18 Drip Irrigation System Design

This first half of this chapter focuses on the design of a dual feed subsurface drip irrigation system, which is the most common agricultural drip system. The first example demonstrates the procedure for design and economic comparison of alternative mainline and submain designs for subsurface drip irrigation. Uniformity is calculated for an entire irrigation zone rather than an individual lateral. Submains are designed with lateral flow rate vs. pressure curves just as laterals are designed with emitter flow rate vs. pressure curves. The economic analysis includes water, energy, and pipe costs. One of the major advantages of a dual feed system is the automated flushing process; the example evaluates the additional pumping installation and pipe costs associated with flushing.

The last half of this chapter provides a rationale for the selection between types of inline drip irrigation laterals. There are many alternatives with different wall thicknesses, tubing diameters, emitter spacings, emitter types, and manufacturer's coefficients of variation. How does one decide which is the best alternative? A computer program is provided that allows the evaluation of the various alternatives. It uses Monte Carlo simulation to simulate the effect of emitter degradation and tubing replacement interval on yield and cost.

Example 18.1 Two possible pipe designs are presented in Figs. 18.1 and 18.2. Because submains are split in design 1, smaller submains can be used and emission uniformity is improved. However, extra pipes are eliminated in design 2. Determine, based on economics, whether design 1 (Fig. 18.1) is better than design 2 (Fig. 18.2). Assume 20 year project life and 8 % ROR. There is a 0.2 % slope in the N-S direction with the upper end at North end. Assume normal head losses in valves and fittings. The canal water surface is 1 m below ground surface. Use the parameters specified in Example 17.7.

The cost of energy is \$0.10/kW-hr, and the cost of water is \$3.27/ha-cm. Annual ET_c is 1 m/y. Irrigation efficiency is 90 % and pumping efficiency is 80 %. Ignore the cost of valves and fittings because the cost of valves and fittings in the two designs is approximately the same.

Use Class 125 PVC pipe for submains and mainlines. Mainlines are defined as those pipes that are upstream from the valves. The design shown in Fig. 18.1 includes E-W submains (1–32) that are fed from the center by EW mains 33–48, which are fed by N-S mainline 49–52. The design shown in Fig. 18.2 includes submains that are fed directly from the N-S mainline 49–52.

Drip irrigation laterals are 200 m length with 16 mm tubing fed from both ends (Fig. 17.21). The cost of 16 mm ID drip tape with turbulent emitters is \$0.10/m. Emitters are turbulent ($x = 0.5$), 2 L/h at 100 kPa ($k = 0.2$), spacing = 0.5 m.

For submain design, a relationship can be developed between lateral inlet pressure at the submain and lateral flow rate. The distal end pressure can be varied in the worksheet in order to generate the inlet pressure vs. flow rate curves (Fig. 18.3). As calculated in Chap. 17, the upper lateral is 106.5 m long (213 emitters) and the lower lateral is 93.5 m long (187 emitters) in the simulations represented in Fig. 18.3. The lateral flow exponents 0.502 and 0.507 are nearly the same as the emitter flow exponents; however, the *Make calcs* program varies the number of emitters in upper and lower sections as inlet pressures change (Fig. 18.4) and has a greater exponent for the upper lateral section and a lower exponent for the lower lateral section.

Design 1

The Design 1 valves and pipes for each zone are shown in Fig. 18.5. The solenoid valve supplies the entire zone (both halves with water) during an irrigation event. Isolation gate valves are used to isolate the two halves of the zone

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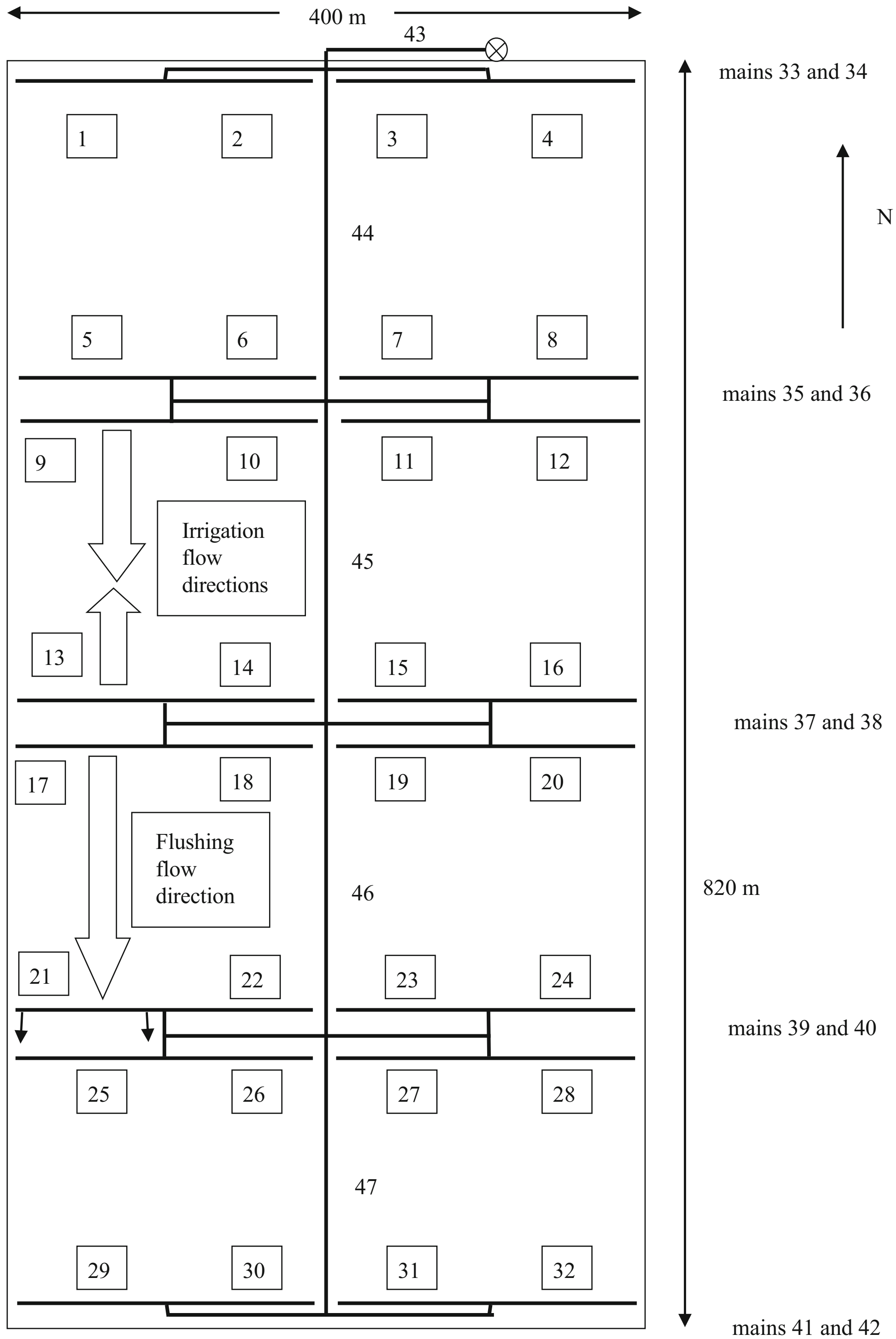


Fig. 18.1 Drip irrigation design number 1 for Example 18.1. Dark lines are PVC pipes

during flushing. Cutting the zones in half during flushing reduces the flow rate and required size of the mainline during flushing. It also enables the farmer to irrigate half of the zone, if necessary. The EW mainline supplying the submains is designed to supply the entire zone with water during irrigation or half the zone during flushing. Laterals on the right half of the zone are not shown in Fig. 18.5.

Design of Submains for Design 1

The submain design is subject to the following criteria. First, pressure loss along the submain should be minimized in order to maintain uniformity. Second, the submains should carry the flow required for flushing, which is significantly higher than the irrigation flow rate.

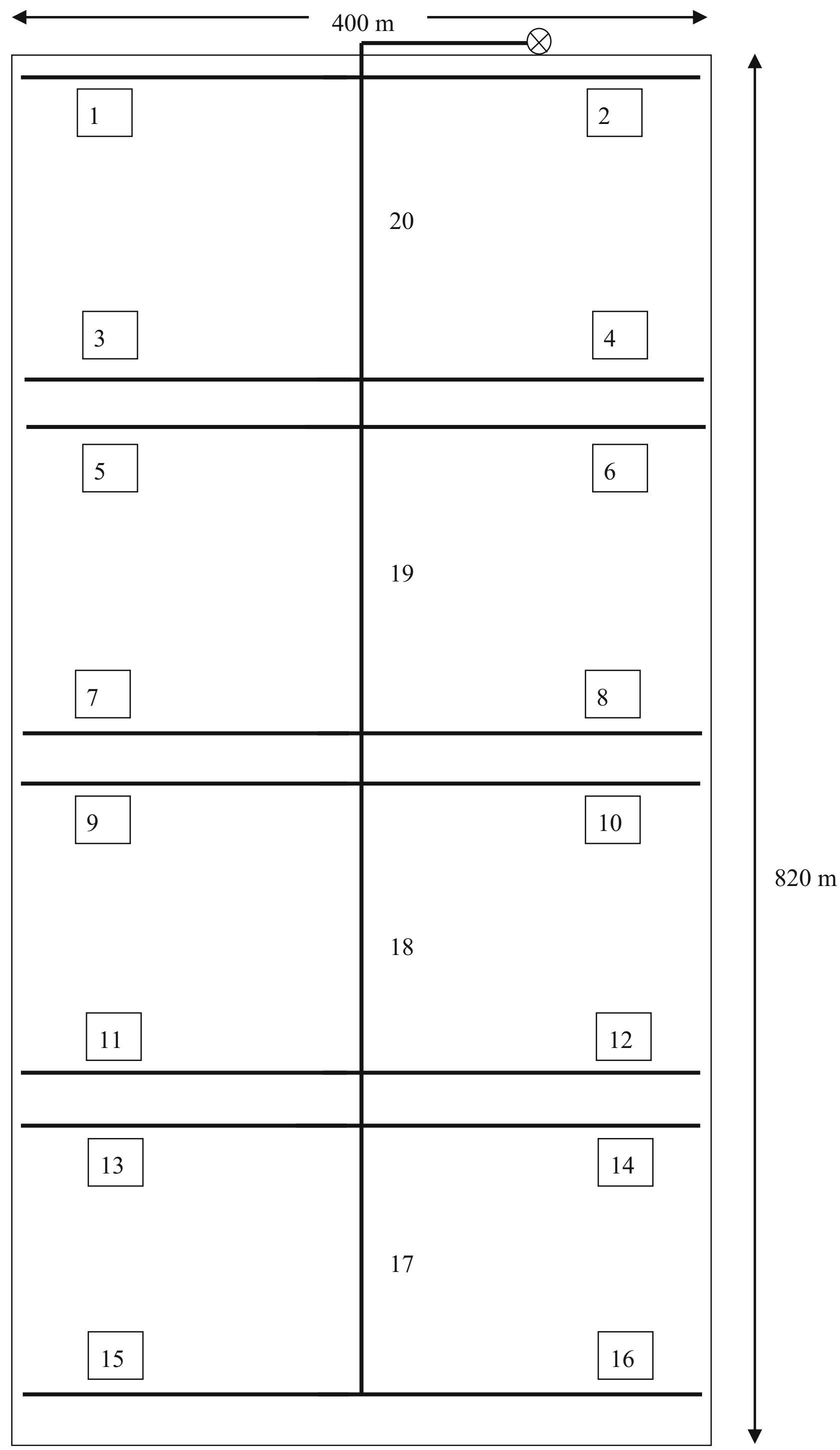


Fig. 18.2 Drip irrigation design number 2 for Example 18.1

The area supplied by each submain in Fig. 18.5 is approximately 1 ha (100 m × 100 m).

$$Q_p = \frac{E_d Q_e A_p}{3,600} = \frac{20,000\ emitters/ha * 2\ LPH*1\ ha}{3,600} = 11.1\ LPS$$

The flow velocity in 83 mm ID (3 in.) Class 125 pipe at 11.1 LPS is 2.2 m/sec. The 83 mm pipe flow velocity decreases below 1.5 over the last third of the submain. The velocity in 107 mm ID (4 in.) Class 125 pipe at 11.1 LPS is 1.3 m/sec. Thus, 107 mm pipe is acceptable based on the 1.5 m/sec rule for the first two-thirds. However, the 1.5 m/sec rule might be ignored in this case because a pressure surge is dissipated by the multiple outlets to laterals.

During flushing, the lateral inlet flow rates in the upper submain are 1,000 LPH (calculated in previous chapter), and

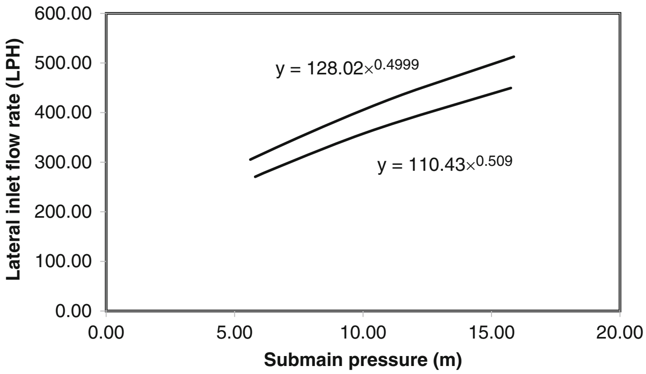


Fig. 18.3 Lateral flow rate versus pressure for upper and lower sections, keeping number of emitters constant on upper and lower sections at 213 and 187, respectively

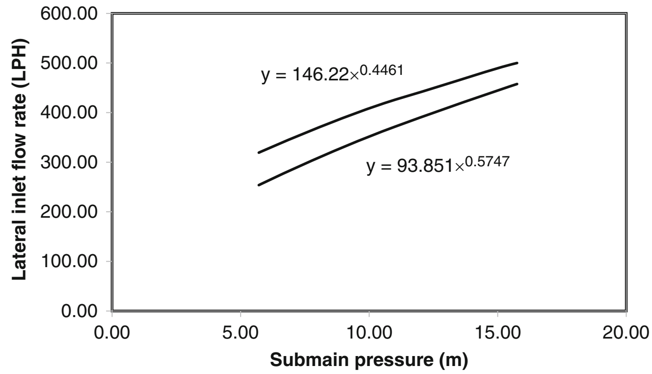


Fig. 18.4 Lateral flow rate versus pressure for upper and lower sections, keeping number of emitters constant on upper and lower sections at 213 and 187, respectively

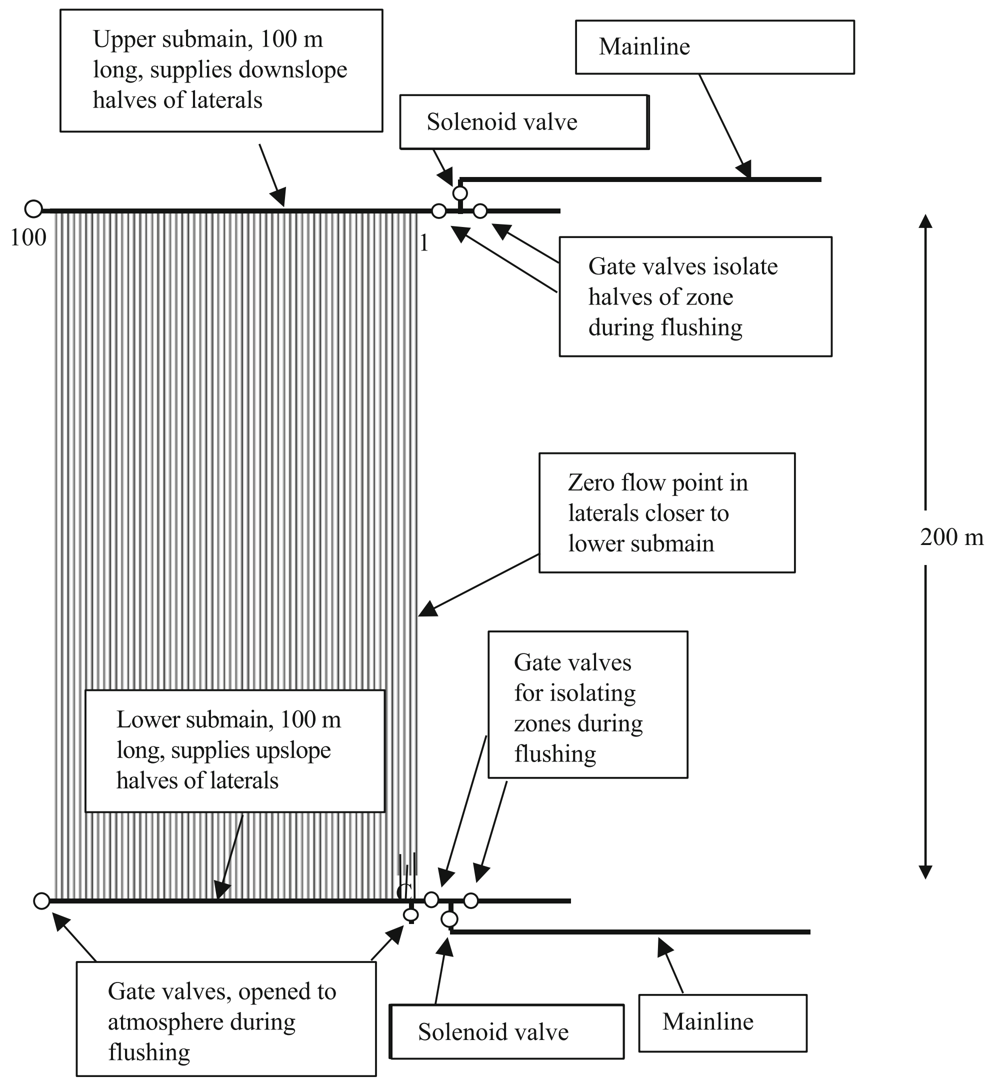


Fig. 18.5 Half of zone for design 1

lateral discharge flow rates to the lower submain are 360 LPH (Fig. 13.22). Thus, the upper submain must carry 1,000 LPH/lateral * 100 laterals = 100,000 LPH = 27.8 LPS. The lower submain divides the flushing discharge flow rate in two directions, so the largest flow rate in the lower submain is 360 LPH * 50 laterals = 18,000 LPH = 5 LPS. The flow velocity in 107 mm ID (4 in.) Class 125 pipe at 27.8 LPS is 3.1 m/sec.

If the criterion for submain diameter is based on the 1.5 m/sec rule, then a 107 mm pipe is not acceptable during flushing (3.3 m/sec velocity at 28 LPS flow rate). However, if slowly-closing 107 mm (4 in. gate valves are used as flushing outlets on the lower submain (Fig. 18.5), then water hammer will not occur because the gate valves require 10 to 20 seconds to close; the velocity will slowly decrease as the gate valves close. Sundance Farms in Arizona has a system that is similar to the design in this example: they use 107 mm submains and 107 mm gate valves, and they have never had water hammer problems during flushing.

In order to derive the lateral inlet flow rate vs. pressure curve for the flushing lateral (Fig. 18.6), the *Flushing dual feed lateral* worksheet varies downstream pressure and records the upstream flow rate and pressure in cells O6:Q15. Based on the information in these cells, the equation for lateral inlet flow rate is $Q_{lateral} = 278H^{0.46}$, where H is the pressure at the lateral inlet. The pressure at the end of the upper submain should be set to 16.2 m in order to have 2 m head at the end of the last lateral (Fig. 18.7).

The lateral inlet flow rates along the submain during irrigation are based on the equation in Fig. 18.4, $Q_{lateral\text{-}upper} = 146\ H_0^{0.45}$, and the requirement that inlet pressure

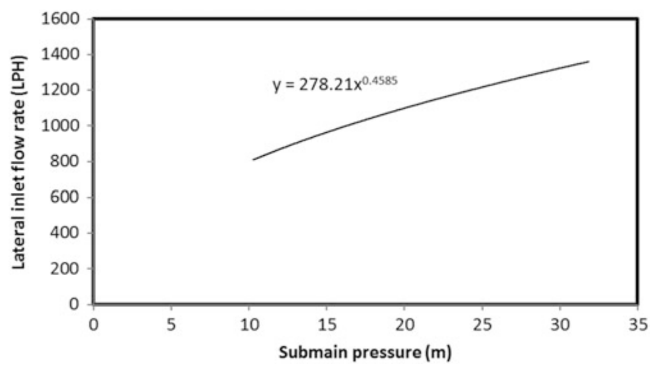


Fig. 18.6 Lateral inlet flow rate and discharge flow rate versus inlet pressure during flushing from upper submain

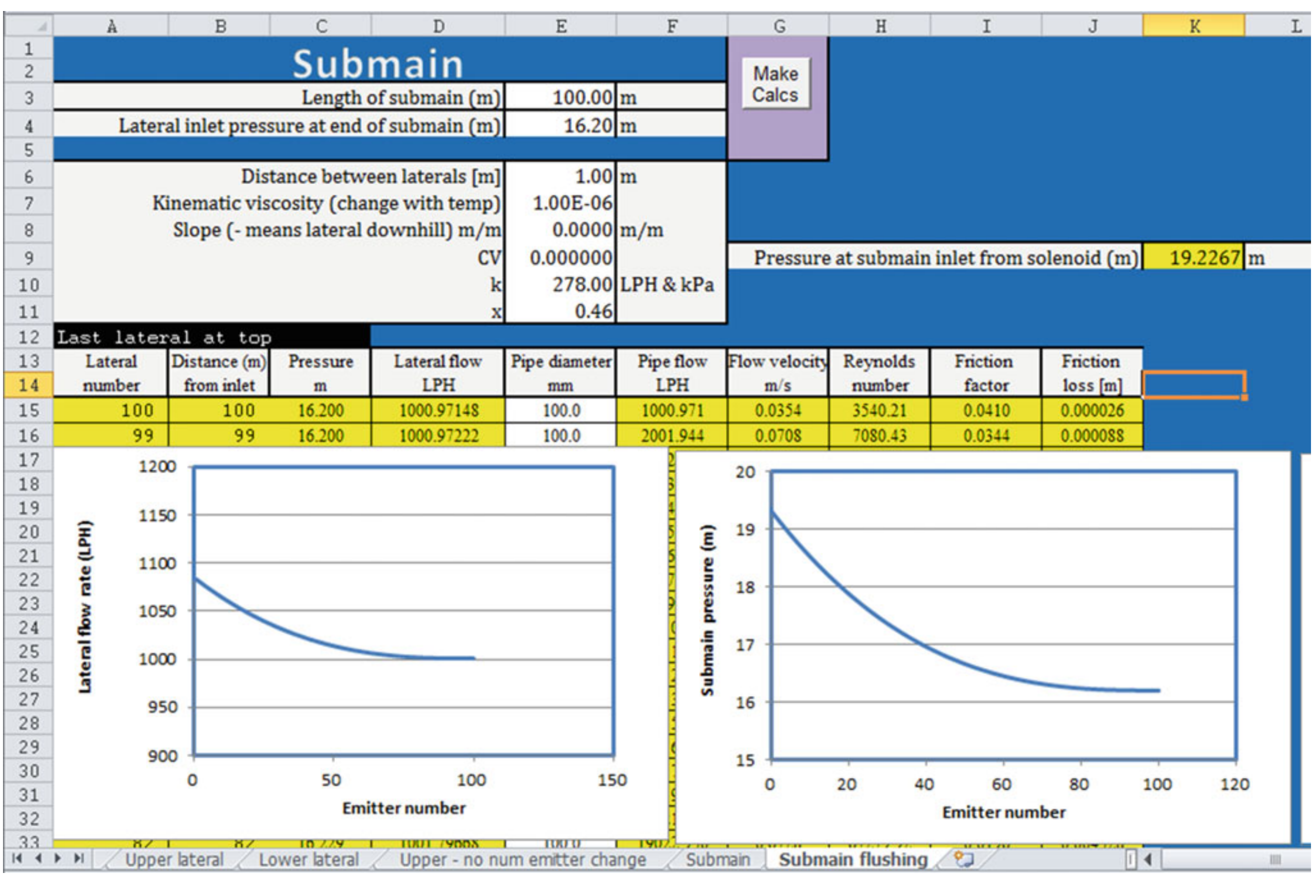


Fig. 18.7 Upper submain pressure and lateral inlet flow rate distribution during flushing for a 107 mm diameter upper submain

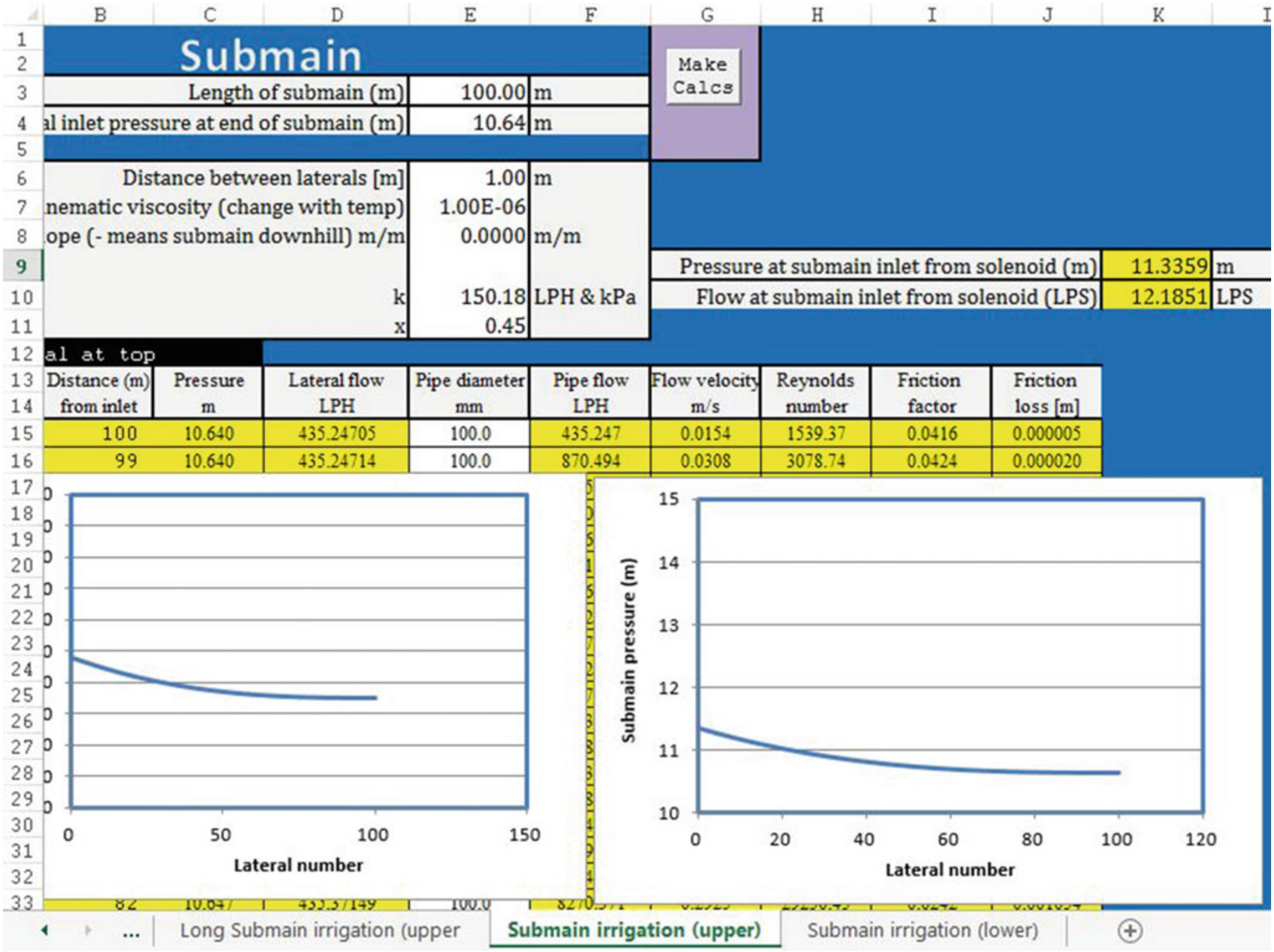


Fig. 18.8 Upper submain pressure distribution and lateral flow rates during irrigation

is 11.4 m. The inlet flow rate and pressure into the upper submain (Fig. 18.8) are 12.1 LPS and 11.3 m, respectively. The calculations for the lower submain are shown in Fig. 18.9.

The inlet pressure and flow rate in the lower submain are 11.9 m and 10.5 LPS. Thus, the total flow rate to the half zone during irrigation is 22.6 LPS. The flow rate to the zone if all emitters had the same pressure and flow rate would be 22.2 LPS (11.1 * 2); thus, the percent wasted water in the zone is (22.6 − 22.2)/(22.2) * 100 % = 1.8 %. The low percentage of wasted water might indicate that the system is overdesigned, but the large diameters are needed for flushing.

Design of Mainlines for Design 1

The E-W mainlines (for example, pipe 33 in Fig. 18.1) cannot exceed the 1.5 m/sec rule because there is a solenoid valve that could close quickly and cause water hammer. During irrigation, the flow rate of the upper mainline that supplies submains 1 and 2 (Fig. 18.1) is twice the single submain flow rate, (12 LPS) (2 zones) = 24 LPS. The flushing flow rate is 27.8 LPS. The flow velocity in 158 mm (6 in.) Cl 125 pipe at 27.8 LPS is 1.4 m/sec < 1.5 m/sec. The pressure loss during flushing in the 100 m mainline at 27.8 LPS is 0.94 m. During irrigation (24 LPS), the pressure loss is 0.73 m. All mainlines (except mains 41 and 42 in Fig. 18.1) must be designed for the upper submain flushing flow rate. Mains 41 and 42 are not used to supply water for flushing laterals; however, their irrigation flow rate of 10.6 * 2 = 21.2 LPS requires 158 mm pipe to remain below the 1.5 m/sec rule.

The N-S mainline should be designed to carry the entire irrigation flow rate (45.2 LPS) to the last zone. This design flow rate for the system is based on the fact that 8 zones are required (Chap. 17) and each of the eight blocks requires 45.2 LPS. First, try 206 mm (8 in. pipe. The flow velocity at 45.2 LPS is 1.4 m/sec, and the friction loss is 0.71 m/100 m. The last section of N-S mainline can be

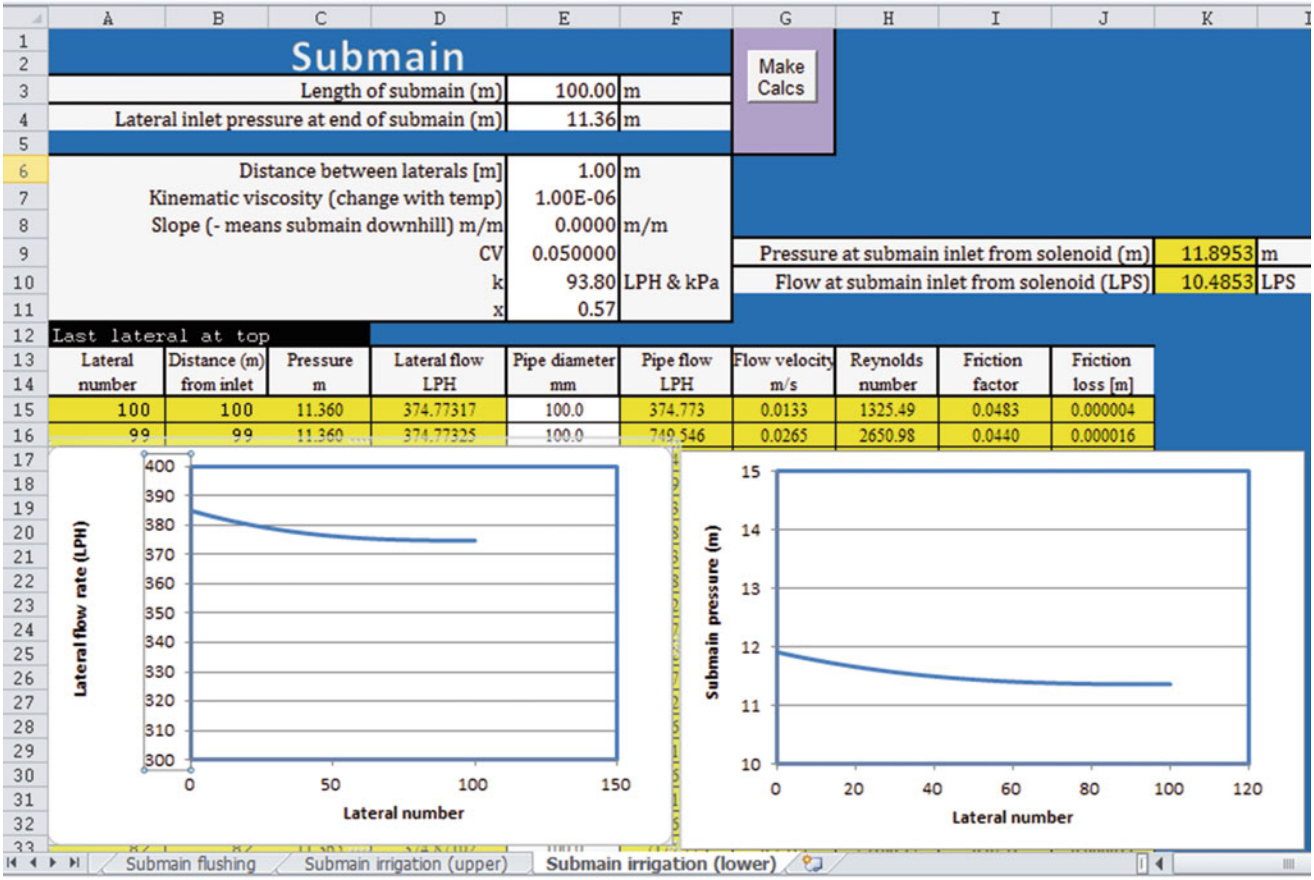


Fig. 18.9 Lower submain pressure distribution and lateral flow rates during irrigation

Table 18.1 Pipe diameters, friction loss, and pressure loss for mainline sections (Fig. 18.1) from pump to worst case mainline (number 42)

	Pipe	43–46 (700 m) 45 LPS		47 (200 m) 21 LPS		42 (100 m) 21 LPS	
Pipe size	cost	h_f (m)	ΔP (m)	h_f (m)	ΔP (m)	h_f (m)	ΔP (m)
6 (158 mm)	$5.87/m	na >1.5	na >1.5	−1.28	−0.88	−0.64	−0.64
8 (206 mm)	$9.71/m	−4.7	−3.5	−0.36	+0.04	−0.18	−0.18
10 (256 mm)	$18.6/m	−1.6	−0.4	−0.12	+0.28	−0.06	−0.06

107 mm (4 in. because mains 41 and 42 carry a maximum 21.2 LPS flow rate. The friction loss in 158 mm pipe at 21.2 m/sec is 0.64 m/100 m. Friction losses for mainline pipe diameters are shown in Table 18.1. The elevation loss between the pump and mains 39 and 40 is 600 m * 0.2 m/100 m = 1.2 m. The pressure gain due to elevation was subtracted from the friction loss in order to calculate ΔP in Table 18.1. The elevation gain is 0.4 m in section 47 and 0 m in section 42.

Slightly higher pressure will be supplied to the upper zones that are closer to the pump because of friction loss in the mainline. If one zone has a pressure that is higher than others, then gate valves can be installed and partially closed to dissipate the excess energy. Using gate valves to dissipate energy decreases their expected life; however, gate valves are relatively inexpensive compared to automatic pressure reducing valves. If flanged gate valves are used, then they are easily replaced.

The next step is to compare pipe costs and energy costs. In sections 43–46, the difference in the pump pressure requirement is 3.1 m (3.5 m and 0.4 m) between the 8 in and 10 in pipe. The depth of water required per year (described in problem statement) at 90 % irrigation efficiency is 1 m/0.9 = 1.11 m. Use Eq. 2.15 to determine the cost of energy.

$$E = \frac{0.0272(1,110\ \ mm)(3.1\ \ m)}{0.8} = 117\ \ kW - hr/ha$$

$$(\$/ha) = \left(\frac{117\ \ kW - hr}{ha}\right)\left(\frac{\$0.10}{kW - hr}\right) = \$11.70/ha$$

Difference between annual cost of 206 mm (8 in.) and 256 mm (10 in.) pipe is $11.70/ha * 32 ha = $374/yr.

Present value of annual energy savings ($374) with 256 mm (10 in.) pipe (20 year, 8 %) is $3,675

The cost of 700 m of 256 mm (10 in.) pipe (Table 18.1) is 700 * $18.60/m = $13,000

The cost of 700 m of 206 mm (8 in. pipe) is 700 * $9.71 = $6,800

The extra cost of 256 mm (10 in.) pipe is $13,000 − $6,800 = $6,200. This is more than the present value of the energy savings with 256 mm (10 in.) so use the 206 mm (8 in.) pipe in sections 43–46.

In section 47, the pressure requirement for 158 mm (6 in.) pipe is 0.88 m greater than the pressure requirement for 8 in. pipe. The cost of energy must be calculated for the entire farm unless a variable frequency pump is purchased.

$$E = \frac{0.0272(1,110\ mm)(0.88\ m)}{0.8} = 33.2\ kW - hr/ha$$

$$(\$/ha) = \left(\frac{33.2\ kW - hr}{ha}\right)\left(\frac{\$0.10}{kW - hr}\right) = \$3.32/ha$$

Total yearly cost for 32 ha = $3.32/ha * 32 = $106/yr.

Present value of energy saving with 206 mm (8 in.) pipe (20 year, 8 %) is $1,043

The cost of 200 m of 206 mm (8 in.) pipe (Table 18.1) is 200 m * $9.71/m = $1,942

The cost of 200 m of 158 mm (6 in. pipe is 200 m * $5.87 = $1,174

The extra cost of the larger pipe is $1,942 − $1,174 = $768. Thus, the energy savings ($1,043) with larger pipe in section 47 is greater than the cost difference ($768): select the larger pipe, 206 mm.

A cost analysis can also be made for E-W mainlines. The difference in pressure loss between 6 in pipe and 8 in pipe (Table 18.1) is 0.64 − 0.18 = 0.46 m. The yearly energy savings is $56, and the present value of energy savings is $545. The difference in cost of pipe for all the 100 m mains is $7,680. Thus, it is more economical to use the smaller pipe for the E-W submains.

Pump Requirement for Design 1

The system pressure requirement is based on supplying the minimum pressure to the worst-case emitter, which is located at the end of the last lateral on submain 25 (Fig. 18.1). Assume typical pressure drops in valves, filters, and fittings: 2 m head loss in the solenoid valve, 8 m head loss in the sand filter, and 5 m head loss in other valves and fittings. The pump is extracting water from a canal with water surface 1 m below the ground surface.

10.2 m	Minimum operating pressure for emitters
+1.2 m	Pressure loss in lateral
+0.4 m	Pressure loss in submain
+2 m	Pressure loss in solenoid valve
+0.7 m	Pressure loss in E-W main
+4.7 m	Pressure loss in 700 m N-S mainline
- 1.2 m	Elevation gain in 700 m N-S mainline
+8 m	Pressure loss in sand filter
+5 m	Friction loss in valves and fittings (check valve, manifold, pump suction)
+1 m	Elevation of ground surface above canal water surface
32 m	Total pump pressure requirement

Thus, the pump flow requirement is 45.2 LPS and pressure requirement is 32 m during irrigation. If pumping efficiency is 80 %, then the power requirement during irrigation is (Eq. 2.17)

$$Pow_{irrigate} = Q\rho gh/Eff = 0.0452*1,000\ kg/m^3* 9.8\ m/\sec^2*32\ m*0.001\ kW/W/0.8 = 17.7\ kW$$

During flushing, the pressure required at the submain inlet is 18.5 m (Fig. 18.7). If isolation valves are used and only half of the zone is flushed at a time, then required flow rate is 27.8 LPS. The total pressure requirement during flushing is

18.5 m	Minimum operating pressure at submain inlet (Fig. 18.7)
+2 m	Pressure loss in solenoid valve
+0.9 m	Pressure loss in E-W main
+2.0 m	Pressure loss in 700 m N-S mainline
- 1.2 m	Elevation gain in 700 m N-S mainline
+8 m	Pressure loss in sand filter
+5 m	Friction loss in valves and fittings (check valve, manifold, pump suction)
+1 m	Elevation of ground surface above canal water surface
35.9 m	Total pump pressure requirement

$$P_{flushing} = Q\rho gh/Eff = 0.0278*1,000\ kg/m^3* 9.8\ m/\sec^2*35.9\ m*0.001\ kW/W/0.8 = 12.2\ kW$$

The power requirement for flushing is less than the power required for irrigation. It would be preferable to find a pump that has both points (45 LPS @ 32 m and 27 LPS @ 37 m) on the pump curve. It is more important to optimize (highest efficiency point) the pump for the irrigation use because that is the primary energy use.

Cost of Tubing and Pipe for Design 1

Total length of drip tubing in design 1 is the field area divided by the lateral spacing.

$$32\ \text{ha}*10,000\ \text{m}^2/\text{ha}/(1\ \text{m/lateral}) = 320,000\ \text{m}$$

Drip tape	320,000 m * $0.10/m	= $32,000
Submain 4 inch	100 * 32 = 3,200 m * $2.72/m	= $8,704
Mainline 6 inch	100 * 10 = 1,000 m * $5.87/m	= $5,870
Mainline 8 inch	900 m * $9.71	= $8,739
Total		= $55,313

Design 2

The second design is not included in the *Chapter 17 and 18 lateral and submain calculations* workbook. Design 2 (Fig. 18.2) does not have E-W mains, but only has E-W submains. During irrigation, a minimum of 4 ha is irrigated at one time (44.4 LPS). During flushing, the gate valve in the center of the lower submain (Fig. 18.13) is shut, and flush valves are only turned on one side of the lower submain at a time.

The lateral design characteristics during irrigation and flushing are the same as design 1 (From Fig. 18.3, K = 127 and x = 0.502). Lateral flow rate vs. pressure was input into the upper submain spreadsheet for a 200 lateral outlet submain (Fig. 18.10). For this design, 106 mm (4 in.) is used for the last 50 m, and 158 mm (6 in.) is used over the first 150 m. The 1.5 m/s rule would allow a switch to 106 mm (4 in.) before 150 m, but energy losses and flow change were excessive with a longer length of 106 mm (4 in.) pipe. The pressure required at the upper submain connection to the N-S mainline is 12.2 m (Fig. 18.10). Total flow is 24.4 LPS.

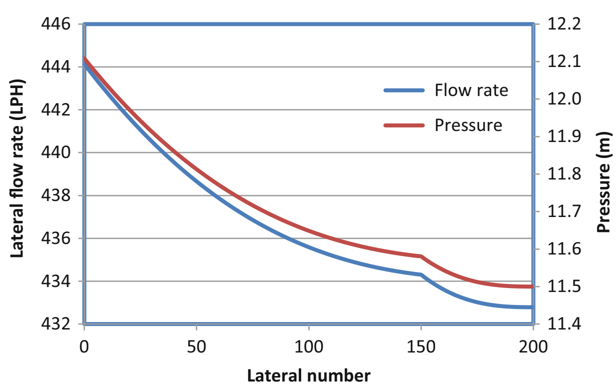


Fig. 18.10 Pressure and flow distribution in upper submain during irrigation for design 2: 106 mm (4 in.) pipe is used for last 50 m and 158 mm (6 in.) pipe is used for first 150 m

For the lower submain laterals, K = 111 and x = 0.507. The lower submain has 125 laterals at 158 mm (6 in.) diameter and the rest at 106 mm (4 in.), and the pressure requirement at the beginning of the submain is 12.5 m because water is going uphill (Fig. 18.11).

The flow rate required during irrigation in the upper submain is 24.4 LPS, and the flow rate required in the lower submain is 22.5 LPS. Thus, the total flow rate required during irrigation is 46.9 LPS (22.5 + 24.4). If the entire zone were irrigated at the design flow rate, then the flow rate would be 44.4 LPS. Thus, the percent wasted water with this design is (46.9–44.4)/44.4 = 5.5 %.

During flushing, the flow rate increases to 58.3 LPS (Fig. 18.12), and the pressure requirement at the upper submain connection to the N-S mainline is 20 m.

Thus, the power requirement during flushing is significantly higher than the irrigation power requirement, and a booster pump is required during flushing. In addition, the N-S mainline flow velocity would slightly exceed the 1.5 m/sec rule with 207 mm (8 in.) pipe at 59 LPS. It might be possible to save energy by flushing half of the zone with the configuration shown in Fig. 18.13. Half of the zone is flushed

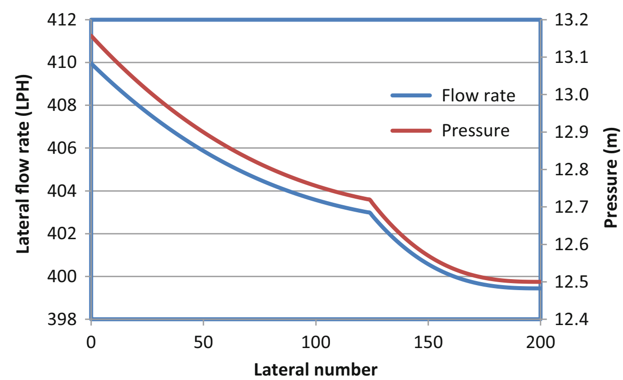


Fig. 18.11 Pressure and flow distribution in lower submain during irrigation for design 2: 106 mm (4 in.) pipe is used for last 75 m and 158 mm (6 in.) pipe is used for first 125 m

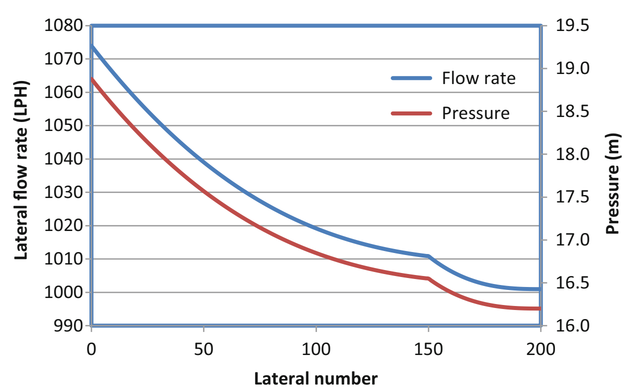


Fig. 18.12 Pressure and flow distribution in upper submain during flushing for design 2

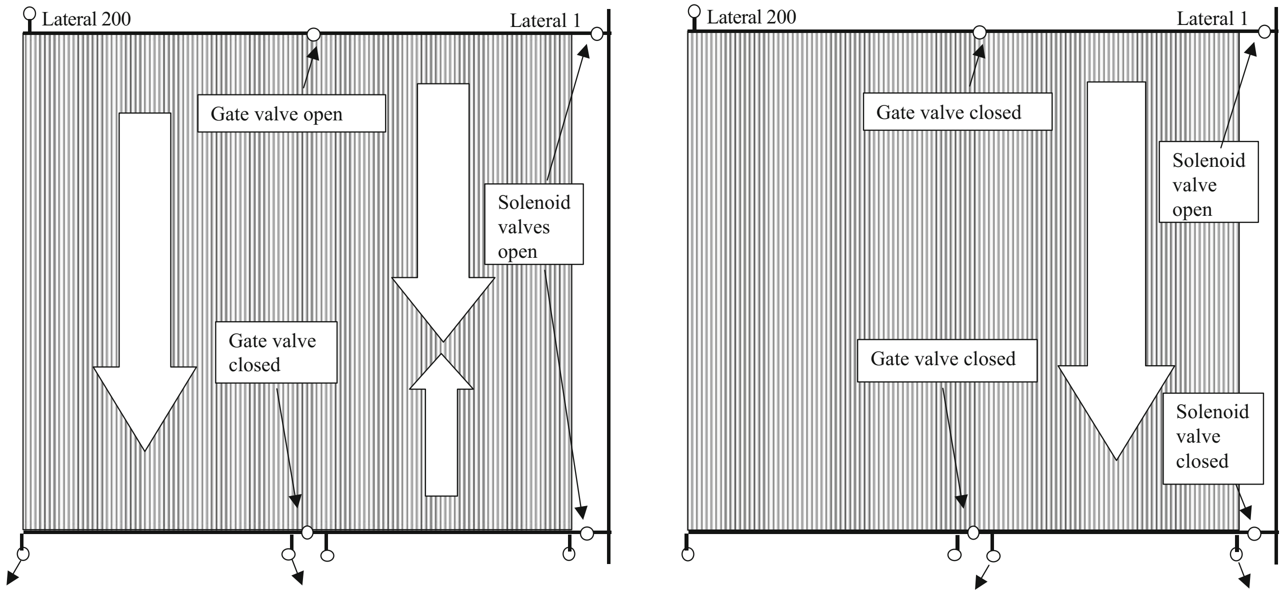


Fig. 18.13 Flow directions during flushing for the two halves of the zones in design 2

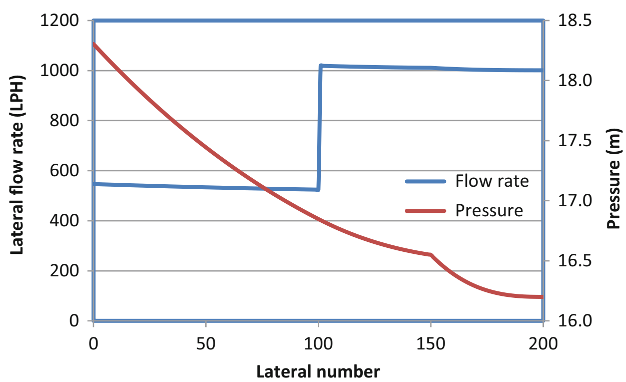


Fig. 18.14 Pressure distribution and flow rates during flushing last half of zone

at a time by dividing submains in half with gate valves. The valve positions and flow directions as the two halves are flushed are shown in Fig. 18.13. When the half of the zone farthest from the N-S mainline is flushed (left side of Fig. 18.13), the lateral flow rates in the first half of the submain (laterals 1–100) are calculated based on irrigation flow rates (Fig. 18.3) and based on flushing flow rates (Fig. 18.6) in the latter half of the lateral.

The pressure distribution and lateral inlet flow rates during flushing of the outer half of the zone (left side of Fig. 18.13) are shown in Fig. 18.14. The total flow rate in the upper submain is 43.3 LPS and the flow rate in the first half of the lower submain is 10.6 LPS (Fig. 18.8) so the total flow rate during flushing is 53.9 LPS. The 1.5 m/sec rule is slightly exceeded in the N-S mainline. The pressure required at the submain inlet is 21.3 m. This flow rate (53.9 LPS) is 7 LPS greater than the irrigation flow rate (46.9 LPS), and increased pressure through use of a booster pump during flushing would be required; thus, a booster pump would still be needed, and the design would be much more complex. Thus, the original design without gates valves is selected (59 LPS).

Pipe Costs for Design 2

Assume that the same N-S mainline pipe sizes are required.

Polyethylene tubing	320,000 m * $0.10/m	= $32,000
L. Submain 106 mm	75 * 8 = 600 m * $2.72/m	= $1,632
U. Submain 106 mm	50 * 8 = 400 m * $2.72/m	= $1,088
L. Submain 158 mm	125 * 8 = 1,000 m * $5.87/m	= $5,870
U. Submain 158 mm	150 * 8 = 1,200 m * $5.87/m	= $7,044
Mainline 206 mm	900 m * $9.71	= $8,739
Total		= $56,373

Pump Requirement for Design 2

The flow rate in both the upper and lower submains during irrigation is 45.2 LPS. The energy required at the inlet to the submains during irrigation is 11.8 m. The worst-case emitter is the emitter at the end of the last lateral on submain 11 (Fig. 18.2). Use the same pressure losses in valves, fittings, and lifting from canal as in design 1.

10.2 m	Minimum operating pressure for emitters
+1.2 m	Pressure loss in lateral
+0.8 m	Pressure loss in submain
+2 m	Pressure loss in solenoid valve
+4.7 m	Pressure loss in 700 m N-S mainline
−1.2 m	Elevation gain in 700 m N-S mainline
+8 m	Pressure loss in sand filter
+5 m	Friction loss in valves and fittings (check valve, manifold, pump suction)
+1 m	Elevation of ground surface above canal water surface
32 m	Total pump pressure requirement

Thus, the pump flow requirement is 46.9 LPS and pressure requirement is 32 m during irrigation.

If pumping efficiency is 80 %, then the power requirement during irrigation is (Eq. 2.17)

$$P_{irrigation} = Q\rho gh/Eff = 0.0469*1,000\ \ kg/m^3* 9.8\ \ m/\sec^2*32\ \ m*0.001\ \ kW/W/0.8 = 18.4\ \ kW$$

If only half of the zone is flushed at a time, then the pressure required at the inlet to laterals is 18.5 m. If isolation valves are used and only half of the zone is flushed at a time, then required flow rate is 59 LPS. The total pressure requirement during flushing is

20 m	Minimum operating pressure at submain inlet (Fig. 18.7)
+2 m	Pressure loss in solenoid valve
+5.9 m	Pressure loss in 700 m N-S mainline
-1.2 m	Elevation gain in 700 m N-S mainline
+8 m	Ressure loss in sand filter
+5 m	Friction loss in valves and fittings (check valve, manifold, pump suction)
+1 m	Elevation of ground surface above canal water surface
45 m	Total pump pressure requirement

$$P_{flushing} = Q\rho gh/Eff = 0.059*1,000\ \ kg/m^3* 9.8\ \ m/\sec^2*45\ \ m*0.001\ \ kW/W/0.8 = 32.5\ \ kW$$

The power requirement for flushing is much greater than the power required for irrigation. Thus, a booster pump is required during flushing. In addition, extra flow rate is required which may be difficult to add, depending on the water source. Possibly, a reservoir would need to be constructed to provide extra water during flushing. The requirement of extra flushing capacity adds costs that are not in design 1.

The Design 1 water application is has higher uniformity so yield should be greater and environmental contamination should be less. However, only capital cost, water cost, and energy cost are included in this economic comparison.

Economic Comparison of Designs 1 and 2

Pipe Design 2 has a higher pipe cost: \$56,373 − \$55,313 = +\$1,060.

Pump Estimate the extra booster pump required for flushing in design 2 costs \$4,000.

Water Cost The percent wasted water in design 1 is 1.8 % while the percent wasted water in design 2 is 5.5 %. The difference in efficiency is used to calculate the extra annual volume of water required for design 2 is

$$\Delta V == (1\ \ m)(32\ \ ha)(0.055 - 0.018) = 1.18\ \ ha - m$$

The annual extra cost of water for design 2 is (1.18 ha-m) (\$3.27/ha-cm) (100 cm/m) = \$387/yr. The present value (20 years, 0.08) of the extra cost is \$3,800 for the entire farm.

Energy Cost Ignore the cost of flushing because it is an insignificant fraction of total energy use. Time of operation is the volume required divided by the minimum (worst-case) application rate.

$$V/Q = (1\ \ m*32\ \ ha*10,000\ \ m^2/ha)/(0.0444\ \ m^3/\sec)/ (3,600\sec/hr) = 2,020\ \ hours$$

The pump power is multiplied by the time of operation to find annual energy use.

Design 1: P*t = 17.7 kW * 2,020 hours = 35,791 kW-hrs → \$3,579/yr @ \$0.10/kW-hr
Design 2: P*t = 18.4 kW * 2,020 hours = 37,168 kW-hrs → \$3,717/yr @ \$0.10/kW-hr

The difference in power cost between design 1 and design 2 is \$158/yr. The present value (20 years, 0.08) of the extra cost of power in design 2 is \$1,600.

Difference in present value between designs 1 and 2 (+ means design 2 is more expensive):

$$+\$5,000(capital) + \$3,800(water) + \$1,600(energy) = + \$\mathbf{10,400}$$

Decision The present value of design 1 is less than design 2. It is also possible that an auxiliary reservoir will be needed to provide extra flow capacity for flushing for design 2. In addition, design 1 adds the flexibility of irrigating half zones. **Select design 1.**

An Economic Rationale for Selecting Between Drip Lateral Types

There are numerous types of inline drip systems. This section shows how to use economics and expected spatial variability and reliability of different drip lateral types to select between inline drip products. Factors that influence variation and cost include tubing diameter and length, emitter type, flow rate, spacing, and expected life. The Chapter 18 *Economic analysis* workbook incorporates these factors in an economic analysis. The variation is combined with crop water production functions (CWPF) to assess the effect of spatial variation on yield and profit. Present value of yields over the life of the project is compared to the present value of the cost of tubing and emitter replacement for various alternatives. In the *Drip lateral CV analysis* worksheet, columns A:I make hydraulic calculations for the lateral. Columns K:V simulate randomized application depths for a range of minimum application depths specified in Row 17 (Fig. 18.15).

If there are multiple emitters per plant, then the manufacturers coefficient of variation for single emitters is divided by the square root of the number of emitters per plant in order to find the variability of water application to plants. This standard statistical procedure is used to calculate the standard deviation of mean values based on the standard deviation of individual members of a sample group.

$$\sigma_{means} = \frac{\sigma}{N^{0.5}} \rightarrow CV_{means} = \frac{CV}{N^{0.5}} \rightarrow CV_{plant} = \frac{CV_{emitter}}{N^{0.5}} \tag{18.1}$$

where

σ_{means} = standard deviation of application rate per plant, mm

N = number of emitters per plant

CV_{means},CV_{plant} = coefficient of variation of application rate per plant, mm.

The *Drip lateral CV analysis* worksheet develops equations for yield and leaching vs. CV for each of the lateral options in the worksheet (Table 18.2). Columns Y: AJ calculate yield as a function of the application depths. Columns AL:AW calculate leaching as a function of

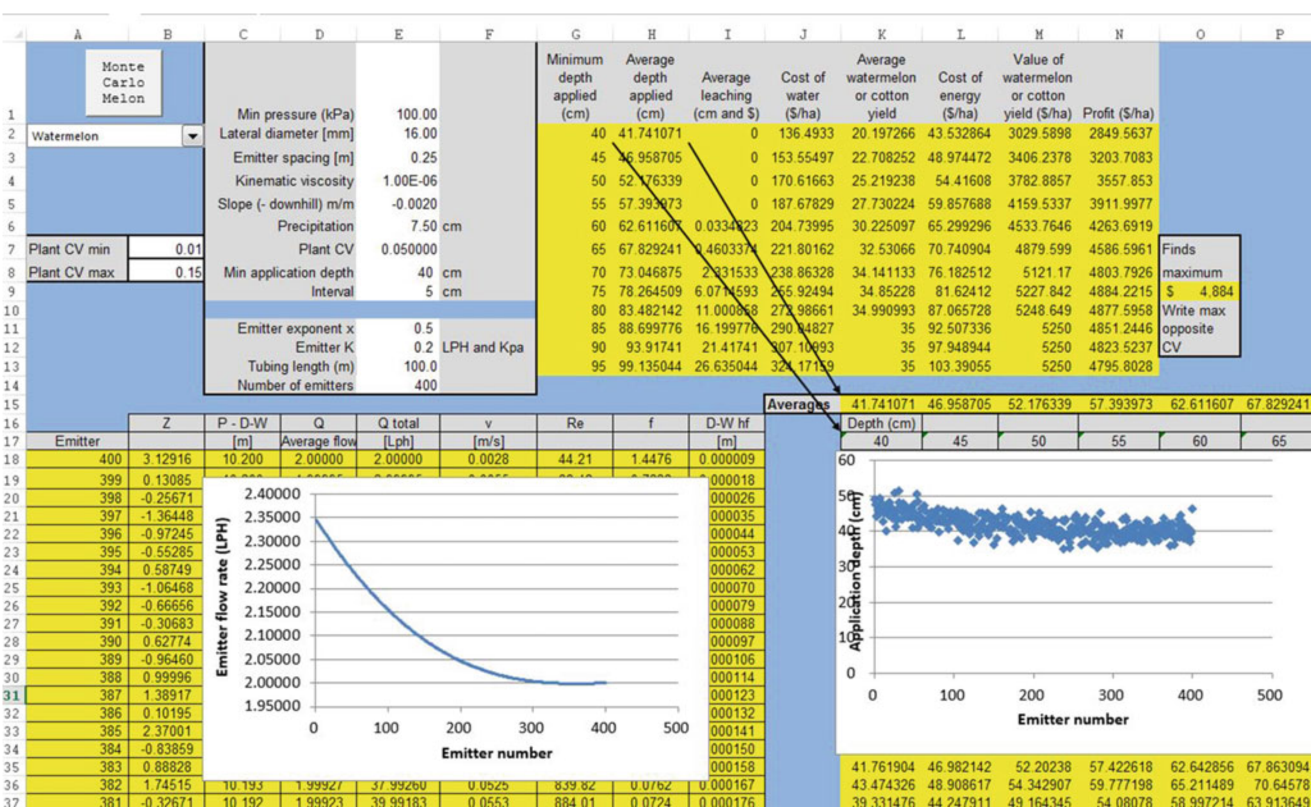


Fig. 18.15 Emitter flow rates over and variable application rates

Table 18.2 Five drip tape alternatives for subsurface drip irrigation of watermelons (*Drip lateral CV analysis* worksheet)

	AK	AL	AM	AN	AO	AP	AQ	AR	AS	AT
2										
3		Type	Cost ($/m)	Repl. (yr)	diam (mm)	k	x	spacing	Min Press (kPa)	type
4	1	8 mil tape	0.09	5	16	0.1	0.5	0.25	50	Turbulent
5	2	8 mil tape,	0.07	5	16	0.2	0.5	0.5	50	Turbulent
6	3	15 mil tape	0.12	10	12	0.2	0.5	0.5	50	Turbulent
7	4	15 mil tape	0.2	10	16	2	0	0.5	100	Pressure comp
8	5	15 mil tape	0.24	10	16	1	0	0.25	100	Pressure comp

application and plant water uptake. A VBA program is triggered with the Monte Carlo simulation button in order to simulate yield and leaching over the range of CV values specified in B7 and B8. The Monte Carlo simulation selects the best irrigation depth for each manufacturer's CV and thus finds the maximum benefit for each alternative and CV value (Fig. 18.19).

Because CV is specified for each year, the benefit vs. CV curves (Fig. 18.19) can be used in the financial analysis (*Watermelon financial calcs* and *Cotton financial calcs* worksheets) in order to calculate the value of each system for the life of the project.

The replacement interval for in-line drip irrigation tubing primarily depends on tubing wall thickness (the common units are mils). In general, 6 and 8 mil tubing are considered thin wall and are only designed to last one or two seasons while 15 mil tubing is considered thick wall and has been observed to last for 15–20 years on subsurface drip irrigated farms. New, high-quality, in-line emitters typically have a coefficient of variation (CV) in the range of 2–3 %. The CV increases over time. This type of information is compiled in Table 18.2 and is used in the Monte Carlo simulation.

Example 18.2 A subsurface drip irrigation system will be installed for irrigation of watermelon. The five drip tape alternatives are shown in Table 18.2. Select the best alternative.

There is a 10 yr project life and 8 % ROR. Initial cost of installation, other than tubing price and tape injection and connection, is the same for all types of tubing. Drip tape replacement cost is $150/ha (tape injection and connection). The cost of energy is $0.10/kW-hr. Pumping efficiency is 80 %. The cost of water is $3.27/ha-cm. The environmental penalty for leaching is $1/ha-cm. Effective seasonal precipitation is 7.5 cm. Fixed costs other than water, energy, tubing, and leaching are $3,700/ha/yr, which includes annualized capital costs (irrigation mainline, submain, and pump station installation) and annual costs such as seed, fertilizer, labor, and fuel, cultivation, and harvesting. Maximum watermelon yield is 35 metric tons/ha @ $150/metric ton.

Laterals are 100 m long and laid on a downward slope (−0.002 m/m). All emitters on 0.5 m spacing have a nominal 2 L/h flow rate. The minimum operating pressure for turbulent emitters is 50 kPa (k = 0.2828 and x = 0.5). The minimum operating pressure for pressure compensating emitters is 100 kPa (k = 2.0 and x = 0). All emitters on 0.25 m spacing have a nominal 1.0 L/h flow rate. All emitters have initial 2.5 % manufacturer's CV and 2.5 % increase in CV per year.

Watermelons are commonly planted in the center of 2 m beds with 0.5 m between plants. In order to increase wetted root volume (larger water and nutrient reservoir) for the watermelons, 3 drip laterals are installed on each bed (Fig. 18.16). All tubing is buried 20 cm below the soil surface.

There has been little research directed toward developing a watermelon CWPF. Thus, the FAO K_Y value will be used to develop a linearized CWPF for yield vs. dry stress. With respect to wet stress, there is often a decrease in watermelon yield due to over watering; however, the decrease is caused by melon splitting or other physiological responses that would be unlikely to occur with subsurface drip irrigation laterals buried at 20 cm depth. Therefore, there is no need to penalize the yield due to overwatering. The seasonal ET_c is 0.8 m, and if greater than or equal to 0.8 m is provided, then yield is the maximum potential yield, 35 metric tons/ha. Watermelon are sensitive to water stress so $K_y = 1.1$ (FAO). An equation for the watermelon yield vs. applied water depth with 7.5 cm precipitation is

$$\begin{aligned} Y_L &= \left(1 - K_y\left(1 - \frac{AW + P}{AW_{req}}\right)\right)Y_{\max} \\ &= \left(1 - 1.1\left(1 - \frac{AW + 0.075}{0.8}\right)\right)35 \ \ metric \ \ tons \end{aligned}$$

where

AW = applied depth, m.

Thus, a step function is used to calculate watermelon yield (Fig. 18.17).

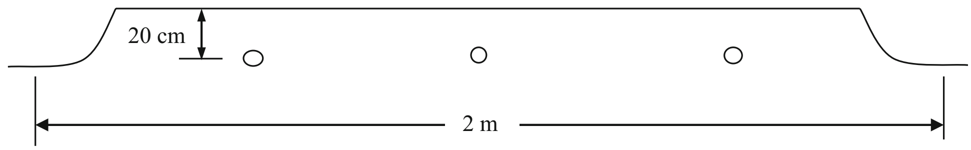


Fig. 18.16 Watermelon bed and drip lateral locations

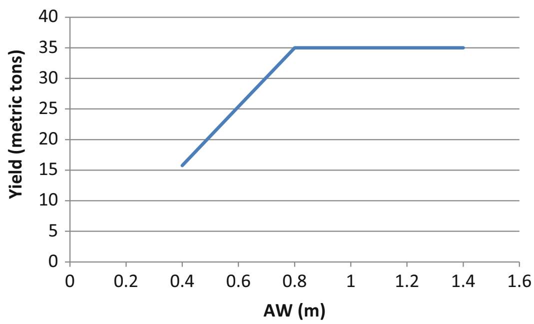


Fig. 18.17 Watermelon yield versus AW with seasonal precipitation = 0.075 m

If AW < 0.725 $Y_L = (0.00312 + 1.375{*}AW){*}35$
Else $Y_L = 35$

Excess water (AW + P > 0.8 m) is leached.

Pipe installation costs include the price of the tubing (Table 18.2) and labor. The length of tubing/ha is the area divided by the spacing.

$$10{,}000\ \text{m}^2/(2\ \text{m}/3\ \text{tubes}) = 15{,}000\ \text{m tubing/ha}.$$

The cost of option 1 installation (just tubing installation, not mainline etc.) is

$$15{,}000\ \text{m}{*}\$0.09/\text{m} + \$150(\text{labor per ha}) = \$1{,}500/\text{ha}$$

Solution

1. Develop an equation for annual yield benefit vs. CV for each of the five tubing alternatives.

Options 2–4 have 3 emitters per plant (emitter spacing = 0.5 m, watermelon spacing = 0.5 m, 3 laterals per plant). As calculated below, the CV_{plant} during the first year is 0.0145 (1.5 %) and increases by the same amount every year, based on the problem definition. With 0.25 m spacing and 6 emitters per plant, options 1 and 5 have a CV_{plant} during the first year equal to 0.01 (1 %) and increase by the same amount each year.

$$CV_{plant} = \frac{CV_{emitter}}{N^{0.5}} = \frac{0.025}{3^{0.5}} = 0.0145$$

$$CV_{plant} = \frac{CV}{N^{0.5}} = \frac{0.025}{6^{0.5}} = 0.010$$

A VBA macro is triggered by the Monte Carlo button that automatically increases CV from the minimum to the maximum (cell B7:B8) for each tubing alternative and finds an optimal depth and profit based on the information in Fig. 18.18. The profit (column N) is calculated as yield – water cost – energy cost – leaching cost.

An equation for maximum profit vs. CV is developed for each tubing option (Fig. 18.19). Only two equations are needed in this example because there are only two different emitter configurations (3 emitters per plant and 6 emitters per plant).

The next step is to incorporate the equations in Fig. 18.19 in an economic analysis. Because. The fixed costs of $3,700 per year are subtracted from the equations derived in Fig. 18.19. The CV_{plant} for each of the tubing alternatives are shown in Table 18.3.

The next steps in the analysis are run in the *Watermelon financial calcs* worksheet. Annual profit vs. year is calculated based on the equations (Fig. 18.19) and expected annual CV values for each alternative (Fig. 18.20). The user must enter the equations into the appropriate columns in rows 2–11.

The annual fixed costs ($3,700/ha) are subtracted from the profits and are then converted to present values in the second and third tables and then summed in line 40 in the *Watermelon financial calcs* worksheet (Fig. 18.21).

Decision Select option 2 because it has the highest present value, $6,098 (the least expensive alternative). The cost of replacing option 2 at the end of the 5th year is more than paid for by the increased uniformity.

Example 18.3 Repeat Example 18.2, but for cotton. There is one drip lateral per row of plants with 1 m spacing between rows. Use the Grimes and El-Zik CWPF (Chap. 2), and the leaching fraction equation based on the Grimes and El-Zik CWPF developed in Chap. 6. Cotton price is $0.92/kg. Fixed annual costs are $600/year. Soil is sandy loam. Emitter spacing is 0.5 m.

Yield is calculated with the Grimes and El-Zik (Fig. 2.1) cotton yield function $Y_L = (-3954 + 1067\,(AW + P)^{0.5} - 54.14\,(AW + P))$. Leached depth = $0.2736e^{0.0469(AW + P)}$

With sandy loam and 2 L/h emitter flow rate, the wetted diameter (Table 15.2) is 0.7 m. Thus, the overlap is 0.35 m/0.5 m * 100 % = 70 %. The 1.0 L/h flow rate emitters have a 0.4 m wetted diameter in the sandy loam soil (estimated

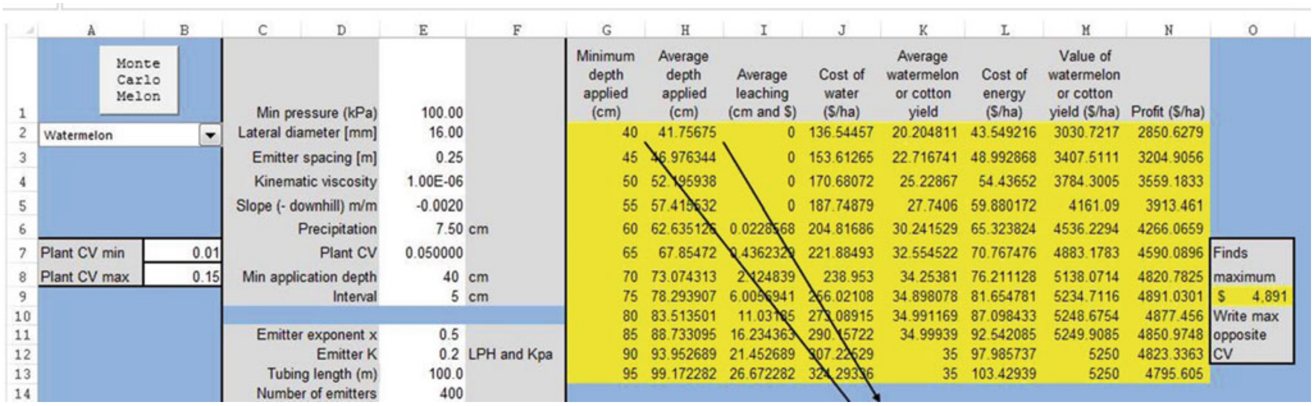


Fig. 18.18 Economic optimization for each tubing alternative for a given CV and irrigation flow characteristics

Fig. 18.19 Profit versus CV for each of the tubing alternatives

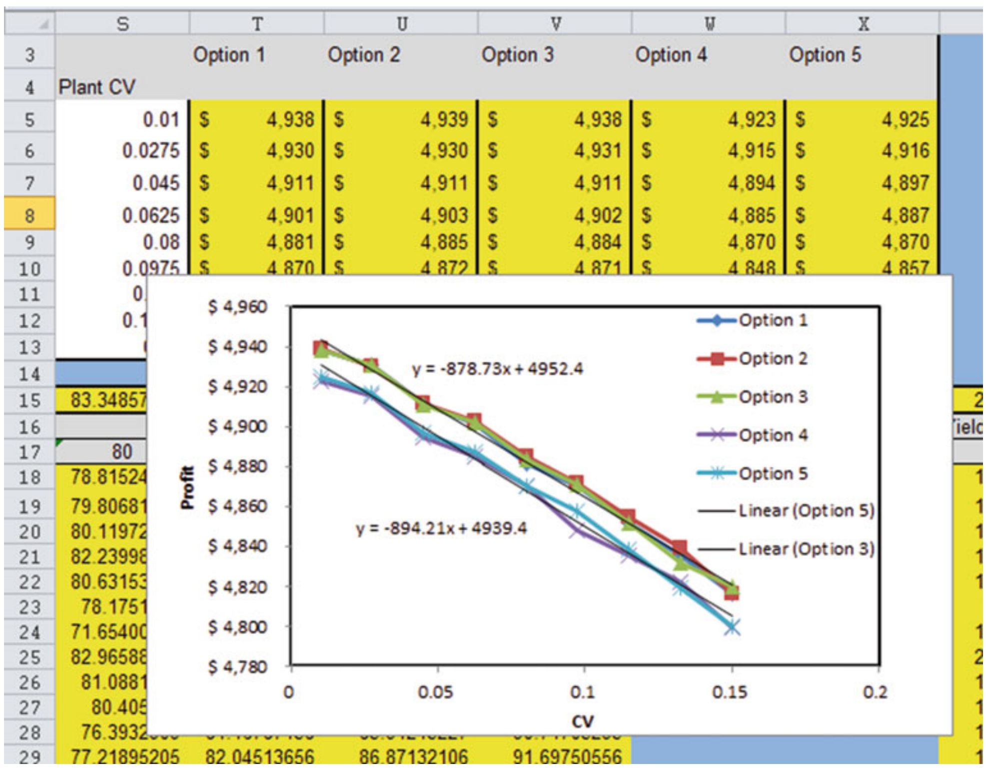
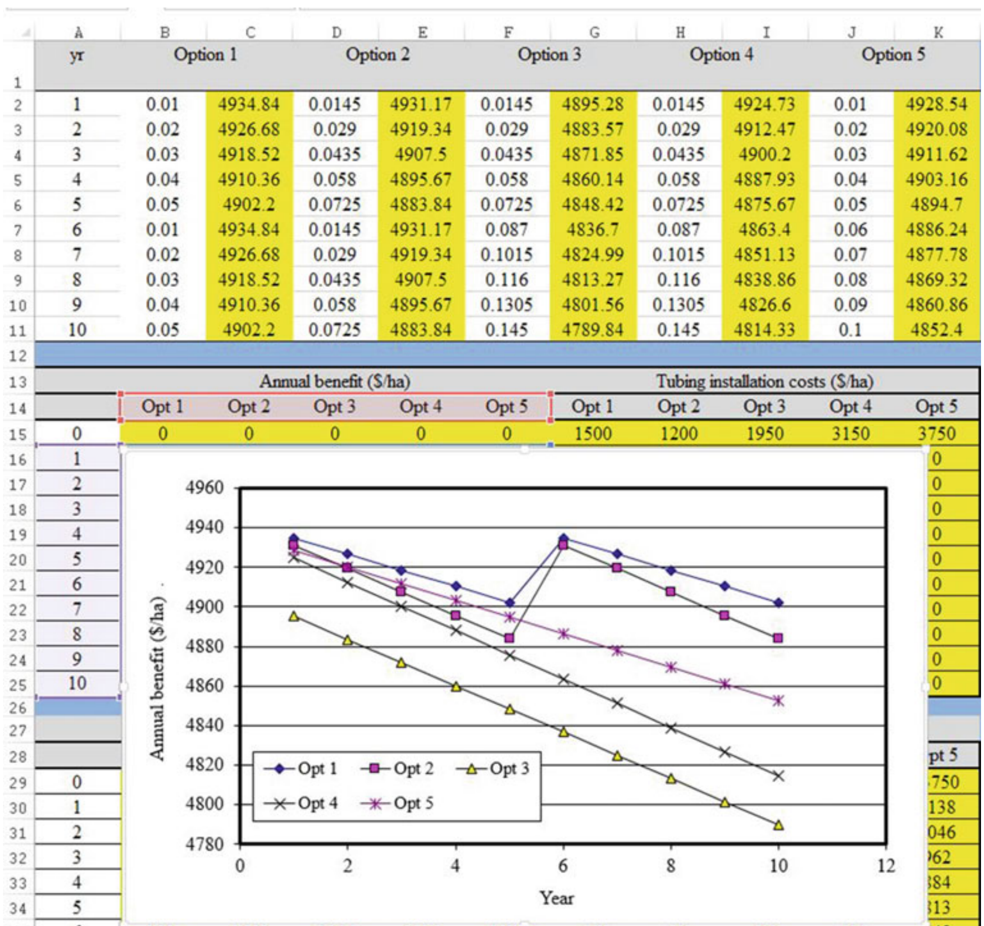


Table 18.3 Annual CV_{plant} for tubing options

yr	Option 1, .25 m	Option 2, .5 m	Option 3, .5 m	Option 4, .5 m	Option 5, .25 m
1	0.01	0.0145	0.0145	0.0145	0.01
2	0.02	0.029	0.029	0.029	0.02
3	0.03	0.0435	0.0435	0.0435	0.03
4	0.04	0.058	0.058	0.058	0.04
5	0.05	0.0725	0.0725	0.0725	0.05
6	0.01	0.0145	0.087	0.087	0.06
7	0.02	0.029	0.1015	0.1015	0.07
8	0.03	0.0435	0.116	0.116	0.08
9	0.04	0.058	0.1305	0.1305	0.09
10	0.05	0.0725	0.145	0.145	0.1

Fig. 18.20 Annual profits (yield – water – energy – leaching cost) for each alternative in *Watermelon financial costs* worksheet



yr	Option 1		Option 2		Option 3		Option 4		Option 5	
1	0.01	4934.84	0.0145	4931.17	0.0145	4895.28	0.0145	4924.73	0.01	4928.54
2	0.02	4926.68	0.029	4919.34	0.029	4883.57	0.029	4912.47	0.02	4920.08
3	0.03	4918.52	0.0435	4907.5	0.0435	4871.85	0.0435	4900.2	0.03	4911.62
4	0.04	4910.36	0.058	4895.67	0.058	4860.14	0.058	4887.93	0.04	4903.16
5	0.05	4902.2	0.0725	4883.84	0.0725	4848.42	0.0725	4875.67	0.05	4894.7
6	0.01	4934.84	0.0145	4931.17	0.087	4836.7	0.087	4863.4	0.06	4886.24
7	0.02	4926.68	0.029	4919.34	0.1015	4824.99	0.1015	4851.13	0.07	4877.78
8	0.03	4918.52	0.0435	4907.5	0.116	4813.27	0.116	4838.86	0.08	4869.32
9	0.04	4910.36	0.058	4895.67	0.1305	4801.56	0.1305	4826.6	0.09	4860.86
10	0.05	4902.2	0.0725	4883.84	0.145	4789.84	0.145	4814.33	0.1	4852.4

	Annual benefit ($/ha)					Tubing installation costs ($/ha)				
	Opt 1	Opt 2	Opt 3	Opt 4	Opt 5	Opt 1	Opt 2	Opt 3	Opt 4	Opt 5
0	0	0	0	0	0	1500	1200	1950	3150	3750

based on linear difference between doubled flow rates in Table 11.4). The overlap is 0.2 m/0.25 m * 100 % = 80 %. Thus, both emitter spacings have approximately ¾ overlap. Plants that are close to one emitter would probably have root systems with access to water from the far emitter, so assume 2 emitters per plant (Fig. 18.22) for the emission uniformity equation.

The CV_{plant} as a function of emitter CV is calculated as follows for all options.

$$CV_{plant} = \frac{CV_{emitter}}{N^{0.5}} = \frac{0.025}{2^{0.5}} = 0.017$$

Likewise, each plant receives water from 4 emitters with the 0.25 spacing. Thus, the CV_{plant} would be calculated as follows:

$$CV_{plant} = \frac{CV_{emitter}}{N^{0.5}} = \frac{0.025}{4^{0.5}} = 0.0125$$

Annual CV values for the different tubing options are shown in Table 18.4.

Using the *Drip lateral CV analysis* worksheet, profit vs. CV curves are not linear for cotton (Fig. 18.23). Thus, polynomial trendlines are used to fit the data.

The next step is to input the annual CVs and profit vs. CV equations into the *Cotton financial calcs* worksheet. Fixed annual costs are $600; thus, for option 5, the annual benefits are calculated as

$$\text{Annual benefit(option 5)} = -1074\ \text{CV}^2 + 11\ \text{CV} + 833600$$

The length of tubing/ha is the area divided by the spacing.

$$10{,}000\ \text{m}^2/(1\ \text{m/tubes}) = 10{,}000\ \text{m tubing/ha}.$$

For example, the cost of option 1 installation (just tubing installation, not mainline etc.) is

$$10{,}000\ \text{m}*\$0.09/\text{m} + \$150(\text{labor per ha}) = \$1{,}050/\text{ha}$$

The calculated benefit per year in the *Cotton financial calcs* worksheet is shown in Fig. 18.24.

	A	B	C	D	E	F	G	H	I	J	K
2	1	0.01	4934.84	0.0145	4931.17	0.0145	4895.28	0.0145	4924.73	0.01	4928.54
3	2	0.02	4926.68	0.029	4919.34	0.029	4883.57	0.029	4912.47	0.02	4920.08
4	3	0.03	4918.52	0.0435	4907.5	0.0435	4871.85	0.0435	4900.2	0.03	4911.62
5	4	0.04	4910.36	0.058	4895.67	0.058	4860.14	0.058	4887.93	0.04	4903.16
6	5	0.05	4902.2	0.0725	4883.84	0.0725	4848.42	0.0725	4875.67	0.05	4894.7
7	6	0.01	4934.84	0.0145	4931.17	0.087	4836.7	0.087	4863.4	0.06	4886.24
8	7	0.02	4926.68	0.029	4919.34	0.1015	4824.99	0.1015	4851.13	0.07	4877.78
9	8	0.03	4918.52	0.0435	4907.5	0.116	4813.27	0.116	4838.86	0.08	4869.32
10	9	0.04	4910.36	0.058	4895.67	0.1305	4801.56	0.1305	4826.6	0.09	4860.86
11	10	0.05	4902.2	0.0725	4883.84	0.145	4789.84	0.145	4814.33	0.1	4852.4
12											
13		Annual benefit ($/ha)					Tubing installation costs ($/ha)				
14		Opt 1	Opt 2	Opt 3	Opt 4	Opt 5	Opt 1	Opt 2	Opt 3	Opt 4	Opt 5
15	0	0	0	0	0	0	1500	1200	1950	3150	3750
16	1	4935	4931	4895	4925	4929	0	0	0	0	0
17	2	4927	4919	4884	4912	4920	0	0	0	0	0
18	3	4919	4908	4872	4900	4912	0	0	0	0	0
19	4	4910	4896	4860	4888	4903	0	0	0	0	0
20	5	4902	4884	4848	4876	4895	1500	1200	0	0	0
21	6	4935	4931	4837	4863	4886	0	0	0	0	0
22	7	4927	4919	4825	4851	4878	0	0	0	0	0
23	8	4919	4908	4813	4839	4869	0	0	0	0	0
24	9	4910	4896	4802	4827	4861	0	0	0	0	0
25	10	4902	4884	4790	4814	4852	0	0	0	0	0
26											
27		Yearly profit ($/ha)					Present value of yearly profit ($/ha)				
28		Opt 1	Opt 2	Opt 3	Opt 4	Opt 5	Opt 1	Opt 2	Opt 3	Opt 4	Opt 5
29	0	-1500	-1200	-1950	-3150	-3750	-1500	-1200	-1950	-3150	-3750
30	1	1235	1231	1195	1225	1229	1143	1140	1107	1134	1138
31	2	1227	1219	1184	1212	1220	1052	1045	1015	1039	1046
32	3	1219	1208	1172	1200	1212	967	959	930	953	962
33	4	1210	1196	1160	1188	1203	890	879	853	873	884
34	5	-298	-16	1148	1176	1195	-203	-11	782	800	813
35	6	1235	1231	1137	1163	1186	778	776	716	733	748
36	7	1227	1219	1125	1151	1178	716	711	656	672	687
37	8	1219	1208	1113	1139	1169	658	652	601	615	632
38	9	1210	1196	1102	1127	1161	605	598	551	564	581
39	10	1202	1184	1090	1114	1152	557	548	505	516	534
40						Total	5664	6098	5766	4749	4274

Fig. 18.21 Annual benefits and costs and present values in *Watermelon financial calcs* worksheet

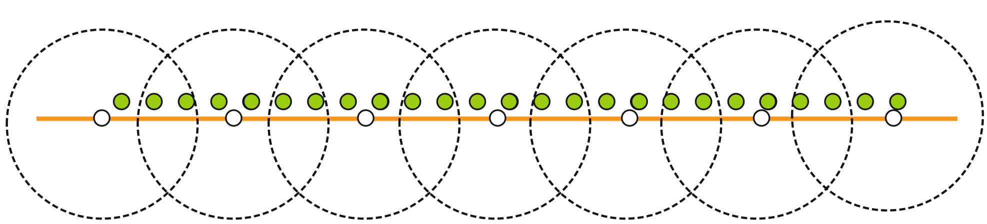


Fig. 18.22 Emitter and plant spacing for 0.5 m spaced emitters in cotton row with 2 L/h flow rate in loam soil

Table 18.4 Annual CV_{plant} for tubing options in cotton

yr	Option 1, .25 m	Option 2, .5 m	Option 3, .5 m	Option 4, .5 m	Option 5, .25 m
1	0.0125	0.0177	0.0177	0.0177	0.0125
2	0.025	0.0354	0.0354	0.0354	0.025
3	0.0375	0.0531	0.0531	0.0531	0.0375
4	0.05	0.0708	0.0708	0.0708	0.05
5	0.0625	0.0885	0.0885	0.0885	0.0625
6	0.0125	0.0177	0.1062	0.1062	0.075
7	0.025	0.0354	0.1239	0.1239	0.0875
8	0.0375	0.0531	0.1416	0.1416	0.1
9	0.05	0.0708	0.1593	0.1593	0.1125
10	0.0625	0.0885	0.177	0.177	0.125

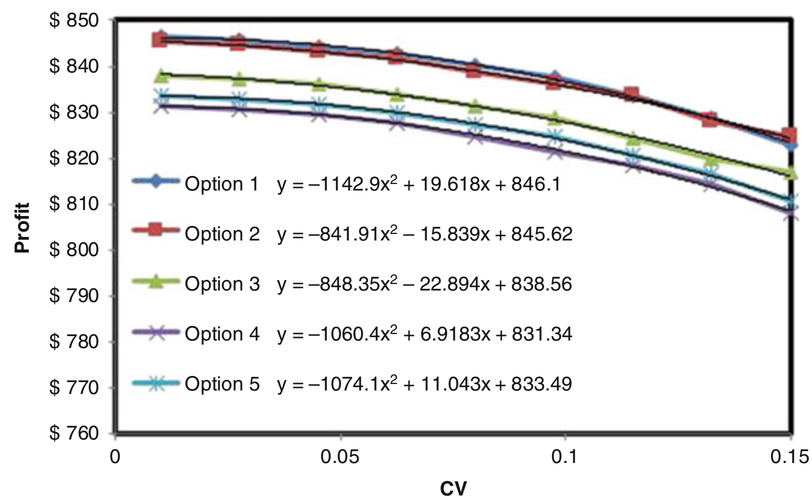


Fig. 18.23 Profit versus CV for cotton analysis in *Drip lateral CV analysis* worksheet

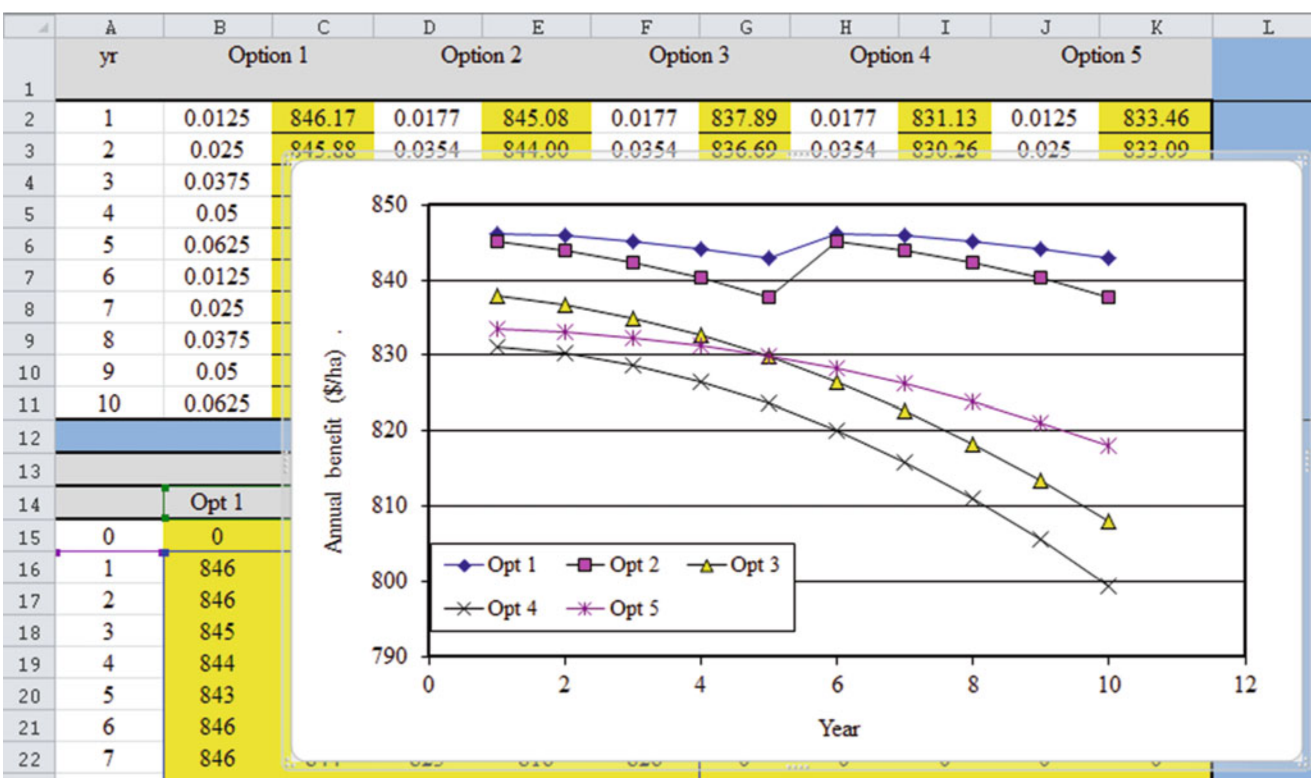


Fig. 18.24 Annual profits (yield – water – energy – leaching cost) in *Cotton financial calcs* worksheet

	A	B	C	D	E	F	G	H	I	J	K
1	yr	Option 1		Option 2		Option 3		Option 4		Option 5	
2	1	0.0125	846.17	0.0177	845.08	0.0177	837.89	0.0177	831.13	0.0125	833.46
3	2	0.025	845.88	0.0354	844.00	0.0354	836.69	0.0354	830.26	0.025	833.09
4	3	0.0375	845.23	0.0531	842.41	0.0531	834.95	0.0531	828.72	0.0375	832.39
5	4	0.05	844.22	0.0708	840.28	0.0708	832.69	0.0708	826.51	0.05	831.36
6	5	0.0625	842.86	0.0885	837.62	0.0885	829.89	0.0885	823.65	0.0625	829.98
7	6	0.0125	846.17	0.0177	845.08	0.1062	826.56	0.1062	820.12	0.075	828.28
8	7	0.025	845.88	0.0354	844.00	0.1239	822.70	0.1239	815.92	0.0875	826.23
9	8	0.0375	845.23	0.0531	842.41	0.1416	818.31	0.1416	811.06	0.1	823.85
10	9	0.05	844.22	0.0708	840.28	0.1593	813.38	0.1593	805.53	0.1125	821.14
11	10	0.0625	842.86	0.0885	837.62	0.177	807.93	0.177	799.34	0.125	818.09
12											
13		Annual benefit ($/ha)					Tubing installation costs ($/ha)				
14		Opt 1	Opt 2	Opt 3	Opt 4	Opt 5	Opt 1	Opt 2	Opt 3	Opt 4	Opt 5
15	0	0	0	0	0	0	1050	850	1350	2150	2550
16	1	846	845	838	831	833	0	0	0	0	0
17	2	846	844	837	830	833	0	0	0	0	0
18	3	845	842	835	829	832	0	0	0	0	0
19	4	844	840	833	827	831	0	0	0	0	0
20	5	843	838	830	824	830	1050	850	0	0	0
21	6	846	845	827	820	828	0	0	0	0	0
22	7	846	844	823	816	826	0	0	0	0	0
23	8	845	842	818	811	824	0	0	0	0	0
24	9	844	840	813	806	821	0	0	0	0	0
25	10	843	838	808	799	818	0	0	0	0	0
26											
27		Yearly profit ($/ha)					Present value of yearly profit ($/ha)				
28		Opt 1	Opt 2	Opt 3	Opt 4	Opt 5	Opt 1	Opt 2	Opt 3	Opt 4	Opt 5
29	0	-1050	-850	-1350	-2150	-2550	-1050	-850	-1350	-2150	-2550
30	1	246	245	238	231	233	228	227	220	214	216
31	2	246	244	237	230	233	211	209	203	197	200
32	3	245	242	235	229	232	195	192	187	182	184
33	4	244	240	233	227	231	180	177	171	166	170
34	5	-807	-612	230	224	230	-549	-417	156	152	157
35	6	246	245	227	220	228	155	154	143	139	144
36	7	246	244	223	216	226	143	142	130	126	132
37	8	245	242	218	211	224	132	131	118	114	121
38	9	244	240	213	206	221	122	120	107	103	111
39	10	243	238	208	199	218	112	110	96	92	101
40						Total	-121	196	181	-664	-1014

Fig. 18.25 Annual benefits and costs and present values in *Cotton financial calcs* worksheet

The annual fixed costs ($600/ha) are subtracted from the profits and are then converted to present values in the second and third tables and then summed in line 40 in the *Cotton financial calcs* worksheet (Fig. 18.25).

Option 1 does not yield a positive present value at the required rate of return, and options 2 and 3 are barely positive. Options 4 and 5 are highly unprofitable. If crop failure were to occur in one or more years, and this analysis was based only on normal yields, then options 2 and 3 would not be profitable in this analysis. This example shows why drip irrigation systems are usually installed for high value crops. The yield may not pay for the added cost of the drip system (typically $2,500/ha capital cost).

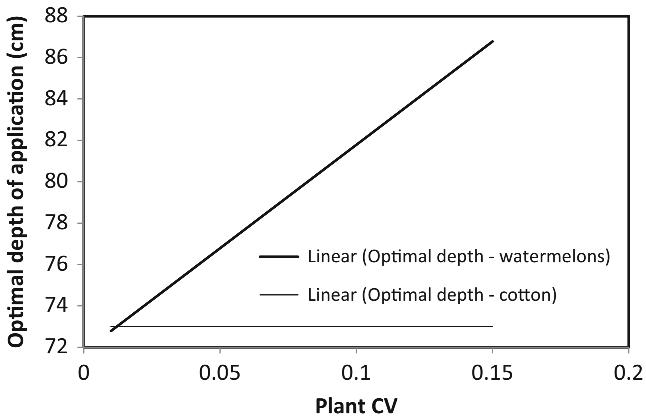


Fig. 18.26 Optimal AW_{min} versus CV_{plant} for cotton and watermelon

Examples 18.2 and 18.3 assumed only one crop per year, and the same crop every year with constant fixed costs, constant yield and crop price. However, many drip systems are installed in areas that support 2 crops per year.

A comparison of the cotton and watermelon examples demonstrates the differences in watering practices between high value and low value crops. Watering can be excessive with high value crops (Fig. 18.26) because the goal is to maintain maximum yield, but under watering of some parts of the field is economically justified with low value crops. When CV increases with cotton, there is no change in the optimal watering depth. The reason that cotton optimal watering depth does not increase with CV is that there is a relatively important financial cost associated with overwatering some parts of the field. The value of the additional water is not justified by an increased income from the crop. However, water is a relatively small cost in comparison to the profit from watermelon. Thus, it is never beneficial to underwater some parts of the field in order to save money on water.

Questions

1. A 90 m long submain supplies 12 mm ID laterals that are 90 m long. This is a single feed system. The laterals are spaced 1 m apart. Emitters are spaced every 0.3 m, k = 0.25, and x = 0.41. Slope of laterals is 1 % downhill. Manufacturer's coefficient of variation is 5 % and number of emitters per plant is 2. Verify that the lateral has at least 90 % emission uniformity. If not, then increase the pipe diameter. The submain is on level ground. Find the lateral flow rate vs. pressure equation (Fig. 18.3) and design the submain (select diameters). Because of flushing, minimum allowable size of the submain is 100 mm. The minimum acceptable pressure is 80 kPa. Find the required inlet pressure for the submain. Also, determine whether the emission uniformity is greater than 90 % for the entire zone.
2. Repeat question 1; however, there is no slope on the lateral. Evaluate emission uniformity on the individual lateral and in the zone. Is the emission uniformity above or below 90 %. Compare the exponent and the coefficient in the lateral flow pressure equation to that of question 1. Explain the differences and similarities.
3. Repeat question 2, but change to dual feed laterals with submains that are 180 m apart. For the purpose of hydraulic calculations, laterals are 90 m long to the midpoint. Emission uniformity should be greater than 90 % for any zone; thus, increase the pipe diameter to 14 mm, and determine whether this diameter results in an emission uniformity that is greater than 90 % for the entire zone. If the emission uniformity is more than 1 % greater than 90 %, then there is no need to make an additional calculation for the zone, because the zone will drop the uniformity by less than 1 %. There is no need to show all the graphs and equations. Just the results are sufficient.
4. Based on the parameters in questions 2 and 3, calculate the inlet pressure needed for the submains. Find the equation for submain inlet flow vs. pressure.
5. Based on the parameters in questions 2–4, evaluate flushing in the dual feed lateral with submains spaced on 180 m intervals. Use the *Flush dual feed lateral* worksheet. Find the inlet pressure required and the equation for lateral flow vs inlet pressure.
6. Based on the parameters in questions 2–5, evaluate flushing in the submain. There are 100 laterals spaced 1 m apart. Use the *Submain flushing* worksheet. Check that flow velocity is not excessive. Pipe flow velocity restrictions (normally < 1.5 m/sec) can be relaxed for flushing mode, as long as the owner slowly closes valves during the flushing process, keep the velocity below 2 m/sec in this question. Find the required inlet flow velocity and pressure. Find the equation for inlet pressure vs. flow rate.
7. Using the information compiled in questions 1–6, design a pump, filter, and mainline system for a level field that has dimensions 400 m × 400 m. Allow 20 m for a central road so the length of laterals (distance between submains) is 180 m. Use the 100 m × 180 m zones that you have already designed. The road travels in the EW direction, and the pump is in the NW corner. Using the structure in Fig. 18.1, specify the required pipe sizes in mains 33–38 and 43–45. The irrigation schedule allows for 8 zones so each zone is run by itself. For example, pipes 1 and 5 are activated at the same time, etc… Mains 33–36 are used for flushing because flushing originates in submains 1, 2, 3, 4, 9, 10, 11, and 12. Use

the *Chapter 18 Mainline* workbook to find flow velocities and head losses. Specify the required pump flow rate and pressure. You do not need to pick a particular pump (unless you want to). 0 year project life and 8 % ROR. The cost of energy is $0.10/kW-hr, and the cost of water is $3.27/ha-cm. Annual ETc is 1 m/y. Irrigation efficiency is 90 % and pumping efficiency is 80 %. Sand filter losses are 7 m and pump station losses are 3 m. Solenoid valve losses are 2 m. Do not worry about the flushing flow rate or pressure or the booster pump that would be required for flushing.

8. Open the *Chapter 18 Economic analysis* workbook and *Cotton Drip lateral CV analysis* worksheet. Reduce the plant CV in cell E7 to 0.05. Select cotton as the crop in cell A2. In the range E1:E14, change the tubing diameter to 12, the plant CV to 0.05, the emitter coefficient to 0.2, and the emitter exponent to 0.5. Note, the Monte Carlo simulation program changes these values during the simulation. Plot the emitter flow rates in column D vs. emitter number in column A. Plot the 40 cm application depth in column K vs. emitter number in column A. Explain why some of the application depths are less than 40. You can highlight one of the cells in Column K and look at the equation in order to find the answer. Plot the yield vs. emitter number curve for the 50 cm depth in column AA and the 75 cm depth in column AE. Explain the shapes of the yield curves.
9. Open the *Chapter 18 Economic analysis* workbook and *Cotton Drip lateral CV analysis* worksheet. Move the graph away from table T5:X13. Clear cells T5:X13. Click the Monte Carlo Cotton button in cell P1. Watch what happens in cells H2:W13. Then click the Monte Carlo Cotton button in cell A1 and watch what happens in column E. and explain how the algorithm works. How many simulations are run at each tubing option and CV value (count the number of blinks in the formula bar for each condition)?
10. Open the *Chapter 18 Economic analysis* workbook and *Cotton Drip lateral CV analysis* worksheet. Select cotton as the crop in cell A2. As shown below, change the replacement period for the 8 mil tape to 2 years (column AN), and run the Monte Carlo simulation by clicking the Monte Carlo button in cell B1. Note: the Monte Carlo simulation requires several minutes running time. Notice that the VBA program changes the parameters in the range E1:E14. Make Trendlines for each of the curves in the profit vs. CV graph in the range T1:X13. Compare with the equations in Fig. 18.23. If they are different, then explain why. Explain why options 1–2 have higher profit vs. CV than options 3–5. Explain why option 3 has higher profit than option 4.
11. In the *Cotton financial calcs* worksheet, change the CV values for the every other year replacement scheme in columns B and D for options 1 and 2, as described in question 10. Add installations costs every other in cells G15:H25. How does every other year replacement affect the annual benefit in rows 2:11 (also shown in the graph)? How does every other year replacement affect the overall profit of the system as shown in row 40? What is the only remaining option with positive