	B	C	D	E
1	**Molarity**	**0.001**	Flow rate of water (L/sec)	**1000**	[H+]
2	**K1**	**4.47E-07**	Initial water pH	**8.3**	5.01E-09
3	**K2**	**4.68E-11**	Final water pH	**6.5**	3.16E-07
4	**Kw**	**1.00E-14**			
5			Species	Concentration (mol/L)	eq/L
6			Initial concentration of CO3	**9.15E-06**	1.83E-05
7			Initial concentration of HCO3	**9.80E-04**	9.80E-04
8			Initial concentration of OH	**2.00E-06**	2.00E-06
9			Initial total alkalinity (eq/L)		1.00016E-03
10					
11				Concentration (mol/L)	eq/L
12			Final concentration of CO3	**8.67E-08**	1.73E-07
13			Final concentration of HCO3	**5.86E-04**	5.86E-04
14			Final concentration of OH	**3.16E-08**	3.16E-08
15			Final total alkalinity (eq/L)		5.86E-04
16					
17			Change in total alkalinity (eq/L)		4.14E-04
18					
19			Initial hydrogen ion concentration (mol/L)		5.01E-09
20			Final hydrogen ion concentration (mol/L)		3.16E-07
21			Change in hydrogen ion concentration		3.11E-07
22					
23			Hydrogen ions (mol/L) and (eq/L) required		4.15E-04
24					
25			Acid concentration (mol/L)		**18.78**
26			moles H / moles acid		**2**
27			Acid concentration (eq/L)		**37.56**
28			Flow rate of acid required (L/sec)		**0.0110**
29			Flow rate of acid required (L/hr)		**39.74**
30					

Fig. 19.3 *Acid injection rate* worksheet



	A	B	C	D	E	F
1	pH_meas	7.96				
2	Temperature	25	C			
3	Ca (as CaCO3)	72	mg/L			
4	CO3 (as CaCO3)	131	mg/L			
5	TDS	610	mg/L			
6						
7	A	0.178532984				
8	B	2.088282615				
9	C	1.457332496				
10	D	2.117271296				
11	pHcalc	7.992211807				
12	LSI	-0.032211807	If positive, then precipitation			

Fig. 19.4 *LSI* worksheet

The positive LSI at 0.16 indicates that precipitation is more likely at a higher temperature.

If the pH is lowered to 6.5 by injecting acid, then the LSI becomes

$$LSI = pH_m - pH_c = 6.5 - 7.80 = -1.3$$

With a negative LSI, it is unlikely that precipitation will occur at pH 6.5.

Biological Control with Chlorine

Fungal or bacterial growth combined with possible bacterial slime within drip irrigation systems can rapidly plug drip emitters and result in disastrous crop losses. Drip irrigation systems are especially susceptible to growth of bacteria and fungi when fertigation provides a nutrient source for bacteria. Chlorine and other biocides are injected in order to kill microorganisms.

The first step is to evaluate whether biocides are necessary. Greenhouses or organic growers may not be able to use chlorine. For example, if water is from a deep well and no carbon (sugar) source (energy) for bacteria is available, then bacteria will not normally grow, and a biocide may not be necessary; however, if well water has been in contact with the atmosphere, then energy sources for bacterial growth and bacteria may diffuse into the water from the atmosphere. Well water that is high in iron may also provide an energy source for certain bacteria that oxidize iron from Fe^{2+} to Fe^{3+} in order to acquire energy. On the other hand, bacterial growth is likely if irrigation water is from an open water source such as a pond or canal.

Chlorine can be added to irrigation water in 3 forms: gaseous (Cl_2), liquid bleach (NaHOCl), or solid ($Ca(OCl)_2$). When chlorine gas is dissolved in water, the following reactions occur:

$$H_2O + Cl_2 = HOCl + H^+ + Cl^- \quad HOCl \leftrightarrow H^+ + OCl^- \tag{19.21}$$

HOCl (hypochlorous acid) and OCl^- (hypochlorite) are referred to as free available chlorine. There is more hypochlorous acid when pH is low and more hypochlorite when pH is high. Hypochlorous acid is 40–80 times more effective at killing biological organisms than hypochlorite because the negative charge on hypochlorite prevents it from entering the cell wall. At a pH of 6.5, 90 % of the chlorine is in the hypochlorous acid form. At a pH of 7, only 73 % of the chlorine is in the hypochlorous acid form, and as pH increases the reaction continues to proceed toward hypochlorite. For this reason, water is normally kept in the range of 6.0–6.5 during chlorination. The form of chlorine also makes a difference. Injection of chlorine gas lowers pH, and injection of bleach (sodium hypochlorite) raises pH.

Recommended chlorine injection rates are 1–2 ppm (elemental chlorine, Cl_2 concentration) for continuous injection, and 4–20 ppm for monthly, ½ to 1-hour, shock treatments. The injection rate depends on the amount of organic matter and other substances that react with chlorine.

Chlorine in the liquid form is the same compound as household bleach. Gaseous chlorine (much more dangerous) is delivered in gas cylinders and injected directly into the irrigation water. The change in weight of the cylinder over time can be used to calculate the mass flow rate of chlorine into the irrigation water. The percent by weight of elemental chlorine in each of the chlorine forms is shown in Table 19.1.

Example 19.4 Calculate the injection rate of chlorine into irrigation water if the desired concentration is 2 ppm (mg/L) (as elemental chlorine) and the irrigation flow rate is 44 L/s.

Table 19.1 Forms of chlorine and percent elemental chlorine (as Cl_2)

Form	Percentage (Cl_2)	Specific gravity
Gas	100	----
5 % bleach	5.1	1.07
7 % bleach	7.1	1.10
12.5 % bleach	12.5	1.19
15 % bleach	15	1.26
Calcium hypochlorite (solid)	51	

Gaseous (mass flow rate)

$$\left(\frac{44\ L\ water}{\text{sec}}\right)\left(\frac{2\ mg\ Cl_2}{L\ water}\right)\left(\frac{3,600\ \text{sec}}{hr}\right)\left(\frac{kg}{10^6\ mg}\right) = 0.317\ kg/hr$$

Liquid (liquid flow rate, use 15 % bleach)

$$\left(\frac{44\ L\ water}{\text{sec}}\right)\left(\frac{2\ mg\ Cl_2}{L\ water}\right)\left(\frac{100\ mg\ bleach}{15\ mg\ Cl_2}\right)\left(\frac{kg}{1*10^6\ mg}\right)\left(\frac{L}{1.26\ kg}\right)\left(\frac{3,600\ \text{sec}}{hr}\right) = 1.7\ L/hr$$

Solid

$$\left(\frac{44\ L\ water}{\text{sec}}\right)\left(\frac{2\ mg\ Cl_2}{L\ water}\right)\left(\frac{mg\ Ca(OCl)_2}{0.51\ mg\ Cl_2}\right)\left(\frac{3,600\ \text{sec}}{hr}\right)\left(\frac{kg}{10^6\ mg}\right) = 0.62\ kg/hr$$

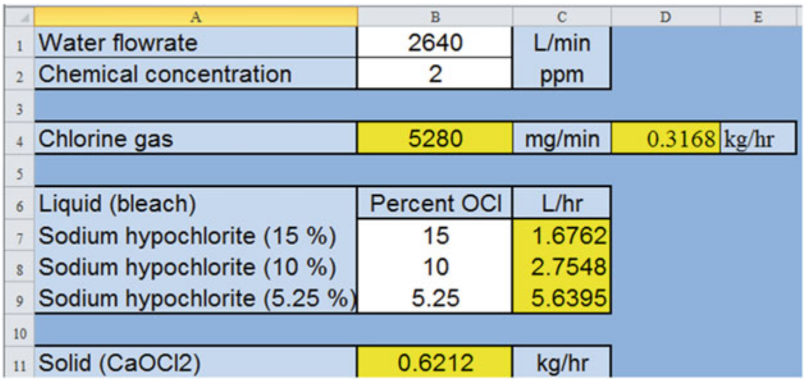
The calculations are made in the *Chlorine* worksheet (Fig. 19.5)

Fertigation

Fertigation is the process of applying fertilizers to crops through irrigation systems. It is a subset of chemigation. One of the advantages of high frequency irrigation systems (center pivot and microirrigation) is the ability to apply fertilizer in frequent, uniform, and small quantities (spoon fed). Because nutrients are applied at the right time and the right place, plant growth is optimized and leaching is minimized. Many studies have shown that plant response to fertigation is generally higher than response to broadcast fertilization (Bar-Yosef 1999), especially on sandy soils with low cation exchange capacities. Low frequency systems such as surface irrigation systems may also by suitable for fertigation but uniformity of application may be a concern.

Effective fertigation requires calculation of nutrient requirements based on plant requirements and soil nutrients, selection of the most effective formulations, preparation of solutions for injection, and scheduling injections to ensure

Fig. 19.5 *Chlorine* worksheet



	A	B	C	D	E
1	Water flowrate	2640	L/min		
2	Chemical concentration	2	ppm		
3					
4	Chlorine gas	5280	mg/min	0.3168	kg/hr
5					
6	Liquid (bleach)	Percent OCl	L/hr		
7	Sodium hypochlorite (15 %)	15	1.6762		
8	Sodium hypochlorite (10 %)	10	2.7548		
9	Sodium hypochlorite (5.25 %)	5.25	5.6395		
10					
11	Solid (CaOCl2)	0.6212	kg/hr		

that essential nutrients are available as needed (Granberry et al. 2001). Fertilizer application rates depend on crop, soil, and time. Individual growers and agronomists use trial and error over many years to develop fertilization schemes that are specifically tailored to elicit the desired crop response, yield, and quality. As one might expect, these fertilization schemes are often kept secret.

Calculation of Plant Nutrient Requirements

Soil nutrient tests are conducted just prior to planting in order to determine the availability of soil nutrients. The seasonal nutrient requirement is the difference between the plant requirement and soil nutrient availability. Plant tissue analysis is used during the growing season to assess the current plant nutrient status and adjust fertilization rates accordingly. Distribution of roots must be considered when determining the availability of nutrients. For many drip irrigated crops, the rhizosphere (root zone) is concentrated in the vicinity of the emitter; thus, plants may have limited access to nutrients in the soil that are far from the emitter.

The nitrogen soil test reports the amount of nitrate – nitrogen (NO_3-N) in soil (as elemental N). Soil tests for nitrogen are conducted from 0- to 60-cm soil depth, and nitrogen content is reported in mg/L. This number is converted to total nitrogen amount in kg/ha by multiplying by 2.2. For example, if nitrate content in soil is reported as 13 mg/L, then there are 28 kg/ha of nitrogen in the soil. If the crop requires 147 kg/ha, then the amount of N that must be applied in fertilizer is 119 kg/ha. For nutrients other than nitrogen, such as potassium or phosphorous, extraction methods are used to determine the amount of available nutrient rather than the total amount of the nutrient in the soil.

General Considerations

The distribution uniformity of chemical application follows the distribution uniformity of water application. Because a well-designed microirrigation system should have a distribution uniformity in the range of 90 % or greater, it is reasonable to expect that the distribution uniformity of chemical application should also be 90 % or greater. Whenever possible, fertilizer injections should be made in small, frequent doses (spoon feeding) that fit within regularly scheduled microirrigation events (designed to match plant water use) to help avoid unnecessary leaching.

Because concentration of injected chemicals in irrigation water is not constant due to time delays in the movement of the water-chemical mixture through the piping system, the one-fourth rule is used: chemigation should start after one-fourth of the total irrigation set time, injection should occur during the middle two-fourths, and the lines flushed with clean water during the last one-fourth of an irrigation event. Fertilizers and other agrochemicals (except chlorine) should never be left in the pipeline when the system is not operating.

Advantages and Disadvantages of Fertigation and Pestigation

Microirrigation potentially offers numerous benefits for chemical application because of its flexible delivery arrangement. Some of the advantages over tractor application of chemicals include fuel and labor savings, less soil compaction, constant nutrient concentration in the root zone, improved productivity, placement of the chemical in the root zone, and decreased worker exposure to chemicals. The downside to chemigation includes higher required management expertise, high capital costs, restricted pesticide use for chemigation, risk of environmental contamination through misapplication, need to coordinate chemical and irrigation applications, and chemical corrosion of metal components.

Fertilization Requirements

Crop nutrient requirements change during the season depending on the growth stage. Total seasonal nutrient requirements for various crops are shown in Table 19.2; the values are based on research by Bar-Yosef (1999) for crops grown in a Mediterranean climate.

The grower makes decisions about applications during each stage based on desired crop response, soil nutrient reserves, available fertilizer formulations, preplant fertilization, irrigation schedules, criteria for maximum nutrient concentration in irrigation water, and other factors. Fertilizer formulations are generally not exactly in the proportions that match relative plant uptake of different nutrients. Thus, the grower application schedule may not be perfectly in sync with the plant uptake of nutrients during the growing season.

Example 19.5 Develop a nutrient application schedule for cantaloupe (cantaloupe). The growing season will be split into five stages: (0–25 days), (25–50 days), (50–75 days), (75–100 days), and (100–120 days) (Table 19.3). Soils are not limited in potassium, so no potassium fertilizer is required. Antecedent nitrogen in the soil is 28 kg/ha. The grower adds phosphorous in stage 3 (Table 19.4).

From Table 19.2, total N, P, and K required are 148 kg/ha, 25 kg/ha and 389 kg/ha. The stage requirements were calculated (left columns in Table 19.4) and the nutrient application schedule was assigned (right columns in Table 19.4). Nitrogen application was allowed to be behind schedule because of antecedent nitrogen in the soil. All phosphorous was applied during the 3rd stage. Potassium was not needed.

Table 19.2 Seasonal nutrient uptake amounts for various crops (based on Bar Yosef)

Crop	N (kg/ha)	P (kg/ha)	K (kg/ha)
Muskmelon (cantaloupe)	148	25	389
Carrot	277	72	592
Sweet corn	237	40	323
Broccoli	183	25	255
Chinese cabbage	137	38	281
Celery	151	36	588
Lettuce	113	22	244
Cotton	233	45	186
Potato	166	n/a	n/a
Eggplant	296	33	399
Bell pepper	206	30	372
Fresh tomato	248	25	367
Greenhouse tomato	431	49	709
Processing tomato	395	56	517

Fertilizer Selection and Calculation of Injection Rates

Fertilizers for fertigation systems are selected based on plant response, solubility, cost, effect on soil pH, formulation, and potential for reaction with other chemicals within the distribution system. Liquid fertilizers can be purchased in liquid form or stock solutions can be mixed on-farm. Fertilizer is often available in premixed liquid form for fertigation systems. Transportation costs are higher for liquid fertilizers than for solid forms. However, premixed fertilizer often save time and labor, and avoids problems associated with poorly prepared on-farm mixes (Granberry et al. 2001). Solid fertilizers used in making liquid fertilizer formulations should be in the granular form. However, some granular fertilizers are not completely soluble in water and should not be injected into microirrigation systems. The maximum amount of a solid that can be dissolved in water is the solubility (kg/L). Solubility changes with temperature and with concentration of other ions in solution. Fertilizers should not be mixed at the maximum solubility because temperature change can cause chemical precipitation and to mixing time is extensive.

The type of nitrogen that is used by the plant has an effect on both the plant and the soil environment. Plants can take

Table 19.3 Percent of seasonal N, P, and K requirements for a muskmelon crop in Yuma, Arizona

Stage	Nitrogen N (kg/ha) % required	Phosphorus P (kg/ha) % required	Potassium K (kg/ha) % required
1 (0–25 days)	3	4	1
2 (25–50 days)	16	16	14
3 (50–75 days)	52	36	43
4 (75–100 days)	22	36	38
5 (100–120 days)	7	8	4

Table 19.4 N, P, and K application rate for a muskmelon crop in Yuma, Arizona.

Stage	Nitrogen N (kg/ha)		Phosphorus P (kg/ha)		Potassium K (kg/ha)	
	Required	Applied	Required	Applied	Required	Applied
1 (0–25 days)	5	5	1	0	4	0
2 (25–50 days)	24	35	4	0	55	0
3 (50–75 days)	77	35	9	25	166	0
4 (75–100 days)	32	35	9	0	150	0
5 (100–120 days)	9	9	2	0	14	0

Table 19.5 Conversions of relevant nutrient units of measurements (After Burt et al. 1995)

Unit	Multiplier		Result	
NO_3-N (mg/L) (elemental N)	×	4.42	∍	NO_3 (mg/L)
NH_4-N (mg/L) (elemental N)	×	1.29	∍	NH_4 (mg/L)
NH_4 (mg/L)	×	0.78	∍	NH_4-N (mg/L)
NO_3 (mg/L)	×	0.226	∍	NO_3-N (mg/L)
P_2O_5 (mg/L)	×	0.67	∍	PO_4 (mg/L)
P_2O_5 (mg/L)	×	0.44	∍	PO_4-P (mg/L)
PO_4-P (mg/L)	×	3.07	∍	PO_4 (mg/L)
K_2O (mg/L)	×	0.83	∍	K (mg/L)

up nitrogen as ammonium, NH_4^+, or as nitrate, NO_3^-. Nitrogen applied as ammonium, a cation, is less likely to be leached from soil than nitrogen applied as nitrate (anion) because cations are adsorbed by the clay particles in the soil. Because the plant must maintain electroneutrality (same number of anions and cations), plants tend to secrete cations (hydrogen ions) when most of the nitrogen is taken up as ammonium. This process tends to acidify the soil. Acidification of some soils may be a problem with acid-based fertilizers, and alternatives such as calcium nitrate should be considered. A balanced fertilization program may require supplemental foliar applications of micronutrients.

Fertilizers are often applied as ammonium-N with the expectation that nitrifying bacteria will slowly convert the ammonium to nitrate during the growing season; typically, plants prefer to take up nitrogen in the nitrate form. At higher pH, the ammonium (NH_4^+)/ammonia (NH_3) equilibrium goes toward ammonia, and thus volatilization of ammonium is more likely at high pH. For surface drip irrigation, ammonia volatilization may result in a significant loss of nitrogen to nitrous oxide or nitrogen gas.

Typically, soil tests report phosphorus (P), and potassium (K) availability in soils as the oxidized forms, P_2O_5 and K_2O, respectively. Fertilizer formulation labels for nitrogen (N), phosphorous (P), and potassium (K) are based on percent N, P_2O_5 and K_2O, respectively (Rosen and Eliason, 1996). Applicable conversion factors are given in Table 19.5. Characteristics of various fertilizers are listed in Table 19.6.

Urea sulfuric acid can be mixed with other solutions such as phosphoric acid, muriate of potash, and sulfate of potash. Urea sulfuric acid mixtures should always be mixed in the correct order and only with approved fertilizers as specified by the manufacturer (Burt et al. 1995).

Proper mixing procedures should always be followed with all fertilizer formulations. Mixing procedures (after Burt et al. 1995) are listed as follows:

1. Always fill the mixing container with 50–75 % of the required water to be used in the mix.
2. Always add the liquid materials to the water before adding the dry, soluble fertilizers.
3. Always add the dry ingredients slowly with circulation or agitation to prevent the formation of large, insoluble, or slowly soluble lumps.
4. Always add acid into water, not water into acid.
5. Never mix an acid or acidified fertilizer with chlorine (gas, liquid, or solid).
6. Do not mix concentrated fertilizer solutions with other concentrated fertilizer solutions.
7. Because fertilizer solutions are applied in very small dosages, and if injected at different locations in the irrigation line, many incompatibility problems are avoided.

Example 19.6 A grower wants to apply 4 kg/ha of potassium (K) as K_2O and 2 kg/ha of nitrate-N to a 20 ha field during a 1-week period. Calculate the mass of KNO_3 fertilizer that must be dissolved and the amount of solution required for the 1-week period. Irrigation schedule is 4 hr/day, every day.

Total potassium required as K_2O is 4 kg/ha × 20 ha = 80 kg.

Total potassium required as K is found by taking the ratio of K to K_2O (0.83 from Table. 19.4)

$$\text{Mass K} = 80 \times 0.83 = 66.4 \text{ kg}$$

Now solve for the number of moles of K required using information from Table 3.1.

$$\begin{aligned}\text{Moles K} &= 66.4 \text{ kg} \times 1000 \text{ g/kg}/(39.1 \text{ g/mole})\\ &= 1,698 \text{ moles K}\end{aligned}$$

Solve for the number of moles of nitrogen required.

$$\begin{aligned}\text{Moles N} &= 2 \text{ kg/ha} \times 20 \text{ ha}\\ &\quad \times 1,000 \text{ g/kg}/(14 \text{ g N/mole})\\ &= 2,857 \text{ moles N}\end{aligned}$$

The number of moles of N and number of moles of K that are applied must be the same because there is a one-to-one ratio of NO_3 and K in the fertilizer. Thus, excess potassium will be applied.

Solve for the mass of fertilizer required.

$$\begin{aligned}&\text{Molecular weight of fertilizer}\\ &\quad = \text{Mol.wt. } NO_3 + \text{Mol wt. K} = 62 + 39.1\\ &\quad = 101.1 \text{ g/mol.}\\ &\text{Mass of fertilizer}\\ &\quad = 2,857\text{moles} \times 101.1\text{g/mol.} \times 0.001 \text{ kg/g} = 289 \text{ kg.}\end{aligned}$$

The solubility of potassium nitrate is 0.133 kg/L (Table 19.5). Volume of water required based on solubility of potassium nitrate.

$$289 \text{ kg}/(0.133 \text{ kg/L}) = 2,172 \text{ L}$$

Table 19.6 Types of fertilizer and suitability for fertigation through microirrigation systems (after Burt et al. 1995 and originally presented in Evans and Waller 2006)

Fertilizer	Compound	Precaution	Characteristics
Anhydrous ammonia	82-0-0	Never inject into microirrigation Sys	n/a
Aqua ammonia	20-0-0	Never inject into microirrigation systems	n/a
Ammonium nitrate solution (AN-20) $NH_4NO_3 *H_2O$	20-0-0	Never mix solution with concentrated acids	Density – 1.29 kg/L Commonly used for fertigation
Urea ammonium nitrate (UAN32) $(NH_2)_2CO*NH_4NO_3$	32-0-0	Don't mix with CAN17 or calcium nitrate solutions	Density – 1.33 kg/L Commonly used liquid fertilizer with highest N.
Calcium ammonium nitrate (CAN17) $Ca(NO_3)_2*NH_4NO_3$	17-0-0-8.8 Ca	Do not combine with solutions containing sulfates/thiosulfate	Density – 1.55 kg/L Effective for obtaining high fruit quality in some crops.
Ammonium phosphate $(NH_4)H_2PO_4$	8-24-0	Can precipitate if injected at high rates or into hard water	Density – 1.26 kg/L Not commonly used for fertigation.
Ammonium polyphosphate $(NH_4)_2H_2P_2O_7$	9-30-0, 10-34-0, 11-37-0	Can precipitate with carbonates in high pH water	9-30-0, Density – 1.36 kg/L 10-34-0, Density – 1.37 kg/L 11-37-0, Density – 1.41 kg/L
Ammonium polysulfide $(NH_4)_2S_x$	20-0-0-45	Dangerous hydrogen sulfide gas results from contact with acid	Density – 1.05 kg/L Solution has very high pH, but can act as soil acidifying agent.
Ammonium thiosulfate $(NH_4)_2S_2O_3$	12-0-0-26	Do not mix with acids or apply to low pH soils	Density – 1.33 kg/L Acidifying agent, ideal for treatment of calcareous soils.
Metal chelates	Most metal micronutrients must be chelated with EDTA, DTPA, or EDDHA to prevent precipitation		Chelated metals are very effective in alkaline soils.
Phosphoric acid H_3PO_4	0-54-0	Never mix phosphoric acid with calcium fertilizer	Density – 1.69 kg/L Green acid is most common, but is less pure than white acid.
Potassium chloride KCl	0-0-60 Dry form	Not recommended for Cl sensitive crops	Solubility – 0.347 kg/L Highest used potassium fertilizer.
Potassium nitrate KNO_3	13-0-44	None	Solubility – 0.133 kg/L Second most popular source of potassium fertilizer.
Potassium phosphate KH_2PO_4	0-52-34	None	Density – 1.26 kg/L Used in greenhouse and nursery
Potassium sulfate K_2SO_4	0-0-50	None	Solubility – 0.12 kg/L Popular for fertigation as good source of sulfur
Potassium thiosulfate (KTS) $K_2S_2O_3$	0-0-25-17 0-0-22-23	KTS blends should have pH less than 6	Contains 0.36 kg/L K_2O and 0.25 kg/L S
Sulfuric acid H_2SO_4	0-0-0	Very Hazardous. Injection w/ CAN17 results in clogging	Density – 1.83 kg/L
Urea solid $(NH_2)_2CO$	46-0-0	Never mix urea with sulfuric acid	Solubility – 1 kg/L
Urea phosphate $(NH_2)_2CO*H_3PO_4$	17-44-0		The acidity prevents ammonia volatilization
Urea sulfuric acid $(NH_2)_2CO*H_2SO_4$	10-55-18 19-49-16 28-19-9	55 Sulfuric acid 18 S 49 Sulfuric acid 16 S 15 Sulfuric acid 9 S	10-55-18 Density – 1.54 kg/L 19-49-16 Density – 1.53 kg/L 28-19-9 Density – 1.42 kg/L

It is easier to dissolve potassium nitrate at a concentration less than the maximum concentration (0.133 kg/L). The grower doubles the volume of liquid used to dissolve the fertilizer to approximately 5,000 L.

If irrigation occurred on daily basis and fertilizer injection was conducted for 2 h each irrigation, then the injection rate for the 20 ha block would be calculated as follows.

$$5{,}000\ \mathrm{L}/(2\ \mathrm{h/day}*7\ \mathrm{days}) = 357\ \mathrm{L/h}$$

The grower could adjust the relative amounts of N and K by mixing a fertilizer that is higher in nitrogen and lower in potassium. One possible combination would be ammonium nitrate and potassium nitrate.

Table 19.7 Nutrient application amounts and irrigation schedule per stage for cantaloupe crop

Stage	Nutrients -kg/block/stage					
	N	P	K	Ca	Irr. events per stage	Fertigation hours/stage
1 (0–25 days)	75	0	0	0	6	12
2 (25–50 days)	525	0	0	0	12	24
3 (50–75 days)	525	375	0	0	16	32
4 (75–100 days)	525	0	0	300	16	32
5 (100–120 days)	135	0	0	300	16	32

Example 19.7 A grower plans to meet the nutrient application requirements specified in Table 19.7. The 75 ha field is divided into 5 blocks of 15 ha each. In addition to N and P fertilization, the grower also adds 20 kg/ha calcium during the fourth and fifth stages. Nutrient application rates (Table 19.7) per block are the product of kg/ha for each stage (Table 19.4) and the area of each block. Water is Colorado River water with pH = 8. Irrigation water is applied at a rate of 4 mm/hr.

The grower injects the fertilizer during the middle 2 h of each 4 h irrigation event. Thus, there are 2 fertigation hours per irrigation event as shown in Table 19.7. In order to save time and avoid possible problems, the grower decides to purchase premixed liquid formulations. Urea-ammonium nitrate (UAN32) is selected during the first 2 stages because only nitrogen is required. For the third stage, liquid formulations of UAN32 and ammonium polyphosphate (10-34-0) are selected and will be injected at two ports into the irrigation pipeline. Ammonium polyphosphate would not normally be selected for injection into Colorado River water (pH ~ 8) because of the danger of precipitation of calcium phosphate ($CaPO_4$). However, the grower injects sulfuric acid in order to lower irrigation water pH to 6.5 at an injection port upstream from the two fertilizer injection ports. Thus, the grower can avoid precipitation of fertilizers with Ca in the Colorado River water source. The soil is alkaline so soil acidification is not a hazard, and lowered pH may improve calcium availability to the plant. For the last two stages, the grower decides to use CAN17 as the calcium source. CAN17 cannot be injected with urea-ammonium nitrate so the grower decides to use ammonium nitrate as the nitrogen source if CAN17 does not supply the nitrogen required during the fourth and fifth stages.

UAN32 will supply 75 kg N per block over 12 h of fertigation (Table 19.6) during the first stage. The density of UAN32 is 1.33 kg/L and the formulation is 32-0-0 (Table 19.5).

$$\begin{aligned}&\text{Volumetric N content of UAN32}\\&\quad = 1.33\ \text{kg/L} \times 0.32 = 0.425\ \text{kg/L of N}\\&\text{UAN32 volume per block during stage 1}\\&\quad = 75\ \text{kg}/0.425\ \text{kg/L} = 176\ \text{L UAN32}\\&\text{Injection rate} = 176\ \text{L}/12\ \text{h of fertigation} = 14.7\ \text{L / h.}\\&\text{Mass of UAN32 applied} = 176\text{L} * 1.33\text{kg / L}\\&\quad = 234\ \text{kg UAN32/block}\end{aligned}$$

UAN32 will supply 525 kg N per block over 24 h of fertigation during stage 2.

$$\begin{aligned}&\text{UAN32 volume per block during stage 2}\\&\quad = 525\ \text{kg}/0.425\ \text{kg / L} = 1,235\ \text{L UAN32}\\&\text{Injection rate} = 1,235\ L/24\ \text{h of fertigation} = 51.5\ \text{L / h.}\\&\text{Mass of UAN32 applied} = 1,235\ \text{L}*1.33\ \text{kg/L}\\&\quad = 1,642\ \text{kg UAN32/block}\end{aligned}$$

Ammonium polyphosphate will supply 375 kg P per block over 32 h of fertigation during the third stage. The density of ammonium polyphosphate (APP) fertilizer is 1.37 and the formulation is 10-34-0 (Table 19.5). Thus, 34 % of the mass of the fertilizer is phosphorous as P_2O_5. P_2O_5 is multiplied by 0.44 (Table 19.4) to convert to elemental P (PO_4-P).

$$\begin{aligned}&\text{Volumetric P content of APP}\\&\quad = 1.37\ \text{kg / L} \times 0.34 \times 0.44 = 0.205\ \text{kg / L of P}\\&\text{APP volume per block during stage 3}\\&\quad = 375\ \text{kg}/0.205\ \text{kg/L} = 1,829\ \text{L of APP}\\&\text{APP Injection rate} = 1,829\ \text{L}/(32\ \text{h of fertigation})\\&\quad = 57\ \text{L / h of APP}\\&\text{Mass of APP applied} = 1,829\ \text{L}*1.37\ \text{kg / L}\\&\quad = 2,500\ \text{kg APP / block}\end{aligned}$$

The nitrogen supplied by the ammonium polyphosphate during stage 3 is calculated as follows:

$$\begin{aligned}&\text{Volumetric N content of APP} = 1.37\ \text{kg/L} \times 0.10\\&\quad = 0.137\ \text{kg / L of N}\\&\text{Mass N applied as APP} = 1,829\ \text{L} \times 0.137\ \text{kg / L}\\&\quad = 250\ \text{kg of N}\end{aligned}$$

If 250 kg N is applied as ammonium phosphate, then the remainder of the nitrogen requirement (525–250 = 275 kg/block) during stage 3 must be supplied by UAN32.

$$\begin{aligned}&\text{UAN32 volume per block during stage 3}\\&\quad = 275\ \text{kg}/(0.425\ \text{kg / L}) = 647\ \text{L of UAN32}\\&\text{Injection rate} = 647\ \text{L}/(32\ \text{h of fertigation})\\&\quad = 20\ \text{L / h of UAN32}\\&\text{Mass of UAN32 applied} = 647\ \text{L}*1.33\ \text{kg / L}\\&\quad = 860\ \text{kg UAN32 / block}\end{aligned}$$

Calcium ammonium nitrate (CAN17) will supply 300 kg Ca per block over 32 h of fertigation during the fourth stage and fifth stages. The density of CAN17 fertilizer is 1.55 and the formulation is 17-0-0-8.8 Ca (Table 19.5). Thus, 8.8 % of the mass of the fertilizer is calcium.

$$\begin{aligned}&\text{Volumetric Ca content for CAN17}\\&\quad = 1.55\ \text{kg / L} \times 0.088 = 0.136\ \text{kg / L of Ca}\\&\text{CAN 17 volume per block during stage 3}\\&\quad = 300\ \text{kg}/(0.136\ \text{kg/L}) = 2{,}205\ \text{L of CAN17}\\&\text{Injection rate of CAN17} = 2{,}205\ \text{L}/(32\ \text{h of fertigation})\\&\quad = 69\ \text{L/h of CAN17}\\&\text{Mass of CAN17 applied} = 2{,}205\ \text{L}*1.55\ \text{kg / L}\\&\quad = 3{,}418\ \text{kg CAN17 / block}\end{aligned}$$

The amount of nitrogen supplied by CAN17 during stages 4 and 5 is calculated as follows.

$$\begin{aligned}&\text{Volumetric N content of CAN17} = 1.55\ \text{kg / L} \times 0.17\\&\quad = 0.264\ \text{kg / L of N}\\&\text{Mass N applied as CAN17}\\&\quad = 2{,}205\ \text{L CAN17} \times 0.264\ \text{kg / L} = 582\ \text{kg of N}\end{aligned}$$

Thus, CAN17 will supply slightly more N per block, 582 kg, than is required during the fourth stage, 525 kg, and much more than is required during the fifth stage, 135 kg. As a result, the grower may decide to apply less N during the third stage and the application of UAN32 during the third stage may not be necessary.

The final step in assessing a fertigation strategy is to check the concentration of nutrients in irrigation water and the impact on the root zone salinity concentration.

The total depth of irrigation water applied to the field is

$$4\ \text{mm / h}*66\ \text{irrigations}*4\ \text{h / irrigation} = 1{,}056\ \text{mm}.$$

The total volume of irrigation water applied to the 75 ha field is

$$1.056\ \text{m}*75\ \text{ha}*10{,}000\ \text{m}^2/\text{ha} = 792{,}000\ \text{m}^3$$

The total mass of fertilizer (salts) applied is the sum of the fertilizer mass applied during all stages * 5

$$\begin{aligned}&5*(234 + 1{,}642 + 2{,}500 + 860 + 3{,}418 + 3{,}418)\\&\quad = 60{,}360\ \text{kg salts}\end{aligned}$$

The average concentration in irrigation water is

$$60{,}360\ \text{kg}/792{,}000\ \text{m}^3 = 0.076\ \text{kg / m}^3 = 76\ \text{mg / L}$$

Extra leaching will be required in order to remove the additional 76 mg/L salts in the irrigation water (leaching fraction in Chap 4). The calculations are made in the *Fertigation* worksheet (Fig. 19.6). Note that white cells are user input and yellow cells are calculated.

Although not necessarily a nutrient, farmers add acid to irrigation water in order to lower the pH of soils because soil pH can have an effect on nutrient availability. One reason that plants may appear nutrient deficient is not a lack of nutrients in the soil but rather a lack of availability of nutrient to the plant due to pH.

Chemigation of Non-Fertilizer Materials

Only chemicals that are labeled for chemigation should be applied with irrigation systems. The pesticide application may also be subjected to additional state regulations above label specifications. The United States Environmental Protection Agency has established criteria for evaluating the leaching potential of pesticides. Pesticides are considered less likely to leach if they have a short life in the soil before degrading, are not very soluble in water, and are likely to be adsorbed onto soils and organic matter.

Pesticide injection rate can be calculated based on irrigation system area and time of application. A typical pesticide application might include one h of water application before pesticide is injected, 3 h of pesticide injection, and then one h of water application after pesticide application in order to flush all pesticides from the irrigation system. Flushing is especially important with the application of soil fumigants in order to prevent crop damage when irrigation is resumed after planting.

The concentration of the pesticide in the irrigation water must also be checked in order to ensure that the concentration of pesticide in the irrigation system is not corrosive to irrigation system components.

Example 19.8 A grower wants to apply Telone EC at a rate of 45 L/ha over a period of 3 h to an irrigation zone that covers 10 ha. The irrigation water flowrate to the irrigation zone is 5,000 L/min. The density of Telone EC is 1.1 kg/L.

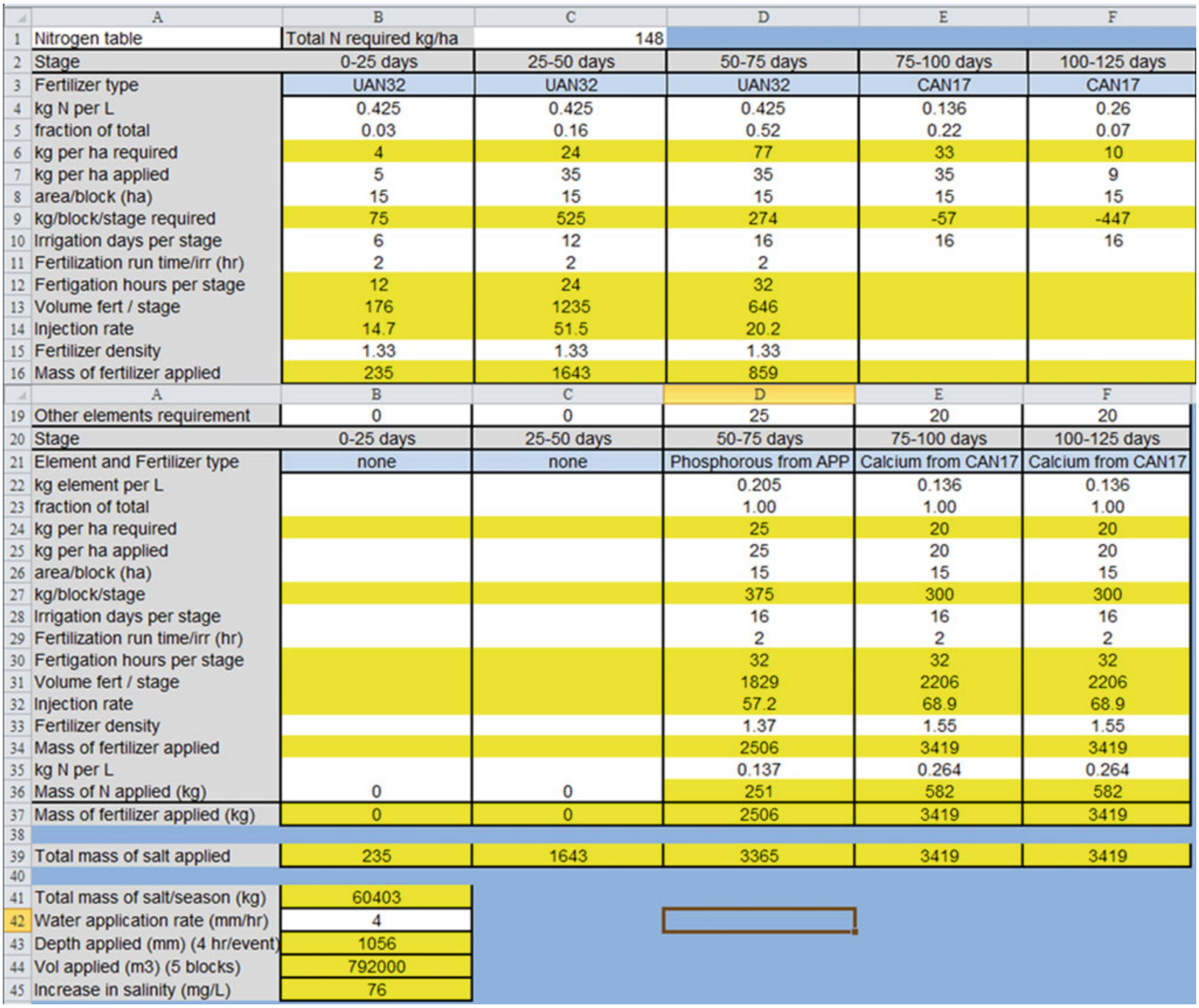
The required injection rate is

$$\begin{aligned}\text{Injection rate, L / h} &= 45\ \text{L / ha} \times 10\ \text{ha}/3\ \text{h} = 150\ \text{L / h}\\&= 2.5\ \text{L / min}\end{aligned}$$

It has been found that Telone EC at concentrations greater than 1,500 mg/L is corrosive to irrigation system components. In order to avoid exceeding one-half of the corrosive concentration (the rule of thumb), the concentration of Telone EC in irrigation water should not exceed 750 mg/L.

$$\begin{aligned}&\text{Telone EC Concentration}\\&\quad = 2.5\ \text{L/min Telone}/5{,}000\ \text{L/min water}\\&\times 1.1\ \text{kg / L Telone} \times 1 \times 10^6\text{mg / kg}\\&\quad = 550\ \text{mg / L Telone}\end{aligned}$$

Thus, at an injection rate of 2.5 L/min, the concentration of Telone in irrigation water is less than 750 mg/L and is acceptable.



	A	B	C	D	E	F
1	Nitrogen table	Total N required kg/ha	148			
2	Stage	0-25 days	25-50 days	50-75 days	75-100 days	100-125 days
3	Fertilizer type	UAN32	UAN32	UAN32	CAN17	CAN17
4	kg N per L	0.425	0.425	0.425	0.136	0.26
5	fraction of total	0.03	0.16	0.52	0.22	0.07
6	kg per ha required	4	24	77	33	10
7	kg per ha applied	5	35	35	35	9
8	area/block (ha)	15	15	15	15	15
9	kg/block/stage required	75	525	274	-57	-447
10	Irrigation days per stage	6	12	16	16	16
11	Fertilization run time/irr (hr)	2	2	2		
12	Fertigation hours per stage	12	24	32		
13	Volume fert / stage	176	1235	646		
14	Injection rate	14.7	51.5	20.2		
15	Fertilizer density	1.33	1.33	1.33		
16	Mass of fertilizer applied	235	1643	859		

	A	B	C	D	E	F
19	Other elements requirement	0	0	25	20	20
20	Stage	0-25 days	25-50 days	50-75 days	75-100 days	100-125 days
21	Element and Fertilizer type	none	none	Phosphorous from APP	Calcium from CAN17	Calcium from CAN17
22	kg element per L			0.205	0.136	0.136
23	fraction of total			1.00	1.00	1.00
24	kg per ha required			25	20	20
25	kg per ha applied			25	20	20
26	area/block (ha)			15	15	15
27	kg/block/stage			375	300	300
28	Irrigation days per stage			16	16	16
29	Fertilization run time/irr (hr)			2	2	2
30	Fertigation hours per stage			32	32	32
31	Volume fert / stage			1829	2206	2206
32	Injection rate			57.2	68.9	68.9
33	Fertilizer density			1.37	1.55	1.55
34	Mass of fertilizer applied			2506	3419	3419
35	kg N per L			0.137	0.264	0.264
36	Mass of N applied (kg)	0	0	251	582	582
37	Mass of fertilizer applied (kg)	0	0	2506	3419	3419
38						
39	Total mass of salt applied	235	1643	3365	3419	3419
40						
41	Total mass of salt/season (kg)	60403				
42	Water application rate (mm/hr)	4				
43	Depth applied (mm) (4 hr/event)	1056				
44	Vol applied (m3) (5 blocks)	792000				
45	Increase in salinity (mg/L)	76				

Fig. 19.6 *Fertigation worksheet*

The Chapter 19 Chemigation workbook has several worksheets that are not reviewed in this chapter: *Units, Mixing, $CaCO_3$ solubility, Sulfuric acid, Hardness, and Gypsum.*

Questions

1. Determine a fertilizer injection schedule for N, P, and K for bell peppers for the following table. All other assumptions, areas, and fertilizer types are as in the chapter 19 examples.

Table HW11-1 Nutrient application rates and times for Bell Peppers

Stage	Nitrogen N (kg/ha)		Phosphorus P (kg/ha)		Potassium K (kg/ha)	
	Required	Applied	Required	Applied	Required	Applied
1 (0–25 days)	17	17	2	0	4	0
2 (25–50 days)	36	35	5	0	55	0
3 (50–75 days)	50	40	9	23	166	0
4 (75–100 days)	65	50	9	0	150	0
5 (100–120 days)	39	36	5	0	14	0

2. Plot carbonate, bicarbonate, and carbonic acid concentration as a function of pH for alkalinity as calcium carbonate equal to 120 mg/L.
3. Calculate the amount of 98 % sulfuric acid required to drop the pH from 7.9 to 6.8 for water with alkalinity as calcium carbonate equal to 120 mg/L.
4. Calculate the LSI for the following water analysis at 25 °C and 35 °C. Measured pH is 7.96.
   - alkalinity as calcium carbonate equal to 120 mg/L.
   - calcium as calcium carbonate equal to 65 mg/L
   - TDS equal to 1,000 ppm
5. Calculate the injection rate of 10 % chlorine bleach required in order to develop a concentration of 3 ppm elemental chlorine in an irrigation system with a 200 LPM flow rate.

References

The Evans and Waller document is the original source of much of this chapter. Dr. Evans was a Federal employee so there is no copyright.

Bar-Yosef B (1999) Advances in fertigation. Adv Agron 65:2–77. Academic Press

Burt CM, O'Connor K, Ruehr T (1995) Fertigation. Irrigation Training and Research Center, California Polytechnic State University, San Luis Obispo, p 320

Evans and Waller (2006) Chemigation. (Ed) Freddy Lamb. Americaan Society of Agricuitural and Biological. Engineers, Published ASABE Irrigation Monograph, St. Joseph

Granberry DM, Harrison KA, Kelley WT (2001) Drip chemigation: injecting fertilizer, acid and chlorine, vol 1130, Bull. University of Georgia, College of Agricultural and Environmental Science, Cooperative Extention Service, Athens, p 13

Rosen CJ, Eliason R (1996) Nutrient management for commercial fruit & vegetable crops in Minnesota. University of Minnesota Ext. Pub. BU-05886. 61 pp. http://www.extension.umn.edu/distribution/cropsystems/DC5886.html