Solutions

Chapter 1: Solution

1. List the components of a farm water balance.

Evaporation, irrigation, canal seepage, operational waste, evapotranspiration, rainfall, runoff, deep percolation, usable return flow

2. Describe the major four irrigation methods (NRCS description).

   Surface, sprinkler, micro and sub irrigation

3. Describe the different types of irrigation efficiency

   Irrigation efficiency has been defined in many ways. In general, efficiency is the amount used divided by the amount applied; however, irrigation efficiency can be thought of in different ways. Conveyance efficiency is the amount of water reaching a field divided by the amount diverted from the irrigation water source. Application efficiency is the amount of water stored in the root zone divided by the amount of water applied to the field. Storage efficiency is the amount of water stored in the root zone during a single irrigation divided by the total water-holding capacity of the root zone. Seasonal irrigation efficiency is the water volume beneficially used by the crop (including leaching) divided by the seasonal amount of water applied.

4. In general, pressurized irrigation systems are considered to be more efficient than surface irrigation systems. What are some factors that may decrease the irrigation efficiency of some sprinkler systems to below that of some surface irrigation systems?

   However, loss of water by evaporation or wind, poorly maintained sprinklers or emitters, and poor uniformity due to spacing or pipe hydraulics decrease application efficiency.

5. How do irrigation systems fail?

If not regulated, water resources naturally become stretched beyond their capability to supply demand. As people begin to develop irrigated farms in a region, well drilling is generally not regulated; thus, the rate of pumping soon exceeds the rate of recharge in a successful farming region. As the groundwater table recedes to hundreds of feet below the ground surface, the cost of pumping increases, and the aquifer yield decreases until farmers eventually start going out of business.

Another source of failure is salinization of soils due to poor irrigation management or lack of drainage.

A third cause of failure is drought.

6. Summarize the virtual water concept.

   Crops grown in one region and shipped to a water stressed region are essentially a shipment of water to the water stressed region.

7. What increases the value of the irrigation engineering?

   An increased value of water resources.

Chapter 2: Solution

1. Why does increasing the depth of irrigation water applied per season reach a point of diminishing returns?

   There are at least three answers to this question.
   (a) Agricultural plants only transpire as much water as they need. Applying more water than the required water does not increase plant growth.
   (b) Excessive water or water in the root zone can decrease oxygen uptake from the root zone for respiration.
   (c) Some processes in some plants, such as tomato production, are enhanced when there is some water stress (dry stress) because the plants put their energy into reproduction in the event of plant death due to water depletion.

2. Why is there a nearly linear relationship between evapotranspiration (ET) and yield and a nonlinear relationship between applied water and yield (Fig. 2.1)?

As water application increases, water waste due to evaporation and leaching increases. Thus, applied water is wasted, but transpiration does not change significantly.

3. How are the crop water production function and engineering economic analysis used to assess or manage irrigation systems?

The crop water production function is used to determine the optimal depth of irrigation water application. Engineering economic analysis is used to make decisions, such as which irrigation system to select or whether a project is economically profitable.

4. Find the profit with the following parameters for the Grimes and El-Zik CWPF for drip irrigated cotton: 15 cm depth of precipitation, cost of water is $0.02/m^3.

The selling price of cotton is $0.90/kg. Depth of applied water, $AW_{CWPF} = 62$ cm. Show your work.

$$Y_a = \left(-3954 + 1067(AW + 15 \text{ cm})^{0.5} - 54.14(AW + 15 \text{ cm})\right)$$
$$Y_a = \left(-3954 + 1067(62 + 15 \text{ cm})^{0.5} - 54.14(62 + 15 \text{ cm})\right)$$
$$= 1,240 \text{kg/ha}$$

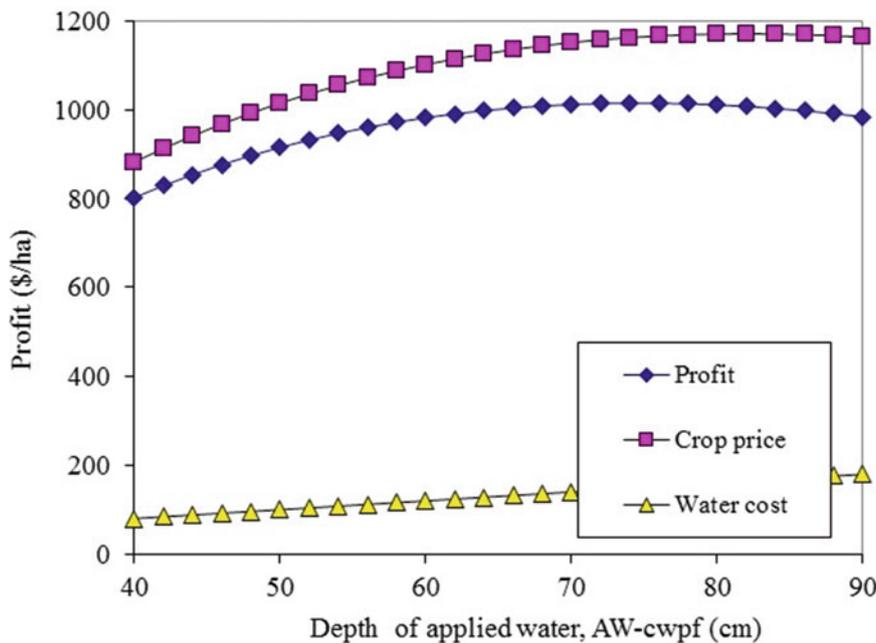$$\text{Crop\_price} = (Y_a)(\$/\text{kg}) = 1,240 \text{ kg/ha}(0.9) = \$1,116$$

$$WC = (\$/\text{m}^3)(100)(AW\text{cwpf(cm)}/(1 - (\text{CWPF\_Eff} - \text{Irr\_Eff})) + \text{Pre})$$
$$WC = (\$0.02)(100)(62/(1 - (0.9 - 0.9)) + 0) = \$124$$

$$Pr = \$1,116 - \$124 = \$992$$

5. For the parameters in question 4, calculate the optimal depth of water application, AW_{CWPF}. Do this problem in Excel and turn in the graph that shows the yield, cost of water, and profit vs. AW_{CWPF}.

The maximum profit is found at 74 cm applied water depth, at which point the profit is $1016.

6. For the parameters in question 4, calculate the profit for a surface irrigation system with 70 % efficiency at $AW_{CWPF} = 70$ cm. Preirrigation is 45 cm. The water from preirrigation provides no benefit for crop growth in this case. Do not consider erosion. Show your work.

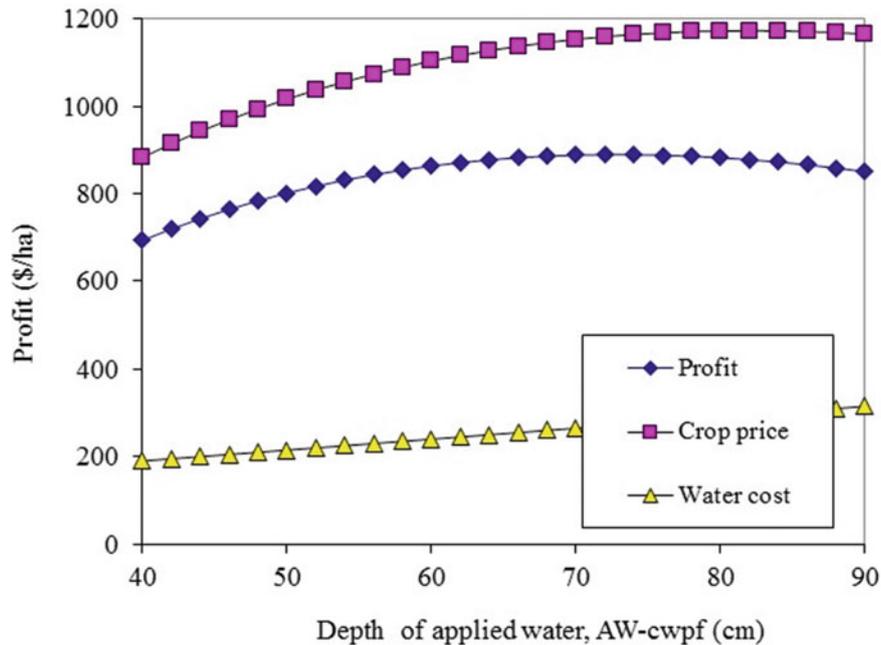$$Y_a = \left(-3954 + 1067(AW + 15 \text{ cm})^{0.5} - 54.14(AW + 15 \text{ cm})\right)$$
$$Y_a = \left(-3954 + 1067(62 + 15 \text{ cm})^{0.5} - 54.14(70 + 15 \text{ cm})\right)$$
$$= 1,240 \text{ kg/ha}$$

$$\text{Crop\_price} = (Y_a)(\$/\text{kg}) = 1,240 \text{ kg/ha}(0.9) = \$1,116$$

$$WC = (\$/m^3)(100)(AWcwpf(cm)/(1 - (CWPF\_Eff - Irr\_Eff)) + Pre)$$
$$WC = (\$0.02)(100)(70/(1 - (0.9 - 0.7)) + 45) = \$265$$

$$Pr = \$1,116 - \$124 = \$888$$

Depth of applied water, AW-cwpf (cm)

7. For the parameters in question 6, find the optimal depth of water application, AW_{CWPF}. Do this problem in Excel, and turn in the graph that shows the yield, cost of water, and profit vs. AW_{CWPF}.

   The optimal depth of water application is 72 cm, at which point the profit is $889

8. For the parameters in question 6, calculate the profit per ha, but include erosion. Calculate erosion with Eq. 2.7. The cost of erosion is $0.4/kg. Show your work.

$$Y_a = \left(-3954 + 1067(AW + 15 \ cm)^{0.5} - 54.14(AW + 15 \ cm)\right)$$
$$Y_a = \left(-3954 + 1067(62 + 15 \ cm)^{0.5} - 54.14(70 + 15 \ cm)\right)$$
$$= 1,240 \ kg/ha$$

$$Crop\_price = (Y_a)(\$/kg) = 1,240 \ kg/ha(0.9) = \$1,116$$

$$WC = (\$/m^3)(100)(AWcwpf(cm)/(1 - (CWPF\_Eff - Irr\_Eff)) + Pre)$$
$$WC = (\$0.02)(100)(70/(1 - (0.9 - 0.7)) + 45) = \$265$$

$$i = 70/(1 - (0.9 - 0.7)) + 45$$
$$= 70/(1 - (0.9 - 0.7)) + 45 = 132.5 \ cm$$

$$Sediment = \left(4.62*10^{-5}*(132.5)^3 - 0.00784*(132.5)^2 + 0.477*(132.5) - 9.4449\right)*10 = 236 \ kg/ha$$

$$EnvC = 236 \ kg/ha*\$0.4/kg = \$94.4/ha$$

$$Pr = \$1,116 - \$265 - \$94 = \$794$$

9. For the parameters in question 8, find the optimal depth of water application, AW_{CWPF}. Do this problem in Excel,

and turn in the graph that shows the yield, cost of water, cost of erosion, and profit vs. AW_{CWPF}.

   The optimal depth of water application is 62 cm, at which point the profit is $806
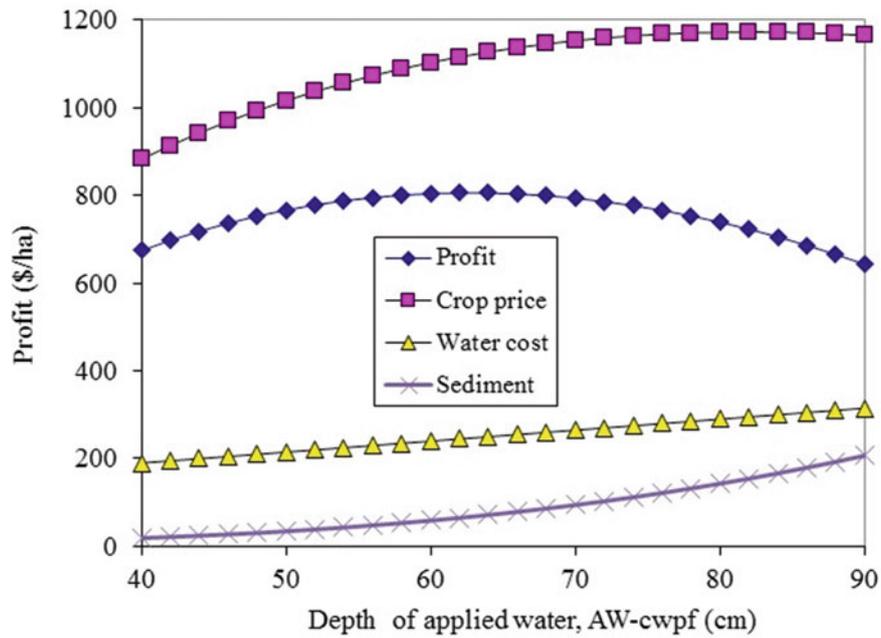
10. Use the *Variable water application* worksheet. Keep all other parameters the same, but double the cost of water. Find the optimal depth of water application.

Vary the value in cell F1 until the profit is highest in cell F9. The peak is at 57 cm.

	A	B	C	D	E	F	G	H I J	K
1	Target AW-CWPF					57		Average AW-CWPF (cm)	58.09
2	Fraction of Target depth at end of furrow (specified)					0.91		Average leached depth (cm)	2.32
3	Runoff percentage (specified)					20%		Average useful depth (cm)	55.78
4	Precipitation					15	cm	Total applied (AW - cm)	117.62
5	Price of crop					0.9	$/kg	Efficiency (w/o preirrigation)	77%
6	Preirr depth					45	cm	Efficiency (including preirrigation	47%
7	Price of water					0.04	$/m3	Cost of water ($/ha)	$ (470.47)
8	Cost of sediment					0.4	$/kg	Cost of sediment ($/ha)	$ (53.51)
9	Benefits - costs					563.1628	$/ha	Average yield benefit ($/ha)	$ 1,087.14
10	Distance (m)	Fraction of end depth	Fraction of target depth	AW-cwpf	Excess Leached depth (cm)	Yield ($/ha)		Hide chart	
11	40	1.20	1.092	62.24	5.24	1117.55		View chart	
12	120	1.18	1.07	61.21	4.21	1111.23			
13	200	1.14	1.04	59.13	2.13	1097.42			
14	280	1.08	0.98	56.02	0.00	1073.65			
15	360	1.00	0.91	51.87	0.00	1035.86			

11. Use the *Variable water application* worksheet but change the number of furrow sections to 6 with the following multipliers of end furrow application. 1.5, 1.45, 1.33, 1.25, 1.13, and 1. Keep all other parameters the same as the original version. Find the optimal depth of water application.

	A	B	C	D	E	F	G	H	I	J	K
1	Target AW-CWPF					49		Average AW-CWPF (cm)			56.93
2	Fraction of Target depth at end of furrow (specified)					0.91		Average leached depth (cm)			8.66
3	Runoff percentage (specified)					20%		Average useful depth (cm)			48.27
4	Precipitation (cm)					15		Total applied (AW - cm)			116.16
5	Price of crop					0.9	$/kg	Efficiency (w/o preirrigation)			68%
6	Preirr depth					45	cm	Efficiency (including preirrigation)			42%
7	Price of water					0.04	$/m3	Cost of water ($/ha)		$	(464.63)
8	Cost of sediment					0.4	$/kg	Cost of sediment ($/ha)		$	(50.36)
9	Benefits - costs					553.8945		Average yield benefit ($/ha)		$	1,068.89
10	Distance (m)	Fraction of end depth	Fraction of target depth	AW-cwpf	Excess Leached depth (cm)	Yield ($/ha)		Hide chart			
11	33.3	1.5	1.365	66.89	17.89	1141.26					
12	100	1.45	1.32	64.66	15.66	1130.78		View chart			
13	166.7	1.33	1.21	59.30	10.30	1098.63					
14	233.3	1.25	1.14	55.74	6.74	1071.30					
15	300	1.13	1.03	50.39	1.39	1020.55					

12. Should government charge farmers with surface irrigation systems that discharge sediment to streams for the cost of dredging and for sediment removal from public drinking water supplies? Why or why not?

Difficult question. The government has chosen to pay farmers in sensitive regions to convert to pressurized irrigation systems in order to reduce sediment discharge to streams. This practice also reduces water use and allows the water to go to other uses such as new farms, cities, or industries.
Why:
Nobody should be able to pollute a public resource. Those who degrade the environment should have to pay for the consequences of their actions. The public should not allow certain practices or industries to degrade public resources.
Why not:
The government has a vested interest in supporting production agriculture. At the most basic level, national food security prevents extortion by other countries. If the government charged farmers for every environmental consequence of farming, then it would be difficult for farmers to continue to farm and to compete against farmers in other countries, who receive direct or indirect subsidies from their government.

13. Should the government pay farmers to convert to pressurized irrigation if a farming region has erosive soils?

It seems like a win-win since water is saved and erosion is decreased. The government actually does not have to pay for the entire irrigation system in order to induce farmers to convert to pressurized irrigation. Other benefits of pressurized irrigation such as reduced labor and water cost also factor into the economic decision to install a new irrigation system. Thus, a practice such as just paying for the mainline can be enough

to cause farmers to make the switch. Economists can determine the level at which assistance can cause farmers to convert to pressurized irrigation systems. The alternative is to close down farms or pay for lawyers to prevent erosion through the legal system. The cost of legal action may be just as high as the cost of paying for mainlines.

14. At the government policy level, should economic analysis of irrigation systems include all environmental degradation due to irrigation?

At the policy level, environmental contamination and sustainability should be part of the analysis of irrigation systems and irrigation projects. The government is responsible for the public welfare; thus, the government should consider the impact of irrigation practices on the environment.

15. Calculate cotton yield if the required depth of applied water in a region is 120 cm, actual applied water depth is 80 cm, and the maximum yield is 1200 t/ha. Look at Fig. 2.6. Is your answer realistic?

$$Y_a = Y_{max}\left(1 - \frac{\%\Delta Y}{\%\Delta AW}\frac{AW_{req} - AW_{CWPF}}{AW_{req}}\right)$$
$$= 1,200\left(1 - 0.75\frac{120 - 80}{120}\right) = 900 \ kg/ha$$

16. There is 10 % yield loss due to pest stress in addition to the loss due to water stress calculated in question 15. What is the expected yield?

The reduced yield is multiplied by the pest stress

$$900 \ kg/ha(0.9) = 810 \ kg/ha$$

17. The expected annual income from a project is $600/yr for 5 years, and the project requires a $2,000 investment. Determine whether or not to invest in the project at a 9 % required rate of return.

The present value of the payments is 2,334 so the decision is made to invest in the project.

18. Determine the present value of the income from cotton 4 years from now for full water application and a required rate of return of 7 %. (1) Assume no inflation. (2) Assume inflation of 5 % per year in costs and no inflation in the selling price of cotton. Current yearly income is $854.25, and current yearly expenses are $721.16

The present value of year 4 profit with no inflation is $451. The present value of year 4 with inflation is -$75.

19. Calculate the cost of energy to pump water for sprinkler irrigation alfalfa for 100 ha of land with an irrigation system that requires a 30 m pressure head, and a pump that operates at 80 % efficiency. The cost of energy is $0.10/kW-hr. Assume that the sprinkler irrigation system water application efficiency is 75 %. Assume that alfalfa requires 5 m of water per year.

The irrigation system must apply 5000 mm/ 0.75 = 6,667 mm

$$E = \frac{0.0272(6,667)(30\ m)}{0.8}(100\ ha)$$

$$= 680,000\ kW - hr(0.1/kW - hr) = \$68,000/season$$

20. Develop a rule of thumb for pump flow rate requirement for an area that has a max ET = 10 mm/d in terms of gpm/acre? The expected irrigation efficiency is 70 %, and the expected downtime is 10 %. What pump flow capacity will be required for a 10 acre farm? If the farm is divided into five irrigation zones, then what pump size is required?

ET rate	10	mm/day
	100	m3/day-ha
	69.44444	L/min/ha
	7.425143	gal/min/acre
Irr eff	0.7	
Rule of thumb	10.60735	gal/min/acre

For a 10 acre farm, the pump should produce 106 gal/ min
The same pump size is required for any number of zones.

21. For the flow rate in question 20, what motor horsepower is required and wattage is required if the pump operates at 100 ft pressure and is 85 % efficient?

$$HP = GPM*FT/(3960*Eff) =$$

Acres	10	
Pump flow	106.0735	gpm
Pressure	100	ft
Pump eff	0.85	
HP	3.151321	

22. Using the *Cash flow diagram* worksheet, redo the analysis for alfalfa planted every year.

	A	B	C	D	E	F	G	H	I	J	K	L
10	0	-	-			-3000	0	0	0	0	$ (3,000.00)	$ (3,000.00)
11	1	Alfalfa	Alfalfa	1000	0.07	-300	1070	-208	-108	-210	$ 244.00	$ 225.93
12	2	Alfalfa	Alfalfa	1000	0.07	-300	1145	-216	-117	-221	$ 291.44	$ 249.86
13	3	Alfalfa	Alfalfa	1000	0.07	-300	1225	-225	-126	-232	$ 342.57	$ 271.95
14	4	Alfalfa	Alfalfa	1000	0.07	-300	1311	-234	-136	-243	$ 397.67	$ 292.30
15	5	Alfalfa	Alfalfa	1000	0.07	-300	1403	-243	-147	-255	$ 457.03	$ 311.05
16	6	Alfalfa	Alfalfa	1000	0.07	-300	1501	-253	-159	-268	$ 520.96	$ 328.29
17	7	Alfalfa	Alfalfa	1000	0.07	-300	1606	-263	-171	-281	$ 589.79	$ 344.14
18	8	Alfalfa	Alfalfa	1000	0.07	-300	1718	-274	-185	-295	$ 663.89	$ 358.68
19	9	Alfalfa	Alfalfa	1000	0.07	-300	1838	-285	-200	-310	$ 743.63	$ 372.00
20	10	Alfalfa	Alfalfa	1000	0.07	-300	1967	-296	-216	-326	$ 829.43	$ 384.19
21	11	Alfalfa	Alfalfa	1000	0.07	-300	2105	-308	-233	-342	$ 921.73	$ 395.31
22	12	Alfalfa	Alfalfa	1000	0.07	-300	2252	-320	-252	-359	$ 1,021.00	$ 405.45
23	13	Alfalfa	Alfalfa	1000	0.07	-300	2410	-333	-272	-377	$ 1,127.74	$ 414.67
24	14	Alfalfa	Alfalfa	1000	0.07	-300	2579	-346	-294	-396	$ 1,242.49	$ 423.02
25	15	Alfalfa	Alfalfa	1000	0.07	-300	2759	-360	-317	-416	$ 1,365.84	$ 430.57
26	16	Alfalfa	Alfalfa	1000	0.07	-300	2952	-375	-343	-437	$ 1,498.40	$ 437.37
27	17	Alfalfa	Alfalfa	1000	0.07	-300	3159	-390	-370	-458	$ 1,640.83	$ 443.47
28	18	Alfalfa	Alfalfa	1000	0.07	-300	3380	-405	-400	-481	$ 1,793.84	$ 448.91
29	19	Alfalfa	Alfalfa	1000	0.07	-300	3617	-421	-432	-505	$ 1,958.20	$ 453.74
30	20	Alfalfa	Alfalfa	1000	0.07	-300	3870	-438	-466	-531	$ 2,134.70	$ 458.00
31												$ 4,448.88

Chapter 3: Solution

1. What is the textural class name of a soil that has 40 % clay, 20 % sand, and 40 % silt?

This is a point between the four different classifications

2. What is the textural class name of a soil that has 35 % clay, 15 % sand, and 50 % silt?

Silty clay loam

3. Download the Soil Water Characteristics calculator from the website listed in the References, and calculate the field capacity and permanent wilting point for the soil described in question 2. Use the field capacity and permanent wilting point values to calculate AWC.

Field capacity = 38 %
Permanent wilting point = 22 %
AWC = 16 %

4. Use the Soil Water Characteristics Calculator to determine whether Field Capacity or Permanent Wilting Point changes more with soil compaction and explain why. What is the percent change from Loose to Hard.

Field capacity changes more, typically by 4 %. This is because larger macropores are lost by compaction.

5. Use the Soil Water Characteristics Calculator to evaluate changes in Field Capacity or Permanent Wilting Point from zero to 8 % organic matter. Make sure your salinity is below 5 dS/m. Is the change greater for a sandy loam or a clay? Does the change increase the AWC?

There is almost no change in PWP or FC for a clay because clay has similar pore sizes as organic matter. Change in PWP is approximately 6 % and change in FC is approximately 13 % for a sandy loam with 8 % increase in organic matter. Adding organic matter does not increase the AWC for clay, but it increases by 7 % for a sandy loam.

6. A soil sample is removed from the field and weighed (130 g). The soil is then dried and the weight is 100 g. What is the gravimetric water content?

$$\theta_{grav} = \frac{m_{water}}{m_{dry\ soil}} = \frac{30\ g}{100\ g} = 0.30 = 30\ \%$$

7. If gravimetric water content θ_{grav} is 30 % and bulk density ρ_b is 1.30 g/cm^3, then what is the volumetric water content? What is the porosity?

$$\theta_V = \theta_{grav} \times \rho_b = 0.3 \times 1.3 = 0.39 = 39\ \%$$

$$\phi = 100 - \left(\frac{\rho_b}{\rho_p}\right)*100 = 100 - \left(\frac{1.3}{2.65}\right)*100 = 51\ \%$$

8. What is the FC, PWP, and AWC of a sandy loam? Use the Soil Water Characteristics Calculator (0 % and 4 % organic matter, salinity = 3 dS/m, gravel = 0 %, and compaction is normal). Discuss the impact of properties other than soil texture on hydraulic properties.

FC = 0.06
PWP = 0.14
$AWC = \theta_{FC} - \theta_{PWP} = 0.14 - 0.06 = 0.08$

There is a dramatic change in hydraulic properties with organic matter, salinity, and compaction. This is why it is necessary to know more than just the soil texture.

9. What is the depth of readily available water (RAW) for sandy loam (4 % organic matter) if the effective root zone depth is 1.5 m and MAD = 0.4?

Estimate AWC for a sandy loam as 0.10 based on the Soil Water Characteristics Calculator.

$$TAW = AWC*z = 0.10*1.5 = 0.15\ m$$

$$RAW = TAW*MAD = 0.15\ m*0.4 = 0.06\ m = 6\ cm.$$

10. Define MAD and answer the following questions. What is meant by 40 % MAD? Does 40 % MAD have a water content closer to PWP or FC?

MAD is defined as the management allowed depletion and is the maximum allowable percent depletion of the AWC. A 40 % MAD refers to the fact that a maximum of 40 % of the AWC can be depleted before irrigation must take place. Thus, 40 % MAD has a water content closer to field capacity.

11. What is the percent depletion if measured water content is 19 %, field capacity is 25 % and permanent wilting point is 10 %? If the MAD is 50 %, at what water content must the next irrigation take place? If the root zone depth is 1.5 m, then what depth of available water remains for plant use before the next irrigation? If evapotranspiration rate is 1 cm/day, then what is the maximum length of time before the next irrigation?

$$\%Dep = \frac{(\theta_{FC} - \theta)}{(\theta_{FC} - \theta_{PWP})}*100 = \frac{(25 - 19)}{(25 - 10)}*100 = 40\ \%$$

The next irrigation must take place before the soil reaches a water content of 17.5 %.

$$TAW = AWC*z = 0.15*1.5 = 0.225 \ m$$

$$RAW = TAW*MAD = 0.225 \ m*0.5 = 0.113 \ m$$
$$= 11.3 \ cm.$$

$$Available \ water = RAW - (\theta_{FC} - \theta)*z$$
$$= 0.113 - (0.25 - 0.19)*1.5 = 0.023 \ m$$
$$= 2.3 \ cm$$

There are 2.3 cm remaining and ET is 1 cm/day, so the irrigation should take place within 2 days.

12. How much irrigation water (ft) should be applied in the next irrigation if porosity is 50 %, field capacity is 27 %, and permanent wilting point is 12 % in all layers? Measured soil water content in the upper 4 ft of soil (root zone) is as follows: 0–1 ft = 21 %, 1–2 ft = 22 %, 2–3 ft = 17 %, and 3–4 ft = 22 %. Assume that the irrigation efficiency is 100 %. Redo assuming that the irrigation efficiency is 80 %.

$$D_r = (1ft(.27 - .21) + 1ft(.27 - .22) + 1ft(.27 - .17)$$
$$+ 1ft(.27 - .22)) = .65 \ ft$$

If irrigation efficiency is 100 %, then 0.65 ft of water should be added.

If irrigation efficiency is 80 %, then 0.65/0.8 = 0.81 ft of water should be added.

13. What is the depth of available water in the root zone if the readily available water in the root zone 1 week ago was 10 cm and the rate of evapotranspiration was 1 cm/day? During this time, a storm added 2 cm water to the soil. When should the next irrigation take place?

$$Soil \ water \ available = 10 \ cm - 7*1 \ cm + 2 \ cm = 5 \ cm.$$

The next irrigation should take place within 5 days.

14. Use the Web Soil Survey (WSS) to find a soil at the agricultural field station in your area (or a location specified by the instructor) and repeat Example 3.8 for your soil. First, go to the WSS URL listed in the References and click "Start Web Soil Survey" in the upper right corner. There are four tabs at the top of WSS. Find your location under the "Area of Interest (AOI)" tab. You can make the scaling process faster by using your mouse and outlining the location you are interested in. Then outline one field at the research station with the red area of interest rectangle tool (Second button from right along top). After outlining the

area of interest, press the Soil Map tab at the top. The soils in the AOI are listed on the left. Click on the soil name for a short description of that soil. For a more extensive description, go to the Natural Resources Conservation Service Soil Series Descriptions at the URL listed in the References. Type in only the name of the series, but not the texture. Define the field capacity and permanent wilting with the Soil Water Characteristics Calculator Assume an appropriate crop in your area. Then calculate the RAW of the soil based on the MAD (Table 3.3) and root zone depth of the crop. Find the root zone depth in Table 3.2.

Answers will vary

15. Estimate the long-term ponded steady-state infiltration rate for a sandy clay loam with the Soil Water Characteristics Calculator.

Assume that the wetting front depth goes to infinity; thus, the steady state infiltration rate is equal to the saturated hydraulic conductivity for sandy loam soil, 25 mm/hr.

16. For the following infiltration data, determine the SCS intake family as shown in Example 3.3.

Time (min)	Infiltrated depth (cm)
0	0.6985
5	1.33
10	1.79
50	4.55
100	7.33
150	9.82
200	12.13

First, subtract out the initial infiltration into cracks.

Intake without cracks	
Time (min)	cm
0	0
5	0.63
10	1.09
50	3.85
100	6.64
150	9.12
200	11.43

Take the natural log values of the data

Natural log of time	Natural log of infiltrated depth
1.61	−0.459
2.30	0.085
3.91	1.348
4.61	1.892
5.01	2.211
5.30	2.437

The graph of natural log of depth vs. natural log of time is constructed and trendline is used to find the slope.

$y = 0.785x - 1.7226$

Cumulative infiltration vs. time for intake family 1.0 soil.
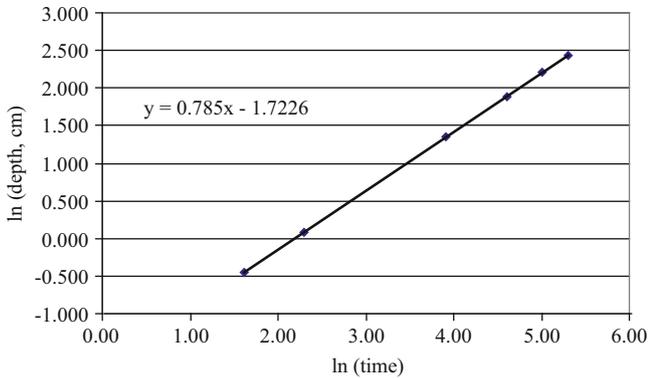
The slope is 0.785, which is equal to b.

Coefficient a is found by substituting 0.785 into the modified form of Eq. 3.19 as follows and selecting a time with a corresponding depth.

$$a = \frac{i}{t^b} = \frac{6.64}{100^{0.785}} = 0.1787$$

Thus the equation for this infiltration curve is

$$i = at^b + c = 0.1787 \ t^{0.785} + 0.6985$$

This equation corresponds with the intake family 1.0 curve.

17. Calculate the depth of infiltration and infiltration rate over time and plot the two curves for an intake family 1.0 soil. Plot your infiltration rate curves in terms of cm/hr and in/hr and calculate out to 1000 minutes. At what time is the intake rate equal to 1.0 in/hr? Is this the steady state intake rate?

The cumulative infiltration is found with the following equation for the intake family 1.0 soil.

$$i = at^b + c = 0.1786 \ t^{0.785} + 0.6985$$

The intake rate is calculated with the derivative.

$$di/dt = ab(t)^{(b-1)} = 0.785 * 0.1786 * t^{(0.785-1)} = 0.14 \ t^{-0.215}$$

Infiltration rate vs. time for intake family 1.0 soil.

The intake rate is equal to 1.0 in/hr at approximately 200 minutes. This appears to be a steady state intake rate. The fact that the model shows a decreasing intake rate as time increases is a relic of the equation and not necessarily the behavior of the soil. The equation is probably accurate up to 200 minutes when 12 cm has infiltrated into the soil, a typical depth of irrigation.

18. Calculate the moisture contents in Table 3.11 in the upper four layers if the calibration slope is changed to 0.2. If permanent wilting point is 11 % in the upper four layers, calculate the total available water in the upper four layers assuming that the neutron measurements were taken a few days after irrigation. Calculate the readily available water in the upper four layers if MAD is 0.45.

Depth	Reading	FC	PWP	FC – PWP	Thickness	TAW
40 cm	13965	0.175582	0.11	0.065582	0.5	0.032791
60 cm	14962	0.190566	0.11	0.080566	0.2	0.040283
80 cm	16963	0.220637	0.11	0.110637	0.2	0.055319
100 cm	18509	0.243871	0.11	0.133871	0.2	0.066936

The assumption is that soil water content a few days after irrigation is equal to FC.

Sum of TAW is 0.195

$$RAW = TAW(MAD) = 0.195(0.45) = 0.09 \ m.$$

Chapter 4: Solution

1. What is the molecular mass (g/mole) of calcium carbonate ($CaCO_3$)?

   $Ca - 40.1 \ g/mole$
   $C - 12 \ g/mole$
   $O - 16 \ g/mole$
   $\therefore$Molecular mass of $CaCO_3 = 14.1 + 12 + 3*16$
   $= 100.1 \ g/mole$

2. What is the molarity and ppm of Na^+ and Cl^- if 0.02 g NaCL is dissolved in 4 L of water?

   The molecular weight for each component is:

   $Na : 22.99 \ g/mole$
   $Cl : 35.43 \ g/mole$
   $NaCL : 58.42 \ g/mole$

   Calculate number of moles

   0.02 g/58.42 g/mole = 0.0034235 moles of NaCl are in the water.

   Calculate molarity

   $$0.00345 \ moles/4L = 8.56E - 04 \ mol/L$$

   Molarity is same for Na and Cl because there is a 1:1 ratio of Na and Cl to NaCl

   Calculate ppm (mg/L) Cl

   $$\left(\frac{0.000856 \ moles \ Cl^-}{Liter}\right)\left(\frac{35.43 \ g}{mole}\right)\left(\frac{1,000 \ mg}{g}\right)$$
   $$= 303 \ mg/L$$

   Calculate ppm (mg/L) Na

   $$\left(\frac{0.000856 \ moles \ Cl^-}{Liter}\right)\left(\frac{22.93 \ g}{mole}\right)\left(\frac{1,000 \ mg}{g}\right)$$
   $$= 196.3 \ mg/L$$

3. What is the concentration of salts (mg/L) in water with $EC_{iw} = 2.4$ dS/m?

   $$C_w = EC_{iw} \times 640$$
   $$\therefore C_w = 2.4 \times 640 = 1,500 \ mg/L$$

4. What is the soil salinity (mg/L) at saturation if the saturated paste extract EC_e is 4 dS/m?

   mg/L = 4 dS/m * 640 = 2,500 mg/L.

5. How many moles of sodium chloride "NaCl" are required in 4 L of water to develop a solution that has 1000 mg/L sodium? What is the concentration of chloride in the water?

   Molecular mass of NaCl = 23 + 35.5 = 58.5 g/mole

   If the concentration of sodium = 1000 mg/L

   $\therefore$Mass of Sodium = concentration(mg/L)*volume of solution(L)
   $= 1000 \ mg/L*4L = 4000 \ mg = 4 \ g - Na$

   No. of moles of sodium = 4/23 = 0.174 mole − Na

   $\because$1 mole of sodium ions is produced for every mole of sodium chloride "NaCl"

   $\therefore$No. of moles of sodium chloride "NaCl"
   $= 0.174 \ mole - NaCl$

   And, No. of moles of chloride = 0.174 mole − Cl = 0.174 *35.5 = 6.177 g

   Concentration of chloride = mass of solute (mg)/
   volume of solution (L)
   $= 6177/4 = 1544.3 \ mg/L$

6. How many grams of NO_3 are dissolved in 4 L of water with a nitrate concentration of 20 mg/L?

   Mass of nitrate (mg) = concentration (mg/L)*volume of
   solution (L) = 20 (mg/L)*4(L)
   $= 80 \ mg = 0.08 \ g$

7. Calculate the mass of ammonium nitrate NH_4NO_3 dissolved in 200 L water to obtain a nitrate concentration of 30 mg/L in water.

   Molecular mass of "NO_3" = 14 + 3*16 = 62 g/mole
   Molecular mass of "NH_4NO_3" = 14 + 4*1 + 14 + 3*16
   $= 80 \ g/mole$

   Mass of nitrate "NO_3" in mg = concentration (mg/L)*
   volume of solution (L)
   $= 30(mg/L)*200 \ (L)$
   $= 6000 \ mg = 6 \ g - NO_3$

   No. of moles of $NO_3 = 6/62 = 0.097$ moles $- NO_3^-$

$\because$ 1 mole of nitrate NO_3^- ions is produced for every mole of ammonium nitrate NH_4NO_3

$\therefore$ No. of moles of ammonium nitrate NH_4NO_3
$= 0.097$ moles $- NH_4NO_3$

Mass of ammonium nitrate NH_4NO_3 in g $=$ molecular mass $(g/mole)$*no. of moles $= 80$ g/mole*0.079 moles
$= 7.76$ g $- NH_4NO_3$

8. If saturated paste extract EC_e is 2 dS/m, then what is the osmotic potential ψ_s of the water if the water content θ is 15 % and the saturated water content θ_s is 45 %?

$$\psi_s = -3.6 \times EC_e \times \frac{\theta_s}{\theta}$$
$$\therefore \psi_s = -3.6 \times 2 \times \frac{0.45}{0.15} = -21.6m = -2.16 \text{atmosphere}$$

9. Explain the effect of salinity in Fig. 4.1.

Salinity increases the negative potential for a given water content. Especially for a salt sensitive plant where water stress begins at a less negative water potential, there is very little available water in the soil.

10. Explain the function of the xylem and the phloem in the plant.

The xylem and phloem constitute the plant vascular system.

– Xylem: Transfer water and nutrients upward from the roots to the leaf surfaces.
– Phloem: Phloem carries sugar downward, which plants create through photosynthesis, from the leaves to the rest of the plant and to the roots.

11. Calculate the Gibb's free energy of water "G" in a cell if the concentration of sucrose in the cell is 0.3 mole sucrose/L water at a temperature of 20 °C. Express your answer in J/mole and J/kg (a.k.a. kPa).

$$mole/Lwater = \left(\frac{1000g}{L}\right)\left(\frac{mole}{18g}\right) = 55.56 mole/Lwater.$$

Mole fraction of water $= 55.56/(55.56 + 0.3) = 0.995$.

$$G = RT\ln(C) = 8.314 \times 293 \times \ln(0.995)$$
$$= -13.12 J/mole.$$

Multiply by 55.56 to obtain the answer in J/kg (kPa)

$$G = RT\ln(C) = 55.56 \times 8.314 \times 293 \times \ln(0.995)$$
$$= -728.83 J/kg(kPa) = -7.29 atm$$

12. Calculate yield for cotton for a growing season if average values of EC_e and water content during the growing season are 12 dS/m and 13.5 %, respectively. $\theta_{fc} = 0.2$, $\theta_{pwp} = 0.1$. $K_y = 0.85$. Max yield $= 1,000$ kg/ha. MAD $= 0.55$. Threshold EC_e is 7.7 dS/m and b is 5.2. $K_y = 0.85$ for cotton.

$$AWC = \theta_{FC} - \theta_{PWP} = 0.2 - 0.1 = 0.1$$
$$TAW = AWC \times z = 0.1 \times 1.5 = 0.15$$
$$D_r = TAW \times \%depletion = 0.15 \times 0.65 = 0.0975$$
$$K_{s-water} = \frac{TAW - D_r}{(1 - MAD)TAW} = \frac{0.15 - 0.0975}{(1 - 0.55) \times 0.15} = 0.778$$
$$K_{s-salt} = 1 - \frac{b}{100 \times K_y}(EC_e - EC_{e-t})$$
$$= 1 - \frac{5.2}{100 \times 0.85}(12 - 7.7) = 0.737$$
$$K_s = K_{s-water} \times K_{s-salt} = 0.778 \times 0.737 = 0.573$$
$$Y_a = \left(1 - K_y(1 - K_s)\right)Y_m$$
$$= (1 - 0.85 \times (1 - 0.573)) \times 1000 = 637 \ kg/ha$$

13. Why does high sodium ruin some soils? What types of soils are most vulnerable?

Excess sodium (Na+) can lead to breakdown of clay particle structure and can clog the soil and reduce infiltration rate to nearly zero. The most vulnerable type of soils is clay because sodium cations are loosely attracted to negative charged clay layers and they maintain a hydration shell of approximately ten water molecules around them. The water molecules in the shells of hydration will force the clay layers apart.

14. Irrigation water has 230 mg/L sodium (Na+), 60.15 mg/L calcium (Ca++), and 24.3 mg/L magnesium (Mg++). If irrigation water salinity is 1,000 ppm, then what level of hazard is presented by sodicity?

Equivalent masses are given in Table 4.1. Calculate meq/L for each cation.

460 mg/L Na^+/23 mg/meq $= 20$ meq / L Na^+
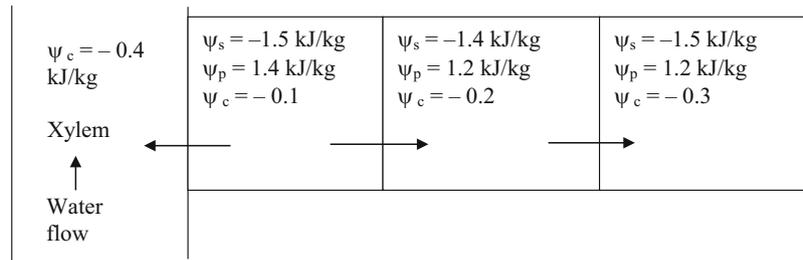20 mg/L Na^+/20.05 mg/meq $= 1$ meq / L Ca^{++}
12 mg/L Na^+/12.15 mg/meq $= 1$ meq/L Mg^{++}

$$SAR = \frac{|Na^+|}{\sqrt{\frac{|Ca^{++}| + |Mg^{++}|}{2}}} = \frac{20}{\sqrt{\frac{1+1}{2}}} = \frac{20}{1} = 20$$

The EC_{iw} of the irrigation water is 960 ppm/640 (dS/m/ ppm) = 1.5 dS/m. From Table 4.4, there is a moderate to severe (more severe than moderate) salinity hazard.

15. Fill in the missing total potential values and show direction of water flow. Are these total potentials more likely to occur in the day or the night?

$$\psi_c = -0.4 \text{ kJ/kg}$$

$\psi_s = -1.5$ kJ/kg	$\psi_s = -1.4$ kJ/kg	$\psi_s = -1.5$ kJ/kg
$\psi_p = 1.4$ kJ/kg	$\psi_p = 1.2$ kJ/kg	$\psi_p = 1.2$ kJ/kg
$\psi_c = -0.1$	$\psi_c = -0.2$	$\psi_c = -0.3$

Xylem

Water flow

These total potential values are more likely to occur at night because turgor pressure is high and total potential is close to zero.

16. Determine the leachate salinity. Irrigation water salinity (EC_{iw}) = 2 dS/m. Applied water depth (d_{in}) = 1,250 mm/season. There is no precipitation during the growing season. Crop water demand (ET_c) = 1,000 mm/season. Average soil moisture content is the same at the beginning and end of the growing season.

$$LF = \frac{i - ET_c}{i} = \frac{1,250 - 1,000}{1,250} = 0.2$$

$$EC_{dw} = \frac{EC_{iw}}{LF} = \frac{2}{0.2} = 10 \ dS/m$$

17. Irrigation water salinity (EC_{iw}) = 2 dS/m. Applied water depth (d_{in}) = 1,300 mm/season. Crop water demand (ET_c) = 900 mm/season and assume that plants extract 40 %, 30 %, 20 %, and 10 % of their water from the upper quarter, next quarter, next, and lowest quarter of the root zone, respectively. Calculate the salinity at the bottom of the root zone by treating the root zone as a whole and calculate salinity at the bottom of each of the 4 layers. Calculate the average salinity in the root zone by assuming that the field capacity is half of the saturated water content (divide average salinity in half for EC_e). Then calculate the leaching fraction that would be required to have this average salinity in the root zone with Eq. 4.20 and compare with the leaching fraction in this problem.

Calculate EC_{dw} treating the entire root as a whole:

$$LF = \frac{d_{in} - ET}{d_{in}} = \frac{1300 - 900}{1300} = 0.31$$

$$EC_{dw} = \frac{EC_{iw}}{LF} = \frac{2}{0.31} = 6.45 \ dS/m$$

Calculate EC_{dw} by calculating the salinity at the bottom of each of the four quarters of the root zone:

$$LF_1 = \frac{1300 - 0.4 \times 900}{1300} = \frac{940}{1300} = 0.72$$

$$\Rightarrow \therefore EC_1 = \frac{EC_0}{LF_1} = \frac{2}{0.72} = 2.8 \ dS/m$$

$$LF_2 = \frac{940 - 0.3 \times 900}{940} = \frac{670}{940} = 0.71$$

$$\Rightarrow \therefore EC_2 = \frac{EC_1}{LF_2} = \frac{2.8}{0.71} = 3.9 \ dS/m$$

$$LF_3 = \frac{670 - 0.2 \times 900}{670} = \frac{490}{670} = 0.73$$

$$\Rightarrow \therefore EC_3 = \frac{EC_2}{LF_3} = \frac{3.9}{0.73} = 5.3 \ dS/m$$

$$LF_4 = \frac{490 - 0.1 \times 900}{490} = \frac{400}{490} = 0.82$$

$$\Rightarrow \therefore EC_4 = \frac{EC_3}{LF_4} = \frac{5.3}{0.82} = 6.46 \ dS/m$$

The calculated EC_{dw} is exactly the same for both calculations.
Calculate the average EC in the root zone for the calculation of the required leaching fraction.

$$EC_{ave} = (2 + 2.8 + 3.9 + 5.3 + 6.46)/5 = 4.1 \ dS/m.$$

If the field capacity is approximately 50 % of saturated water content, then, the average EC_e in the soil is:

$$EC_{e(sat)} = EC_{ave} * (\theta_{fc}/\theta_{sat}) = 4.1*0.5 = 2.05 \ dS/m$$

Calculate the leaching fraction required to have an average EC_e equal to 2.05 dS/m.

$$LF = \frac{EC_{iw}}{5(EC_e) - EC_{iw}} = \frac{2}{5(2.05) - 2} = 0.24$$

This calculated leaching fraction, 0.24, is less than the actual leaching fraction, 0.31, but it is reasonably close given all of the assumptions that were made.

18. Calculate the depth of irrigation water required (average for the field), IR, for cotton based on Eq. 4.23. The MAD is 50 %, the irrigation system efficiency is 60 %, the irrigation water EC_{iw} is 2 dS/m, and the TAW is 20 cm.

Max. soil salinity in the saturated paste extract (Table 4.4) for cotton with no yield reduction $= 7.7$ dS/m.

$$LF = \frac{EC_{iw}}{5(EC_e) - EC_{iw}} = \frac{2}{5(7.7) - 2} = 0.054$$

$$IR = \frac{100}{IE(1 - LF)}RAW = \frac{100}{60(1 - 0.054)}(0.5*20 \ cm) = 17.6 \ cm$$

Chapter 5: Solution

1. Atmospheric pressure is 100 kPa and the atmosphere is 2 % water by volume. What is the partial pressure of water in the atmosphere?

2 kPa

2. Why is relative humidity an important factor in evapotranspiration?

The energy gradient due to the vapor pressure difference between the leaf and the atmosphere drives the evaporated water from the plant canopy to the atmosphere

3. Calculate the relative humidity if the partial pressure, e_a, of water in the air is 1.1 kPa and T $= 40\ °C$.

First, calculate the saturated vapor pressure
$e_s = \exp\left(\frac{16.78(30)-116.9}{30+237.3}\right) = 4.25 \ kPa$

Calculate the ratio of partial pressure of water to saturated vapor pressure.

$$RH = e_a/e_s = 1.1/7.4*100\% = 15\%$$

4. The density of water in the atmosphere at sea level is 0.018 kg/m^3, atmospheric pressure is 101 kPa, and temperature is 40 °C. What is the relative humidity?

The molar volume (mol/m^3) is

$$n = (18g/m^3)/(18g/mol) = 1.0\,mol/m^3$$

Rearrange the ideal gas law and solve for partial pressure of water in the atmosphere

$$p = nRT/V = 1(mol/m^3)*8.314*313 = 2,600 \ Pa = 2.6 \ kPa.$$

First, calculate the saturated vapor pressure
$e_s = \exp\left(\frac{16.78(30)-116.9}{30+237.3}\right) = 4.25 \ kPa$

$$RH = 2.6/7.4*100\% = 35\%$$

5. Calculate the total resistance to water vapor transfer and the water vapor transfer conductance for a well-watered turf crop. The wind speed at 2 m elevation is 2 m/sec and the bulk surface resistance is 70 s/m. Calculate the maximum depth of water vapor transfer during 1 hour if the relative humidity is 60 %, temperature is 30 °C, and elevation is sea level.

$$r_s = 70 \ s/m$$
$$r_{av} = 208/U_2 = 208/2 = 138 \ s/m$$
$$r_{total} = r_s + r_{av} = 70 + 138 = 208 \ s/m$$

$$h_v = \frac{1}{r_{total}} = \frac{1}{208} = 0.0048 \ m/s$$

Calculate canopy vapor pressure.

$$e_c = e_s = \exp\left(\frac{16.78(30) - 116.9}{30 + 237.3}\right) = 4.25 \ kPa$$

The atmospheric vapor pressure is the product of saturation vapor pressure and relative humidity

$$e_a = e_s*RH = 4.25 \ kPa*0.6 = 2.54 \ kPa$$

Calculate ET.

$$ET_0 = \rho_a h_v \frac{(e_c - e_a)0.622}{P}$$
$$= 1.29*0.0048 \frac{(4.25 - 2.54)0.622}{101.3}$$
$$= 0.00017 \ kg/(m^2 - \ sec\ )$$
$$= 0.00017 \ mm/\ sec = 0.61 \ mm/hr$$

6. Write a *sentence* describing each of the four terms in the crop evapotranspiration energy balance equation.

Latent heat of vaporization, LE is the energy used to convert liquid water to water vapor. Soil heat flux, G, is the quantity of energy that enters the soil. Net radiation, R_n is the total solar radiation minus the sum of the reflected short wave radiation and the long wave infrared radiation. Sensible heat flux, H, is the energy transfer from the crop to the atmosphere.

7. Calculate cumulative net radiation (MJ/m^2) over turf for 2 hours if average hourly radiation energy input (R_S) is 50 Langleys (cal/cm^2).

Calculate average incoming solar radiation (W/m²). First convert Langleys to MJ/m²/hr

$$50 \text{ cal/cm}^2/\text{hr}*4.18 \text{ Joules/calorie} = 2.1*10^2 \text{J/cm}^2$$

$$= 2.1*10^6 \text{J/m}^2 = 2.1 \text{ MJ/m}^2$$

Calculate net radiation over turf (MJ/m²) for 2 hr.

$$R_n = 277.8*(-0.3 + 0.77*2.1)$$

$$= 366 \text{ W/m}^2*7200 \text{ sec } /2 \text{ hr}*10^{-6}\text{J/MJ} = 2.6 \text{ MJ/m}^2.$$

8. The plant canopy of a transpiring plant is generally cooler than the atmosphere above it. Why?

When water evaporates from the leaf, it removes heat from the leaf due to the latent heat of vaporization.

9. How would the height of the crop influence the 2 m wind speed measurement? Would a calculation of aerodynamic resistance based on 2 m wind speed without accounting for roughness elevation be in error? Why isn't this a problem for reference evapotranspiration calculations?

The wind speed would begin to increase at the roughness elevation. Thus, the wind speed would be zero for corn that is greater than 2 m tall. This factor is not a problem for reference evapotranspiration calculations because the reference crop is turf, which has a 10 cm (low) canopy height.

10. Explain why there is a difference between the stable wind speed and the unstable wind speed profile.

As with pipe flow, under turbulent conditions (unstable atmosphere) the velocity is distributed more uniformly in the radial direction in the pipe. Laminar flow has a large difference between the velocity of flow near the edges of the pipe and the velocity in the center of the pipe. The stable atmosphere has more laminar flow. The fact that the stable atmospheric condition is shown with a higher velocity is not significant, it is just how the picture was drawn in order to show a steeper gradient for the laminar flow.

11. Explain why all of the curves in Fig. 5.6 have the same aerodynamic resistance at 3 m/sec wind speed. Why does the −2 °C curve have a higher aerodynamic resistance than the +2 °C curve?

The lowest resistance to energy and vapor transfer is observed when surface/canopy temperatures are higher than air temperature (Ts − Ta = +2 °C): a buoyant condition with intensive mixing. There is no decrease in resistance as wind speed increases because maximum mixing is already occurring. The maximum resistance to energy and water vapor transfer occurs when wind speed is low and air temperature is higher than surface/canopy temperature; there are very few eddies, and energy and vapor must transfer by molecular diffusion.

12. Conduct dimensional analysis of Eqs. 5.15, 5.17, 5.19, and 5.20, and 5.22 and make sure that the units in the equations are consistent.

The units for Eq. 5.15 are consistent if the units for latent heat of vaporization are J/kg (J/mm-m), evaporation are m/s, and radiation are J/m². The units are W/m² on both sides

$$\lambda ET_0 = R_n - \frac{\rho_a c_p h_a}{\Delta}[(e_{sc} - e_{sa})]$$

$$\frac{J}{mm\ m^2}*\frac{m}{s} = \frac{J/s}{m^2} - \frac{\left(\frac{kg}{m^3}\right)\left(\frac{J}{kg\ °C}\right)\left(\frac{m}{s}\right)(kPa)}{\left(\frac{kPa}{°C}\right)} = \frac{W}{m^2}$$

(5.15)

The units for Eq. 5.24 are consistent if the units for latent heat of vaporization are J/kg (J/mm-m) and the units for ET are mm/s.

$$\frac{\gamma \lambda ET_0}{\rho_a c_p h_v} = (e_c - e_a)$$

$$\frac{\left(\frac{kPa}{°C}\right)\left(\frac{J}{mm\ m^2}\right)\left(\frac{mm}{s}\right)}{\left(\frac{kg}{m^3}\right)\left(\frac{J}{kg°C}\right)\left(\frac{m}{s}\right)} = kPa$$

(5.17)

The units for Eq. 5.19 are consistent.

$$\lambda ET_0 = \frac{(R_n - G)\Delta + \rho_a c_p h_a[(e_{sa} - e_a) - (e_{sc} - e_c)]}{\left(\Delta + \gamma \frac{h_a}{h_v}\right)}$$

$$\left(\frac{J}{mm\ m^2}\right)\left(\frac{mm}{s}\right) = \frac{\left[\left(\frac{J/s}{m^2}\right) - \left(\frac{J/s}{m^2}\right)\right]\left(\frac{kPa}{°C}\right) + \left(\frac{kg}{m^3}\right)\left(\frac{J}{kg°C}\right)\left(\frac{m}{s}\right)kPa}{\left(\frac{kPa}{°C}\right) + \left(\frac{kPa}{°C}\right)} =$$

(5.19)

The units for Eq. 5.22 are consistent if the units for h_a are mm/s.

$$\lambda ET_0 = \frac{\Delta}{(\Delta + \gamma)}(R_n - G) + \frac{0.622\lambda h_a\gamma(e_{sa} - e_a)}{P(\Delta + \gamma)}$$

$$\left(\frac{J}{mm\ m^2}\right)\left(\frac{mm}{s}\right) = \frac{\left(\frac{kPa}{°C}\right)}{\left(\frac{kPa}{°C}\right)}\left[\left(\frac{J/s}{m^2}\right) - \left(\frac{J/s}{m^2}\right)\right] + \frac{\left(\frac{J}{mm\ m^2}\right)\left(\frac{mm}{s}\right)\left(\frac{kPa}{°C}\right)kPa}{kPa\left(\frac{kPa}{°C}\right)} =$$

Equation 5.23 is consistent if the units for the wind transfer function are W/(m^2 kPa)

$$\lambda ET_0 = \frac{\Delta}{(\Delta + \gamma)}(R_n) + \left(\frac{\gamma}{\Delta + \gamma}\right)f(u)(VPD)$$

$$\left(\frac{J}{mm\ m^2}\right)\left(\frac{mm}{s}\right) = \frac{\left(\frac{kPa}{°C}\right)}{\left(\frac{kPa}{°C}\right)}\left(\frac{J/s}{m^2}\right) + \frac{\left(\frac{kPa}{°C}\right)}{\left(\frac{kPa}{°C}\right)}\left(\frac{J/s}{m^2\ kPa}\right)kPa$$

The units for Eq. 5.24 are not consistent.

$$ET_{sz} = \frac{0.408\ \Delta\ (R_n - G) + \gamma\dfrac{C_n}{T + 273}U_2(e_s - e_a)}{\Delta + \gamma(1 + C_dU_2)}$$

$$\left(\frac{mm}{d}\right) = \frac{\left(\frac{kPa}{°C}\right)}{\left(\frac{kPa}{°C}\right)}\left[\left(\frac{J/s}{m^2}\right) - \left(\frac{J/s}{m^2}\right)\right] + \frac{\left(\frac{kPa}{°C}\right)\left(\frac{1}{°C}\right)\left(\frac{m}{s}\right)kPa}{\left(\frac{kPa}{°C}\right)} =$$

13. In Eq. 5.19, the radiation term on the left and the aerodynamic term on the right are independent. Can Eq. 5.20 be broken down in the same way?

$$ET_{sz} = \frac{0.408\ \Delta\ (R_n - G) + \gamma\dfrac{C_n}{T + 273}U_2(e_s - e_a)}{\Delta + \gamma(1 + C_dU_2)}$$

The radiation term is

$$\frac{0.408\Delta\ (R_n - G)}{\Delta + \gamma(1 + C_dU_2)}$$

The aerodynamic term is

$$\frac{\gamma\dfrac{C_n}{T + 273}U_2(e_s - e_a)}{\lambda(1 + C_dU_2)}$$

The radiation term in equation includes wind speed in the denominator. The fact that the radiation term includes wind speed would imply that energy loss due to radiation is partially a function of wind speed. The aerodynamic term includes a dependence on temperature so this would imply that the aerodynamic losses are partially a function of temperature.

14. Compare the results of Examples 5.4 and 5.6. Discuss the reason for the difference.

The Hargreaves-Samani equation predicts a value that is 25 % lower than the standardized Penman equation.

$$(6.65 - 5.2)((6.65 + 5.2)/2)*100\% = 25\%$$

The most likely factor is wind speed. Lowering the wind speed to 1 m/sec yields the same result for the standardized Penman and the Hargreaves-Samani equations.

15. Use data from April 10, 2009, Tucson weather station data (http://ag.arizona.edu/azmet/data/0109eh.txt) to make hand calculations of daily ET with the equations. Then use the *Chapter 5 ET calculator* program and compare with your results. The latitude of Tucson is 33.95°N. Elevation is 655 m. Maximum temperature is 28 °C and minimum temperature is 8 °C. Relative humidity minimum is 7 % and relative humidity maximum is 57 %. Measured solar radiation is 27 MJ m^{-2} day^{-1}. Average wind speed at 3 m elevation is 2.8 m/sec.

Max T	28	C	Latitude	33.95	degrees	Elevation	655	m
Min T	8	C	DOY	100	days	Measured Rs	27	MJ/m2/
Tave	18.00	C	Phi	0.59		solar radiation		
es Max T	3.78	kPa	dr	1.00		Wind speed	2.8	m/s
es Min T	1.07	KPa	delta	0.13		Wind z	3	m
es-ave	2.43	kPa	w	1.66		Wind, 2 m	2.58	
RH max	0.57	fraction	Ra	35.24	MJ/m2/d			
RH min	0.07	fraction	Rs/Rso	1.004				
ea RH max	0.61							
ea RH min	0.26		Calculation of daily ET with standardized Penman equation					
ea-ave	0.44	kPa DP ea 0.67	Input data required in white cells					
VPD (es-ea)	1.99	ave VPD 0.69						
Rso	26.89	MJ/m2/d	AZMET unit conversion		Max T	82	F	
Rnl	8.82	MJ/m2/hr			Max T	27.78	C	
Rns	20.79	MJ/m2/d	RS	641.7	Lang Min T	47	F	
Rn	11.97	MJ/m2/d	RS	26.82	MJ/m/d Min T	8.33	C	
P	93.79	kPa	Dewpt	34.3	F Wind	6.3	MPH	
DELTA	0.13		Dewpoint ea	1.28	C Wind	2.82	m/s	
gamma	0.06							
U2	2.58	m/s						
G	0	MJ/m2/d	USE AZMET AVERAGES for VPD			FALSE		
R(f) rad. Fn.	0.634							
w(f) wind Fn.	0.989							
denominator	0.247							
ET0	6.5747	mm/day						
ET0	0.2588	in/day						

16. Use hand calculations to calculate hourly ET over turf in Tucson, Arizona on DOY 100. Solar radiation is 2.84 MJ m^{-2} hr^{-1}. Average temperature is 27 °C, and wind speed is 4.2 m/s at 3 m elevation. Elevation is 655 m, relative humidity is 9 %. Longitude of Tucson is 113.18°. Tucson is in the Mountain Time Zone (Lm = 105). The longitude of the Mountain Time meridian is 105°. The period is from 2 to 3 p.m. Check your results against the spreadsheet calculations.

Tave	27	C	Latitude	33.95		Elevation	655	m
es	3.57	kPa	DOY	100		Rs measured	2.84	MJ/m2/
RH	0.09		Phi	0.593				
ea	0.32	kPa	dr	0.995		Wind speed	4.2	m/s
			delta	0.133		Wind z	3	m
Rso	2.43	MJ/m2/hr	w	1.661				
Rnl	0.53	MJ/m2/hr				Calculation of hourly ET during day		
			b	0.33		Input data required in white cells		
Rns	2.19	MJ/m2/hr	Sc	-0.027				
Rn	1.66	MJ/m2/hr	Lz	113.183	station degrees			
P	93.8	kPa	Lm	105	time zone meridian degrees			
DELTA	0.209		end time	15	end of hour (military time)			
gamma	0.062		w	0.790				
U2	3.87	m/s	w1	0.659				
G	0.166	MJ/m2/hr	w2	0.92				D
ET	0.679	mm/hr	sin(q)	0.170				Dew
			Ra	3.19	MJ/(m2 hr)			

17. Use average *monthly* values of ET_0, maximum temperature, and minimum temperature from a weather series in your area to calculate Fourier series coefficients for maximum and minimum temperature and ET_0.

Answers will vary.

Chapter 6: Solution

1. Reference ET_0 is 10 mm/day for 1 week, and the crop coefficient is 0.5. What is the depth of water required during 1 week?

The crop uses 5 mm/day or 35 mm/week.

2. Reference ET_0 is 7 mm/day, pan evaporation is 8 mm/day, and measured crop evapotranspiration is 5 mm, as measured by a lysimeter. What are the pan and reference ET_0 crop coefficients?

$$K_p = 5/8 = 0.62$$
$$K_m = 5/7 = 0.71$$

3. Explain the difference between the single crop coefficient and the dual crop coefficient.

The single crop coefficient is defined as the ratio between ET_c (crop evapotranspiration) and ET_o (reference evapotranspiration); thus, it combines transpiration and evaporation. On the other hand, the dual crop coefficient separates the basal crop coefficient (transpiration) and the soil evaporation coefficient (evaporation from the soil surface).

4. Explain the spikes in transpiration rate in Fig. 6.4 and the average crop coefficient in Fig. 6.5.

During the initial and development states, irrigation effects are greatest when the soil is wetted. As a result, evaporation spikes due to wet soil and irrigation during the early season, and can be as great as midseason ET. In addition, Fig. 6.5 indicates that average crop coefficient, which is the sum of crop basal coefficient and soil evaporation coefficient is greater than the basal crop coefficient during the early season because of the influence of evaporation.

5. Find the Kcb values for winter wheat (dual crop coefficient) in FAO56 Table 17, and adjust K_{cb-mid} for average minimum relative humidity during mid-season and late season growth stages equal to 20 % and 30 %, respectively. Average wind speed at 2 m elevation is 2 m/sec during mid and late season growth stages. There is less than 10 % ground cover during the initial phase. There is high grain moisture at harvest. The crop is grown in California. Plot the linearized crop coefficient curve for the dual component model.

Because there is less than 10 % ground cover during the initial phase, $k_{cb\ ini} = 0.15$

$$k_{cb-mid} = k_{cb(table\ 17)} + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)]\left[\frac{h}{3}\right]^{0.3}$$

From Table 17:

$$K_{cb\ mid} = 1/15$$

From Table 12:

$$h = 1$$

$$k_{cb\ mid} = 1.15 + [0.04(2 - 2) - 0.004(20 - 45)]\left[\frac{1}{3}\right]^{0.3}$$
$$\boldsymbol{k_{cb\ mid} = 1.22}$$

From Table 17, kcb-end for high moisture content at harvest is 0.30

$$k_{cb\ end} = 0.30 + [0.04(2 - 2) - 0.004(30 - 45)]\left[\frac{1}{3}\right]^{0.3}$$
$$\boldsymbol{k_{cb\ end} = 0.343}$$

Lengths of stages are given in FAO Table 11 for California.

Initial	20 days
Development	60 days
Midseason	70 days
Late	30 days
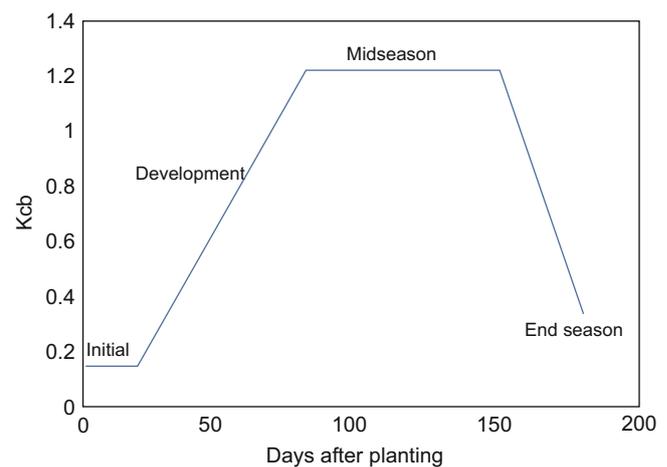
6. Repeat question 5, but plot the single crop coefficient curve (FAO Table 12) for winter wheat. Average depth of irrigation during the initial phase is 50 mm. Average number of days between irrigations during the initial period is 20 days. Minimum relative humidity is 20 % and average wind speed is 2 m/sec. The crop is machine harvested (late season K_c). During the early season, the crop is irrigated every 10 days, irrigation depths are greater than 40 mm, and the ET_0 is 7 mm/day. Also plug values into the Example 6.10 worksheet in order to solve the problem.

The stage lengths are found in FAO56 Table 6.11. The $K_{c\text{-ini}}$ values are found in FAO56 Table 6.12. The final Kc value is 0.25 because the crop is machine harvested. For early season $K_{c - ini}$, from Figure 30, the 10 day, 7 mm/day value is 0.21. Because the wetting is greater than 40 mm/ irrigation, the value in Figure 30 is used, and the value from

Figure 29 is not required. The kcb-mid is the same as in Example 5 since the equation adjustment is the same, which is reasonable since a full canopy cover has little to no evaporation and full transpiration. Thus Kc is 1.22.
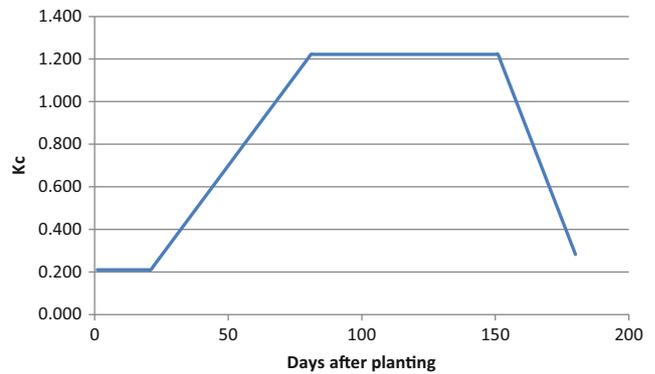
The spreadsheet solutions are in yellow

	stage length	Days after planting	Kc	Root (m)	Crop height
Initial	20	20	0.21	0.40	0.10
Dev	60	80			
Mid	70	150	1.15	0.80	1.00
End	30	180	0.25		

Winter wheat in California desert — Plant on Jan 1

Stage lengths and Kc from Tables 11 and 12 in FAO 56

Adjust Kc ini based on the following values with Table 29 and 30	
Average depth applied during initial phase (mm)	50.00
Average number of days between irrigations	10.00
Maximum gross depth applied per day or irrigation (mm)	100.00
Typical midseason minimum relative humidity %	20.00
Typical midseason average daily wind speed (m/s)	2.00
Adjusted midseason crop coefficient	1.22

7. Calculate the single day crop basal transpiration for winter wheat 70 days after planting. Reference ET_0 is 7 mm/ day and the crop stress coefficient is 0.8. Relative humidity is 20 %, and wind speed is 3 m/sec at 3 m elevation.

After 70 days of planting, winter wheat is in the midseason state, then:

$$k_{cb} = k_{cb(table\ 17)} + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)]\left[\frac{h}{3}\right]^{0.3}$$

Calculate wind speed at 2 m, U_2.

$$U_2 = U_z\frac{4.87}{\ln(67.8z - 5.42)}$$

$$U_2 = 3\frac{4.87}{\ln(67.8*3 - 5.42)} = 2.76\ m/sec$$

From Table 17:

$$k_{cb\ mid} = 1.10$$

From Table 12:

$$h = 1$$

$$k_{cb} = 1.10 + [0.04(2 - 2.76) - 0.004(20 - 45)]\left[\frac{1}{3}\right]^{0.3}$$
$$\textbf{\textit{k}}_{cb\ mid} = \textbf{1.16}$$
$$ET_c = ET_o*k_a$$
$$k_a = k_s\,k_{cb} + k_e$$

Then, assuming that k_e is neglected:

$$k_a = 0.8*1.16$$
$$k_a = 0.93$$
$$ET_c = 7mm/d*0.94$$
$$\textbf{\textit{ET}}_c\textbf{=6.54}\ \textbf{\textit{mm/day}}$$

8. Plot the winter wheat root growth curve as defined in FAO56. Initial depth is 0.4 m and the final depth is 0.8 m.
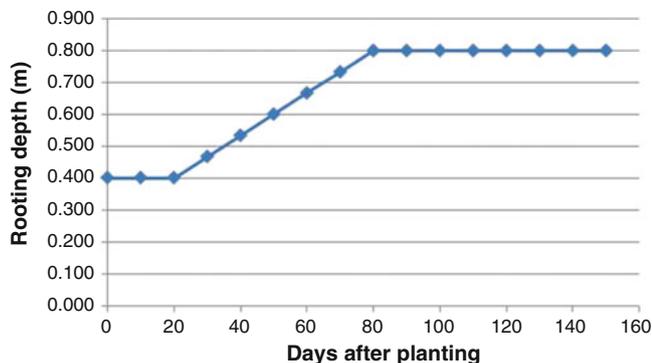
9. What is the reason that soil evaporation + basal transpiration cannot exceed K_{c-max}?

$K_{c\ -\ max}$ is constrained by the energy available for evaporation; thus, the basal crop coefficient plus evaporation coefficient cannot exceed $k_{c-max.}$

10. Calculate $K_{c\ -\ max}$ if relative humidity is 20 %, crop height is 0.5 m, and wind speed is 2 m/sec.

$$k_{c-max} = 1.20 + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)]\left[\frac{h}{3}\right]^{0.3}$$
$$k_{c-max} = 1.20 + [0.04(2 - 2) - 0.004(20 - 45)]\left[\frac{0.5}{3}\right]^{0.3}$$
$$\textbf{\textit{k}}_{c-max}\textbf{=1.25}$$

11. Explain the difference between REW and TEW.

The evaporation of REW during stage 1 is unrestricted by the soil. However, TEW takes place as the soil increasingly resists water transfer to the atmosphere. Thus, at the threshold between REW and TEW, the evaporation rate begins to decrease.

12. Field capacity is 20 % and permanent wilting point is 10 %. The depth of the surface layer is 0.11 m. REW = 7 mm. Calculate TEW. Calculate K_r for the surface layer depletion equal to 4 mm.

$$TEW = 1,000(\theta_{FC} - 0.5\theta_{PWP})Ze$$
$$TEW = 1,000(0.20 - 0.5*0.10)*0.11$$
$$TEW = 16.5\ mm$$

$k_r = 1.0$ because D_r does not exceed REW

13. Alfalfa has a low ET just after cutting and high ET just before cutting. For arid conditions with moderate wind, calculate alfalfa evapotranspiration just before and just after cutting if reference ET_0 is 10 mm/day. Use FAO 56 Table 12.

From Table 12 from FAO 56:
$K_c = 0.4$ after cutting
$K_c = 1.15$ before cutting

$$ET_c = ET_o*k_c$$
$$ET_c = 10mm/d*0.4$$
$$\textbf{\textit{ET}}_c\textbf{=4}\ \textbf{\textit{mm/day}}$$
$$ET_c = 10mm/d*1.15$$
$$\textbf{\textit{ET}}_c\textbf{=11.5}\ \textbf{\textit{mm/day}}$$

14. During the first week after planting watermelons, t_{max} and t_{min} are 32 °C and 8 °C, respectively. Calculate the number of growing degree days accumulated after 1 week.

THR and UPP for watermelon are 10 and 30, respectively.

Average ambient temperature does not exceed UPP so GDD is calculated as follows.

$$(t_{max} + t_{min})/2 - THR = (32 + 8)/2 - 10 = 10.$$

GDD accumulation after 7 days would be $7 * 10 = 70$ days °C.

15. Calculate heat unit Fourier series K_c and ET_c curves for watermelon and corn for (Instructor selects year and location) weather data. You can download this data with the *Chapter 5 ET Calculator – Active Year Weather* worksheet from a city in Arizona or use weather from your home state. Click the *Run Weather Form* button. Calculate the Fourier W coefficients for the Tmax, Tmin and ETo curves in the *Chapter 5 ET Calculator – Fourier T and ETo* worksheet. Then, insert your W coefficients for Tmax, Tmin and ETo into the *Chapter 6 Crop ET and scheduling – Fourier T and ETo* worksheet. Then, copy your Tmax, Tmin and ETo values into the *Chapter 6 Crop ET and scheduling – ETo and temp – ch 5* worksheet. Soil is heavy-textured.

Results for Arizona:

The corn MAD will be adjusted based on the following equation with the expectation that the ETc for corn averages around 8.0 mm/day.

The p value (threshold for water depletion due to crop stress in Table 22) for corn is 0.5. Adjust with the following equation.

$$p = p_{Table\ 22} + 0.04(5 - ET_c) = 0.5 + 0.04(5 - 8)$$
$$= 0.5 - 0.12 = 0.38$$

Adjust MAD downward for heavy-textured soil to 0.33

$$MAD = 0.38 - 0.05 = 0.33.$$

The following average monthly averages were acquired from AZMET in order to calculate the W coefficients. Note that the ET STD values at the bottom of each summary page are monthly sums in English units that must be divided by 30 and multiplied by 25.4 in order to calculate mm/day. Likewise, temperatures must be converted to metric.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	The monthly averages (white columns) are averages of monthly data for each parameter														
2	Spreadsheet calculates sin P and cos P, etc.., in yellow columns based on P in the blue column														
3	Follow instructions below to perform regression on one of the three parameters														
4						P = 2*PI()*DOY/365									AZME
5	Date	ETo	Tmax	Tmin	DOY	P	cos P	sin P	cos 2P	sin 2P	cos 3P	sin 3P			ET (in
6	15-Jan	3.07	17.78	2.22	15	0.258	0.967	0.255	0.87	0.494	0.715	0.699			2.6
7	15-Feb	3.78	20.56	2.78	46	0.792	0.703	0.712	-0.01	1	-0.72	0.693			3.2
8	15-Mar	6.61	24.44	5.00	75	1.291	0.276	0.961	-0.85	0.531	-0.74	-0.67			5.6
9	15-Apr	8.86	28.33	7.22	105	1.807	-0.23	0.972	-0.89	-0.46	0.652	-0.76			7.5
10	15-May	10.04	30.56	11.67	136	2.341	-0.7	0.718	-0.03	-1	0.738	0.674			8.5
11	15-Jun	11.46	38.33	18.33	166	2.858	-0.96	0.28	0.843	-0.54	-0.66	0.753			9.7
12	15-Jul	9.57	36.11	22.78	197	3.391	-0.97	-0.25	0.878	0.479	-0.73	-0.68			8.1
13	15-Aug	8.62	35.56	22.22	228	3.925	-0.71	-0.71	0.004	1	0.703	-0.71			7.3
14	15-Sep	7.91	34.44	19.44	259	4.458	-0.25	-0.97	-0.87	0.486	0.69	0.724			6.7
15	15-Oct	6.38	31.11	10.56	289	4.975	0.26	-0.97	-0.87	-0.5	-0.71	0.706			5.4
16	15-Nov	4.13	24.44	6.11	319	5.491	0.703	-0.71	-0.01	-1	-0.72	-0.69			3.5
17	15-Dec	2.60	18.89	2.78	350	6.025	0.967	-0.26	0.87	-0.49	0.715	-0.7			2.2
18	You may need to add the Data Analysis Tool from Tools --> Add-ins														
19	Multiple regression (Tools → Data Analysis → Regression (Excel 2003) or Data, Data Analysis, and Tools in Excel 200														

Pivot water requirement / Fourier_Crop_data / **number 16** / Fourier T and ETo / Number 16 corn schedule / Numb

These W coefficients were substuted into the Fourier T and ETo Worksheet as shown below. Note that the ET and Tmax curves aren't symmetrical and reflect the monsoon activity in JJ. It is more interesting that the Tmin curve does not seem to be affected by the monsoon.
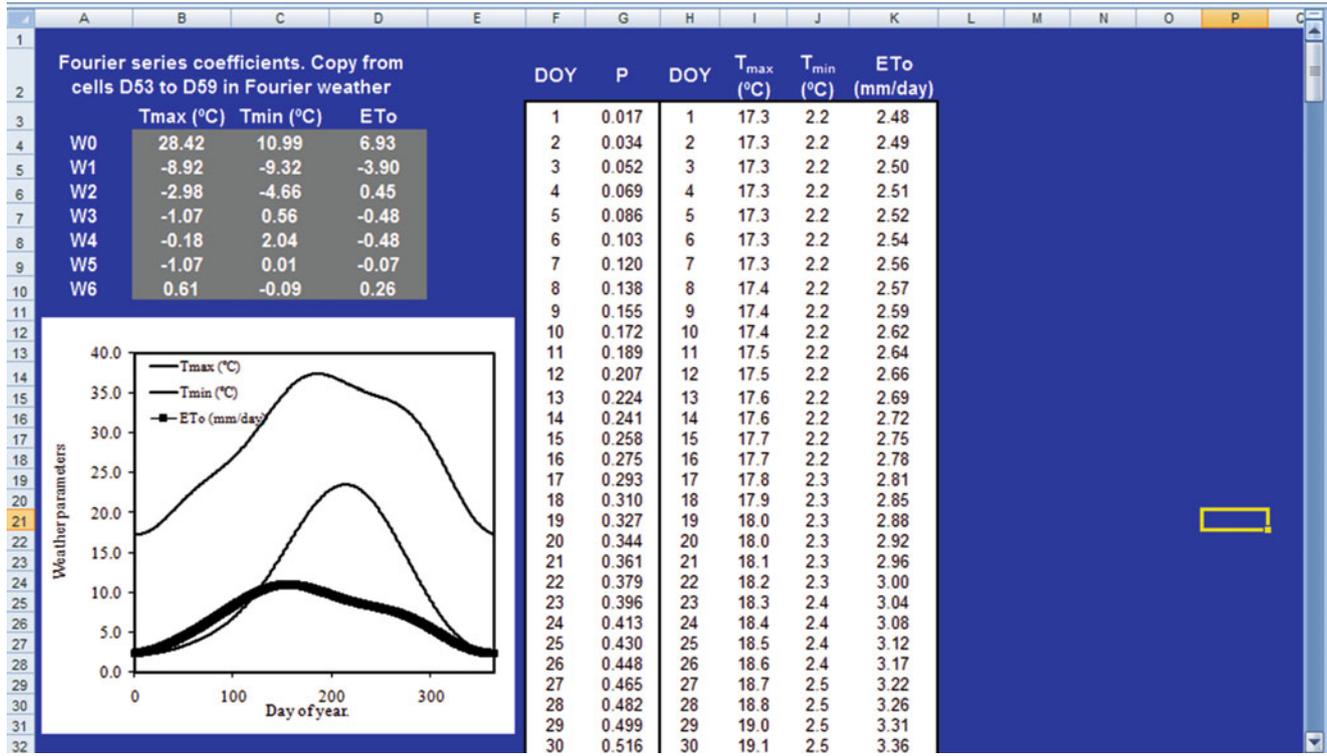
The environmental data was copied from DOY 70 into the Irrigation schedule Worksheet, the MAD, LF and IE efficiency data were added, and the following graphs were generated for corn.
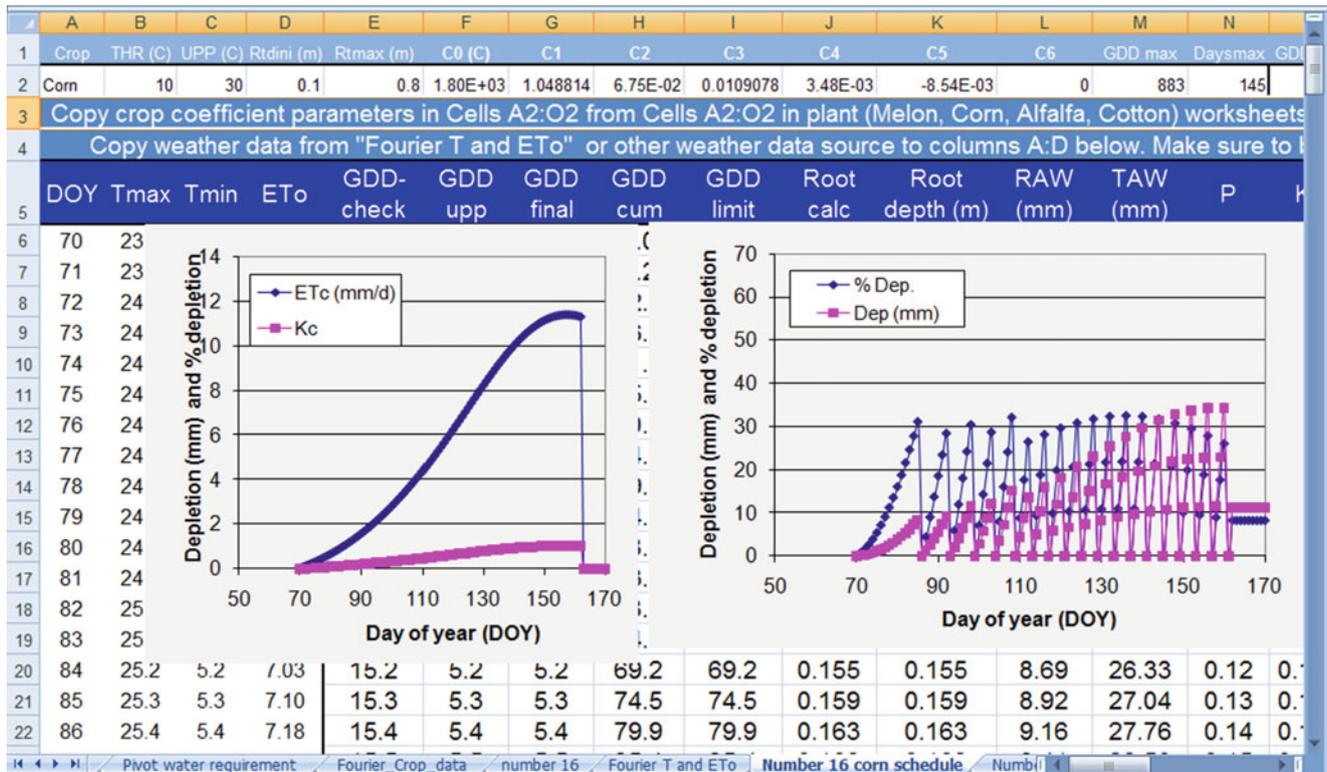
The depth of irrigation and ETc were 1149 and 654 mm, respectively, for corn.

The depth of irrigation and ETc were 1121 and 588 mm, respectively, for melons.

16. As in Example 6.6, calculate corn K_c and ET_c 50 days after planting by hand (with a calculator) and show that calculated K_c and ET_c in the spreadsheet agree with the equations.

The corn GDD 50 days after planting (DOY 120) is 328, and C_0 is 1800.
Thus K_c is calculated as follows.

$$P = \pi*GDD_{cum}/C_0 = \pi*328/1,800 = 0.572$$

C values for corn are in the following table.

C_1	1.05
C_2	0.0675
C_3	0.0109
C_4	0.00348
C_5	−0.00854
C_6	0

$$K_c = C_1*\sin(P) + C_2*\sin(2P) + C_3*\sin(3P) \\ + C_4*\sin(4P) + C_5*\sin(5P) + C_6*\sin(6P)$$

$$K_c = 1.05*\sin(0.572) + 0.0675*\sin(2*0.572) \\ + 0.0109*\sin(3*0.572) + 0.00348*\sin(4*0.572) \\ - 0.00854*\sin(5*0.572) = 0.640$$

In Cell O56, the K_c is 0.64.
The ETo on that day is 9.75. Thus, the ETc is $0.64 * 9.75 = 6.25$, which agrees with the value in Cell P56.

Environmental data was copied from DOY 80 for the melons. The following figure was generated.

17. According to the Fourier series GDD equations, calculate the rooting depth for melons when GDD = 500 and 1,000. AWC is 10 %, MAD is 0.5, and ET_c is 7 mm/day at the first rooting depth and 9 mm/day at the second rooting depth. What is the required frequency of irrigation at the two rooting depths.

Required frequency of irrigation at GDD = 500

$$Z_i = Z_{ini} + (Z_{max} - Z_{ini})*(GDD_{cum}/GDD_{root})$$

$$Z_{500} = 0.15 + (1.0 - 0.15)(500/1,500) = 0.43 \text{ m}$$

$$RAW = AWC*Z*MAD = 0.1*0.43*0.5 = 0.021 \text{ m} \\ = 2.1 \text{ cm}.$$

If ET_c is 7 mm/day, then irrigation must take place every 3 days.

Required frequency of irrigation at GDD = 1,000

$$Z_i = Z_{ini} + (Z_{max} - Z_{ini})*(GDD_{cum}/GDD_{root})$$

$$Z_{500} = 0.15 + (1.0 - 0.15)(1,000/1,500) = 0.72 \text{ m}$$

$$RAW = AWC*Z*MAD = 0.1*0.72*0.5 = 0.021 \text{ m} \\ = 3.6 \text{ cm}.$$

If ET_c is 9 mm/day, then irrigation must take place every 4 days.

18. ***For the 2008 Fourier series Tucson weather data, and the Fourier series crop coefficient for alfalfa,***

input the cutting cycle with peak ET into the High frequency alfalfa Irr. Worksheet. Then determine the required depth of irrigation per day with a center pivot irrigation system in order to keep up with crop water needs. Check to make sure that the percent depletion does not exceed 50 %. Use TAW = 140 mm. Assume a leaching fraction of 10 % and irrigation efficiency of 90 % in order to calculate the required gross application rate (divide net application rate in Worksheet by efficiency and (1 − LF)).

Add the alfalfa parameters into a new fourier worksheet.

Set the root depths in column J = 1.8 m(Cell $D$2).

For the alfalfa GDD calc in column I, the equation for setting GDD back to zero after each cutting must be modified as follows.

$$= IF(I6 + G7 > \$M\$2, 0, I6 + G7)$$

After these modifications are made, the Fourier spreadsheet appears as follows.
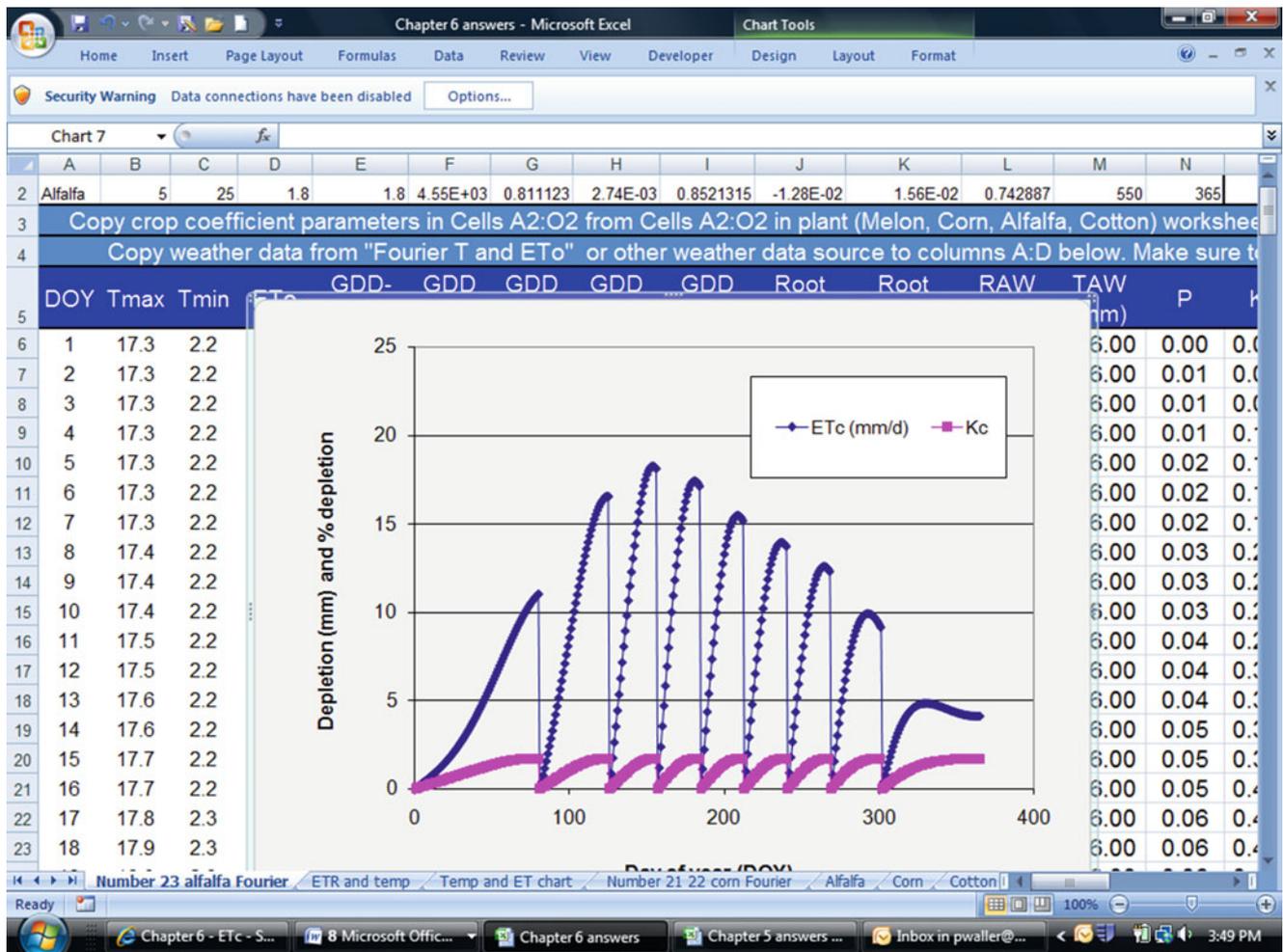
It appears that the peak water user is the third curve, so this data will be inserted into the high frequency alfalfa Worksheet. This period begins with DOY 122. The application rate is adjusted to 13.2 such that the final depletion percentage is approximately 50. There is not quite enough readily available water to carry the crop through the cycle. This is known because the curve drops below 0 % depletion. Perhaps a higher application rate is needed during the late cycle in order to carry the crop through. This worksheet is not equipped to evaluate this scenario.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1			TAW	140		Net irrigation	13.2 mm/day								
2			MAD	0.5											
3			RAW	70 mm		Final depletion	55.2 mm								
4															
5			DOY	ETc (mm)	i_n (mm)	Depletion (mm)	% Depletion								
6			122	0	0	70	50			Copy ETc data to this worksheet from the alfalfa worksheet.					
7			123	0.86	0	70.9	50.6								
8			124	1.74	13.2	59.4	42.4								
9			125	2.63	13.2	48.8	34.9								
10			126	3.53	13.2	39.2	28.0								
11			127	4.43	13.2	30.4	21.7								
12			128	5.34	13.2	22.5	16.1								
13			129	6.25	13.2	15.6	11.1								
14			130	7.16	13.2	9.5	6.8								Series1
15			131	8.06	13.2	4.4	3.1								
16			132	8.95	13.2	0.1	0.1								
17			133	9.82	13.2	-3.2	-2.3								
18			134	10.67	13.2	-5.8	-4.1								
19			135	11.49	13.2	-7.5	-5.3								
20			136	12.29	13.2	-8.4	-6.0								
21			137	13.06	13.2	-8.5	-6.1								

Number 21 22 corn FAO / Number 16 melon schedule / **Num 23 H.Freq. alfalfa Irr.** / WDI / Empirical CWSI calculation

If the required net application rate is 13.2 mm/day, then the required gross application rate is

$$13.2/0.9/0.9 = 16.2 \text{ mm/day.}$$

19. Calculate the CWSI for potatoes if the air temperature is 25 °C, canopy temperature is 24 °C, and actual vapor pressure is 1.32 kPa. Determine whether irrigation is needed.

From Table 6.17, intercept $= 1.17$ and slope $= -1.83$ for potatoes

$$e_{s-30} = \exp\left(\frac{16.78(25) - 116.9}{25 + 237.3}\right) = 3.17 \ kPa$$

$$\text{VPD} = e_s - e_a = 3.17 - 1.32 = 1.85 \ kPa$$

$$dT_l = \text{Intercept} + \text{Slope(VPD)} = 1.17 - 1.34(1.85) = -1.31$$

$$T_a + \text{intercept} = 25 + 1.17 = 26.17$$

Chapter 7: Solution

1. One cubic foot of water weighs 62.4 pounds. Assume you have a 1 ft × 1 ft × 1 ft container filled with water.

(a) What is the pressure at the bottom of the container in pounds per square foot?
ANSWER: 62.4 pounds per square foot

(b) What is the pressure at the bottom of the container in pounds per square inch (psi)?
ANSWER: 0.433 pounds per square inch (psi)

(c) What is the pressure in the container at a depth 0.5 ft below the top of the container (psi)?

ANSWER: 0.22 psi

2. What is the pressure (in feet of head) when the pressure is 2 psi? Remember that 1 psi = 2.31 ft of head.

ANSWER: 0.22 psi

What is the pressure (in ft) when the pressure is 50 psi?

ANSWER: 4.62 ft .

3. Calculate the pressure in units of feet at the bottom of a one cubic foot container.

ANSWER: 1 ft of head

4. Calculate the pressure (psi and ft of head) at the bottom of the swimming pool (at sea level) that is 9 ft deep.

ANSWER: 3.9 psi

5. Using the table below, write down the static pressure in psi and ft of head at each of the fittings found in Fig. 7.1:

	PSI	FT
A	8.66	20
B	8.66	20
C	32.5	75
D	32.5	75
E	39.4	91
F	39.4	91

6. What is the minimum acceptable inside pipe diameter for a Class 200 PVC pipe with a flow rate 90 gpm?

ANSWER: 2.7 inches is calculated, but in reality, you can't purchase that size pipe, so the real answer is 3 inches

7. Using Fig. 7.1, calculate the dynamic pressure (in ft of head) at each point of the fittings if the flow rate is 30 gpm through a 2″ Schedule 40 PVC pipe.

ANSWER:

Ft of Head	
A	20
B	20.14
C	75.75
D	75.93
E	92.11
F	105.3

8. Describe the relationships between the Z distribution, standard deviation, coefficient of variation, and mean, and describe how you can use those concepts to generate a normal distribution with mean equal to average sprinkler flow rate or application. Ignore pipe hydraulics, and use an equation to convert from Z values to the sprinkler distribution.

The Z distribution is the normal (0, 1) distribution, which means that it has mean zero and standard deviation 1. In order to generate this distribution in Excel, you use $Z = $ NORMSINV(+RAND()), which generates a uniform 0,1 distribution and then converts it to the Z distribution. The Z distribution can be converted to a distribution of sprinkler application depths by $i = \bar{i} + Z*CV*\bar{i}$ where i is the observed application depth and CV (coefficient) is the observed standard deviation over the mean of application depths.

9. Generate 50 values that are normally distributed with mean 5 and standard deviation 1.

Use this equation $ = $ NORMINV(RAND(), mean, SD)
Copy the equation into 50 cells,
   $ = $ NORMINV(RAND(), 5, 1)

10. Generate 50 values that are normally distributed with mean 50 and coefficient of variation 5 %.

Use this equation $ = $ NORMINV(RAND(), mean, mean*CV
Copy the equation into 50 cells,
   $ = $ NORMINV(RAND(), 50, 50*0.05)

11. Changing no more than 5 pipe sizes, adjust the pipe sizes in the *Irrigation Simulation with VBA* worksheet (column D) such that the energy cost is equal to or less than pipe cost. State which pipe lengths were changed. Describe how the process of selecting pipe sizes might be automated in a computer program so that total annual energy cost + pipe cost was a minimum.

Sizes for lengths 20, 21, 9, 10, and 11 were increased by one size.

If I designed a computer program for the purpose of selecting pipe sizes, then the computer program would begin with setting pipe sizes based on maximum flow velocity, such as 1.5 m/sec. Then pipes at the boundaries between sizes would be sequentially increased or decreased by one pipe size until the sum of annual value of total pipe cost and energy cost were minimized.

12. Observe the spatial variation of yield for sprinkler CV (cell E1) 0.05 and 0.5 in the *Irrigation Simulation with VBA* worksheet and observe the effect on profit, rounding to the nearest $/ha. In the high variability case, you might get a flow rate that is negative. Put an IF statement in the spreadsheet that prevents negative flow rates. In each case, observe whether the major cause of application variability and yield variability is due to pressure variation in the pipeline or nonuniformity of application.

CV	Profit
0.05	$124/ha
0.5	$104/ha

In the first case, the major cause of variation in pressure variation. In the second case, the major cause of variation is nonuniformity of application.

13. Using the *Standard deviation Fig. 7.15* worksheet, increase the standard deviation to 200 LPH, and report the profit. If the standard deviation is 200, then what is the coefficient of variation at the first sprinkler (column C). How does using the standard deviation rather than the coefficient of variation change the distribution along the pipeline. In your estimation, which is more representative of variation along a pipeline and why.

$116/ha

The coefficient of variation is the standard deviation over the mean: 200/1000 * 100 % = 20 %. With the coefficient of variation, the standard deviation increases with sprinkler flow rate along the pipeline. The standard deviation, the deviation is not a function of sprinkler flow rate. In most cases, it would seem that the coefficient would be a better representation since higher overall application would have a correspondingly larger variation in application rates.

14. Using the *Standard deviation Fig. 7.15* worksheet, decrease the standard deviation to 20 LPH, and increase the pipe sizes so that energy cost decreases to $37/hr and pipe cost increases to $61. Report the profit. Does the overall profit change significantly from question 7–12, with low CV? Why or why not.

$122/ha

The profit is approximately the same because the savings in energy cost is offset by the increase in pipe cost.

15. Increase the number of sprinklers in the *Irrigation Simulation with VBA* worksheet to 40 by changing the value in cell A7 and copying row 36 downward. Keep end pressure the same (cell B3) and redo the pipe sizes so that the inlet pressure is no more than 20 m (no more than 20 % pressure variation). Try to vary pipe sizes such that flow rate decreases linearly along the pipeline. The next largest pipe size above 100 is 150. Report the number of sections with each pipe size.

$59/ha

Answers will vary:

150 mm	9 sections
100 mm	15 sections
75 mm	13 sections
50 mm	3 sections

16. Adjust the depth in cell E2 in the *Irrigation Simulation with VBA* worksheet, with CV = 0.05, to the nearest integer value such that profit is maximized. The value is between 65 and 70 cm. Also, make a graph of profit vs. depth applied at 5 cm intervals between 40 and 80 cm. Click the Depth Opt. button and make a graph for profit vs. depth applied (Columns S and T). Explain the cause of the curve.

69 cm The yield variability is primarily due to pressure loss.
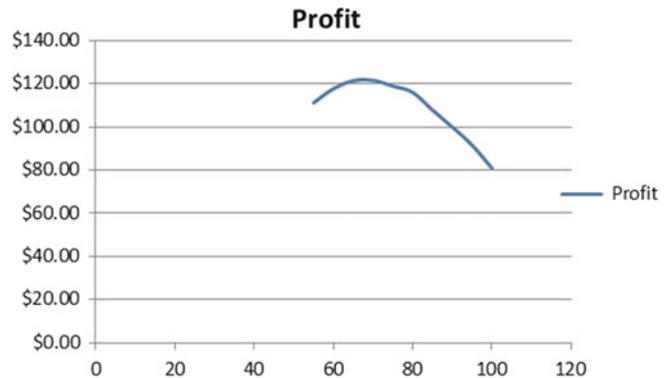
At low applied depth, the yield is reduced, and at high applied depth, the yield is reduced and expenses are high.

17. Using the *Irrigation_simulation with VBA* worksheet, observe the flow rate vs. distance plot with all pipe diameters equal to 75 mm. Explain the difference from the original graph with varying pipe size. Why wouldn't you want to use constant pipe size if friction loss is less?

With constant pipe size, there is almost no pressure loss at the end of the pipeline. Thus the curve is more of a parabola with constant pipe size. With constant pipe size, excess money is spent on large pipe at the end of the pipeline.

18. Insert actual inside pipe diameters for schedule 40 pipe in rather than the nominal pipe diameters column D rather than the nominal diameters in the *Irrigation_simulation with VBA* worksheet. Actual inside pipe diameters can be found in Table 8.1. Compare pressures in cell B36 and calculate total pressure loss in both cases, and calculate the percent difference in pressure loss by subtracting them from each other and dividing by the mean. State whether this is a significant difference and whether it is important to use actual pipe diameters in pressure loss calculations rather than nominal pipe diameters.

	Pressure	Pressure loss
Nominal pipe diameter pressure:	25.84 m	25.84–16.2 = 9.64
Actual pipe diameter pressure:	23.78 m	23.78–16.2 = 7.58

Percent different is 24 %

Based on this analysis, it is very important to use actual pipe diameters rather than nominal pipe diameters.

19. The roughness of pipes is characterized by the Hazen-Williams C value, which is included in the equation in column F in the spreadsheet. As pipes age, the roughness can increase, which decreases the C value. Using the actual pipe sizes from question 18, for the equations in column F, decrease the C value from 140 to 100 and report the total pressure loss. Compare to the pressure losses in question 18. What does this example say about the need to estimate long term pipe roughness in sprinkler systems.

The pressure loss increases to 15.58 m. It is approximately double the pressure loss with smooth pipe. Thus, it is very important to estimate the long-term pipe roughness. In many cases, the pipe will remain smooth, but there are cases in which the roughness will increase due to water chemistry or pipe quality, and this might cause major problems with uniformity.

20. Beginning with the spreadsheet with actual pipe sizes from question 18, change the Sprinkler K to 100 and x to 0.5 and input new pipe diameters such that pressure loss from one end of the lateral to the other is 20 %. Calculate the percent difference based on the average of the inlet and distal end pressure. Report the decrease in pipe cost and copy the pipe sizes into the answer.

The pipe cost for the unchanged pipeline is $49.45/ha/year.

$$0.2 = (inlet - 16.2)/(inlet + 16.2)*2$$
$$0.1(inlet + 16.2) = inlet - 16.2$$
$$0.1(inlet + 16.2) + 16.2 = inlet$$

Solve by iteration
Inlet pressure = 19.8 m
Total pipe cost is $42.75/ha/year
Answers will vary:

102.3 mm	3 sections
77.9 mm	13 sections
52.5 mm	9 sections
26.6 mm	5 sections

21. Write a VBA program to optimize energy cost and pipe sizing in the Irrigation Simulation worksheet.

Answers will vary

22. With the *Irrigation Simulation* worksheet, write a VBA program to calculate lateral end pressure if lateral input pressure is known. This will probably require an iterative procedure.

Answers will vary

23. Increase the slope to 3 % in the *Irrigation with slope* worksheet. Using the nominal pipe sizes, adjust the pipe sizes so that the difference between maximum and minimum pressure in the pipeline is no more than 2 m. Report on the number of each pipe length.

100 mm	1 sections
75 mm	16 sections
50 mm	11 sections
25 mm	2 sections

24. Make an algorithm in the Irrigation Simulation worksheet that calculates the percent difference between the maximum and minimum pressure in the lateral.

Answers will vary

25. Write a VBA program that evaluates and changes pipe sizes to column D in the *Irrigation Simulation* worksheet such that maximum pressure difference in the lateral is no more than 20 % and pipe cost is minimized.

Answers will vary

26. Using the *Leaching analysis* worksheet, run the "leach cost evaluation" for CV values of 5 %, 25 %, and 50 %, all at 80 cm applied depth. Copy the graphs of profit vs. leach price and evaluate. The current title of the graph is "Leach price analysis at 90 cm applied water." Make sure that you paste pictures of the figures into the Word document. Otherwise, they will be automatically updated when you rerun the simulation. You might need to rerun the simulation a few times if you get NAN for the 50 % CV. Determine whether the decrease in profit is primarily due to lost yield or increased leaching cost.

Leach price analysis at 80 cm applied water, $0.20/kg, and 0.05 CV

$y = -31.776x + 132.74$

Leach price analysis at 80 cm applied water, $0.20/kg, and 0.25 CV

$y = -34.818x + 115.02$

Leach price analysis at 80 cm applied water, $0.20/kg, and 0.5 CV

$y = 5.6394x + 19.221$
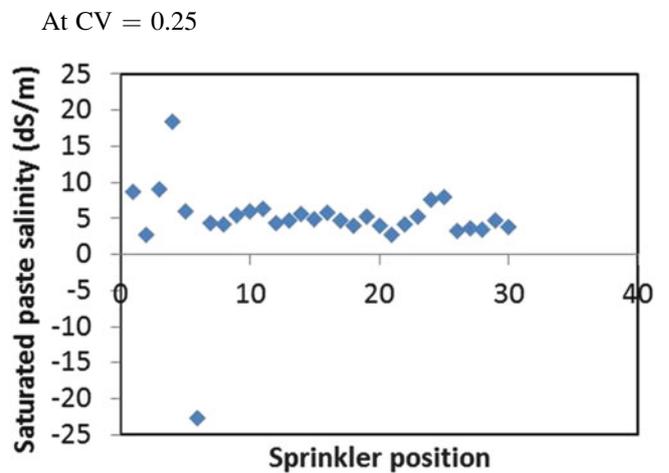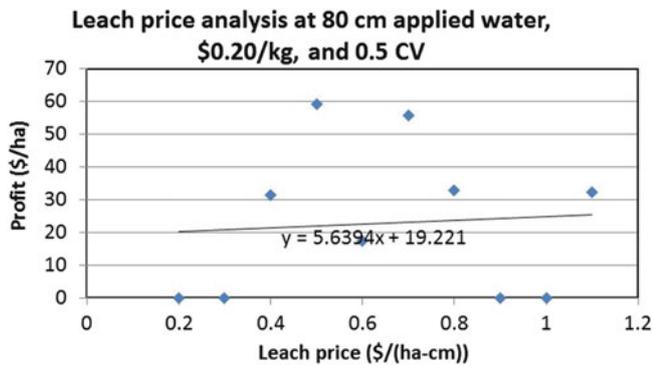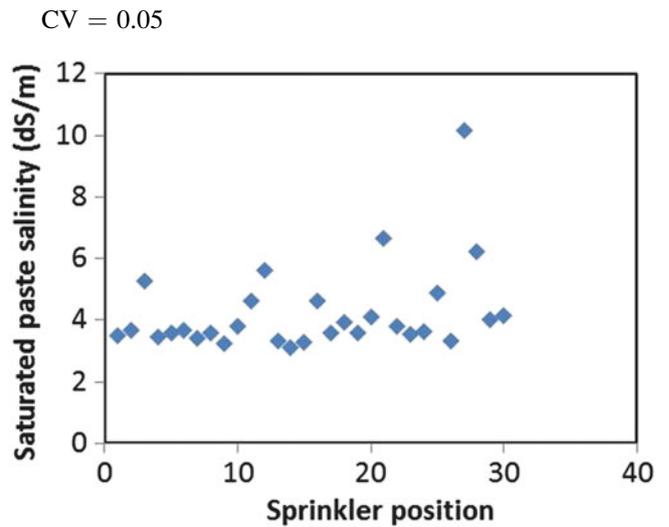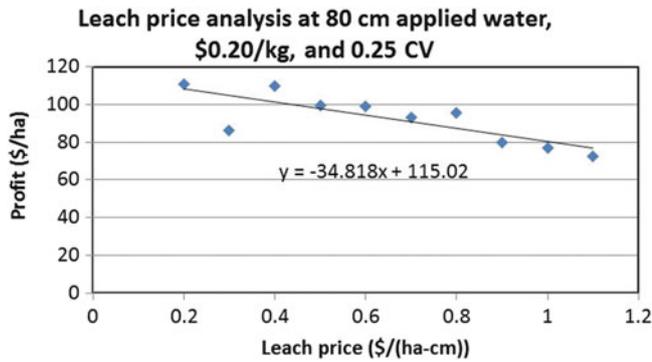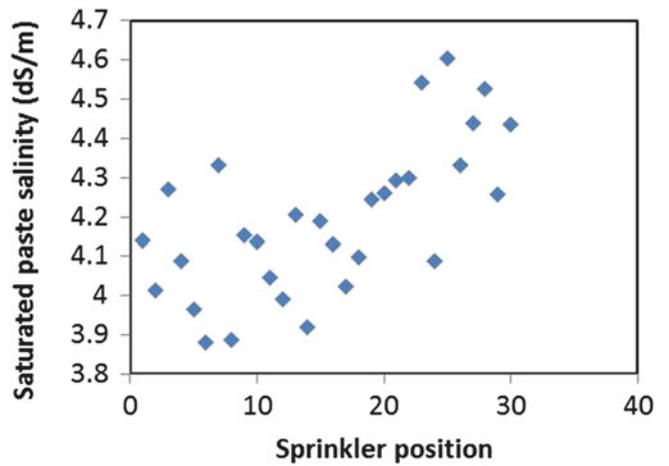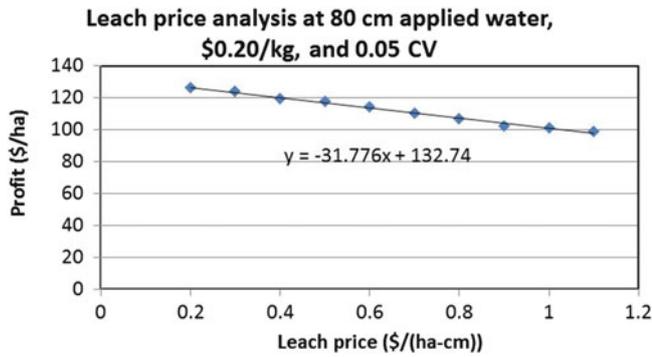
There is much more variability in profit with high CV values. The primary cause of decreased profit with high CV is decreased yield rather than leaching cost. There is little relationship between leaching cost and profit at high CV.

27. Using the Salinity analysis worksheet, copy the plots of saturated paste extract salinity vs. distance for CV values of 5 %, 25 %, and 50 %. Let irrigation water salinity equal 6 dS/m. State whether variability is primarily due to hydraulics or spatial variation of application in each case

CV = 0.05

At CV = 0.25

At CV = 0.5

For the low CV, the primary cause of variation is hydraulics. For CV = 0.25 and 0.5, the main cause of variation is spatial variation of application.

28. Write a VBA program that evaluates and changes pipe sizes in column D in the *Irrigation Simulation* worksheet, such that profit is maximized.

    Answers will vary

Chapter 8: Solution

1. On the following drawing of a drip irrigation system network, label the type in the well, pump station, submains, mainlines, and laterals.
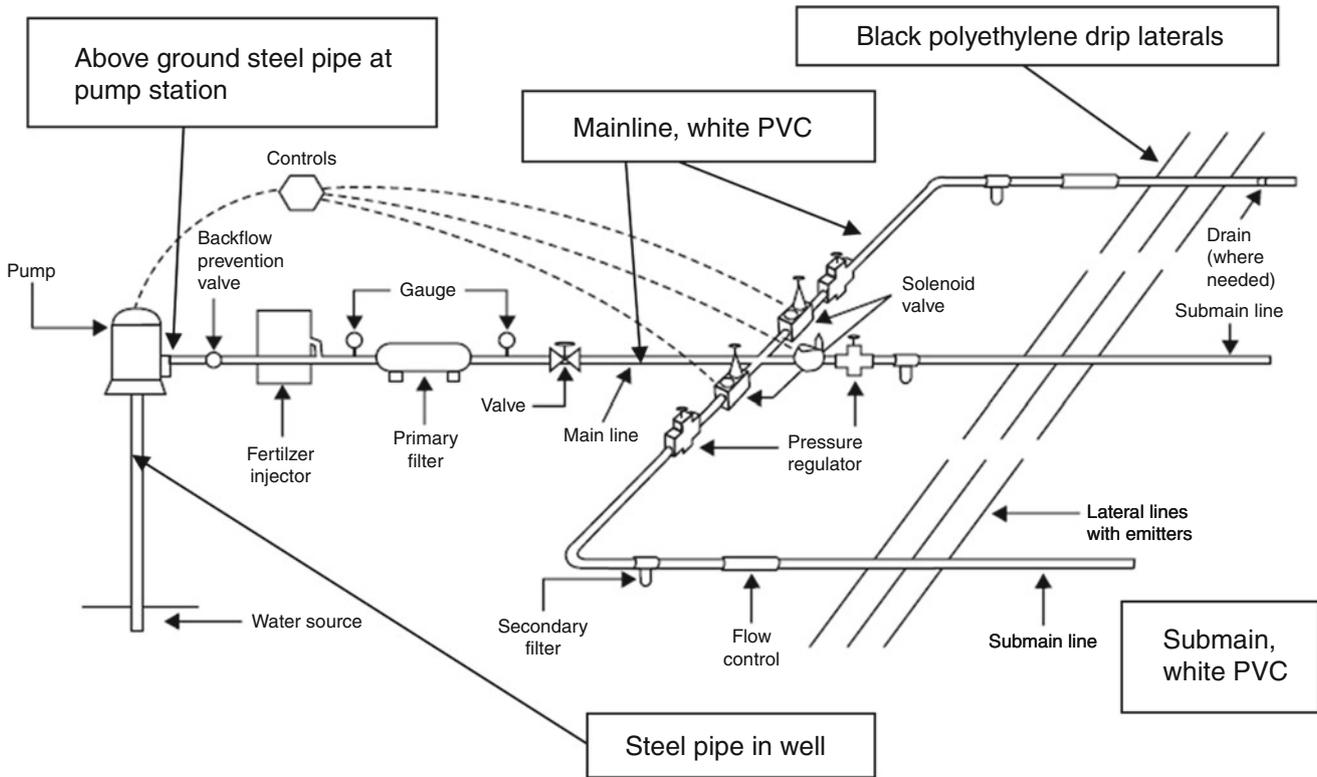
2. What is the hydraulic head and total energy of water in a pipe that is 5 m above the datum with pressure 350 kPa and water velocity 1.5 m/sec?

    Velocity head = $1.5^2/(2*9.81) = 0.114$ m
    Pressure head = $350,000/(9.81*1000) = 35.7$ m
    Hydraulic head = $35.7 + 5 = 42.7$ m
    Total energy = 42.7 m $+ 0.114$ m $= 42.8$ m.

3. When does nonsteady state flow occur, and what are the possible hazards associated with nonsteady state flow?

    Non steady state flow takes place when valves are opened or closed or pumps are turned on or off. When the system is turned and the pipe is filled the possible hazard is water hammer. When the system is turned off and the pipe is drained the possible hazard is creating a negative pressure in the pipe, which may lead to collapse of the pipe.

4. Maximum allowable flow velocity in PVC irrigation pipes is typically specified as 1.5 m/sec. What is the kinetic energy of water at this velocity? Express your answer in terms of m (length) and kPa (pressure). If the irrigation system operates at 350 kPa, then what percent of the energy is kinetic?

    KE $= v^2/(2g) = 1.5^2/(2*9.8$ m/ sec $) = 0.11$ m $= 1.1$ kPa.
    KE/Pressure $= 1.1/350*100\% = 0.31\%$

5. What two forces are included in the Reynolds number, and why is turbulent flow observed at higher Reynolds numbers?

    Reynolds number is the ratio of momentum to viscous forces. Higher momentum (larger pipe diameter and higher velocity) and Reynolds number tends to propagate turbulent eddies while higher viscosity (lower Reynolds number) dampens out eddies and leads to laminar flow.

6. Calculate the friction loss in 1,000 m of 50 mm nominal diameter class 125 pipe. Calculate for flow velocities of 0.05, 1, and 3 m/sec with the Hazen-Williams and Darcy-Weisbach equations. Use C = 140 and 150 in the Hazen-Williams equation. Show your work.

Velocity = 1 m/sec
Analysis with Darcy-Weisbach.

$$ID = 56.6 \text{ mm.}$$
$$A = \pi D^2/4 = \pi 0.056^2/4 = 0.00246 \text{ m}^2$$
$$Q = V*A = 1*0.00246 = 0.00246 \text{ m}^3/\text{sec}$$

$$Q = \left(\frac{0.0246 \ m^3}{\text{sec}}\right)\left(\frac{3,600 \ \text{sec}}{hr}\right)\left(\frac{1,000 \ L}{m^3}\right) = 8,860 \ L/hr$$

$$Re = \frac{vD}{\nu} = \frac{1*0.0566}{1*10^{-6}} = 56,600$$

The flow is turbulent so the Blasius equation is used to calculate f

$$f = \frac{0.316}{Re^{1/4}} = \frac{0.316}{56,600^{1/4}} = 0.0205$$

$$h_f = 6.377 fL\frac{Q^2}{D^5} = 6.377*0.0205*1000*\frac{8,860^2}{56.6^5} = 18.45 \ m$$

Analysis with Hazen-Williams for v = 1 m/sec, C = 140, $h_f = 20.95$

$$h_f = kL\frac{\left(\frac{Q}{C}\right)^{1.85}}{D^{4.87}} = 1.22*10^{10}*1000*\frac{\left(\frac{2.516}{140}\right)^{1.85}}{56.6^{4.87}} = 20.95 \ m$$

Analysis with Hazen-Williams for v = 1 m/sec, C = 150, $h_f = 18.43$

Thus, for v = 1 m/sec, which is a normal flow velocity in irrigation pipes, the Hazen-Williams equation agrees with the Darcy-Weisbach equation with C = 150.

Analysis with Darcy-Weisbach, for v = 3, $h_f = 126$ m
Analysis with Hazen Williams for v = 3, C = 140

$$h_f = kL\frac{\left(\frac{Q}{C}\right)^{1.85}}{D^{4.87}} = 1.22*10^{10}*1000*\frac{\left(\frac{7.548}{140}\right)^{1.85}}{56.6^{4.87}} = 160 \ m$$

Analysis with Hazen-Williams for v = 3, C = 150

$$h_f = kL\frac{\left(\frac{Q}{C}\right)^{1.85}}{D^{4.87}} = 1.22*10^{10}*1000*\frac{\left(\frac{7.548}{150}\right)^{1.85}}{56.6^{4.87}} = 141 \ m$$

In this range, which is greater than normal irrigation flow velocity, the Hazen-Williams equation overpredicts the friction loss when compared with the Darcy-Weisbach equation.

Analysis with Darcy-Weisbach, for v = 0.05 m/sec,

$$Re = \frac{vD}{\nu} = \frac{0.03*0.0566}{1*10^{-6}} = 1,700$$

$$f = 64/Re = 64/1,700 = 0.0377 \rightarrow h_f = 0.03 \text{ m.}$$

Analysis with Hazen-Williams for v = 0.03 m/sec, C = 150, $h_f = 0.028$
Analysis with Hazen-Williams for v = 0.03 m/sec, C = 140, $h_f = 0.032$

7. Redo Example 8.2, but the pipe discharges into a pond with a water surface elevation that is 100 meters below the upper pond water surface elevation. The pipe inlet projects into the upper pond. Use the Hazen-Williams equation.

This problem is first solved by hand and the Worksheet is at the end.
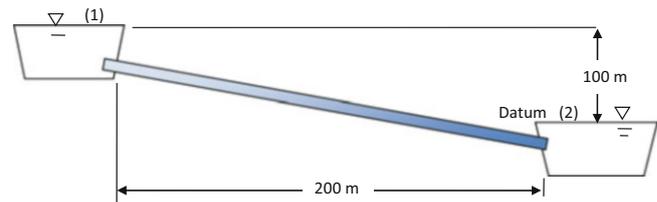
Set the control points at the water surfaces as shown in Fig. 8.3. The minor loss coefficient for a pipe projecting into the upper pond is 0.78 and for discharge to a reservoir is 1.0. The inside diameter of 2″ Class 125 pipe is 56.6 mm (Table 8.5).

$$\frac{v_2^2}{2g} + \frac{P_2}{\rho g} + z_2 = \frac{v_1^2}{2g} + \frac{P_1}{\rho g} + z_1 - h_f - h_m + H_p$$

Rearrange and solve for friction and minor losses.

$$h_f + H_m = \frac{v_1^2}{2g} + \frac{P_1}{\rho g} + z_1 - \left(\frac{v_2^2}{2g} + \frac{P_2}{\rho g} + z_2\right) + H_p$$

$$= \frac{0^2}{2g} + \frac{0}{\rho g} + 100 - \left(\frac{0^2}{2g} + \frac{0}{\rho g} + 0\right) +$$

$$0k_1L\frac{\left(\frac{Q}{C}\right)^{1.85}}{D^{4.87}} + K_{entrance}\frac{v^2}{2g} + K_{exit}\frac{v^2}{2g} = 100$$

Calculate the Hazen-Williams friction loss in terms of velocity because the minor loss term also uses velocity. Use units of L/sec and convert to m3/sec by multiplying by 1,000. The entrance coefficient for a pipe projecting into the pond is 0.78, and the discharge coefficient is 1.0.

$$1.22*10^{10}*200\frac{\left(\frac{vA*1000}{C}\right)^{1.85}}{D^{4.87}}+(0.78+1)\frac{v^2}{2g}=100m$$

$$1.22*10^{10}*200\frac{\left(\frac{v\left(\frac{\pi*0.0566^2}{4}\right)*1000}{150^{1.85}}\right)^{1.85}}{56.6^{4.87}}+(1.78)\frac{v^2}{2*9.81}$$

$$=100m$$

The problem must be solved iteratively by guessing a velocity and then successively adjusting the velocity until the losses on the left side of the equation = 100 m.

A reasonable first guess is 1.5 m/sec since this is the maximum allowable velocity in many (closed end) pipe systems.

$$1.22*10^{10}*200\frac{\left(\frac{1.5\left(\frac{\pi*0.0566^2}{4}\right)*1000}{150^{1.85}}\right)^{1.85}}{56.6^{4.87}}+(1.78)\frac{1.5^2}{2*9.81}$$

$$=8.01\ m$$

In the Hazen-Williams equation, where pressure loss varies primarily as velocity to the 1.85 power, the solution converges most rapidly by taking the ratio of the desired loss to calculated

loss to the 1/1.85 power. It converges in one iteration as follows.

$$v_2=v_1\left(\frac{actual\ losses}{calculated\ losses}\right)^{(1/1.85)}=1.5\left(\frac{100}{8.01}\right)^{(1/1.85)}$$

$$=5.87\ m/\sec$$

Substitute 1.286 for v in order to check the answer.

$$1.22*10^{10}*200\frac{\left(\frac{5.88\left(\frac{\pi*0.0566^2}{4}\right)*1000}{150^{1.85}}\right)^{1.85}}{56.6^{4.87}}+(1.78)\frac{(5.87)^2}{2*9.81}$$

$$=100\ m$$

Thus, 5.87 m/sec is the correct answer as calculated by the Hazen-Williams equation. The flow rate at an average velocity of 5.87 m/sec is

$$Q=1,000*3,600*5.87*\left(\frac{\pi*0.0566^2}{4}\right)=53260.30\ L/hr$$

$$Q=\ \textbf{14.77 L/s}$$

The problem can also be solved in the Worksheet

	A	B	C	D	E	F	
1	Hazen-Williams calculation of velocity				Darcy-Weisbach calculation of velocity (main pi		
2	Minor + vel. losses Km	1.78			Minor + vel. losses Km	1.78	
3	Pot + Press. Energy diff	100 m			Pot + Press. Energy diff	100 m	
4	Pipe parameters				Kinematic viscosity	1.00E-06 m2/se	
5	C	150			Surface roughness K	0.00000 mm	
6	Pipe length	200 m			Pipe length	200 m	
7	Inside pipe diameter	0.0566 m			Inside pipe diameter	0.0566 m	
8	Cross-sectional area	0.0025 m2			Cross-sectional area	0.0025 m2	
9	Adjust cell C10 until cell C13 = cell C3				Laminar flow?	FALSE	
10	Initial main velocity guess	1.5 m/sec			Velocity from Hazen-W	5.871 m/sec	
11	Initial energy diff	8.01 m			Reynolds number	332270	
12	Adjusted velocity	5.8705 m/sec			f factor	0.0132	
13	Calculated energy diff	100.579 m			Initial energy diff	84.8185 m	
14	Flow rate	14.77 LPS			Adjusted velocity	6.417 m/sec	
15	Velocity head	1.7565 m			Adjusted f factor	0.0129	
16					Adjusted flow rate	16.15 LPS	
17					Calculated energy diff	99.20 m	
18	Input data in white cells				Velocity head	2.0987 m	

Note that the Hazen-Williams answer is significantly lower than the Darcy-Weisbach answer at the high flow rate.

8. For the parameters in Example 8.3, find the flow rate with the Hazen-Williams equation: the inside diameter is 56.6 mm, the pipe length is 200 m, and the Hazen-Williams C value is 150. Recalculate flow rate with the Darcy-Weisbach equation. The inlet pipe projects into the reservoir.

The minor loss coefficient, K_m, for a square edged inlet is 0.5. Thus, total K = 1.5.

As a first guess, try velocity = 1.5 m/sec, since this is a typical PVC pipe design velocity.

$$1.22*10^{10}*200\frac{\left(\frac{1.5*0.002516*1000}{150}\right)^{1.85}}{56.6^{4.87}} + (1.5)\frac{1.5^2}{2*9.801}$$

$$= 7.98 \ m$$

In a problem where pressure loss varies as velocity squared or 1.85, the solution converges in one iteration as follows.

$$v_2 = v_1\left(\frac{actual \ losses}{calculated \ losses}\right)^{1.85} = (1.5)\left(\frac{1}{7.98}\right)^{1.85}$$

$$= 0.488 \ m/\sec$$

$$1.22*10^{10}*200\frac{\left(\frac{0.488*0.002516*1000}{150}\right)^{1.85}}{56.6^{4.87}} + (1.5)\frac{0.488^2}{2*9.801}$$

$$= 0.997 \ m$$

Thus, the answer, according to the Hazen-Williams equation is v = 0.488 m/sec → 1.23 L/sec.

The final answer from the Hazen-Williams equation is used as the first guess for the Darcy-Weisbach equation. Results can be calculated in the Worksheet. The D-W solution is very close to the H-W solution.

	Hazen-Williams calculation of velocity		
1	Hazen-Williams calculation of velocity		
2	Minor + vel. losses Km	1.5	
3	Pot + Press. Energy diff	1	m
4	Pipe parameters		
5	C	150	
6	Pipe length	200	m
7	Inside pipe diameter	0.0566	m
8	Cross-sectional area	0.0025	m2
9	Adjust cell C10 until cell C13 = cell C3		
10	Initial main velocity guess	1.5	m/sec
11	Initial energy diff	7.98	m
12	Adjusted velocity	0.4881	m/sec
13	Calculated energy diff	0.997	m
14	Flow rate	1.23	LPS
15	Velocity head	0.0121	m
16			
17			
18	Input data in white cells		
19			

	Darcy-Weisbach calculation of velocity (main pip		
	Minor + vel. losses Km	1.5	
	Pot + Press. Energy diff	1	m
	Kinematic viscosity	1.00E-06	m2/se
	Surface roughness K	0.00000	mm
	Pipe length	200	m
	Inside pipe diameter	0.0566	m
	Cross-sectional area	0.0025	m2
	Laminar flow?	FALSE	
	Velocity from Hazen-W	0.488	m/sec
	Reynolds number	27628	
	f factor	0.0245	
	Initial energy diff	1.0700	m
	Adjusted velocity	0.471	m/sec
	Adjusted f factor	0.0247	
	Adjusted flow rate	1.18	LPS
	Calculated energy diff	1.00	m
	Velocity head	0.0113	m

9. Calculate the pressure rating in metric units and convert to psi for 4 inch (100 mm) class 160 PVC (1120) pipe.

The dimension ratio for Class 160 pipe is 26. S = 13.8 MPa for PVC

$$PR = \frac{2S}{DR - 1} = \frac{2*13.8}{26 - 1} = 1.102 \ MPa$$

$$= 1102 \ kPa/6.91 \ kPa/PSI = 160 \ PSI$$

10. Ten inch (250 mm) Class 160 bell end pipe has expansion joints. Calculate the velocity and magnitude of the pressure wave if the operating velocity is 2.3 m/sec, and a valve suddenly closes. If the operating pressure is 50 psi (345 kPa), then what is the maximum surge pressure?

The answer is calculated in the surge worksheet. GPM is set to 1820 so that v = 2.3 m/sec in right column.

The maximum allowable surge pressure is 1654, and the design + surge pressure is 1104. Thus, the design is OK even though the velocity is greater than 1.5 m/sec.

The answer can also be calculated manually.

Calculate the velocity of the pressure wave.

$$a = \frac{\left[\frac{K}{\rho}\right]^{0.5}}{\left[1 + \left(\frac{K}{E}\right)\left(\frac{D}{t}\right)C_1\right]^{0.5}} = \frac{\left[\frac{2.2*10^9}{1,000}\right]^{0.5}}{\left[1 + \left(\frac{2.2*10^9}{2.76*10^9 \ Pa}\right)\left(\frac{252.1}{10.49}\right)*1\right]^{0.5}}$$

$$= 330 \ m/\sec$$

Calculate the magnitude of pressure wave.

$$\Delta H = \Delta v \frac{a}{g} = 2.3 * \frac{330}{9.8} = 77 \ m$$

Calculate the surge pressure

$P + \Delta H = 50$ psi $(6.9$ kPa/psi$) + (77)(10.2$ kPa/m$)$ $= 1130$ kPa, which is the same as 1104 kPa calculated in the spreadsheet.

11. Flow rate is 10 GPM (37.9 L/min) and the design pressure is 50 psi (345 kPa). Select a pipe class and diameter that does not exceed the maximum allowable surge pressure. Use the surge equations in this case and not just the 1.5 m/s rule. Also perform an economic analysis for the best pipe diameter. Project parameters are $3,000/m³ PVC, 20 year, 8 %, 1440 hr/year, $0.1/kW-hr, pump efficiency = 80 %.

The 18 mm (3/4 inch) pipe is acceptable.

	Option 1	Option 2	Option 3
PVC Pipe			
Pipe Length (m)	100		C 140
Q (LPS)	0.631	← Q (GPM)	10
Design Pressure (kPa)	345	← PSI	50
% max due to temperature and fittings	100%		
PVC pipe diameter and class (mm)	18 SCH 40	25 CL 200	31 CL 125
Nominal diameter (in)	3/4"	1"	1 1/4"
ID (mm)	20.96	30.2	39.6
OD (mm)	26.7	33.4	42.2
Wall thickness (mm)	2.87	1.60	1.3
SDR	9.30	20.88	32.46
Head loss (m)	20.23	3.42	0.91
Velocity (m/s)	1.828	0.881	0.512
C1 (this value must be entered)	1.00	1.00	1.00
Surge pressure (kPa)	1038	326	151
Design + surge pressure (kPa)	1382.6	670.9	496.0
Max surge + design (1.5) (% max)	4986	2083	1316
Surge pressure < 1.5 * design pressure	Yes	Yes	Yes
Velocity < 1.5 m/sec	No	Yes	Yes
Acceptable based on surge and velocity?	No	Yes	Yes
Pressure wave velocity a (m/sec)	568	370	295
Minimum valve closure time (seconds)	0.35	0.54	0.68
Volume of PVC (m3/m)	0.000215	0.000160	0.000167
Cost of PVC ($/m3)	3000.00	3000.00	3000.00
Cost of PIPE ($/m)	$ 0.645	$ 0.480	$ 0.501

Polyethylene	
Length (m)	200
Q (LPH)	300
Design kPa	530
C	140
Temp and fittings (% max)	100%
ID (mm)	12
OD (mm)	12.7
Wall thickness (mm)	0.35
SDR	36.29
Head loss (m)	14.40
Velocity (m/s)	0.737
C1	1.00
Surge pressure (kPa)	104
Design + surge (kPa)	448.9
Max (1.5) (%max)	468
Surge pressure check	Yes
Velocity < 1.5 m/sec	Yes
Acceptable surge and v?	Yes
a (m/sec)	141
Closure time (seconds)	1.42

Tabs: Pipe flow calc / **Surge** / Energy Cost / Air vent surge / No air

It is also interesting to evaluate the problem from an economic point of view. In order to do this, click on the energy cost button. For the assumed project parameters ($3,000/m³ PVC, 20 year, 8 %, 1440 hr/year, $0.1/kW-hr, pump efficiency = 80 %), the total cost including energy and capital is much lower for the 1 ¼ pipe.

Based on PVC pipe dimensions from surge page

Pump Efficiency (%)	80	Rate Return (%) 8
Cost energy ($/kW)	0.1	# Years 20
Hours operation per Year	1440	

	Option #1	Option #2	Option #2
Nominal Diam (in)	3/4"	1"	1 1/4"
Head Loss (m/m)	0.2023	0.0342	0.0091
Power (kW/m)	0.015639	0.002641	0.000706
Annual cost energy ($/m)	$ 2.252	$ 0.380	$ 0.102
Present value of energy ($/m)	$ 22.11	$ 3.73	$ 1.00

Based on price on surge page	Option #1	Option #2	Option #2
Pipe capital cost ($/m)	$ 0.64	$ 0.48	$ 0.50

	Option #1	Option #2	Option #2
Total present Value ($/m)	$ 22.76	$ 4.21	$ 1.50

Tabs: Pipe flow calc / Surge / **Energy Cost** / Air vent surge / No air

12. Calculate the maximum surge pressure in a long (100 m) drip irrigation tube (12 mm ID polyethylene). Solve the problem in two ways: assume an air vent and no air vent. Inlet pressure is 210 kPa. Conclude by discussing whether pressure relief valves and air vents are needed on long drip irrigation tubes and state the reason for your answer. Also consider sprinkler laterals (PVC) with and without sprinklers along the pipe.

The air vent surge is calculated as shown on the next page. The K value from cell K2 was used in Cell G6. Keep the inlet pressure the same as in the previous problem, but it should probably be lower for a drip system. Also note that we are neglected any pressure dissipation that may occur from having drip emitters on the lateral.
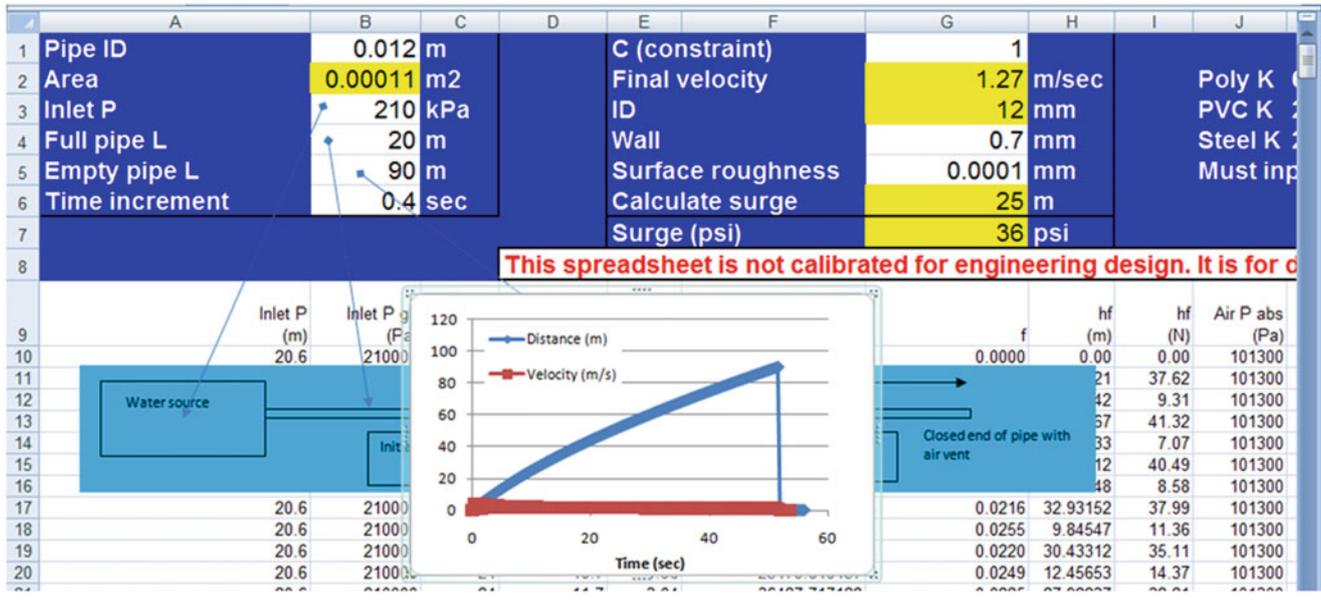
The no air vent surge is calculated as shown below. Note that you must change the increment in time in order to get the result shown in the next screen capture. Also note that the surge associated with drip tubing is not very large. This is why you don't need air vents on small drip tubes.
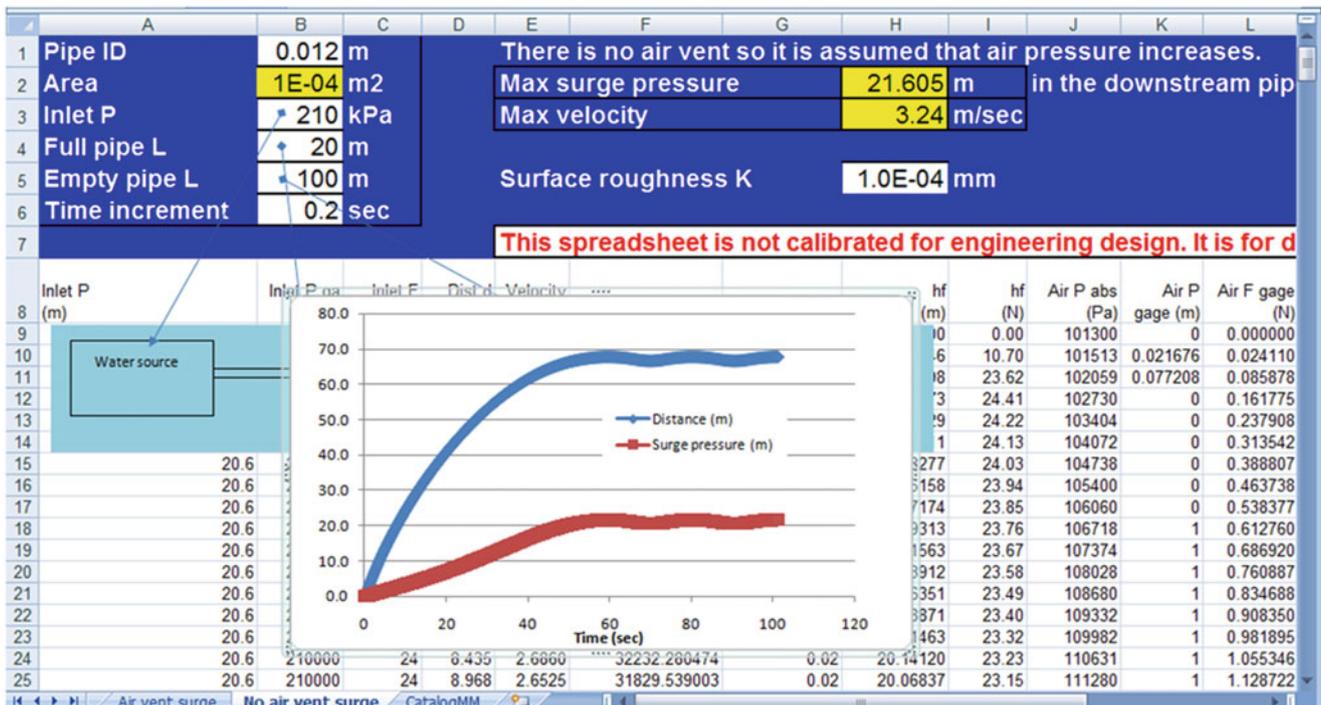
13. For the following parameters, find the best economic pipe size. The price of PVC is $3,000/m^3. Project parameters are 20 year, 8 %, $0.1/kW-hr, pump efficiency = 80 %.

2 pivots operating at one time (191 L/sec):	294 hr
1 pivot operating alone (96 L/sec):	2,076 hr

For the surge pressure check, the surge Worksheet was used. The following three pipe sizes and classes are acceptable, and of course larger sizes are also acceptable with respect to surge pressure.

12 inch class 200

14 inch schedule 40

16 inch schedule 40

		PVC Pipe				Polyethylene	
Energy Cost >>	Pipe Length (m)	800		C	140	Length (m)	200
	Q (LPS)	191.016	← Q (GPM)	3028		Q (LPH)	300
	Design Pressure (kPa)	531.3	←	PSI	77	Design kPa	530
	% max due to temperature and fittings	78.3%				C	140
		Option 1	Option 2	Option 3			
	PVC pipe diameter and class (mm)	300 CL200	350 SCH 40	400 SCH 40		Temp and fittings (% max)	100%
	Nominal diameter (in)	12"	14"	16"			
	ID (mm)	293.12	333.8	380.6		ID (mm)	12
	OD (mm)	323.9	356	406		OD (mm)	12.7
	Wall thickness (mm)	15.39	11.10	12.7		Wall thickness (mm)	0.35
	SDR	21.05	32.07	31.97		SDR	36.29
	Head loss (m)	16.78	8.91	4.70		Head loss (m)	14.40
	Velocity (m/s)	2.831	2.183	1.679		Velocity (m/s)	0.737
	C1 (this value must be entered)	1.00	1.00	1.00		C1	1.00
	Surge pressure (kPa)	1043	647	499		Surge pressure (kPa)	104
	Design + surge pressure (kPa)	1574.4	1178.8	1030.2		Design + surge (kPa)	635.2
	Max surge + design (1.5) (% max)	1617	1043	1047		Max (1.5) (%max)	468
	Surge pressure < 1.5 * design pressure	Yes	No	Yes		Surge pressure check	No
	Velocity < 1.5 m/sec	No	No	No		Velocity < 1.5 m/sec	Yes
	Acceptable based on surge and velocity?	No	No	No		Acceptable surge and v?	No
	Pressure wave velocity a (m/sec)	369	297	297		a (m/sec)	141
	Minimum valve closure time (seconds)	4.34	5.39	5.38		Closure time (seconds)	11.34
	Volume of PVC (m3/m)	0.014916	0.012027	0.015692			
	Cost of PVC ($/m3)	3000.00	3000.00	3000.00			
	Cost of PIPE ($/m)	$ 44.749	$ 36.082	$ 47.076			

Surge / Energy Cost / Air vent surge / No air vent surge / Ca

The next step is to use economics to select the best pipe diameter. Click the Energy Cost button on the Surge Worksheet. First evaluate at the high flow rate for 294 hours.

Based on PVC pipe dimensions from surge page ☒

Pump Efficiency (%)	80	Rate Return (%)	8
Cost energy ($/kW)	0.1	# Years	20
Hours operation per Year	294		

	Option #1	Option #2	Option #2
Nominal Diam (in)	12"	14"	16"
Head Loss (m/m)	0.0210	0.0111	0.0059
Power (kW/m)	0.491069	0.260781	0.137648
Annual cost energy ($/m)	$ 14.437	$ 7.667	$ 4.047
Present value of energy ($/m)	$ 141.75	$ 75.27	$ 39.73

Based on price on surge page	Option #1	Option #2	Option #2
Pipe capital cost ($/m)	$ 44.75	$ 36.08	$ 47.08

| Total present Value ($/m) | $ 186.50 | $ 111.36 | $ 86.81 |

☒

| e Return (%) | 8 |
| # Years | 20 |

	Option #2
	18"
	0.0033
	0.077365
	$ 2.275
	$ 22.33

	Option #2
	$ 59.66

| | $ 82.00 |

Evaluate the low flow rate

Based on PVC pipe dimensions from surge page ☒

Pump Efficiency (%)	80	Rate Return (%)	8
Cost energy ($/kW)	0.1	# Years	20
Hours operation per Year	2076		

	Option #1	Option #2	Option #2
Nominal Diam (in)	12"	14"	16"
Head Loss (m/m)	0.0058	0.0031	0.0016
Power (kW/m)	0.068015	0.036119	0.019065
Annual cost energy ($/m)	$ 14.120	$ 7.498	$ 3.958
Present value of energy ($/m)	$ 138.63	$ 73.62	$ 38.86

Based on price on surge page	Option #1	Option #2	Option #2
Pipe capital cost ($/m)	$ 44.75	$ 36.08	$ 47.08

| Total present Value ($/m) | $ 183.38 | $ 109.70 | $ 85.94 |

☒

| e Return (%) | 8 |
| # Years | 20 |

	Option #2
	18"
	0.0009
	0.010715
	$ 2.225
	$ 21.84

	Option #2
	$ 59.66

| | $ 81.51 |

The sum of present value costs are shown below. The pipe diameter with the lowest present value cost for the sum of energy and capital is the 20″ pipe.

Pipe Diam.	Capital	Low flow rate	High flow rate	Total
12 inch	44.75	138.63	141.75	Astronomical
14 inch	36.08	73.62	75.27	Astronomical
16 inch	47.08	38.86	39.73	$126/m
18 inch	59.86	21.84	22.33	$104/m
20 inch	70.15	12.84	13.12	$95/m***
21 inch	76.54	10.13	10.36	$96/m

Chapter 9: Solution

1. The revolutionary speed of electric pumps is slightly less than divisors of 3600. Typical pump rpm's are 875, 1750, and 3500. Why are most pumps manufactured with these revolutionary speeds?

Electrical current is 60 cycles per second, which is 3,600 cycles per minute. Pump motors have sets of windings that provide torque to the pump by varying the electric field. If there are two windings, then the pump rpm with no load is 3,600 rpm. If there are four windings, then the pump rpm is 1,800. If there are six windings, then the pump rpm is 900. The load on the motor from the pump slows the motor down slightly.

2. What would be a typical TDH for a centrifugal pump with flow rate 1,000 m³/hr based on the typical specific speed for a centrifugal pump? Recalculate for pump flow rates of 100 m³/hr and 10 m³/hr. What type of pump would be appropriate for a very high flow rate and very low head?

$$1000 \ \text{m}^3/\text{hr} = 16,700 \ \text{L/min}$$

$$N_s = .2108N*\left(Q^{.5}/ H^{.75}\right) = 500 \ \text{ for centrifugal pump.}$$
$$500 = .2108(1800)*\left(16,700^{.5}/H^{.75}\right)$$
$$1.32 = \left(16,700^{.5}/H^{.75}\right)$$
$$H = 451 \ \text{m}$$

$$\text{At } Q = 100 \ \text{m}^3/\text{hr}, H = 97 \ \text{m}$$
$$\text{At } Q = 10 \ \text{m}^3/\text{hr}, H = 21 \ \text{m}$$

An Archimedes screw pump would be appropriate for a very high flow rate and very low head.

3. Using the equations for the relationships between power, flow rate, and head, describe the shape of the head/capacity curve if efficiency was constant over a range of flow rates?

The shape would be concave up

4. Verify that the water horsepower generated by the 5.9375 impeller curve in Fig. 9.4 corresponds with the efficiency and brake horsepower curves. Calculate at the point of highest efficiency.

Water HP output is calculated with the following equation.

HP = (Q TDH)/(3960 * Eff) where Q is gpm and H is ft.
The highest efficiency is found at Q = 60 gpm. The head and efficiency at this flow rate are 28 ft and 69 %, respectively.

$$\text{HP} = 60*28/(3960*0.69) = 0.61 \ \text{HP}$$

The corresponding point on the HP curve (darkest line) is also 0.61 HP

5. Describe the relationship between efficiency and flow rate in Fig. 9.4.

The efficiency is a maximum in the middle of the curve. It drops off slowly on either side of the high efficiency point but then drops off rapidly at the ends of the flow curve.

6. An irrigation system requires 600 gpm and 160 ft head. Select the best impeller for this application on the B4JPBH (Fig. 9.5) pump curve.

The 12 3/8″ impeller provides the required total dynamic head.

7. What is the maximum allowable flow rate of a B4JPBH pump (Fig. 9.5) with a 12 3/8″ impeller and a 40 HP motor? What is the maximum flow rate for the 50 HP motor with the same impeller?

The 40 HP curve exceeds the head-capacity curve above 1,000 gpm. The flow rate should never be allowed to exceed this value. The 12 3/8″ impeller curve never exceeds the 50 HP motor curve; however, the impeller curve ends at 1240 gpm so this is the maximum allowable flow rate. If necessary, the pump should be started with the throttling valve partially closed until the pipe system is pressurized in order to prevent high flow rates when discharging into an empty pipe. If the flow exceeds the maximum value, then amperage will become high and the pump will overheat.

8. An irrigation system requires TDH = 168 ft and Q = 600 gpm. Select an impeller diameter (trimmed if necessary) and select a motor HP with the B4JPBH pump.

The operating point is slightly above the 30 HP motor curve so a 40 HP motor must be selected. In order to select an impeller diameter, follow the slope of the efficiency curve down to the next smaller impeller. The point at which

the slope crosses the 12 3/8″ curve is at Q = 580 gpm and TDH = 157 ft. Calculate the impeller diameter based on the difference in TDH since that is more sensitive to impeller diameter than flow rate at the operating point; however, it could also be calculated based on the difference in flow rate.

$$D_{\text{Im}-2} = D_{\text{Im}-1}\sqrt{\frac{H_2}{H_1}} = 12.375\sqrt{\frac{168}{157}} = 12.8''$$

9. The 16BZ pump (Fig. 9.7) with a 5¾″ impeller is used to run a sprinkler system. There is a 2 m pressure loss in pump fittings and filters. Find the operating point. Plot the two curves and verify that the calculated point is the correct point. The 5¾″ head-capacity curve and the irrigation system curve are:

$$\text{TDH(m)} = -0.00170 \; Q^2 + 0.0743 \; Q + 43.76$$

$$Q_{\text{system}}(\text{m}^3/\text{h}) = 14.175\left(H_{\text{system}}\right)^{0.531}$$

Adjust the system curve to account for pump fitting and filter losses ($H_{\text{system}} = \text{TDH} - 2$ m).

$$Q_{\text{system}}(\text{m}^3/\text{h}) = 14.175(\text{TDH} - 2)^{0.531}$$

Substitute the head capacity equation for TDH in the system equation

$$Q = 14.175\left(-0.00170 \; Q^2 + 0.0743Q + 43.76 - 2\right)^{0.531}$$

Solve for Q by iteration, Q = 92.8 m³/hr, TDH = 36.1 m
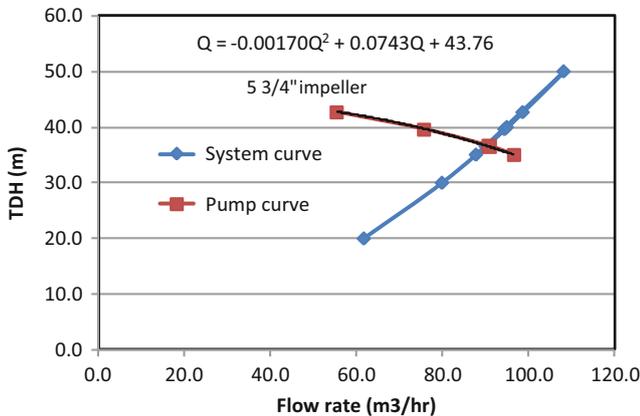
10. In Example 9.6, change the elevation of pivot 2 to 100 m elevation and pivots 3 and 4 to 120 m elevation. Select the pump operating pressure. Each pivot requires 100 L/sec. Determine the number of pumps, flow rate, and TDH of the pump station. Discuss options to reduce energy.

Four pumps must be installed. Each must have a flow rate of 100 L/sec, and TDH = 59 m. In order to reduce energy

cost, booster pumps could be installed after pivot 2 in order to provide extra pressure for pivots 3 and 4. This would enable the four pumps at the pump station to have a TDH = 30 m.

Pressure requirement (All in meters)	Pivot 1	Pivot 2	Pivot 3	Pivot 4
Sprinkler pressure (+ elevation) required	15	15	15	15
Elevation difference (max pivot – pump elev.)	5	2	22	22
Pressure loss in pivot pipeline	2.8	5.4	15	15
Screen filter	2	2	2	2
Pump fittings losses	3	3	3	3
Safety factor	2	2	2	2
Total pressure requirement (TDH)	29.8	29.4	59	59

11. A variable speed pump controller is used to vary the flow rate of the 16BZ pump with the 5 3/4″ impeller. The revolutionary speed is lowered from 3500 to 3000 RPM. The system curve is Q_{system} (m³/h) = 14.175 $(H_{\text{system}})^{0.531}$. There is 3.5 m head loss in the pump fittings and filters. Find the operating point TDH and flow rate.

Using the *variable speed pump* spreadsheet, the following curve was obtained.
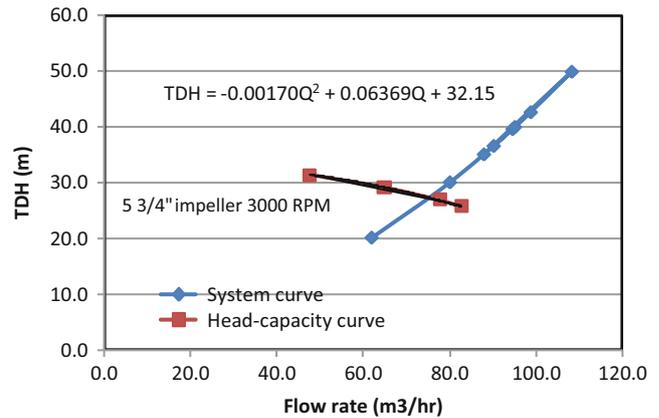
After iteration, the flow rate and TDH are 70 m³/hr and 23 m, respectively.

12. Imagine that a new technology was developed that enabled farmers to produce biodiesel from crop residue. The biodiesel production unit has a capital equipment cost of $50,000; a labor, maintenance, and energy cost of $0.30/L, and produces 15,000 L of biodiesel per year. Calculate whether this would be a less expensive alternative than the electric pump system in Example 9.9. Use the *Fuel and pump costs* worksheet in Chapter 9 Excel program.

The annual costs of biodiesel production would be $14,729 L * $0.30/L = $4,400

Present value for 20 yr supply of fuel = PV(0.08, 20, 4,400) = $44,000

Assume that diesel pump capital and replacement costs are the same

Total PV cost of the **biodiesel system** is $44,000 + $50,000 + $21,000 + $876 + $5,106 = **$122,000**

The biodiesel system is not economically competitive with the electric system.

13. Redo Example 9.9 with a solar powered pump. Based on the cost of materials and the service life and replacement cost of solar components, the solar panel array provides electrical energy at a cost of $0.08/kW-hr for the 20 year project life. The solar pump can only be used during daylight; thus a larger pump is required and a reservoir must be constructed for storage. Increased capital cost of hydraulic components is $50,000 and replacement and maintenance costs remain the same as Example 9.9. Recalculate if carbon credits for the system are worth $1,000/yr.

Electric power costs.

The cost of energy is $0.08/kW-hr

BHP required by the pump is 36 HP. Convert to electrical power units: 36 * 0.746 = 26.9 kW

Electric power required = (26.9/Motor efficiency) = 26.9/ 0.9 = 29.89 kW = 40 HP

The pump runs for 1,800 hours to the energy required is 29.89 * 1800 = 53,800 kW-hr

Annual cost of electricity is 53,800 kW-hr * $0.08/kW-hr = $4,297

Present value for 20 yr supply of energy = PV(0.08, 20, 4,297) = $42,188

Electric pump costs

Initial purchase and installation of equipment = $6,000 + $50,000 = $56,000

The present value of a centrifugal pump purchased in year 16 is $3,000 (1 + 0.08)$^{-16}$ = $876

Annual maintenance cost is $400 so present value of maintenance cost is $3927

Total present value cost of the solar powered system is $56,000 + $42,188 + $876 + $3,927 = **$102,991**

The cost of the system without carbon credits is more than the conventional electric supply system in Example 9.9. The present value of carbon credits is PV (0.08,20,1,000) = $9,818. This would bring the cost of the system down to **$93,173**, which would be less expensive than the electric system ($98,265).

14. A pump sucks water from a canal and discharges to a reservoir 100 m above the canal. Pump station valves and fittings are the same as in Example 9.11 except that the pipe diameters are 6″, 3″, 2.5″, and 4″ instead of 4″, 2″, 1 ½″, and 3″. Two other changes are that the eccentric angle is 50^0 and the cone angle is 40°. Flow rate is 20 L/ sec. All pump station pipe is 6 gage steel, and the main-line pipe is 4″ SCH 40 and is 500 m long. Assume an open discharge to the upper reservoir. Calculate the pump TDH required. Show calculations for the pressure loss in the eccentric reducer and the concentric cone. Calculate the percent of required TDH due to pump station losses, and the percent of total friction loss that is due to pump station losses. (Use worksheet).

NTS

100 m
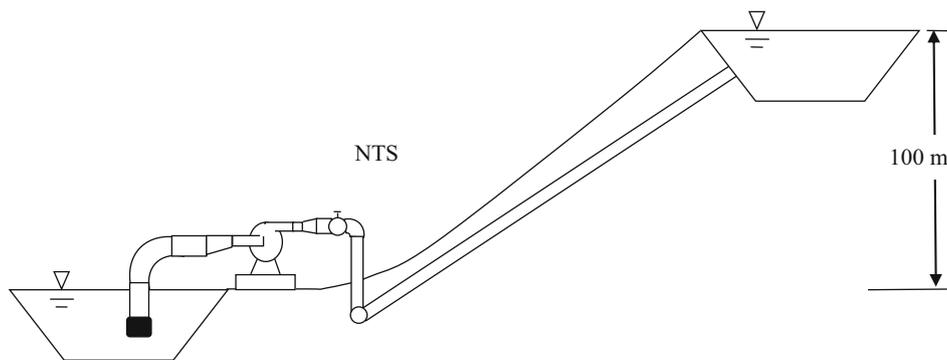
Head loss is calculated in the *Centrifugal pump calc* worksheet as follows. The required TDH is 129.56 m.

The outside diameter of 6 inch pipe is 168.3 mm. Six gage pipe has a wall thickness equal to 5.16 mm. Thus, the inside

diameter of 6 inch 6 gage pipe is 168.3–10.3 = 158.0 mm. The outside diameter of 2 ½ inch 6 gage pipe is 73.0 mm. Thus the inside diameter is 73.0–10.3 = 62.7 mm.

Use 507 m length for mainline to account for PVC fittings.

Answer. Pump station losses are 1.74. As a percentage of TDH, they are (1.74/130) (100 %) = 1.3 %

As a percentage of friction losses (1.74/29.56) (100 %) = 5.9 %

	A	B	C	D	E	F	G	H	I	J	K	L
1	Component		Head requirement			Input data in			Steel pipe diameter			
2	Required pump TDH			129.56 m		white cells			6 gage	OD	t	ID (mm)
3	Total friction loss			29.56 m					6	168.3	5.16	158.0
4	Mainline friction loss			27.81 m					4	114.3	5.16	104.0
5	Total pump station friction			1.74 m					2.5	73	5.16	62.7
6	Elevation gain			100 m					2	60.3	5.16	50.0
7	Flow rate	20 L/sec				72	m3/hr		1.5	48.3	5.16	38.0
8	Steel pipe C	120		Head loss					3	88.9	5.16	78.6
9	Suction pipe total			0.1415 m								
10	Suction pipe length	2 m		0.0174 m		Pipe friction			PVC mainline diameter			
11	Suction pipe diameter	0.158 m							Sch 40	OD	t	ID (mm)
12	Basket strainer K	1.3		0.0690 m		Fittings			4	114.3	6.02	102.3
13	Entrance coefficient K	0		0.0000 m								
14	Foot valve K	0.8		0.0424 m								
15	Sweep 90 K	0.24		0.0127 m								
16	Cross-sectional Area	0.0196 m3										
17	Flow velocity	1.02 m/sec										
18	Inlet pipe total			0.2256 m								
19	Inlet pipe length	0.2 m		0.0521 m		Pipe friction						
20	Inlet pipe diameter	0.0786 m										
21	Eccentric angle (degrees)	60										
22	Eccentric K	0.20		0.1734 m		Fittings						
23	Cross-sectional Area	0.004852 m2										
24	Flow velocity	4.12 m/sec										
25	Outlet pipe total			0.8022 m								
26	Outlet pipe length	0.04 m		0.0313 m		Pipe friction						
27	Outlet pipe diameter	0.0627 m										
28	Cone angle	40										
29	Cone expansion K	0.36		0.7708 m		Fittings						
30	Other fittings K	0.0		0.0000 m								
31	Cross-sectional Area	0.003088 m2										
32	Flow velocity	6.48 m/sec										
33	Discharge pipe total			0.5747 m								
34	Discharge pipe length	4 m		0.2666 m		Pipe friction						
35	Discharge pipe diameter	0.104 m										
36	Discharge valve K	0.09		0.0254 m		Fittings						
37	Discharge loss K (kinetic)	1		0.2826 m								
38	Angle bends K (sum)	0		0.0000 m								
39	Cross-sectional Area	0.008495 m2										
40	Flow velocity	2.35 m/sec										
41	Mainline pipe total			27.8149 m								
42	Mainline pipe length	507 m		27.5323 m		Pipe friction						
43	Mainline pipe diameter	0.1023 m										
44	Mainline pipe C	140										
45	Mainline pipe total K	1		0.2826 m		Fittings						
46	Cross-sectional Area	0.008219 m2										
47	Flow velocity	2.43 m/sec										

15. Redo question 15, but discard the eccentric. Suction pipe is 75 mm (3 in.) pipe. Second, use a bushing on the discharge side (sudden expansion) rather than a cone expansion. Determine which change results in the greatest increase in head loss.

Use the Centrifugal pump calc worksheet to calculate the head loss on the suction side.

Component			Head requirement		Input data in		Steel pipe diameter			
1 Component			Head requirement		Input data in		Steel pipe diameter			
2 Required pump TDH			133.16	m	white cells		6 gage	OD	t	ID (mm)
3 Total friction loss			33.16	m			6	168.3	5.16	158.0
4 Mainline friction loss			27.81	m			4	114.3	5.16	104.0
5 Total pump station friction			5.35	m			2.5	73	5.16	62.7
6 Elevation gain			100	m			2	60.3	5.16	50.0
7 Flow rate	20	L/sec			72	m3/hr	1.5	48.3	5.16	38.0
8 Steel pipe C	120		Head loss				3	88.9	5.16	78.6
9 Suction pipe total			2.5485	m						
10 Suction pipe length	2	m	0.5213	m	Pipe friction		PVC mainline diameter			
11 Suction pipe diameter	0.0786	m					Sch 40	OD	t	ID (mm)
12 Basket strainer K	1.3		1.1262	m	Fittings		4	114.3	6.02	102.3
13 Entrance coefficient K	0		0.0000	m						
14 Foot valve K	0.8		0.6930	m						
15 Sweep 90 K	0.24		0.2079	m						
16 Cross-sectional Area	0.0049	m3								
17 Flow velocity	4.12	m/sec								
18 Inlet pipe total			0.0521	m						
19 Inlet pipe length	0.2	m	0.0521	m	Pipe friction					
20 Inlet pipe diameter	0.0786	m								
21 Eccentric angle (degrees)	0									
22 Eccentric K	0.00		0.0000	m	Fittings					
23 Cross-sectional Area	0.004852	m2								
24 Flow velocity	4.12	m/sec								
25 Outlet pipe total			2.1707	m						
26 Outlet pipe length	0.04	m	0.0313	m	Pipe friction					
27 Outlet pipe diameter	0.0627	m								
28 Cone angle	0									
29 Cone expansion K	0.00		0.0000	m	Fittings					
30 Other fittings K	1.0		2.1394	m						
31 Cross-sectional Area	0.003088	m2								
32 Flow velocity	6.48	m/sec								
33 Discharge pipe total			0.5747	m						
34 Discharge pipe length	4	m	0.2666	m	Pipe friction					
35 Discharge pipe diameter	0.104	m								
36 Discharge valve K	0.09		0.0254	m	Fittings					
37 Discharge loss K (kinetic)	1		0.2826	m						
38 Angle bends K (sum)	0		0.0000	m						
39 Cross-sectional Area	0.008495	m2								
40 Flow velocity	2.35	m/sec								
41 Mainline pipe total			27.8149	m						
42 Mainline pipe length	507	m	27.5323	m	Pipe friction					
43 Mainline pipe diameter	0.1023	m								
44 Mainline pipe C	140									
45 Mainline pipe total K	1		0.2826	m	Fittings					
46 Cross-sectional Area	0.008219	m2								
47 Flow velocity	2.43	m/sec								

The head loss on the suction side increased from $0.1415 + 0.2256 = 0.37$ m to $2.55 + 0.05 = 2.6$ m Thus, the increase is approximately 2.2 m on the suction side. One the discharge side, the increase is $0.802 + 0.575 = 1.37$ m to $2.17 + 0.57 = 2.74$ m. Thus, the increase is 1.37 m on the discharge side. There, the change in suction pipe geometry results in a greater change in losses than removing the cone. However, the cone removal is in the similar range of losses as changing the entire suction section. This shows that the expansion cone is very important.

16. Use the 16BZ pump with 5 3/4″ impeller (M) to deliver water to the upper reservoir for the system shown below. Select pipe diameters equal to 6″, 4″, 3″, and 4″ for the four pump station pipe sections. Use 4″ Schedule 40 PVC for the mainline, which is 493 m long. Draw a system curve (develop with *Centrifugal pump fittings* worksheet by inputting different flow rates and corresponding TDH requirement) and pump head-capacity curve based on Fig. 9.6. Find an exponential equation for the system curve and equation for the head-capacity curve, and calculate the point of intersection (operating point) for the system.
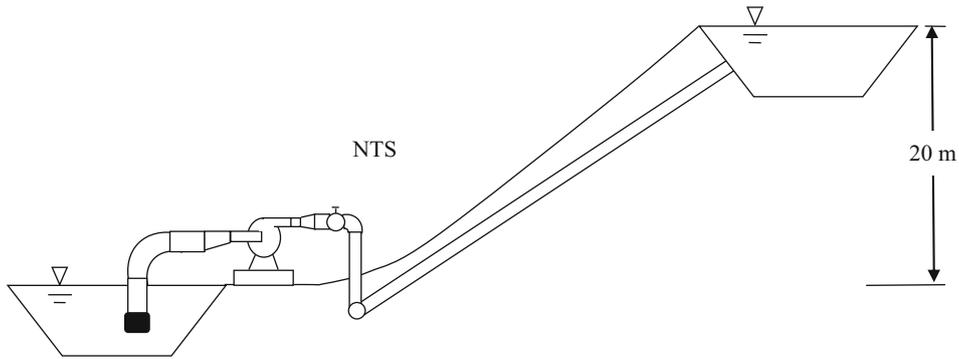
Based on Fig. 9.6 the pump discharge and inlet diameters are

Three flow rates were used to define the system curve with the *Centrifugal pump calc* worksheet.

L/sec	m³/hr	m
10	36	30.6
15	54	42.8
20	72	59.2

Component			Head requirement		Input data in
Required pump TDH			48.60	m	white cells
Total friction loss			28.60	m	
Mainline friction loss			27.43	m	
Total pump station friction			1.17	m	
Elevation gain			20	m	
Flow rate	20	L/sec			
Steel pipe C	120		**Head loss**		
Suction pipe total			0.1681	m	
Suction pipe length	2	m	0.0174	m	**Pipe friction**
Suction pipe diameter	0.158	m			
Basket strainer K	1.3		0.0690	m	**Fittings**
Entrance coefficient K	0.5		0.0265	m	
Foot valve K	0.8		0.0424	m	
Sweep 90 K	0.24		0.0127	m	
Cross-sectional Area	0.0196	m3			
Flow velocity	1.02	m/sec			
Inlet pipe total			0.0428	m	
Inlet pipe length	0.2	m	0.0133	m	**Pipe friction**
Inlet pipe diameter	0.104	m			
Eccentric angle (degrees)	50				
Eccentric K	0.10		0.0295	m	**Fittings**
Cross-sectional Area	0.008495	m2			
Flow velocity	2.35	m/sec			
Outlet pipe total			0.1521	m	
Outlet pipe length	0.04	m	0.0104	m	**Pipe friction**
Outlet pipe diameter	0.0786	m			
Cone angle	40				
Cone expansion K	0.16		0.1417	m	**Fittings**
Other fittings K	0.0		0.0000	m	
Cross-sectional Area	0.004852	m2			
Flow velocity	4.12	m/sec			
Discharge pipe total			0.8037	m	
Discharge pipe length	1.5	m	0.1000	m	**Pipe friction**
Discharge pipe diameter	0.104	m			
Discharge valve K	0.09		0.0254	m	**Fittings**
Angle bend K (sum)	2.4		0.6783	m	
Cross-sectional Area	0.008495	m2			
Flow velocity	2.35	m/sec			
Mainline pipe total			27.4348		
Mainline pipe length	500	m	27.1521	m	
Mainline pipe diameter	0.1023	m			
Mainline pipe C	140				
Mainline pipe total K	1		0.2826	m	
Cross-sectional Area	0.008219	m2			

The system curve and pump curve were graphed and equations were found with Trendline in Excel.
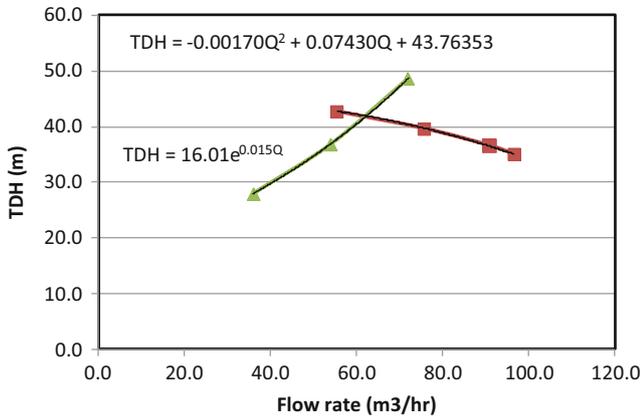
There are two equations and two unknowns, and substitution was used to solve for Q

$$TDH = -0.00170Q^2 + 0.07430Q + 43.76353$$
$$TDH = 16.01e^{0.015Q}$$
$$16.01e^{0.015Q} = -0.00170Q^2 + 0.07430Q + 43.76353$$
$$e^{0.015Q} = \left((-0.00170Q^2 + 0.07430Q + 43.76353)/16.01\right)$$
$$0.015Q = \ln\left((-0.00170Q^2 + 0.07430Q + 43.76353)/16.01\right)$$
$$Q = \left(\ln\left((-0.00170Q^2 + 0.07430Q + 43.76353)/16.01\right)\right)/0.015$$

Iteration was used to find Q (note that the iterative solution does not converge if the equation is not converted from exponential to logarithmic form).

The operation point is 63.7 m³/hr at 42.8 m TDH.

17. Venturi injectors are designed based on the principle that if water velocity increases, then pressure decreases as shown by the Bernoulli equation. A narrow throat increases the velocity at the suction point. Concentric cones are used to gradually increase flow rate to the throat and decrease flow rate from the throat. Based on what you know about concentric cones, draw a Venturi injector geometry that has minimum head loss.

The Venturi has a much smaller angle on the discharge side because expansion cone pressure loss is much higher than reducer cone (inlet cone) pressure loss. If the angle on the discharge side is minimized, then head loss on the discharge side is minimized.
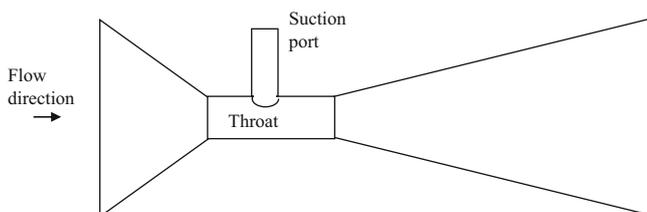
18. Some people recommend creating the pressure differential across a Venturi by restricting mainline flow. It is a much better idea to have a separate centrifugal pump provide the pressure differential, as shown in this example. Mainline flow rate is 200 L/sec, and Venturi flow rate is 0.90 L/sec. Venturi injection time is 1,000 hours per year. The required pressure differential across the Venturi is 283 kPa. The cost of energy is $0.10/kW-hr. Calculate the energy cost per year for providing the required pressure differential across the Venturi by constricting the mainline flow with a valve. Calculate the energy cost of using a centrifugal pump in the bypass line to provide the pressure differential needed by the Venturi.

The power requirement for the case with a valve in the mainline that creates a pressure differential

Power calculations		
Pump flow rate	12000	LPM
Pump head	28.83	m
WHP	74.67	mhp
Efficiency	75.0 %	
BHP	99.56	mhp
Power (kW)	75.07	kW

The energy requirement is 0.75 kW*1,000 hr = 75,000 kW − hr.
The cost of energy is 75,000 kW-hr*$0.10/kW-hr = $7,500/yr

The power requirement for the centrifugal pump in the bypass line.

Power calculations		
Pump flow rate	54	LPM
Pump head	28.83	m
WHP	0.34	mhp
Efficiency	75.0 %	
BHP	0.45	mhp
Power (kW)	0.34	kW

The energy requirement is 0.34 kW*1,000 hr = 340 kW-hr.

The cost of energy is 340 kW-hr*$0.10/kW-hr = $34/yr

19. How could a Venturi be used within a pump to lift groundwater up to the surface in a well. (Hint: look up jet pumps).

A jet pump uses a Venturi as follows. A Venturi is placed below the water level in a well. The pump pushes water down one pipe to the Venturi. The Venturi then sucks in groundwater and the water is then forced back up another pipe to the ground surface.

The following are extra problems that weren't on the homework. They won't be on the exam, but you may be interested in them.

20. Calculate throat pressure (gage pressure and absolute pressure) and discharge pressure in a Venturi injector that that has a 30 mm internal diameter at both ends and that has a flow rate of 0.9 L/sec. The length of the entire Venturi is 15 cm and the length of the throat is 2 cm; however, assume that the equivalent length of the throat is 10 cm due to flow entering the throat through the suction tube. The upstream pressure is 300 kPa. The reducer cone angle (inlet side), θ, is 30°, and the expansion cone angle (discharge side) is 15°. Assume that Hazen-Williams C in the throat is 100. The inside diameter of the throat is 7 mm.
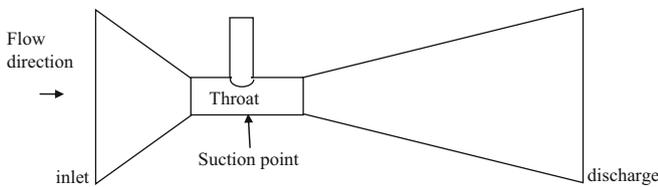
Friction loss in the throat is calculated as follows.

$$h_f = 1.22 * 10^{10} * 0.1 \; m \left(\frac{\left(\frac{0.9/1000}{100} \right)^{1.852}}{7^{4.87}} \right) = 15.2 \; m$$

Calculate inlet cone head loss. The large and small diameters are 0.03 m and D_t, respectively

$$\theta < 45^0 \quad K = 0.8 \; \sin \frac{\theta}{2} \left(1 - \frac{d_1^2}{d_2^2} \right)^2$$

$$= 0.8 \; \sin \frac{30}{2} \left(1 - \frac{0.007^2}{0.03^2} \right)^2 = 0.185$$

Flow velocity for expansion and reduction cone losses is based on flow within throat. Flow rate is

$$v_t = \frac{Q}{A} = \frac{0.9 \, L/\sec \; / \; 1,000}{\pi \; 0.007^2 / _4} = 23.4 \; m/s$$

$$h_{mi} = K_i \frac{v_t^2}{2g} = 0.185 \frac{23.4}{2*9.8} = 5.16 \; m$$

Calculate discharge cone head loss

$$\theta < 45° \quad K = 2.6 \; \sin \left(\frac{15(\pi/180)}{2} \right) \left(1 - \frac{0.007^2}{0.03^2} \right)^2 = 0.30$$

$$h_{md} = K_i \frac{v_t^2}{2g} = 0.30 \frac{23.4}{2*9.8} = 8.49 \; m$$

Total pressure loss is the sum of losses

$$= 8.49 + 5.16 + 15.2 = 28.85$$

Discharge pressure is inlet pressure – pressure loss.

$$= 300 - 28.85*9.8 = 17 \; kPa$$

Pressure in the throat is calculated based on the Bernoulli equation and the friction loss in the inlet cone and half of the throat.

$$\frac{v_1^2}{2g} + \frac{P_1}{\gamma} = \frac{v_S^2}{2g} + \frac{P_S}{\gamma} + h_{mi} + 0.5 h_f$$

$$P_S = \gamma \left(\frac{P_1}{\gamma} + \frac{v_1^2}{2g} - \frac{v_S^2}{2g} - h_{mi} - 0.5 h_f \right)$$

where h_f is throat pressure loss.

$$P_S = 9.8 \left(\frac{300}{9.8} + \frac{1.27^2}{2*9.8} - \frac{23.39^2}{2*9.8} - 5.16 - 0.5*15.2 \right)$$

$$= -10.0 \; m$$

Thus, gage pressure is −98 kPa.

If gage pressure is 101.3 absolute pressure, then the absolute pressure in the throat is 3.3 kPa.

21. Redo question 20 but optimize the inlet and discharge angle in order to minimize pressure loss across the Venturi. Keep the same throat dimension and Venturi length. Derive an equation based on the geometry of the system that calculates discharge angle as a function of inlet angle.
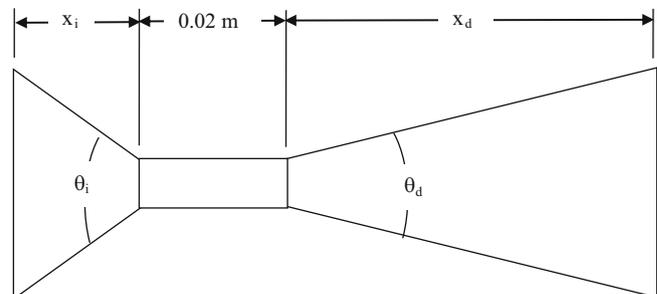
The length of the system is the sum of in two cones and the throat.

$$x_i + 0.02 + x_d = 0.3 \; m$$

$$x_i = \frac{0.015 - \frac{D_t}{2}}{\tan\left(\frac{\theta_i}{2}\right)}$$

$$x_d = \frac{0.015 - \frac{D_t}{2}}{\tan\left(\frac{\theta_d}{2}\right)}$$

Where D_t is the throat diameter.

Solve for the discharge angle as a function of the inlet angle

$$x_i + 0.02 + x_d = 0.3 \text{ m}$$

$$\frac{0.015 - \frac{D_t}{2}}{\tan\left(\frac{\theta_i}{2}\right)} + 0.02 + \frac{0.015 - \frac{D_t}{2}}{\tan\left(\frac{\theta_d}{2}\right)} = 0.3$$

$$\frac{0.015 - \frac{D_t}{2}}{\tan\left(\frac{\theta_d}{2}\right)} = 0.3 - \frac{0.015 - \frac{D_t}{2}}{\tan\left(\frac{\theta_i}{2}\right)} - 0.02$$

$$\tan\left(\frac{\theta_d}{2}\right) = \frac{0.015 - \frac{D_t}{2}}{0.3 - \frac{0.015 - \frac{D_t}{2}}{\tan\left(\frac{\theta_i}{2}\right)} - 0.02}$$

$$\theta_d = 2\,\tan^{-1}\left(\frac{0.015 - \frac{D_t}{2}}{0.3 - \frac{0.015 - \frac{D_t}{2}}{\tan\left(\frac{\theta_i}{2}\right)} - 0.02}\right)$$

A spreadsheet was set up to calculate pressures as a function of inlet and discharge angle. Solver was used to maximum discharge pressure as a function of inlet cone angle.

Inlet diameter	0.03	m
Throat diameter	0.007	m
Throat length	0.02	m
Device length	0.15	m
Reductiion cone angle (full angle)	28.43	degrees
Discharge angle (full angle)	15.48	degrees
	Length (m)	
Reduction cone	0.0454	m
Throat	0.02	m
Expansion cone	0.0846	m
Total length	0.15	m
Flow rate (L/sec)	0.9	
Inlet flow velocity (m/sec)	1.27	m/sec
Throat velocity (m/sec)	23.39	m/sec

(continued)

Inlet cone Km	0.176	
Pressure loss reduction cone	4.90	m
Throat equivalent length	0.1	m
Throat pressure loss	15.2	m
Expansion cone Km	0.313	
Expansion cone pressure loss	8.73	m
Total pressure loss	28.83	
Inlet pressure	300	kPa
Inlet pressure	30.59	m
Total friction loss in Venturi	28.83	m
Discharge pressure	1.76	m
Discharge pressure	17.24	kPa
Pressure difference across Venturi	283	kPa
Pressure at suction	−9.7	m
Absolute zero pressure	−101	kPa
Absolute zero pressure	−10.31	m
Difference between throat pressure and abs. zero	5.844	kPa

Chapter 10: Solution

1. What are the five major types of aquifers?

Unconsolidated sand and gravel aquifers, semi-consolidated sand and gravel aquifers, volcanic aquifers, sandstone and carbonate rock aquifers, and sandstone aquifers.

2. Describe four different types of aquifers commonly used for irrigation and give an example of each.

There are three types of unconsolidated sand and gravel aquifers: basin fill, blanket sand and gravel, and glacial-fill. Basin fill aquifers are formed as sediment fills in basins between mountains. Basin fill aquifers are common in the Southwest United States. Blanket sand aquifers are formed by wind blown sand. The Ogallala aquifer is a blanket sand aquifer. Glacial-fill aquifers are deposited by glaciers and are common in the Northern Midwest. Semiconsolidated sand aquifers have sloping layers of sand and aquitards and are found on the East Coast.

3. Draw a confined and unconfined aquifer.

See Fig. 10.2.

4. Discuss groundwater recharge and discharge components for a basin

Groundwater recharge components include surface infiltration (rainfall or irrigation), mountain front recharge, underflow, interbasin flow, and surface infiltration.

5. Discuss the impact of overpumping on stream flow in arid climates.

Overpumping depletes the aquifer and lowers the water table. A stream that used to be supplied by flow from the aquifer loses water to the aquifer and stops flowing.

6. Discuss the natural condition and impact of man on the Ogallala aquifer.

Natural history:

The High Plains Aquifer (contains the Ogallala aquifer) in Nebraska, Colorado, Kansas, Oklahoma, Texas, South Dakota, Wyoming, and New Mexico (Fig. 10.11) is a blanket sand and gravel aquifer. These aquifers are primarily formed from wind blown sand, unconfined by impermeable layers above, and confined below by bedrock (Fig. 10.12).

Impact of man:

Some parts of the High Plains Aquifer in Nebraska have such high levels of nitrogen from nitrogen leaching in agricultural fields that farmers in the area do not even have to add nitrogen fertilizer to the pumped groundwater. Although the lack of need for fertilizer is nice for farming, the farmers cannot drink the water because it is not potable.

Because the rate of pumping has exceeded the recharge rate, primarily in the southern part of the Ogallala aquifer, water tables have declined by more than 30 m (100 ft) in some locations (Fig. 10.11). However, in regions of the aquifer where irrigation water is supplied by surface streams, the level of the aquifer has risen by 10–20 m. The water balance for the High Plains aquifer was 24 million cubic feet per day in and 24 million cubic feet per day out in the natural state (Fig. 10.12). Irrigation began during a drought in the 1930s and eventually the recharge rate (irrigation leaching and runoff) increased to 510 million cubic feet per day while the rate of extraction rose from zero to 810 million cubic feet per day. The lateral discharge dropped from 24 to 10 million cubic feet per day. The difference between recharge and extraction grew very large, 330 million cubic feet per day. As the aquifer became depleted in some areas such as Texas, the rate of withdrawal began to decrease in the 1970s.

7. Discuss the impact of irrigation on water table elevation and salinization.

Irrigation, especially inefficient irrigation, adds water to the aquifer and raises the water table. Eventually, the water table rises to the soil and subsurface drainage systems must be installed in order to leach salts from the soil. If subsurface drainage is not installed, then the soil becomes salinized and unfarmable.

8. Calculate the porosity, storativity, specific yield, and specific retention for an aquifer that has 40 % water below the water table, and yield of 1.2 m of water for every 5 m drop in water table elevation.

Porosity is equal to saturated water content = 40 %
Specific yield is 1.2/5 * 100 % = 24 %
Specific retention is equal to porosity – specific yield = 40 % – 24 % = 16 %
Field capacity is equal to specific retention = 16 %

9. A coarse sand aquifer has a water table slope of 1 m/100 m. Evaluate at the upper and lower limits of coarse sand hydraulic conductivity. What is the Darcy velocity of the water in the aquifer? The cross sectional area of the aquifer is 100 m × 1,000 m. What is the volume of water flow in 1 year? Convert water volume to acre-ft. How many acres of cotton could be irrigated with this volume per year? Also calculate for a silt aquifer with a hydraulic conductivity at the lower end of silt conductivities.

Low end of coarse sand hydraulic conductivity 10 m/day.

$v = K \, dH/dz = 10*0.01 = 0.1$ m/day.
$Q = vA = 0.1$ m/day (100 m x 1,000 m) $= 10,000$ m^3/day
$V = Q \, t = 10,000$ m^3/day*365 $= 3.65$ million m^3

3.65 million m^3*0.00081 m^3/ac − ft $= 3,000$ ac − ft.

This volume of water would irrigate approximately 1,000 acres of cotton, assuming that the gross depth of application would be 3 ft/year

Upper end of coarse sand hydraulic conductivity 1,000 m/day.

$v = K \, dH/dz = 1,000*0.01 = 10$ m/day.
$Q = vA = 10$ m/day (100 m x 1,000 m) $= 1,000,000$ m^3/day
$V = Q \, t = 1,000,000$ m^3/day*365 $= 365$ million m^3

365 million m^3*0.00081 m^3/ac − ft $= 300,000$ ac − ft.

This volume of water would irrigate approximately 100,000 acres of cotton, assuming that the gross depth of application would be 3 ft/year

Lower end of silt hydraulic conductivity 0.01 m/day.

$v = K \, dH/dz = 0.01*0.01 = 0.0001$ m/day.
$Q = vA = 0.0001$ m/day (100 m x 1,000 m) $= 10$ m^3/day
$V = Q \, t = 10$ m^3/day*365 $= 3,650$ m^3

3,650 m^3*0.00081 m^3/ac − ft $= 3$ ac − ft.

This volume of water would irrigate approximately one acre of cotton, assuming that the gross depth of application would be 3 ft/year.

10. Find the hydraulic gradient and the direction of flow with the East axis (x-axis) as zero degrees for the following three wells. Show your work (work it by hand), and check your work with the *Groundwater* program.

	East	North	Elevation
Well 1	50	600	104
Well 2	400	250	105
Well 3	200	50	108

Step a. The first step is to find the well with the intermediate water level. This is well 2, and the elevation is 105.

Steps b and c. Find the ratio of the high and low well elevations and the point at which the contour line crosses the line between the high and low wells.

$$\text{Ratio}_{H,L} = ((z_H - z_M)/(z_H - z_L))$$
$$= (108 - 105)/(108 - 104) = 0.75$$

$$x_{Int} = x_H - (x_H - x_L)*\text{Ratio}_{H,L} = 200 - (200 - 50)*0.75$$
$$= 87.5 \text{ m}$$

$$y_{Int} = y_H - (y_H - y_L)*\text{Ratio}_{H,L} = 50 - (50 - 600)*0.75$$
$$= 462.5 \text{ m}$$
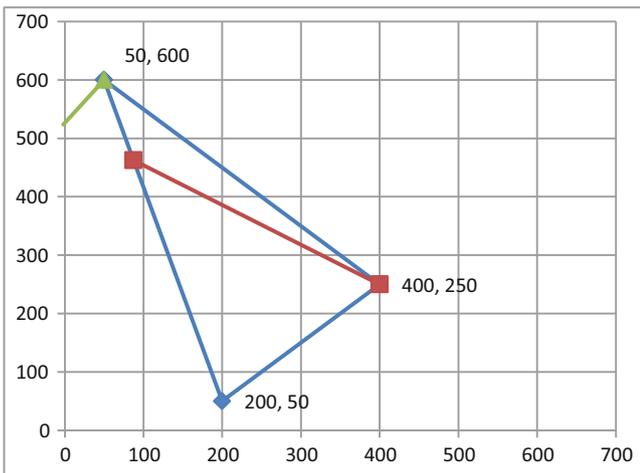
Determination of flow direction based on water table elevations in three wells.

The next step is to find the equation for the contour line.

$$m = (y_{Int} - y_M)/(x_{Int} - x_M) = (462.5 - 250)/(87.5 - 400)$$
$$= -0.68$$
$$y = mx + b \quad b = y_{Int} - mx_{Int}$$
$$b = 462 - (-0.68)*87.5 = 522$$
$$y = -0.68 \text{ x} + 522$$

The slope of the line that is perpendicular to this line, which is the direction of flow is

$$m_{Flow} = -(-1/-0.68) = 1.47$$

The y-intercept of the flow direction is found with the coordinates of the well with the lowest elevation.

$$b_{Flow} = y_L - m_{Flow}x_L = 600 - 50*1.47 = -526.5$$

The intersection point of the two lines is found by solving the two equations simultaneously

$$y = (-m_{Flow}*b/m + b_{Flow})/(1 - m_{Flow}/m)$$
$$y = (-1.47*522/(-0.68) + 526.5)/(1 - 1.47/(-0.68))$$
$$= 523.4$$
$$x = (y - b)/m = (523.4 - 522)/(-0.68) = -2.1$$

The distance between the point and the line is found with the Pythagorean Theorem.

$$\text{Distance} = \left((50 - (-2.1))^2 + (600 - 523.4)^2\right)^{0.5} = 92.6$$

The hydraulic gradient, dH/dL is the elevation difference between the contour line and the lowest well divided by the distance. The elevation of the contour line is 104 m.

$$dH/dL = (104 - 100.8)/92.6 = 0.0108 \text{ m/m}.$$

11. If the aquifer in question 10 is a coarse sand aquifer with hydraulic conductivity equal to 100 m/day and porosity of 0.40, then calculate the Darcy velocity and the rate that a contaminant plume would travel through the aquifer.

The Darcy velocity is calculated with the Darcy equation.

$$v_{Darcy} = -K\frac{\Delta H}{L} = 100 \ m/day*0.0108 \ m/m = 1.08 \ m/day$$

The actual velocity is the Darcy velocity divided by the porosity.

$$v = \frac{v_{Darcy}}{\phi} = 1.08/0.4 = 2.7 \ m/day$$

12. What is the reason that aquifer pollution is much more difficult to correct than surface water pollution?

The rate of exchange in aquifers is much slower than for surface waters so the pollutants are not flushed out of an aquifer.

13. What are the primary pollutants from agriculture that have contributed to aquifer pollution?

Nutrients and pesticides.

14. What often happens to shallow aquifers when irrigation is introduced to a region?

Excess water from irrigation leaches to the aquifer and the water table rises. Eventually, the water table rises to near to soil surface, which makes it impossible to leach salts out of the soil profile. The soil becomes salinized unless subsurface drainage systems are installed.

15. Find the transmissivity and conductivity of confined aquifer in which the flow rate to a well is 400 gpm, and observation wells at distances of 100- and 200-m from the pumping well have depths to the water table of 100-m and 98-m, respectively. The upper surface of the aquifer is 140 m below ground and the aquifer is 40 m thick. Check your calculations with the Confined aquifer Worksheet.

	Distance	Ground surface elevation	Depth to water table	Water table elevation above aquitard
Pumping well	0	180		
Observation well 1	100	180	100	80
Observation well 2	200	180	98	82

Lower boundary with aquitard	0	m
Well flow rate	400	GPM
Flow rate	2180	m3/day
Transmissivity	120	m2/day
Aqufer thickness	40	m
Conductivity	3.006	m/day

16. Find the conductivity and transmissivity in an unconfined aquifer in which the flow rate to a well is *400 gpm,* and observation wells at distances of 100- and 200-m from the pumping well have depths to the water table of 100-m and 98-m, respectively. The lower boundary of the aquifer (upper surface of aquitard) is 150 m below the ground.

	A	B	C	D	E	F
1		Distance	Ground surface elevation	Depth to water table	Water table elevation above aquitard	
2	Pumping well	0	150			
3	Observation well 1	100	150	100	50	
4	Observation well 2	200	150	98	52	
5			above datum			
6	Lower boundary of aquifer	0 m				
7	with respect to datum					
8				This section calculates K and T based on Q and h		
9	Well flow rate (U.S. units)	400	GPM	for an unconfined aquifer		
10	Well flow rate (metric units)	2180	m3/day			
11						
12	Conductivity	2.36	m/day			
13	Average aquifer thickness	51.00	m			
14						
15	Transmissivity	120.26	m2/day			

17. Calculate the transmissivity and storativity of a confined aquifer. The following drawdown data was collected from an observation well 100 m from the pumping well. The well flow rate was 2,000 m^3/day.

Time after initiation of pumping	Drawdown s (m)
1 min	0.44
2 min	0.55
4 min	0.66
8 min	0.77
0.01 day	0.86
0.02 day	0.97
0.04 day	1.08
0.08 day	1.19
0.16 day	1.30
0.32 day	1.41
0.64 day	1.52
1 day	1.59

Convert to t/r2.

t/r^2 (day/m^2)	Drawdown s (m)
6.9E-08	0.44
1.4E-07	0.55
2.8E-07	0.66
5.6E-07	0.77
0.000001	0.86
0.000002	0.97
0.000004	1.08
0.000008	1.19
0.000016	1.30
0.000032	1.41
0.000064	1.52
0.0001	1.59

Now use the scroll bar. You can extend the theoretical curve to include smaller values of t/r2 by lowering the initial value in cell A5: enter 0.00000001. Change the flow rate in cell B1 to 2,000 m^2/day. The scroll bars are adjusted until the storativity is equal to 0.00001, and the transmissivity is equal to 1,000 m^2/day. Results are shown below.
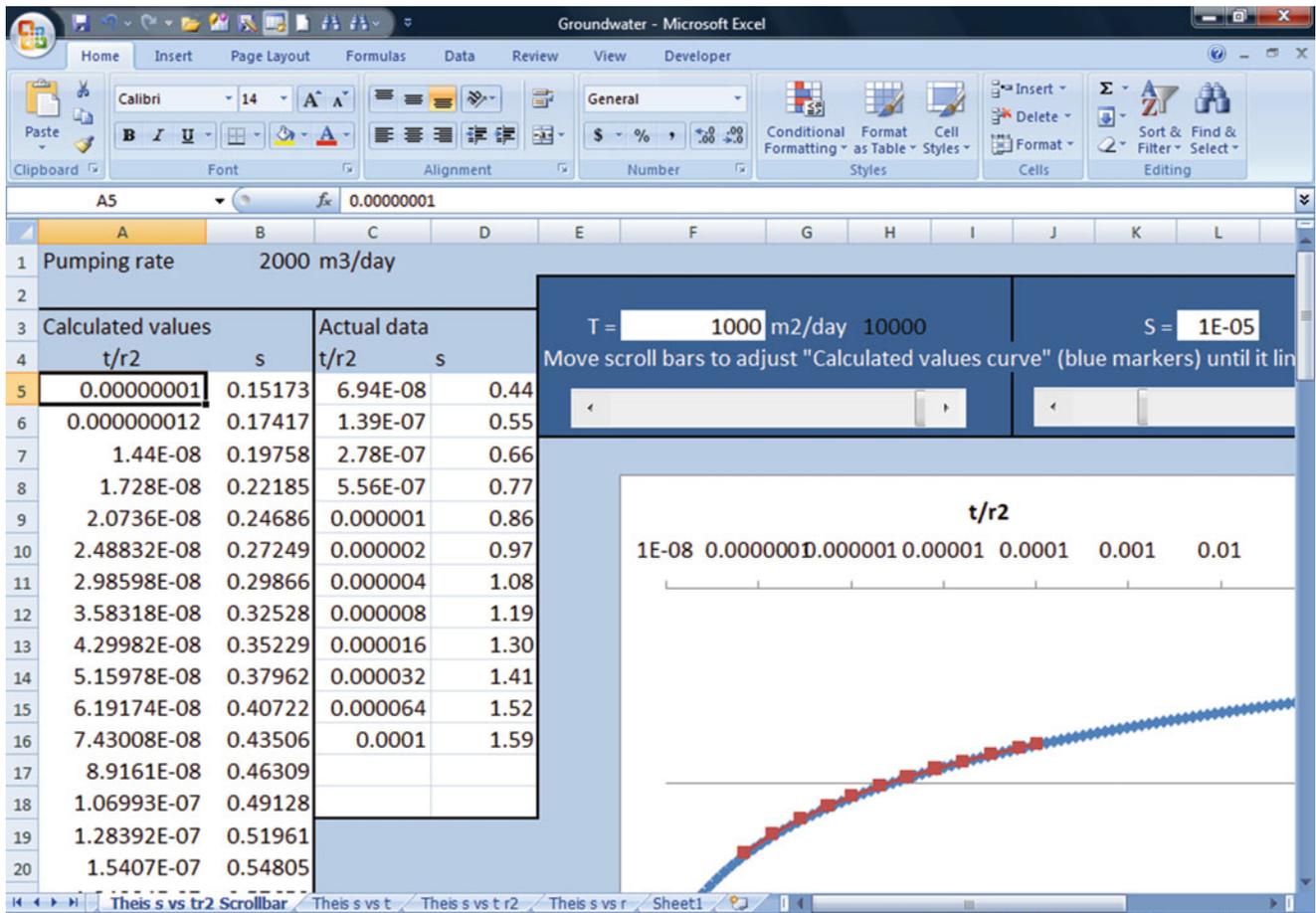
18. For the aquifer in question 17, calculate the drawdown in the well for a series of points between 1 hr and 1 week. The well diameter is 50 cm (use r = 0.25 m in the *Theis s* vs. *t* worksheet). The pump flow rate is 3,000 m³/day.

The well radius is 0.25 m.

Time	Drawdown (m)
1 hr	4.49
1 day	5.25
7 days	5.72

Hand calculation

$$u = r^2 S/(4Tt)) = 0.00001*0.25^2/(4*1,000*7) = 2.23*10^{-11}$$

$$W(u) = \left[-0.5772 - \ln u + u - \frac{u^2}{2*2!} + \frac{u^3}{3*3!} - \frac{u^4}{4*4!}\right] = 23.9$$

$$s = \frac{Q}{4\pi T} W\left(\frac{r^2 S}{4Tt}\right) = \frac{3,000}{4\pi(1,000)}*23.9 = 5.72 \ m$$

19. The well described in questions 17 and 18 has a maximum acceptable drawdown of 20 m inside the well. The pressure loss in the casing is flow rate (m³/day)/4,600. Calculate the maximum allowable pump flow rate and the drawdown at 80 %, 60 %, 40 %, and 20 % of maximum. Plot the drawdown vs. flow rate curve. What is the shape of the curve? Convert the maximum flow rate to units of GPM and report whether this well would be considered a good well. Assume that the drawdown after 7 days is the steady state drawdown.

Input the aquifer parameters into the *Theis s* vs. *t* Worksheet and adjust Cell B4 until the drawdown is approximately 18 m after 7 days.

	A	B	C	D
1	Distance from pumping well r	0.25	m	
2	Storativity (S)	0.00001		
3	Transmissivity (T)	1000	m2/day	
4	Pumping rate (Q)	9200	m3/day	
5	Piezometric Surf. above aquitard	100	m	
6				
7	t (days)	s (m)	h (m)	
8	0.001	11.05	88.95	
9	0.002	11.56	88.44	
10	0.004	12.07	87.93	
11	0.008	12.57	87.43	
12	0.016	13.08	86.92	
13	0.032	13.59	86.41	
14	0.064	14.10	85.90	
15	0.1	14.42	85.58	
16	0.2	14.93	85.07	
17	0.4	15.44	84.56	
18	0.8	15.94	84.06	
19	1.6	16.45	83.55	
20	3.2	16.96	83.04	
21	6.4	17.47	82.53	
22	12.8	17.97	82.03	
23	25.6	18.48	81.52	
24	51.2	18.99	81.01	

Confined aquifer Thiem   Unconfined aquifer Thiem   Theis scrollbar   Theis s vs t

When Cell B4 is 9200 m³/day, the drawdown is just less than 18. Two m head loss takes place in the well screen when the drawdown outside the casing is 18 m. (9200/4600) = 2 m. Thus, the total drawdown is 17.5 + 2 = 19.5. Close enough.

Thus, the maximum pumping rate is 9,200 m³/day (1,700 GPM), and this well can be classified as a good well since it has a flow rate greater than 1,000 GPM.

The shape of the drawdown vs. pump flow rate curve is nearly linear. The upper line is outside the casing, and the

lower line is inside the casing. The difference is the energy loss within the casing. (2 m at 9200 m3/day).
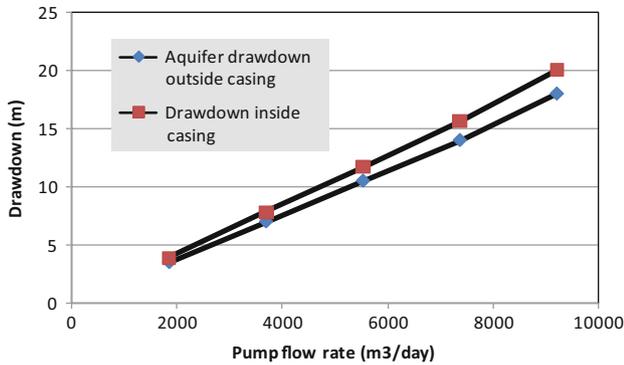
Figure. Drawdown vs. flow rate.

20. The static water table in the aquifer described in problems 17–19 is 40 m below the ground surface. The pump in the well has a pump curve as shown below. The pump has an open discharge 0.5 m above the ground surface, and the sum of minor losses (K) = 3.9 (including velocity head losses at the discharge). The pump hangs on a 12 inch pipe (Schedule 40) at an elevation 80 m below the ground surface, and there is a 2 m section of pipe above the ground surface (total 82 m pipe). The pipe has a Hazen Williams C = 100. Include the minor losses. Calculate the discharge flow rate.
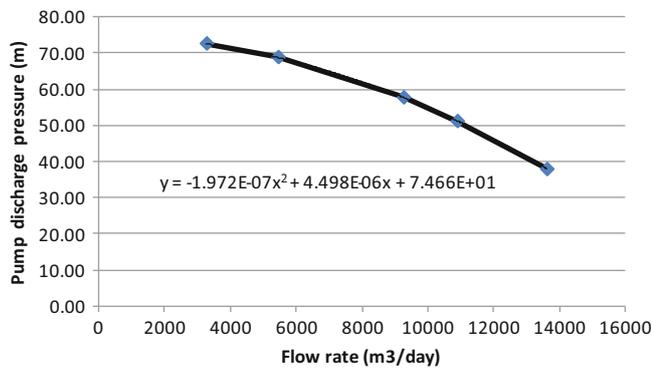
12 inch Schedule 40 pipe has 0.406 inch thickness, and outside diameter = 12.75 inches. Thus, the inside diameter is 12.75–0.812 = 11.94 in. (this figures are found in both Tables 8.2 and 10.3.) The metric ID is 303.2 mm.

The minor losses and pipe losses are subtracted from the total head produced by the pump.

$$H = -1.972*10^{-7}*Q + 4.498*10^{-6}*Q + 74.66 - \left(k_1 L \frac{\left(\frac{Q_{3600*24}}{C}\right)^{1.85}}{D^{4.87}} + K_m \frac{v^2}{2g} \right)$$

$$H = -1.972*10^{-7}*Q^2 + 4.498*10^{-6}*Q + 74.66 - \left(1.22*10^{10}*82 \frac{\left(\frac{Q_{3600*24}}{100}\right)^{1.85}}{303^{4.87}} + 3.5 \frac{\left(\frac{Q}{3600*24*\pi*(0.303/2)^2}\right)^2}{2*9.8} \right)$$

An equation was calculated with the Trendline function for drawdown vs. pumping rate.
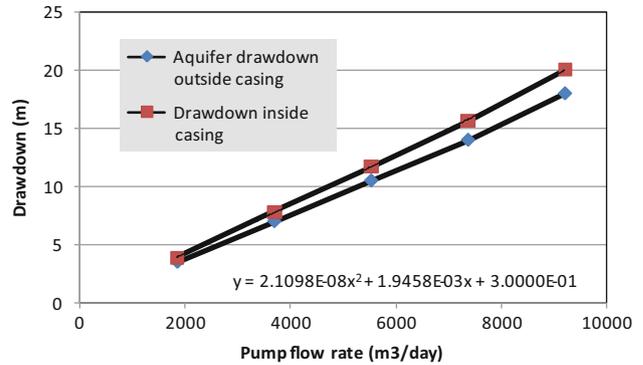
The distance of water in the well from the outlet at the surface (also equal to total head H as calculated in the pump and pipe equation above) is

$$H = 40 \text{ m} + 0.5 \text{ m} + 2.1098E - 8*Q^2 + 1.9458E - 3*Q + 0.3$$

Set the two equations equal to each other in order to solve for the flow rate.

$$40.8 + 2.1098E - 8*Q^2 + 1.9458E - 3*Q$$
$$= -1.972*10^{-7}*Q^2 + 4.498*10^{-6}*Q + 74.7 -$$
$$\left(1.22*10^{10}*62 \frac{\left(\frac{Q_{3600*24}}{100}\right)^{1.85}}{303^{4.87}} + 3.5 \frac{\left(\frac{Q}{3600*24*\pi*(0.303/2)^2}\right)^2}{2*9.8} \right)$$

Set the problem up to be solved by iteration in Excel (solve for Q).

$$Q = \left(\begin{array}{c} -2.183 * 10^{-7} * Q^2 + 33.9 - 1.22*10^{10}* \\ 82 \frac{\left(\frac{Q_{3600*24}}{100}\right)^{1.85}}{303^{4.87}} - 3.5 \frac{\left(\frac{Q}{3600*24*\pi*(0.303/2)^2}\right)^2}{2*9.8} \end{array} \right) \Big/ 1.941*10^{-3}$$

Q = 8010 m³/day.

The pressure loss in the pipe and minor losses are calculated as follows.

$$h_f = 1.22*10^{10}*82 \frac{\left(\frac{8010_{3600*24}}{100}\right)^{1.85}}{303^{4.87}} - 3.5 \frac{\left(\frac{8010}{3600*24*\pi*(0.303/2)^2}\right)^2}{2*9.8}$$

$$= 0.295 \text{ m}$$

21. What are the two types of groundwater pollution? Which comes from field agriculture?

Point source and nonpoint source. Nonpoint source comes from field agriculture.

Chapter 11: Solution

1. **Describe the different types of canals.**

- Main canals: Large canals constructed by the Federal Government that carry water between regions.
- Irrigation district main canals: the large canals that carry water to different parts of irrigation districts.
- Secondary (subsystem) canals: these canals deliver water from main canals to lateral (tertiary) canals.
- Irrigation district lateral canals: canals that deliver water to farm turnouts.
- On-farm irrigation ditches: irrigation ditches distribute water in fields. They deliver water to fields in a variety of ways such as open discharge to basins, alfalfa valves connected to spiles (pipes under the canal), or siphon tubes which are placed over the canal bank.
- Drainage channels: these channels remove drainage water from the project. Drainage channels are normally installed below grade in order to remove drainage water by gravity flow.

2. **How is water diverted from a main canal to a lateral canal?**

The diversion of water from a main canal to a lateral canal has several design features. A diversion structure is placed just downstream from the turnout in order to increase upstream depth. This technique is also used in irrigation head ditches where water is blocked just downstream from the part of the field that is irrigated.

3. **How is water diverted from a lateral canal to a field?**

Water is diverted from a lateral canal to a field through irrigation ditches. They can deliver water to fields in a variety of ways such as open discharge to basins, alfalfa valves connected to spiles (pipes under the canal), or siphon tubes which are placed over the canal bank. The canals are often blocked just downstream from where water is applied in order to increase canal elevation and flow rate to the field.

4. **What is the reason for energy dissipation structures in canals and in canal outlets?**

Energy is dissipated in canal outlets to fields in order to prevent the erosion of soil. Energy is dissipated in structures within canals in order to have subcritical flow on a slope that would otherwise have supercritical flow (steep slope).

5. **Calculate the conveyance efficiency and water duty for a canal that is 20 km long, has a wetted top width $= 20$ m, wetted perimeter $= 26$ m, and cross-sectional area $= 100$ m^2? Average canal flow velocity is 1 m/sec. Reference ET is 10 mm/day. Average seepage rate is 5 mm/day. In addition to reporting the water duty and efficiency, convert the seepage rate to $L/m^2/day$.**

$$Q = Av$$
$$Q = 100*1 = 100 m^3/sec$$
$$Q = \frac{100 m^3}{sec} * \frac{3600 sec}{1 hr} * \frac{24 hr}{1\ day} = 8,640,000 m^3/day$$

Assuming that the canal is a rectangular channel, then b = top width.

$$V_{Evap/day} = (20,000\ m)(20\ m)(0.010\ m/day) = 4,000\ m^3/day$$
$$V_{Seepage/day} = (20,000\ m)(26\ m)(0.005\ m/day) = 2,600\ m^3/day$$

The percent evaporation is $(4,000/8,640,000)(100\%) = 0.046\%$.

The percent evaporation is $(2,600/8,640,000)(100\%) = 0.030\%$.

$$Total\ water\ duty = \%seepage\ losses$$
$$+ \%evaporation\ losses$$
$$= 0.046\% + 0.030\% = 0.076\%.$$

Conveyance efficiency is $100\% - 0.076\% = 99.92\%$.

$$V_{Seepage/day} = 2,600\ m^3/day$$
$$= 2,600,000\ L/day/(20,000*26)\ m^2$$
$$= 5\ L/m^2/day.$$

6. **Calculate the conveyance efficiency to field 1 in Fig. 11.9 from the point of water diversion to the irrigation district. The conveyance efficiency of the irrigation district up to the farm turnout is 80 %. The main concrete canal on the farm has a conveyance efficiency of 80 %, and the earth-lined canal has a conveyance efficiency of 80 %.**

$$Efficiency = (0.8)(0.8)(0.8)(100\%) = 51.2\%$$

7. **Redo Example 11.4, but the ditch is constructed in loam and sandy loam soils (Fig. 11.8) with a seepage rate of 1.5 m³/m²/day.**

The wetted perimeter is

$$P = b + 2*y*(1 + z^2)^{0.5} = 0.3 + 2*0.75*(1 + 2^2)^{0.5} = 3.65 \ m$$

The seepage rate is 1,500 L/m²/day. Then,

$$
\begin{aligned}
V_{Seepage/day} &= 3.65 \ m*1,000 \ m*1500 \ L/m^2/day \\
&= 5,475,000 \ L/day/km \\
V_{Seepage/yr} &= 5,475,000 \ L/day*60 \ days*0.001 \ m^3/ \\
&\quad L*0.01 \ ha - cm/m^3 = 3,285 \ ha - cm/yr \\
\$_{Seepage/yr} &= 3,285 \ ha - cm/yr*\$3.27/ha - cm \\
&= \$10,741.95/year.
\end{aligned}
$$

The present value of $10,741/yr for a 20 yr project at 8 % interest is approximately $110,000/km (multiply annual value by 10 for this period and interest rate). Therefore, it is profitable to line the irrigation ditch because the present value is bigger than the liner cost ($60,000/km).

8. **Describe the method used to run canal water past a road, drainage ditch, or river valley.**

Pipes (culverts or siphons) are used in irrigation districts to go under or over obstructions, and to deliver water to farmers. Huge siphons are sometimes used on large canals to move water past river valleys.

9. **A concrete lined trapezoidal channel (Fig. 11.14) has a slope of 0.3 % = 0.003 m/m. Flow rate in the channel is 300 L/sec, and the Manning's roughness coefficient, n, of the channel is 0.015. Calculate the depth of flow in the channel. The bottom width is 1 m and side slope z = 1.5.**
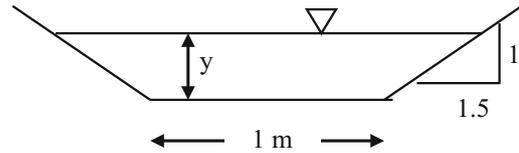
Solve for left side of Eq. 11.9. The following procedure is in the *Canal Depth* Worksheet.

$$\frac{Qn}{S_0^{0.5}} = \frac{0.3*0.015}{0.003^{0.5}} = 0.082$$

Use iteration to find y. First try y = 30 cm = 0.30 m.

$$AR^{2/3} = (b + zy)y\left(\frac{(b + zy)y}{b + 2y\sqrt{1 + z^2}}\right)^{2/3}$$

$$AR^{2/3} = (1 + 1.5*0.30)*0.30\left(\frac{(1 + 1.5*0.30)*0.30}{1 + 2(0.30)\sqrt{1 + 1.5^2}}\right)^{2/3}$$

$$AR^{2/3} = 0.15$$

Adjust y as follows (this is a fast iteration procedure).

$$y_2 = y_1\left(\frac{\left(AR^{2/3}\right)_{actual}}{\left(AR^{2/3}\right)}\right)^{0.5}$$

$$y_2 = 0.3\left(\frac{0.082}{0.15}\right)^{0.5} = 0.21$$

Another iteration results in 0.21. Thus, final answer is 0.21 m = 21 cm water depth.

Add 25 % freeboard elevation.

$$0.21*1.25 = 0.266 \ m$$

			Trapezoidal or rectangular canal only			
2	Q	0.30000 m3/sec				
3	z	1.5				
4	n	0.015				
5	b	1.000 m				
6	S	0.003 m/m				
7						
8	SF	0.082158				
9	yguess	0.3000	0.3000	0.2197	0.2133	0.2126 Final y value (depth in m)
10	AR23	0.0822	0.15318	0.0871632	0.0826873	0.0822162
11						
12	Freeboard	25%				
13	Canal depth	26.6 cm				
14						
15	Area	0.280 m2				
16						
17	Velocity	1.070 m/sec				
18						
19	Top width	1.638 m				
20						
21	Q Froude	0.826				
22						
23	y Froude	0.826				

10. **Calculate the Froude number for the previous problem, and determine whether the channel has supercritical or subcritical flow.**

You must use the Froude number equation for a trapezoidal canal.

$$Fr = \frac{v}{\left(A_{T}g\right)^{0.5}}$$

$$v = \frac{Q}{A}$$

$$A = (b + zy)y = (1 + 1.5*0.21)*0.21 = 0.28m^2$$

$$T = b + 2\,zy = 1 + 2*1.5*0.21 = 1.64 \text{ m}$$

$$v = \frac{0.3 \; m^3/sec}{0.28 \; m^2} = 1.07 \; m/sec$$

$$Fr = \frac{1.07}{\left(\left(0.28/_{1.64}\right)(9.81)\right)^{0.5}} = 0.826$$

Thus, the flow is subcritical.

11. **If a canal were to travel down a relatively steep slope, what strategy could be used to prevent supercritical flow in the canal?**

In order to maintain subcritical flow over the majority of the canal, energy is dissipated in a series of structures such as steeply sloped chutes, weirs, concrete apron or blocks in order to dissipate energy.

12. **For the canal dimensions described in problem 9, calculate the chute slope required to have a stable hydraulic jump with Froude number = 6.**

Using the spreadsheet, the chute slope required is: 0.216 m/m (21.6 %). In this problem, you cannot solve for the depth of the downstream hydraulic jump with the information provided in this chapter since the channel is trapezoidal. This was an error in the problem statement.
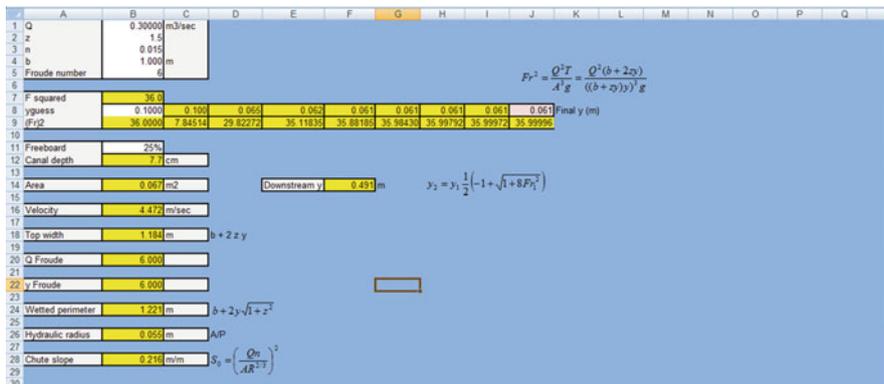
13. **Describe why a Froude number 6 is desirable before a hydraulic jump.**

An upstream Froude number between 4.5 and 9.0 maintains a stable hydraulic jump and high energy loss so this is the desired range of Froude number for upstream flow.

14. **Calculate the flow over a standard contracted rectangular weir. The head over the weir is 0.13 m and the weir blade is 0.6 m across.**

$$Q = 1.74H^{3/2}(L_b - 0.2H)$$

$$= 1.74(.13m)^{3/2}\left(.6m - (0.2)(.13m)\right) = .047\frac{m^3}{\text{sec}}$$

Chapter 12: Solution

Question 12.1. Discuss the different types of sprinkler nozzles and systems used on center pivots. Discuss the strengths and weakness of the systems.

Top mounted impact sprinklers
Strengths: Large wetted diameter leads to lower runoff. Lower cost. Suitable for humid regions. Easy to detect if sprinkler is malfunctioning. No need for furrows or planting in circle.
Weaknesses: High evaporation leads to loss of efficiency. Wetting of foliage (may be disadvantage). Higher pressure required so energy cost is higher. Affected by wind. Droplet impact may cause crusting. May not be suitable for application to foliage with salty water.

LEPA
Strengths: Low energy requirement. Low evaporation loss. Don't wet foliage. Suitable for all climates (arid and humid). Suitable for salty water use, however, must be careful of salt buildup in beds if water applied to furrows.
Weaknesses: Higher cost of closely spaced drop tubes and nozzles. Need dikes and furrows. Harder to see emitter operation.

LESA
Strengths: Evaporation is relatively low so suitable for ARID climates. Suitable for broadcast crops that are not planted in rows.
Weaknesses: High cost of closely spaced drop tubes and nozzles. Low wetted diameter so may need multiple passes per day. May not be suitable for use with salty water if foliage is wetted.

MESA
Strengths: Larger wetted diameter than LESA, especially with rotors. Relatively low pressure requirement. Water distribution less affected by wind. More even application pattern. Relatively easy to see is sprinklers are not working. No need to plant in circle or construct furrows. Lower evaporation than impacts.
Weaknesses: Smaller wetted diameter than impact sprinklers. More evaporation than LESA or LEPA. May

not be suitable for ARID climates. May cause soil crust formation by droplet impact. May not be suitable for use with salty waters.

Question 12.2. What is the difference between a linear move and a center pivot irrigation system?
Linear moves travel in a straight line and irrigate square fields. Linear moves irrigate from a canal or use a movable hose system.
Center pivots irrigate in a circle and draw water from a central pipe. Center pivots can only irrigate field corners with an arm at the end of the pivot or partially with a big gun that turns on in the corners.

Question 12.3. Calculate the percent evaporation from sprinkler droplets for the parameters in Example 12.1 part 1 except that relative humidity is 50 %. If the application depth is 25 mm to a mature corn crop from overhead impact sprinklers, then what is the total depth of evaporation + canopy interception loss?

$$e_s - e_a = 0.61 \ \exp\left(\frac{17.27(40)}{40 + 237.3}\right)(1 - 0.5) = 3.68 \ kPa$$

$$L_e = \big[(1.98(3.57)^{-0.72} + 0.22(3.68)^{0.63} \\ + 3.6*10^{-4}(490)^{1.16} + 0.14(4.44)^{0.72}\big]^{4.2} = 26\%$$

Estimate that canopy interception would be 10 % (2.5 mm). 26 % of 25 mm would be 6.5 mm. Thus, total loss would be 9 mm or 36 %.

$$e_s - e_a = 0.61 \ \exp\left(\frac{17.27(25)}{25 + 237.3}\right)(1 - 0.5) = 1.58 \ kPa$$

$$L_e = \big[(1.98(3.57)^{-0.72} + 0.22(1.58)^{0.63} \\ + 3.6*10^{-4}(490)^{1.16} + 0.14(4.44)^{0.7}\big]^{4.2} = 12\%$$

Estimate that canopy interception would be 10 % (2.5 mm). 12 % of 25 mm would be 3 mm. Thus, total loss would be 5.5 mm or 22 %.

Question 12.4. Calculate the percent evaporation from overhead sprinklers for the parameters in Example 12.1

part 2 except that relative humidity is 60 %. What is the depth of evaporation for an application depth of 25 mm to a mature corn crop from overhead impact sprinklers? Consider canopy interception and droplet evaporation?

$$e_s - e_a = 0.61 \ \exp\left(\frac{17.27(40)}{40 + 237.3}\right)(1 - 0.6) = 2.94 \ kPa$$

$$L_e = \left[(1.98(3.57)^{-0.72} + 0.22(2.94)^{0.63}\right.$$
$$\left. + 3.6*10^{-4}(490)^{1.16} + 0.14(4.44)^{0.7}\right]^{4.2} = 23\%$$

Estimate that canopy interception would be 10 % (2.5 mm). 23 % of 25 mm would be 5.75 mm. Thus, total loss would be 8.25 mm or 33 %.

$$e_s - e_a = 0.61 \ \exp\left(\frac{17.27(25)}{25 + 237.3}\right)(1 - 0.6) = 1.26 \ kPa$$

$$L_e = \left[(1.98(3.57)^{-0.72} + 0.22(1.26)^{0.63}\right.$$
$$\left. + 3.6*10^{-4}(490)^{1.16} + 0.14(4.44)^{0.7}\right]^{4.2} = 11\%$$

Estimate that canopy interception would be 10 % (2.5 mm). 11 % of 25 mm would be 2.75 mm. Thus, total loss would be 5.25 mm or 21 %.

Question 12.5. Calculate the flow rate of a center pivot that has a length of 350 m, and gross application depth 15 mm/day. The pivot operates for 21 hours/day.

$$A = \pi r_{max}^2 = \pi (350^2)(1 \ ha/10,000 \ m^2) = 38.5 \ ha$$

$$Q_p = 0.116 \frac{i_g A}{1 - L_{r-m}} = 0.116 \frac{(16.2 \ mm) \ (38.5 \ ha)}{1 - (3/24)} = 76.5 \ L/s$$

	A	B
1	Pivot length (radius)	350 m
2	Pivot area	38.5 ha
3	Hours per day operation	21 hr
4	Gross application rate	15 mm/day
5	Pivot flow rate	76.5 L/sec

Question 12.6 Calculate the maximum application rate for the parameters in question 12.5. The sprinkler wetted diameter is 4 m and the percent evaporation is 14 %. Then, show that the maximum application rate is the same if the pivot rotates three times per day (7 hour rotation). Show calculation and explain why the maximum application rate is the same in both cases.

Case 1: 1 rotation

$$T_a = T_r \left(\frac{D_w}{2\pi \ r}\right) = 21 \ hr\left(\frac{4 \ m}{2\pi (350 \ m)}\right) = 2.29 \ min$$

$$i_a = i_g(L_e) = 15 \ mm/day \ (1 - 0.14) = 12.9 \ mm$$

$$\frac{di}{dt}_{max} = \left(\frac{4}{\pi}\right)\left(\frac{i_a}{T_a}\right) = \left(\frac{4}{\pi}\right)\left(\frac{12.9}{2.28}\right) = 7.2 \ mm/min$$

D	E	F	G	H	I
Sprinkler distance	350	m	Fraction evap	0.14	
Wetted diameter	4	m	ia	12.90	mm/day
Rotation rate	21	hr/day	net depth/pass	12.90	mm/pass
Ta	2.29	minutes	di/dt-max	7.17	mm/min

Case 2: 3 rotations

$$T_a = T_r \left(\frac{D_w}{2\pi \ r} \right) = 7 \ hr \left(\frac{4 \ m}{2\pi (350 \ m)} \right) = 0.76 \ min$$

$$\frac{di}{dt}\text{max} = \left(\frac{4}{\pi} \right) \left(\frac{i_a}{T_a} \right) = \left(\frac{4}{\pi} \right) \left(\frac{12.9/3}{0.76} \right) = 7.2 \ mm/min$$

D	E	F	G	H	I
Sprinkler distance	350	m	Fraction evap	0.14	
Wetted diameter	4	m	ia	12.90	mm/day
Rotation rate	7	hr/day	net depth/pass	4.30	mm/pass
Ta	0.76	minutes	di/dt-max	7.17	mm/min

The maximum is the same because the sprinkler sizes and spacings are the same. One-third of the application depth is applied in one-third of the time.

Question 12.7. Using the parameters in question 12.6, calculate the depth of runoff and maximum application rate during each pass for an intake family 3 soil with 2 mm surface storage. Include the 0.6985 initial infiltration depth. Calculate for one revolution and three revolutions per day. The percent evaporation is 14 %. Use Chapter 12 Center pivot program and hand calculations.

Case 1: 1 revolution/day. There is 3.51 mm runoff.

	A	B	C	D	E
1	Pivot length (radius)	350 m		Sprinkler distance	350 r
2	Pivot area	38.5 ha	Hide graph	Wetted diameter	4 r
3	Hours per day operation	21 hr		Rotation rate	21 h
4	Gross application rate	15 mm/day	Show graph	Ta	2.29 r
5	Pivot flow rate	76.5 L/sec			
6					Input data is
7					
8	Surface storage	2	mm	Number steps	
9	Intake family for infiltration functions (write intake family number in cell B7)			40	
10	Intake family	3	Put intake family to left	fraction	
11	NRCS_a	0.3650	a and b are automatically	0.025	
12	NRCS_b	0.8160	updated	0.05	
13	Include the initial depth	TRUE	This is the 0.6985 mm infilt	0.075	
14	Runoff	3.51	mm	0.1	
15	Infiltration + storage	9.40	mm	0.125	
16	Sprinkler application	12.92	mm	0.15	

Case 2: 3 revolutions/day. There is zero runoff

	A	B	C	D	E	F
1	Pivot length (radius)	350 m		Sprinkler distance	350 m	
2	Pivot area	38.5 ha	Hide graph	Wetted diameter	4 m	
3	Hours per day operation	21 hr		Rotation rate	7 hr/day	
4	Gross application rate	15 mm/day	Show graph	Ta	0.76 minutes	
5	Pivot flow rate	76.5 L/sec				
6					Input data is entered
7						
8	Surface storage	2	mm	Number steps		
9	Intake family for infiltration functions (write intake family number in cell B7)			40		
10	Intake family	3	Put intake family to left	fraction		50
11	NRCS_a	0.3650	a and b are automatically	0.025		45
12	NRCS_b	0.8160	updated	0.05		
13	Include the initial depth	TRUE	This is the 0.6985 mm infilt	0.075		40
14	Runoff	0.00	mm	0.1		35
15	Infiltration + storage	4.31	mm	0.125		
16	Sprinkler application	4.31	mm	0.15		30

For one revolution per day, total area of columns to right is 6.21. Subtract 2 mm surface storage and 0.6985 from 6.21 mm. This equals 3.5 mm, the answer in Cell B14. There is no runoff for three revolutions per day.

L mm/min	M mm	N Total (mm)	O Total (mm)	P Sum (mm)
ves		Actual infiltration and runoff		
3		6.21	6.70	12.916
0.365	Infilt	Runoff	Infiltration	Step
0.816	mm	mm	mm	number
5.726	0.328	0.000	0.091	1
4.678	0.268	0.000	0.156	2
4.259	0.244	0.000	0.199	3
4.003	0.229	0.003	0.229	4
3.822	0.219	0.041	0.219	5
3.684	0.211	0.072	0.211	6
3.572	0.205	0.098	0.205	7
3.479	0.199	0.121	0.199	8
3.400	0.195	0.141	0.195	9
3.331	0.191	0.159	0.191	10
3.270	0.187	0.174	0.187	11
3.216	0.184	0.187	0.184	12
3.167	0.181	0.199	0.181	13
3.123	0.179	0.209	0.179	14
3.082	0.177	0.218	0.177	15
3.044	0.174	0.226	0.174	16
3.009	0.172	0.232	0.172	17
2.977	0.171	0.237	0.171	18
2.947	0.169	0.241	0.169	19
2.918	0.167	0.243	0.167	20
2.892	0.166	0.245	0.166	21
2.866	0.164	0.245	0.164	22
2.842	0.163	0.245	0.163	23
2.820	0.162	0.243	0.162	24
2.798	0.160	0.240	0.160	25
2.778	0.159	0.236	0.159	26
2.758	0.158	0.230	0.158	27
2.739	0.157	0.224	0.157	28
2.721	0.156	0.216	0.156	29
2.704	0.155	0.206	0.155	30
2.688	0.154	0.195	0.154	31

CP_summary_data CP_yield_output CP_flow_output

Microsoft Excel - WI...

Question 12.9. Calculate the flow rate and runoff at the middle sprinkler (175 m from pivot point) for the pivot described in questions 12.6 through 12.9 for a single 21 hour rotation per day. Sprinkler spacing is 2 m at the middle of the center pivot. Fraction evaporation is 14 %. Sprinkler wetted diameter is 3.5 m. The soil intake family is 1. Surface storage is 4 mm.

	WINDS 2011 - Microsoft Excel

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B9 f_x Intake family for infiltration functions (write intake family number in cell B7)

	A	B	C	D	E
1	Pivot length (radius)	350 m		Sprinkler distance	175
2	Pivot area	38.5 ha	Hide graph	Wetted diameter	3.5
3	Hours per day operation	21 hr		Rotation rate	21
4	Gross application rate	15 mm/day	Show graph	Ta	4.01
5	Pivot flow rate	76.5 L/sec			
6					Input data is
7					
8	Surface storage	4	mm	Number steps	
9	Intake family for infiltration functions (write intake family number in cell B7)			40	
10	Intake family	1	Put intake family to left	fraction	
11	NRCS_a	0.1786	a and b are automatically	0.025	
12	NRCS_b	0.7850	updated	0.05	
13	Include the initial depth	TRUE	This is the 0.6985 mm infilt	0.075	
14	Runoff	3.18	mm	0.1	
15	Infiltration + storage	9.74	mm	0.125	
16	Sprinkler application	12.92	mm	0.15	

Question 12.10. Derive the Christensen's F factor in Eq. 12.12 by assuming that a center pivot has four sprinklers (1/4, 1/2, 3/4, and full length down the pivot).

This is not the same as the pivot F factor; however, if 30 sprinklers were used in the calculation, then, the answer would be the same. The difference is due to truncation error.

Question 12.11. Low-pressure sprinkler nozzles at Paradise Cattle Company have a wetted diameter (Dw) of 2 m. The average rotation period of the center pivot is 8 hours. The pivot is 400 m radius and the flow rate is 95 L/sec. 5 % of water is lost to evaporation. Calculate the daily gross application rate, and plot the instantaneous application rate as a function of time at the 400 m.

Answer: max application rate is 102 cm/hr

	A	B	C	D	E	F	G	H	I
1	Pivot length (radius)	400 m		Sprinkler distance	400 m		Fraction evap	0.05	
2	Pivot area	50.3 ha	Hide graph	Wetted diameter	2 m		ia	15.49 mm/day	
3	Hours per day operation	24 hr		Rotation rate	8 hr/day		net depth/pass	5.16 mm/pass	
4	Gross application rate	16.3 mm/day	Show graph	Ta	0.38 minutes		di/dt-max	17.21 mm/min	
5	Pivot flow rate	95.0 L/sec							
6						Input data is entered into white cells			
7									
8	Surface storage	3	mm						
9	Intake family for infiltration functions (write intake family number in cell B7)								
10	Intake family	2	Put intake family to left						
11	NRCS_a	0.0000	a and b are automatically						
12	NRCS_b	0.0000	updated						
13	Include the initial depth	TRUE	This is the 0.6985 mm infilt						
14	Runoff	1.47	mm						
15	Infiltration + storage	3.70	mm						
16	Sprinkler application	5.17	mm						
17									
18									
19	Intake families	a (cm/hr)	b						
20	0.05	0.0533	0.618						
21	0.1	0.062	0.661						
22	0.15	0.0701	0.683						
23	0.2	0.0771	0.699						
24	0.25	0.0853	0.711						
25	0.3	0.0925	0.72						
26	0.35	0.0996	0.729						
27	0.4	0.1064	0.736						

Question 12.12. Plot the instantaneous application rate vs. time for at 200 m for the same parameters as in question 12.11. Answer: max application rate is 51 cm/hr.

	A	B	C	D	E	F	G	H	I
1	Pivot length (radius)	400 m		Sprinkler distance	200 m		Fraction evap	0.05	
2	Pivot area	50.3 ha	Hide graph	Wetted diameter	2 m		ia	15.49 mm/day	
3	Hours per day operation	24 hr		Rotation rate	8 hr/day		net depth/pass	5.16 mm/pass	
4	Gross application rate	16.3 mm/day	Show graph	Ta	0.76 minutes		di/dt-max	8.60 mm/min	
5	Pivot flow rate	95.0 L/sec							
6						Input data is entered into white cells			
7									
8	Surface storage	3	mm						
9	Intake family for infiltration functions (write intake family number in cell B7)								
10	Intake family	2	Put intake family to left						
11	NRCS_a	0.0000	a and b are automatically						
12	NRCS_b	0.0000	updated						
13	Include the initial depth	TRUE	This is the 0.6985 mm infilt						
14	Runoff	1.47	mm						
15	Infiltration + storage	3.70	mm						
16	Sprinkler application	5.17	mm						
17									
18									
19	Intake families	a (cm/hr)	b						
20	0.05	0.0533	0.618						
21	0.1	0.062	0.661						
22	0.15	0.0701	0.683						
23	0.2	0.0771	0.699						
24	0.25	0.0853	0.711						
25	0.3	0.0925	0.72						
26	0.35	0.0996	0.729						
27	0.4	0.1064	0.736						
28	0.45	0.113	0.742						

Question 12.13. Calculate the pressure loss in a center pivot that has a length of 350 m, and gross application depth applied during each pass is 5 mm. Time of rotation is 8 hours. Use 198 mm pipe. There is no down time.

With three rotations, the daily gross application depth is 15 mm in 24 hours. The pivot flow rate is 67 L/sec.

	A	B
1	Pivot length (radius)	350 m
2	Pivot area	38.5 ha
3	Hours per day operation	24 hr
4	Gross application rate	15 mm/day
5	Pivot flow rate	67.0 L/sec

Calculate head loss with Hazen-Williams equation.

$$H_L = kL\left(\frac{\left(\frac{Q}{C}\right)^{1.852}}{D^{4.87}}\right) = 1.22*10^{10}*350*\left(\frac{\left(\frac{67}{130}\right)^{1.852}}{197^{4.87}}\right) = 7.8 \ m$$

$$H_{act} = H_{LP}F = (7.8)(0.54) = 4.20m$$

Question 12.14. A sprinkler has a flow rate of 5 GPM at 20 PSI. What is the flow rate at 25 PSI?

$$Q_2 = Q_1\sqrt{\frac{H_2}{H_1}} = Q_1\sqrt{\frac{25}{20}} = 1/0.91 \ (5) = 5.6 \ GPM$$

Question 12.15. Use the *Chapter 12 Center pivot* model to find the optimal water application depth for CV values of 0.1 and 0.3.

For CV = 0.3, the maximum profit is found at 66 cm average depth applied.

Total	64	66	68	70	72	74
Yield (kg/ha)	1144.04	1156.59	1167.45	1176.07	1184.64	1191.67
Leached (cm)	12.90	14.19	15.56	17.00	18.51	20.08
ECe (dS/m)	0.00	0.00	0.00	0.00	0.00	0.00
Ks-salt	1.01	1.01	1.01	1.01	1.01	1.01
Yield ($/ha)	1052.52	1064.06	1074.06	1081.99	1089.87	1096.34
Water ($/ha)	220.38	227.26	234.15	241.04	247.93	254.81
Envir. ($/ha)	12.90	14.19	15.56	17.00	18.51	20.08
Energy ($/ha)	90.26	93.08	95.90	98.72	101.54	104.36
Profit ($/ha)	728.98	729.53	728.45	725.22	721.89	717.08
Pro.(no Env.)	741.88	743.72	744.00	742.22	740.40	737.16

For CV = 0.1, the maximum profit is found at 68 average depth applied.

Total	64	66	68	70	72	74
Yield (kg/ha)	1239.02	1252.47	1264.12	1274.04	1282.30	1288.97
Leached (cm)	10.89	12.10	13.44	14.91	16.51	18.25
ECe (dS/m)	0.00	0.00	0.00	0.00	0.00	0.00
Ks-salt	1.01	1.01	1.01	1.01	1.01	1.01
Yield ($/ha)	1139.90	1152.27	1162.99	1172.12	1179.72	1185.85
Water ($/ha)	229.19	236.35	243.52	250.68	257.84	265.00
Envir. ($/ha)	10.89	12.10	13.44	14.91	16.51	18.25
Energy ($/ha)	90.26	93.08	95.90	98.72	101.54	104.36
Profit ($/ha)	809.56	810.73	810.13	807.81	803.82	798.24
Pro. (no Env.)	820.44	822.83	823.57	822.71	820.33	816.49

Question 12.16. Is it worth adding pressure regulators for the elevations shown in Fig. 12.23? Regulators cost is $5.00 per. This is the same as question 12.15, but add the regulators.

First try 0.3 CV with regulators. For the case that considers environmental cost, the maximum profit with pressure regulators is found at 70 cm but it is only $727.29, which is less than the maximum profit with no pressure regulators, $729.53. Thus, pressure regulators are not worth it for 0.3 CV.

10	seasonal			
11	simulation	Pressure Regulator?		TRUE

Total	64	66	68	70	72	74
Yield (kg/ha)	1138.08	1152.02	1164.25	1174.83	1183.83	1191.29
Leached (cm)	12.79	14.06	15.41	16.84	18.32	19.85
ECe (dS/m)	0.00	0.00	0.00	0.00	0.00	0.00
Ks-salt	1.01	1.01	1.01	1.01	1.01	1.01
Yield ($/ha)	1047.03	1059.86	1071.11	1080.85	1089.12	1095.99
Water ($/ha)	218.61	225.44	232.27	239.11	245.94	252.77
Envir. ($/ha)	12.79	14.06	15.41	16.84	18.32	19.85
Energy ($/ha)	90.48	93.31	96.14	98.97	101.79	104.62
Profit ($/ha)	725.15	727.05	727.29	725.94	723.06	718.75
Pro.(no Env.)	737.94	741.11	742.70	742.77	741.39	738.60

0.1 CV with pressure regulators. The maximum profit with pressure regulators is 804.01 at 72 cm applied depth. This is less than the maximum profit of 810.73 without pressure regulators.

Total	64	66	68	70	72	74
Yield (kg/ha)	1196.33	1213.46	1228.90	1242.70	1254.93	1265.65
Leached (cm)	8.18	9.01	9.92	10.93	12.03	13.24
ECe (dS/m)	0.00	0.00	0.00	0.00	0.00	0.00
Ks-salt	1.01	1.01	1.01	1.01	1.01	1.01
Yield ($/ha)	1100.62	1116.39	1130.59	1143.28	1154.54	1164.40
Water ($/ha)	210.40	216.97	223.55	230.12	236.70	243.27
Envir. ($/ha)	8.18	9.01	9.92	10.93	12.03	13.24
Energy ($/ha)	90.48	93.31	96.14	98.97	101.79	104.62
Profit ($/ha)	791.56	797.10	800.98	803.27	804.01	803.26
Pro.(no Env.)	799.74	806.10	810.90	814.20	816.05	816.50

Question 12.17. A center pivot irrigation system requires 200 kPa sprinkler pressure. There are five pivots each with a flow rate of 110 L/sec. Pressure regulators are used. Sprinklers are 1 m above the land surface. There is a 4 m pressure loss in the pivot pipeline, and 10 m head loss in the pipe network between the pumps and the worst case pivot. The maximum elevation of the land surface is 20 m higher than the reservoir. Make all other necessary assumptions. How many pumps are required? At what pressure and flow rate should the pumps operate?

The total pump pressure required is the sum of:

- **Sprinkler pressure: 200 kPa = 20 m**
- **Sprinklers elevation: 1 m**
- **pressure loss in the pivot pipeline: 4 m**
- **head loss in the pipe network between the pumps and the pivot: 10 m**
- **maximum elevation of the land surface (higher than the reservoir): 20 m**

The total pressure required = 20 + 1 + 4 + 10 + 20 = 55

If an extra 2 m pressure is added to account for degradation of the pump over time and if the pivot requires a flow rate of 95 LPS then five pumps with 57 m pressure and 95 LPS flow rate should be used.

Chapter 13: Solution

1. Describe the major categories of turf sprinklers

   - Fixed spray sprinklers cover small areas (<5 m radius) and, as the name indicates, have a fixed spray that does not rotate. They generally have flow rates of 8, 4, and 2 LPM for full, half, and quarter circle sprinklers, respectively. This results in application rates of between 25 and 50 mm/hour.
   - Rotors have gear mechanisms that slowly rotate the sprinkler. These sprinklers cover a larger area (>5 m radius), and thus have a lower application rate (<25 mm/hr).

2. Which turf sprinklers have the highest application rate?
   - Fixed spray sprinklers

3. What is the maximum precipitation rate in mm/hr for a coarse sandy loam with a 6 % slope?
   - With cover: 51 mm/hr
   - Bare: 38 mm/hr

4. Discuss the reason for placing sprinklers in corners of turf areas.
   - Sprinkler application rate decreases with distance from the sprinkler; thus, if there would be no sprinkler in the corner, plants in the corner would receive a small depth of water in comparison to locations closer to sprinklers.

5. Describe head to head coverage.
   - Sprinklers should be designed for head-to-head coverage, which means that the wetted area from one sprinkler just touches the next sprinkler. The need for head to head coverage is based on the fact that sprinklers have a triangular pattern of application depth vs. distance from the sprinkler.

6. Why must sprinklers with different application rates be placed on different valves?
   - All sprinklers with the same application rate must run for the same length of time.

7. What are the advantages of swing joints?
   - Sprinklers should be installed on swing joints for two reasons:
     - First, people step on sprinklers and equipment runs over sprinklers, and this force can break the lateral pipe if the sprinklers are installed directly over the pipe. Swing joints allow the sprinkler to be pushed down without breaking the pipe.
     - The second advantage of swing joints is that they make positioning sprinklers easy during installation.

8. What is the application rate for a 1.8 m spray SRS spray head with half circle coverage? Assume 1.8 × 1.8 m

spacing. Comment on whether this is a low, average, or high application rate.
- 3.71 l/min, spacing = 1.8 m
- mm/hr = lpm * 120/(m * m) = 3.7 * 120/(1.8 * 1.8) = 137 mm/hr

This is an high application rate. For most soils, the sprinkler cannot be left on for an extended period without runoff.

9. What is the application rate for a full circle 5 GPM (19 LPM) sprinkler on 50 ft × 50 ft (15.2 m × 15.2 m) spacing? Calculate for U.S. (Imperial) and metric units.

$$\text{Full-circle sprinkler}$$
$$in/hr = \frac{GPM*96.3}{ft*ft}$$
$$mm/hr = \frac{LPM*60}{m*m}$$

$$in/hr = ((5gpm*96.3)/(50ft*50ft)) = 0.1926 \ in/hr$$

$$mm/hr = 19*60/(15.2*15.2) = 5 \ mm/hr$$

10. What is the application rate for the sprinkler in question 9 with half circle coverage?

$$\text{Half-circle sprinkler}$$
$$in/hr = \frac{GPM*193}{ft*ft}$$
$$mm/hr = \frac{LPM*120}{m*m}$$

$$in/hr = ((5 \ gpm*193)/(50ft*50ft)) = 0.386 \ in/hr$$

11. Lay out sprinklers in zones in a 45 ft × 45 ft (13.7 m × 13.7 m) turf area with the SRS spray heads with 4.6 m radius (Table 13.2). City water pressure is 40 PSI (276 kPa) and maximum flow rate for the system is 12 GPM (45.4 LPM). Divide the turf area into zones so that the maximum flow rate is not exceeded. You do not need to show pipes in the drawing. Reference ET rate is 12 mm/day and the crop coefficient for turf is 0.7. Scheduling coefficient is 1.3 and there is 7 % evaporation from sprinkler droplets. Determine the watering time per day.
- Image see below

The 4.6 m diameter sprinklers have a maximum flow rate of 15.6, 7.8, and 3.9 LPM for the full, half, and quarter circle sprinklers, respectively. Use the higher flow rate in the table because the city water pressure is higher than the maximum listed pressure in the table (241 kPa).

Space the sprinklers on 4.6 m (15 ft) spacing, thus, the configuration in the image below. Calculate the application rate based on the full circle sprinkler. All other sprinklers have the same application rate.

$$mm/hr = 15.6*60/(4.6*4.6) = 44 \ mm/hr(1.7 \ in/hr)$$
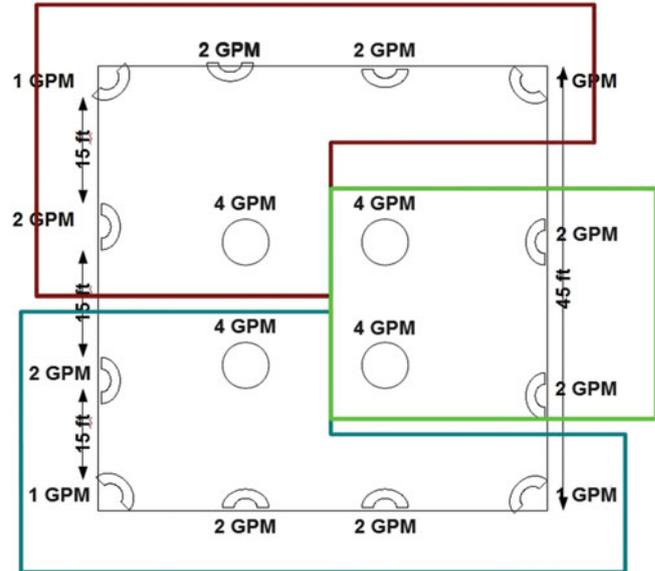
- ET_{rate} * crop coefficient = actual ET_{rate}
- 12 mm/d * 0.7 = 8.4 mm/d = $^1/_3$ in/d
- Watering time per day:
  - ET_{rate}/application rate = watering time per day
  - $^1/_3$ in/d/1.7 in/hr = 0.176 hrs = 10.58 min

12. A pipe system has 10 sprinklers that are 15 m apart and each sprinkler has a flow rate of 20 L/min. The field is level. Select appropriate pipe sizes for each section so that total pressure loss in the system is no more than 5 PSI. Show a hand calculation for two sections but you can use the Simple Lateral Worksheet for the entire lateral design. Repeat for a 2 % uphill slope and a 2 % downhill slope with the Simple Lateral Worksheet.

5 PSI pressure loss is the same as 3.5 m.
The 0 % slope solution

	E	F	G	H	I	J
be design - starts at the end of the lateral (Row 15)					by Armando Barreto and Peter Waller	
C Value	150					
prinklers	10					
(+ = up)	0					
ral (kPa)	441					
teral (m)	45.0					
	Select diameter	**Inside diameter**	**Spr flow (LPM)**	**Distance (m)**	**Friction loss (m)**	**Head, next (m)**
nkler 10	25 SCH 40 ▼	26.64	20.00	15.00	0.255	45.25
Spr. 9	25 CL 200 ▼	30.2	20.00	15.00	0.500	45.75
Spr. 8	37 CL 125 ▼	45.32	20.00	15.00	0.147	45.9
Spr. 7	37 CL 125 ▼	45.32	20.00	15.00	0.250	46.2
Spr. 6	37 CL 125 ▼	45.32	20.00	15.00	0.378	46.5
Spr. 5	37 CL 125 ▼	45.32	20.00	15.00	0.529	47.1
Spr. 4	50 CL 125 ▼	56.58	20.00	15.00	0.239	47.3
Spr. 3	50 CL 125 ▼	56.58	20.00	15.00	0.306	47.6
Spr. 2	50 CL 125 ▼	56.58	20.00	15.00	0.381	48.0
Spr. 1	50 CL 200 ▼	54.56	20.00	15.00	0.552	48.5

The 2 % downhill solution

	E	F	G	H	I	J
be design - starts at the end of the lateral (Row 15)					by Armando Barreto and Peter Waller	
C Value	150					
prinklers	10					
(+ = up)	-2					
ral (kPa)	441					
teral (m)	45.0					
	Select diameter	**Inside diameter**	**Spr flow (LPM)**	**Distance (m)**	**Friction loss (m)**	**Head, next (m)**
nkler 10	25 SCH 40 ▼	26.64	20.00	15.00	0.255	44.95
Spr. 9	25 CL 200 ▼	30.2	20.00	15.00	0.500	45.15
Spr. 8	25 CL 200 ▼	30.2	20.00	15.00	1.059	45.9
Spr. 7	31 CL 125 ▼	39.6	20.00	15.00	0.482	46.1
Spr. 6	31 CL 125 ▼	39.6	20.00	15.00	0.728	46.5
Spr. 5	31 CL 125 ▼	39.6	20.00	15.00	1.021	47.2
Spr. 4	37 CL 125 ▼	45.32	20.00	15.00	0.704	47.6
Spr. 3	37 CL 125 ▼	45.32	20.00	15.00	0.902	48.3
Spr. 2	50 CL 125 ▼	56.58	20.00	15.00	0.381	48.3
Spr. 1	50 CL 125 ▼	56.58	20.00	15.00	0.463	48.5
n/a	75 CL 160 ▼					

The 2 % uphill solution

	E	F	G	H	I	J
e design - starts at the end of the lateral (Row 15)					by Armando Barreto and Peter Waller	
C Value	150					
inklers	10					
+ = up)	2					
al (kPa)	441					
eral (m)	45.0					
	Select diameter	Inside diameter	Spr flow (LPM)	Distance (m)	Friction loss (m)	Head, next (m
kler 10	37 CL 125	45.32	20.00	15.00	0.019	45.32
Spr. 9	37 CL 125	45.32	20.00	15.00	0.069	45.69
Spr. 8	50 CL 125	56.58	20.00	15.00	0.050	46.0
Spr. 7	50 CL 125	56.58	20.00	15.00	0.085	46.4
Spr. 6	50 CL 125	56.58	20.00	15.00	0.128	46.9
Spr. 5	75 CL 125	83.42	20.00	15.00	0.027	47.2
Spr. 4	75 CL 125	83.42	20.00	15.00	0.036	47.5
Spr. 3	75 CL 125	83.42	20.00	15.00	0.046	47.9
Spr. 2	100 CL 125	107.28	20.00	15.00	0.017	48.2
Spr. 1	100 CL 125	107.28	20.00	15.00	0.021	48.5
n/a	75 CL 160					

Much larger pipe is needed on the uphill slope to conserve energy. It is cheaper to run the submain along the top of the hill and then to run sprinkler laterals downhill.

13. What is the scheduling coefficient for the U of A high pressure sprinkler in the *Chapter 13 Sprinkler Uniformity* program on the following grids? Discuss the reasons for the highest SC with the last spacing.

    14 m × 14 m square. SC 1.51

    13 m × 15 m triangle SC 1.50

    16 × 16 m square SC 1.66

    15 × 17.3 triangle SC 2.10

    20 × 20 square SC 1.68

    19 × 22 triangle SC 1.33

This is the best spacing of all. Most of the area is low. Thus, the SC is not high. Other spacings had a single or limited low spot, so the entire area was overwatered because of the low spot.

14. Use the *Economic summary* worksheet for the U of A high pressure sprinkler. Cost of each sprinkler head installation is $30. Cost of trenching and pipe is $5.00/m. Life of the project is 10 years. Interest rate is 9 %. Required water depth/year is 2 m. Evapotranspiration rate is 25 %. Cost of water is $0.50/m^3. Determine the lowest present value for the square or triangular spacing. Which is lowest?

This is a strange result, but the optimal spacing is 8 × 9.2 with the triangular grid. The SC is the main criterion since the water cost is so high.

Triangle	11 Excel rows					
Row (m)	Head (m)	SC	Annual	20 year	Capital	Total cost
5	5.8	1.389	$ 13,925	$ 89,368	$20,380	$ 109,748
6	6.9	1.4191	$ 14,226	$ 91,301	$15,542	$ 106,842
7	8.1	1.2936	$ 12,969	$ 83,229	$12,439	$ 95,667
8	9.2	1.1072	$ 11,100	$ 71,235	$10,305	$ 81,540
9	10.4	1.1391	$ 11,419	$ 73,285	$ 8,759	$ 82,045
10	11.6	1.2039	$ 12,070	$ 77,459	$ 7,595	$ 85,054
11	12.7	1.3142	$ 13,175	$ 84,555	$ 6,690	$ 91,245
12	13.9	1.394	$ 13,975	$ 89,689	$ 5,969	$ 95,658
13	15.0	1.507	$ 15,108	$ 96,957	$ 5,382	$ 102,339
14	16.2	1.7733	$ 17,778	$ 114,092	$ 4,895	$ 118,988
15	17.3	2.096	$ 21,012	$ 134,850	$ 4,487	$ 139,337

Square	16 Excel rows					
Row (m)	Head (m)	SC	Annual	20 year	Capital	Total cost
5	5	1.3043	$ 13,076	$ 83,916	$22,000	$ 105,916
6	6	1.2283	$ 12,314	$ 79,028	$16,667	$ 95,695
7	7	1.1671	$ 11,700	$ 75,087	$13,265	$ 88,352
8	8	1.2214	$ 12,244	$ 78,579	$10,938	$ 89,516
9	9	1.2545	$ 12,577	$ 80,713	$ 9,259	$ 89,972
10	10	1.2331	$ 12,362	$ 79,336	$ 8,000	$ 87,336
11	11	1.1963	$ 11,993	$ 76,968	$ 7,025	$ 83,993
12	12	1.3915	$ 13,950	$ 89,525	$ 6,250	$ 95,775
13	13	1.5128	$ 15,165	$ 97,327	$ 5,621	$ 102,948
14	14	1.5062	$ 15,100	$ 96,904	$ 5,102	$ 102,006
15	15	1.5511	$ 15,550	$ 99,793	$ 4,667	$ 104,459
16	16	1.6607	$ 16,649	$ 106,848	$ 4,297	$ 111,145
17	17	1.8915	$ 18,962	$ 121,692	$ 3,979	$ 125,671
18	18	1.695	$ 16,992	$ 109,052	$ 3,704	$ 112,755
19	19	1.5169	$ 15,207	$ 97,591	$ 3,463	$ 101,054

15. Redo Example 13.3. In this case, the city can provide 70 gal/min (fewer zones are required). Set up a spreadsheet to calculate lateral losses. Leave sprinklers in the same positions.

It would not be impossible to divide the field into two zones because there is a total 142 GPM out of all the sprinklers. This is just slightly higher than 2 * 70 GPM. All of the central sprinklers should be run as one zone, and they should not be mixed with the outer sprinklers. The total flow of outer sprinklers is almost 100 GPM. Thus, the outer sprinklers must be split into two zones. The new sprinkler layout is shown in the following figure.

The hydraulics of each of the three zones is shown in the copied Worksheets after the drawing of the sprinklers and pipes.

Scheduling is not a problem since there was no problem with 5 zones in the example.

Zone 1 hydraulics.

A:C	D	E	F	G	H	I	J	K	L
4	C Value	140				Nominal ID			
6	Number sprinklers	7			Nozzle 1	4	k1	0.523	
8	Slope (%) (+ = up)	0			Nozzle 2	6	k2	0.778	
10	Design P, end of lateral (PSI)	50			Nozzle 3	8	k3	1.05	
12	Pressure at end of lateral (ft)	115.5							

		Select diameter	ID (in)	Nozzle ID	Spr flow (GPM)	Distance (ft)	Friction (ft)	Head, next (ft)	#
15	Last sprinkler, Sprinkler 7	1" CL 200	1.19	8	7.42	50.00	0.978	116.5	7
16	Spr. 6	1 1/4" CL 125	1.56	6	5.52	50.00	0.732	117.2	6
17	Spr. 5	1 1/2" CL 125	1.78	8	7.48	50.00	0.883	118.1	5
18	Spr. 4	1 1/2" CL 125	1.78	6	5.56	50.00	1.379	119.5	4
19	Spr. 3	2" CL 125	2.23	8	7.55	50.00	0.750	120.2	3
20	Spr. 2	2" CL 125	2.23	6	5.61	57.00	1.139	121.4	2
21	Spr. 1	2" CL 125	2.23	6	5.64	2.00	0.051	121.4	1
22	ot used	2 1/2" CL 125							0
23	ot used	2 1/2" CL 125							-1
24	ot used	2 1/2" CL 125							-2
25	n/a	2 1/2" CL 125							-3

Zone 2 hydraulics.

A:C	D	E	F	G	H	I	J	K	L
4	C Value	140				Nominal ID			
6	Number sprinklers	7			Nozzle 1	4	k1	0.523	
8	Slope (%) (+ = up)	0			Nozzle 2	6	k2	0.778	
10	Design P, end of lateral (PSI)	50			Nozzle 3	8	k3	1.05	
12	Pressure at end of lateral (ft)	115.5							

		Select diameter	ID (in)	Nozzle ID	Spr flow (GPM)	Distance (ft)	Friction (ft)	Head, next (ft)	#
15	Last sprinkler, Sprinkler 7	1" CL 200	1.19	4	3.70	40.00	0.215	115.7	7
16	Spr. 6	1 1/4" CL 125	1.56	8	7.43	40.00	0.442	116.2	6
17	Spr. 5	1 1/2" CL 125	1.78	8	7.45	50.00	0.740	116.9	5
18	Spr. 4	1 1/2" CL 125	1.78	8	7.47	40.00	1.107	118.0	4
19	Spr. 3	2" CL 125	2.23	8	7.50	47.00	0.706	118.7	3
20	Spr. 2	2" CL 125	2.23	4	3.75	45.00	0.822	119.5	2
21	Spr. 1	2" CL 125	2.23	8	7.55	48.00	1.234	120.8	1
22	ot used	2 1/2" CL 125							0
23	ot used	2 1/2" CL 125							-1
24	ot used	2 1/2" CL 125							-2
25	n/a	2 1/2" CL 125							-3
26	n/a	2 1/2" CL 125							-4
27	n/a	2 1/2" CL 125							-5

Zone 3 hydraulics.

D	E		F	G	H	I	J	K	L
C Value	140					Nominal ID			
Number sprinklers	8				Nozzle 1	4	...	k1	0.523
Slope (%) (+ = up)	0				Nozzle 2	6		k2	0.778
Design P, end of lateral (PSI)	50				Nozzle 3	8		k3	1.05
Pressure at end of lateral (ft)	115.5								

	Select diameter		ID (in)	Nozzle ID	Spr flow (GPM)	Distance (ft)	Friction (ft)	Head, next (ft)	#
Last sprinkler, Sprinkler 8	1 1/4" CL 125	▼	1.56	6	5.50	0.20	0.001	115.5	8
Spr. 7	1 1/4" CL 125	▼	1.56	6	5.50	50.00	0.541	116.0	7
Spr. 6	1 1/2" CL 125	▼	1.78	6	5.51	0.20	0.002	116.0	6
Spr. 5	1 1/2" CL 125	▼	1.78	6	5.51	50.00	1.015	117.1	5
Spr. 4	1 1/2" CL 125	▼	1.78	6	5.54	0.20	0.006	117.1	4
Spr. 3	1 1/2" CL 125	▼	1.78	6	5.54	50.00	2.159	119.2	3
Spr. 2	2" CL 125	▼	2.23	8	7.54	0.20	0.004	119.2	2
Spr. 1	2" CL 125	▼	2.23	6	5.59	50.00	1.360	120.6	1
ot used	2 1/2" CL 125	▼							0
ot used	2 1/2" CL 125	▼							-1
n/a	2 1/2" CL 125	▼							-2
n/a	2 1/2" CL 125	▼							-3
n/a	2 1/2" CL 125	▼							-4

(Chart: Spr flow (GPM), Lateral Pr. (PSI) vs Sprinkler number)

16. Answers will vary

Chapter 14: Solution

1. An orchard is on a hill. How should the mainline, submain, and laterals be positioned so that all the sprinklers on the property have nearly the same operating pressure?

The mainline should be run to the top of the hill, the submain should run along the top of the hill, and all the laterals should run downhill.

2. True or false. The two main causes of nonuniformity of application in wheel-line sprinkler systems are hydraulic variation along the pipeline and spatial variability of soils.

False, the two sources of nonuniformity are hydraulic variation and nonuniformity of application. In theory, you shouldn't have any runoff with sprinkler systems so soil properties would not influence distribution uniformity

3. True or false. Water hammer is a major problem in sprinkler laterals.

False, each of the sprinklers acts like an air vent and pressure relief valve.

4. The last two sprinklers on a PVC pipeline have a flow rate of 20 L/min. The end pressure is 350 kPa. The distance between sprinklers is 15 m. The slope is 3 % downhill. Select pipe sizes for the last two pipe sections so that the three sprinklers have no more than a 0.2 m variation in head between them. Use a Hazen-Williams C value of 150. You can use the Worksheet to find the pipe sizes, but also make the two calculations of pipe pressure losses and change in pressure from one sprinkler to the next by hand.

The pressure at the last sprinkler is 35.7 m (350 kPa)
The two pipe sizes that will work are 18 (3/4", 23.66 mm) Class 200 and 25 (1", 30.2 mm) Class 200
The friction loss in the last pipe section is

$$H_L = 1.22*10^{10}*15 \ m \left(\left(\frac{20/60}{150} \right)^{1.852} / 23.66^{4.87} \right)$$

$$= 0.454 \ m$$

Calculate pressure at the next to last sprinkler with Eq. 14.1.

$$H_{n-1} = H_n + H_L + (s_L)(S/100)$$
$$= 35.7 + 0.454 + 15(-0.03) = 35.7 \ m$$

The friction loss in the next to last pipe section is

$$H_L = 1.22 \ast 10^{10} \ast 15 \ m \ \left(\left(\frac{40/60}{150} \right)^{1.852} / 30.2^{4.87} \right) = 0.500 \ m$$

$$\begin{aligned} H_{n-1} &= H_n + H_L + (s_L)(S/100) \\ &= 35.7 + 0.5 + 15(-0.03) = 35.75 \ m \end{aligned}$$

5. A ¼ mile wheel-line has a downhill slope of 2 %. Use 3/16″ nozzles (ID = 4.8 mm). Calculate an equation for sprinkler flow rate vs. pressure. Then, determine whether pressure would have less variation with a 4 in (97.9 mm) or 5 in (123 mm) pipe.

$$Q = 0.0666 \ D^2 H^{0.5} C_d = 0.0666 (4.8^2) (H^{0.5})(0.97)$$

$$= 1.49 \ H^{0.5}.$$

The pressure graph with 4 inch pipe and 2 % slope would be:
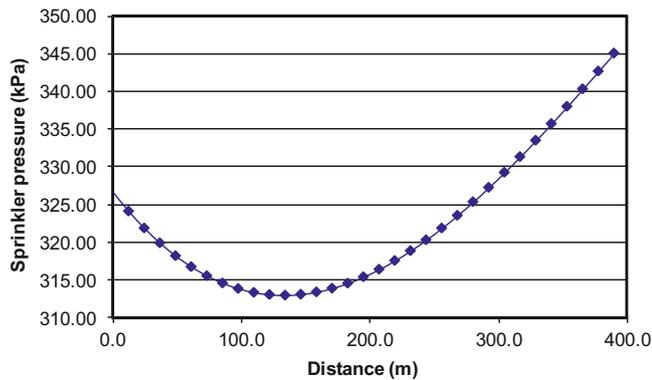
The pressure graph with the 5 inch pipeline and 2 % slope would be as follows. The pressure would be much more uniform with the 4 inch pipe.
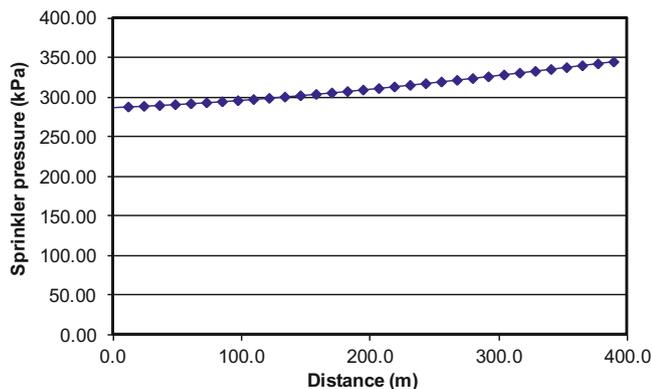
6. For the parameters in Example 14.2, calculate the seasonal depth of water application at the last sprinkler, 6.1 m row position, 0 m head position. Then calculate the depth of water application at the 2.4 m row position, 0 m head position for the first sprinkler. Are these the extremes of application depth? What is the percent difference between the maximum and minimum application rates? The average seasonal depth of water application to a field is 75 cm. Calculate the application depths at the maximum and minimum positions. Evaporation rate is 10 %.

From the worksheet, the relative depth of application at the first sprinkler is 1.04. The relative depth in at the 6.1 × 0 position is 1.45. Thus, the maximum relative application rate is found by multiplying the sprinkler relative rate by the maximum relative application position: 1.04 (1.45) = 1.51

The relative depth of application for the last sprinkler is 1.0. The relative depth at the 2.4 × 0 position in Table 14.4 is 1.0. Thus, the relative depth at this position is (1)(1) = 1.

These are the extremes in the system. Thus, there is approximately 50 % difference in the high and low application depths.

The next step is to find the average relative application depth. Ave_rel = 1.205. This can be found in Cell M2 in the Spatial_data_output or it could be found by taking the average of all the data points in Columns B:K.

The average gross application depth is 75 cm. Calculate the application depth at the maximum and minimum positions. Remember to include the $(1 - Le)$.

$$\begin{aligned} AW_{max} &= (max/average)(1 - Le)(i) \\ &= 1.51/1.205(0.9)(75 \ cm) = 84.6 \ cm \\ AW_{min} &= 1/1.205(0.9)(75 \ cm) = 56.0 \ cm \end{aligned}$$

If you set up the Crop_data_and_summary sheet to only run 75 cm (max and min = 75), then you can find these values in Cells O330 and O7, respectively.

7. Redo Examples 14.1 and 14.2, but don't offset the wheel-line positions with respect to the hydrants. Compare the total profit, and the optimal depths with those found in Example 14.2. Recalculate the energy and water costs.

Everything is the same as Example 14.2 except that Cell A2 is changed to FALSE.

	A	B	C	D	E	F	G	H	I	J	K	L
1	Offset	K	1.018 Kpa LPM	Kh	1.22E+10	coefficent	Diameters		97.9	4-inch	Pipe length	390.10
2	FALSE	x	0.5	Slope	0	m/m	(mm) ID		123.0	5-inch	Hide flow graph	
3	Inlet Pr.	End Press	345 Kpa	CV	9%	sd/mean	Extra Press.		40	kPa	Show flow graph	
4	375.64	Spr. Spac.	12.20 m	C	130	H-W	Pump eff.		70%		Hide pressure graph	
5		Hyd. Spac	18.3 m	Evap	10	%	Total flow		631.36	LPM	Show pressure graph	
6												

	Sprinkler	Distance	Pressure (m)	Pressure (kPa)	Flow (LPM)	Diameter (mm)	Pipe flow (LPM)	Fric loss (m)	% diff flow	Rel	CV simulation	Z-dist
7												
8	33	390.1	35.20	345.00	18.91	97.90	18.91	0.00043	0.00%	1	19.0968149	0.113425
9	32	377.9	35.20	345.00	18.91	97.90	37.82	0.00155	0.00%	1.0000061	20.8171915	1.149616

The results are shown on the following worksheet. Max profit is found at average gross applied depth equal to 100 cm.

$$\text{Water cost} = 100 \; cm \left(\$0.02/m^3\right)\left(\left(100 \; m^3\right)/(ha\text{-}cm)\right)$$
$$= \$200.00/ha$$

$$E(kW - hr/ha) = \frac{0.0272 \; (i_{mm})(h)}{Eff}$$
$$= \frac{0.0272 \; (1000mm)(42.3m)}{0.7}$$
$$= 1,640 \; kW - hr/ha$$

$$\text{Energy cost} = 1,640(\$0.10/\text{kW-hr}) = \$164.00/ha$$

	A	B	C	D	E	F	G	H	I	J	K
1	Eff. Precipitation		7.50 cm		CWPF (tons/cm)		x^1	Alfalfa	Wheel line		
2					Coefficients		0.083	NW USA			
3	Minimum Gross AW		75.00 cm		Yield value		100.0 $/ton				
4	Maximum Gross AW		120.00 cm		AWlimit		100.0 cm		Max benefit depth		
5	AW interval		5 cm		Energy cost		0.10 kW-hr		Ave net depth (cm)		90.00
6	Number columns		10		Leach cost		1.00 $/ha-cm		Ave gross depth		100.00
7	Number rows		10		Water cost		0.0200 $/m3				
8	Number sprinklers		33	Average gross depth applied (cm)							
9			75	80	85	90	95	100	105	110	
10	Yield (kg/ha)		6.20	6.51	6.80	7.08	7.33	7.54	7.70	7.85	
11	Leached depth(cm)		0.				4.63	6.63	9.20	11.88	
12	Yield benefit ($/ha)	$	619.				.47	$754.19	$770.22 $	785.36	
13	Water cost ($/ha)	$	150.				.00	$200.00	$210.00 $	220.00	
14	Energy cost ($/ha)	$	123.				.46	$164.69	$172.93 $	181.16	
15	Environmental cost ($/ha)	$	0.				.63	$ 6.63	$ 9.20 $	11.88	
16	Total benefit ($/ha)	$	345.				.38	$382.86	$378.09 $	372.32	
17	Total benefit w/o Env. ($/ha)	$	346.				.01	$389.49	$387.29 $	384.20	

Main / Principal / Square / Triangle / Evaporation / Wheel-line / Crop_data_and_summary / Spatial_data_output / Lateral design / Submain design / Lateral des
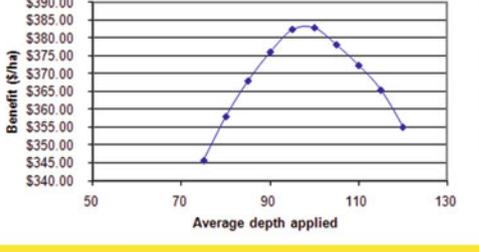
Notice the much deeper drop in application rates between laterals with the wider lateral spacing. The profit is much lower, $378 instead of $440. The optimal depth is 105 cm instead of 100 cm.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1		0	1.83	3.66	5.49	7.32	9.15	10.98	12.81	14.64	16.47	18.3			0	
2	0	1.490683	2.327178	1.740008	1.282191	1	1.347826	1	1.282191	1.740008	2.327178	1.490683		0	83.72277	130.7
3	1.22	2.02795	2.182768	1.610854	1.297921	1.118584	1.337767	1.118584	1.297921	1.610854	2.182768	2.02795		1.22	113.8979	122.5

(3-D surface charts — left legend: □ 2-3, ■ 1-2, □ 0-1; right legend: □ 100-150, ■ 50-100, □ 0-50)
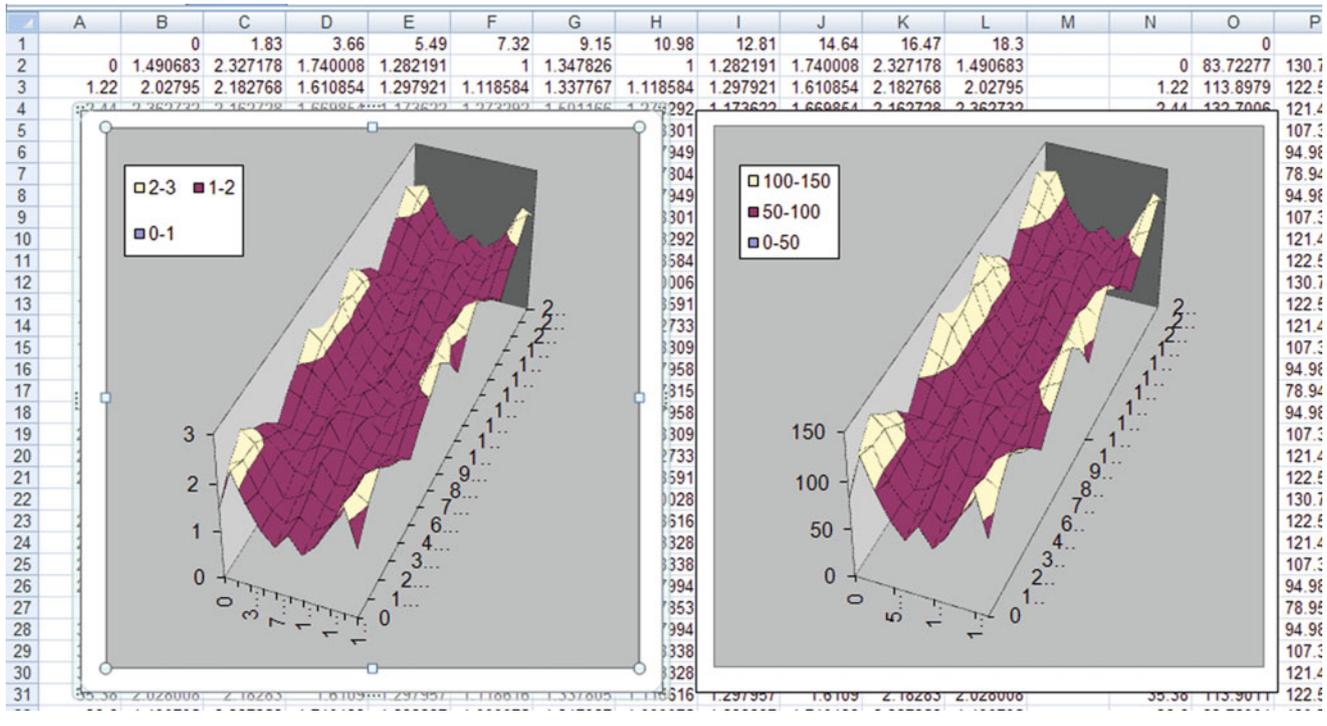
8. Redo Examples 14.1 and 14.2, but use handlines. The normal design for handlines is 40 ft along the mainline and 30 ft between nozzles. Select a nozzle and flow rate from catalogs at the following web sites. The length of the run is 1/8 mile long and the handlines use 3″ aluminum pipe. The slope is 0.005 m/m in the downhill direction. Use the same evapotranspiration, precipitation, power, and production functions as in Example 14.1. Don't offset the handlines. Select sprinklers based on catalog data below. Show the variability due to hydraulics and variation in wetting due to sprinkler patterns. Maximum application rate in 0.3 in/hr. Operate the handlines at 45 PSI pressure.

http://www.rainbird.com/ag/products/impacts/30H.htm
http://www.rainbird.com/documents/ag/chart_20JH.pdf.

Based on the 30 H catalog data, a 9/64″ nozzle operating at 45 PSI would have an application diameter of 42 ft (12.8 m) and flow rate of 3.80 GPM (14.4 LPM or 0.863 m³/hr).

The maximum application rate can be found with Eq. 14.4.

$$\left(\frac{di}{dt}\right)_{max} = \frac{0.863 \ m^3/hr}{\frac{\pi}{3} \ (12.8)^2} = 5.03 \ mm/hr$$

The maximum application rate is 0.3 in/hr (7.6 mm/hr). Because there is very little overlap, there is very little chance that there would be runoff since the maximum application rate would be slightly greater than 5.0 mm/hr.

Assume that the application is a perfect wedge with 13 m diameter.

The equation for the wedge would be as follows.

di/dt = (5.03) (13 − x)/(13) where × is the distance from the sprinkler. This results in an extra column in the Principal Worksheet. An extra line can be added to the list and the ComboBox range.

Format Control

Size | Protection | Properties | Web | Control

Input range: Principal!$C$7:$C$12

Cell link: Principal!$C$2

Drop down lines: 8

☐ 3-D shading

Selection | 5
Distance | 10 m
App. Rate | 2.00 mm/hr

Selection | Sprinkler name
1 | I-41 45.8 L/min 48
2 | U of A test (low pre
3 | U of A test (high pr
4 | 18 LPM 14 m radiu
5 | 18 LPM 14 m radiu
6 | Rainbird 30H perfe

Application rate (mm/hr)

3	4	5	6
7.0	5.8	3.0	5.03
9.5	5.3	5.0	4.64
14.0	4.9	6.0	4.26
16.0	4.5	5.0	3.87
14.0	4.1	4.0	3.48
10.0	3.7	3.5	3.10
8.0	3.3	2.3	2.71
7.0	2.9	2.2	2.32
6.5	2.5	2.2	1.93
6.5	2.1	2.2	1.55
5.5	1.6	2.0	1.16
4.5	1.2	1.0	0.77
3.0	0.8	1.0	0.39
2.0	0.4	0.5	0.0

The new line has been added to the Worksheet for the Rainbird 30H sprinkler pattern represented by a perfect wedge (not realistic).

Select sprinkler | Rainbird 30H perfect wedge

Distance (m) | 10 | Change distance with scroll bar
App rate(mm/hr) | 1.16

Application rate (mm/hr) vs. Distance (m)

Legend:
I-41 45.8 L/min 482.6 kPa
U of A test (high pressure)
U of A test (low pressure)
18 LPM 14 m radius (perfect wedge)
18 LPM 14 m radius
Series6
Rainbird 30H perfect wedge

Main / Principal / Square / Triangle / Evaporation / Wheel-line / Crop_data_and_summary / Spatial_data_output / Lateral design / Submain design / Lateral des

The next step is to calculate the k value.

This will be done with the flow data. 45 PSI/ 0.145 = 310 kPa.

$$Q = kH^x$$
$$K = Q/(H^x) = 14.4 \ LPM/(310^{0.5}) = 0.818$$
$$1/8 \ \text{mile} = 201 \ m.$$

The inside diameter of 3 inch pipe is 74.0 mm. The C value is low because of the couplings and damage to pipes. Estimate as 90. The Wheel-line worksheet is set up as follows.
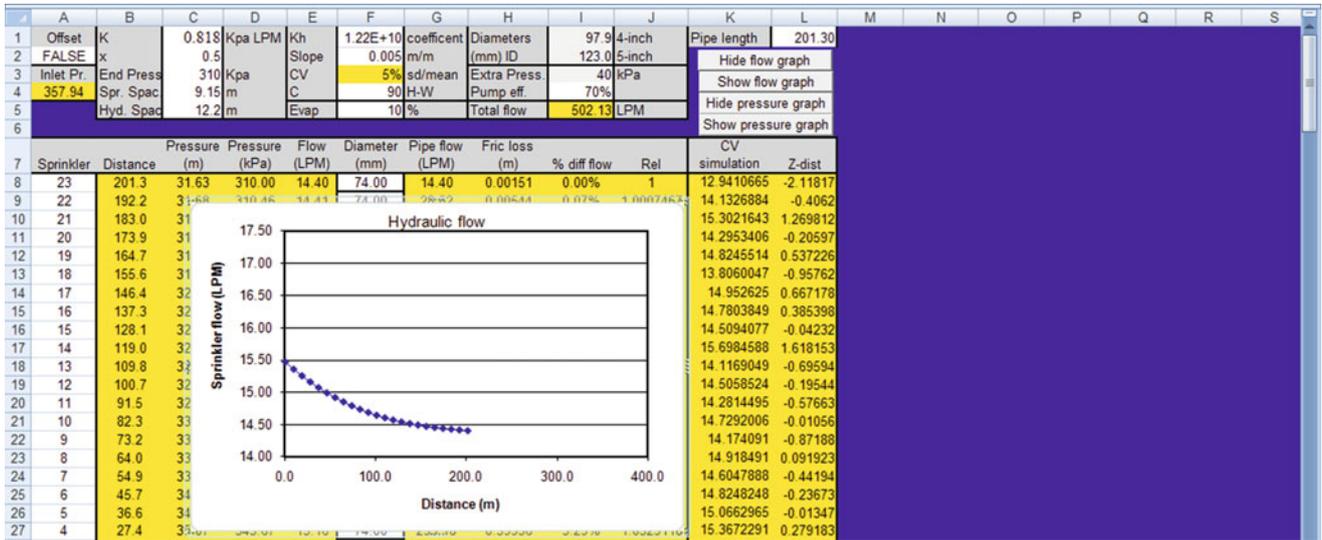
There are 23 sprinklers on the line so the Crop_data_and_summary Worksheet is set up as follows. The best average gross depth applied is 100 cm.

The variability due to sprinkler patterns is low since the wedge application pattern was specified. The CV is only 5 %.

Spreadsheet (Spatial_data_output):

#	A	B=0	C=1.22	D=2.44	E=3.66	F=4.88	G=6.1	H=7.32	I=8.54	J=9.76	K=10.98	L=12.2	M=Ave_rel	N	O=0	P=1.22	Q=2.44	R=3.66	S=4.88
2	0	1.012076	1.266353	1.238012	1.249732	1.283357	1.294497	1.283357	1.249732	1.238012	1.266353	1.012076	1.249071	0	72.92367	91.24525	89.20318	90.04766	92.47043
3	0.915	1.265072	1.245899	1.238924	1.249454	1.239285	1.283605	1.239285	1.249454	1.238924	1.245899	1.265072		0.915	91.15296	89.77142	89.26889	90.0276	89.2949
4	1.83	1.198637	1.19885	1.237752	1.256281	1.250901	1.251305	1.250901	1.256281	1.237752	1.19885	1.198637		1.83	86.36604	86.38128	89.18441	90.51952	90.13184
5	2.745	1.124332	1.156619	1.217684	1.243761	1.24316	1.242235	1.24316	1.243761	1.217684	1.156619	1.124332		2.745	81.01214	83.33852	87.73844	89.61738	89.57411
6	3.66	1.042472	1.123574	1.18526	1.233362	1.259384	1.2676	1.259384	1.233362	1.18526	1.123574	1.042472		3.66	75.11381	80.9575	85.40218	88.86813	90.74308
7	4.575	1	1.112181	1.191209	1.240699	1.267506	1.275964	1.267506	1.240699	1.191209	1.112181	1		4.575	72.05355	80.13661	85.83084	89.39677	91.32828
8													9384		80.9575	85.40218	88.86813	90.74308	
9													4316		83.33852	87.73844	89.61738	89.57411	
10													0901		86.38138	89.18441	90.51952	90.13184	
11	1												9285		89.77142	89.26889	90.0276	89.2949	
12	1												4315		91.31338	89.26978	90.1149	92.53947	
13	1												0211		89.83846	89.33554	90.09482	89.36157	
14	1												1835		86.44588	89.25101	90.5871	90.19914	
15	1												4089		83.40074	87.80395	89.6843	89.64099	
16	1												0324		81.01794	85.46595	88.93448	90.81084	
17	1												8452		80.19644	85.89493	89.46352	91.39647	
18	1												0324		81.01794	85.46595	88.93448	90.81084	
19	1												4089		83.40074	87.80395	89.6843	89.64099	
20	1												1835		86.44588	89.25101	90.5871	90.19914	
21	1												0211		89.83846	89.33554	90.09482	89.36157	
22		1.5											5352	100	91.38712	89.34187	90.18767	92.6142	
23	1												1212		89.911	89.40768	90.16758	89.43374	
24	2	1											2846		86.51569	89.32308	90.66026	90.27198	
25	2												5093	50	83.46809	87.87486	89.75672	89.71339	
26	2	0.5											1342		81.08337	85.53497	89.0063	90.88417	
27	2												9476		80.26121	85.96429	89.53577	91.47028	
28	2	0											1342		81.08337	85.53497	89.0063	90.88417	
29	2												5093	0	83.46809	87.87486	89.75672	89.71339	
30	2												2846		86.51569	89.32308	90.66026	90.27198	
31	2												1212		89.911	89.40768	90.16758	89.43374	
32	2												5512		91.46957	89.42248	90.26904	92.69776	

Left chart legend: 1-1.5, 0.5-1, 0-0.5. Right chart legend: 50-100, 0-50.

Sheet tabs: Main, Principal, Square, Triangle, Evaporation, Wheel-line, Crop_data_and_summary, Spatial_data_output, Lateral design, Submain design, Lateral des...

Even though the variability due to sprinkler application rates is low, it still looks to be more significant than the hydraulic variation.

9. Redo Example 14.3 with 14 × 14 ft tree spacing. Leave all other parameters the same.

Select a 28 × 28 ft sprinkler spacing; all of the sprinklers would have head to head coverage. The farmer drives in the same direction as the slope. Thus, the installation will either need to be slotted or diagonal. In order to save pipe and trenching, select the slotted spacing with pipes every other row and slots every other tree.

The application rate for the 2.58 GPM (1/8″ nozzle) sprinkler would be too high (>0.3 in/hr)

$$di/dt = \frac{(2.58)(96.3)}{(28)(28)} = 0.32 \ in/hr$$

The application rate with the 7/64″ nozzle would be

$$di/dt = \frac{(1.98)(96.3)}{(28)(28)} = 0.24 \ in/hr$$

The application rate with the LF sprinkler would be

$$di/dt = \frac{(1.63)(96.3)}{(28)(28)} = 0.20 \ in/hr$$

The application rates would be

$$\left(7/64'' \text{nozzle}\right) \quad i = (0.24 \ in/hr)(24 \ hours)(1 - 0.05)$$
$$= 5.5 \ inches \ in \ 24 \ hours.$$
$$(\text{LF}) \quad i = (0.20 \ in/hr)(24 \ hours)(1 - 0.05)$$
$$= 4.6 \ inches \ in \ 24 \ hours.$$

Both of the sprinklers would apply too much water in 24 hours (>4 inches). Thus, the farmer could either wait slightly longer between irrigation events or irrigate for a shorter period. If the farmer has a 12 hour irrigation cycle, then the 7/64″ nozzle is preferable since it would apply more water. If the irrigation period is 24 hours, then the LF sprinkler is preferable. Possibly, a smaller LF nozzle could be used with a reduced wetted radius. This is acceptable since the sprinkler significantly exceeds the requirement of head to head coverage.

10. Calculate a microsprinkler irrigation schedule for an orchard with 4 m × 3 m tree spacing and microsprinkler spacing. Each tree has a peak summer water use rate of 25 L/day. Microsprinklers have a 0.7 L/min flow rate and a 3 m diameter wetted area. Rooting depth is 1 m and allowable MAD is 0.35. The AWC is 12 % for a sandy loam soil, the expected loss to evaporation is

12 %, and the irrigation efficiency is 90 %. Specify an irrigation schedule for his system.

Calculate the schedule

$$S = 780 \quad Z \quad AWC \quad MAD \quad D_b^2$$
$$= 780(1 \; m)(0.12)(0.35)(3^2) = 295 \; L$$

$$(295 \; L)/(25 \; L/day) = 12 \; days$$

Calculate the irrigation run time

$$Q_{net} = Q_{gross}(1 - L_e)(Eff) = 0.7 \; L/min(1 - 0.12)(0.9)$$
$$= 0.55 \; L/min(295 \; L)/(0.55 \; L/min)$$
$$= 536 \; min = 9 \; hours$$

11. Repeat Example 14.5, except use 12 laterals by 12 sprinklers geometry, and the pump curve is $H = -5.18 * 10^{-5} Q^2 + 0.00828 * 10^{-3} Q + 900$. Find the operating point of the system.

The Lateral spreadsheet is set up first
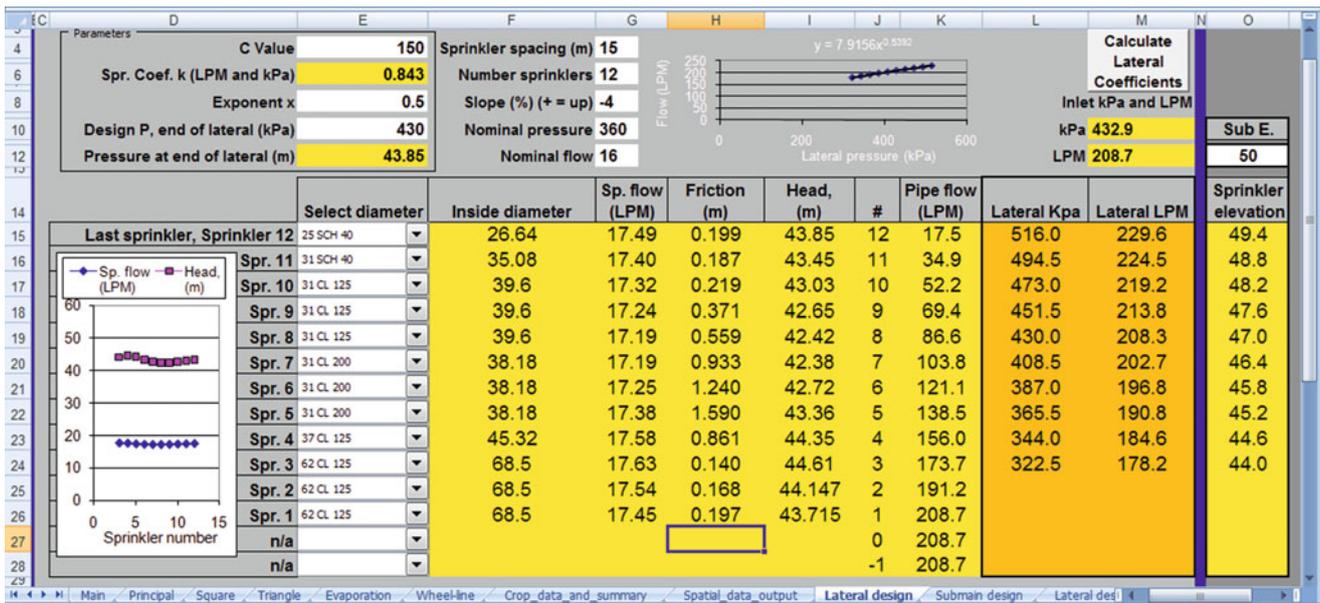
The next step is to enter the lateral exponential equation and inlet pressure at the last lateral into the submain worksheet.
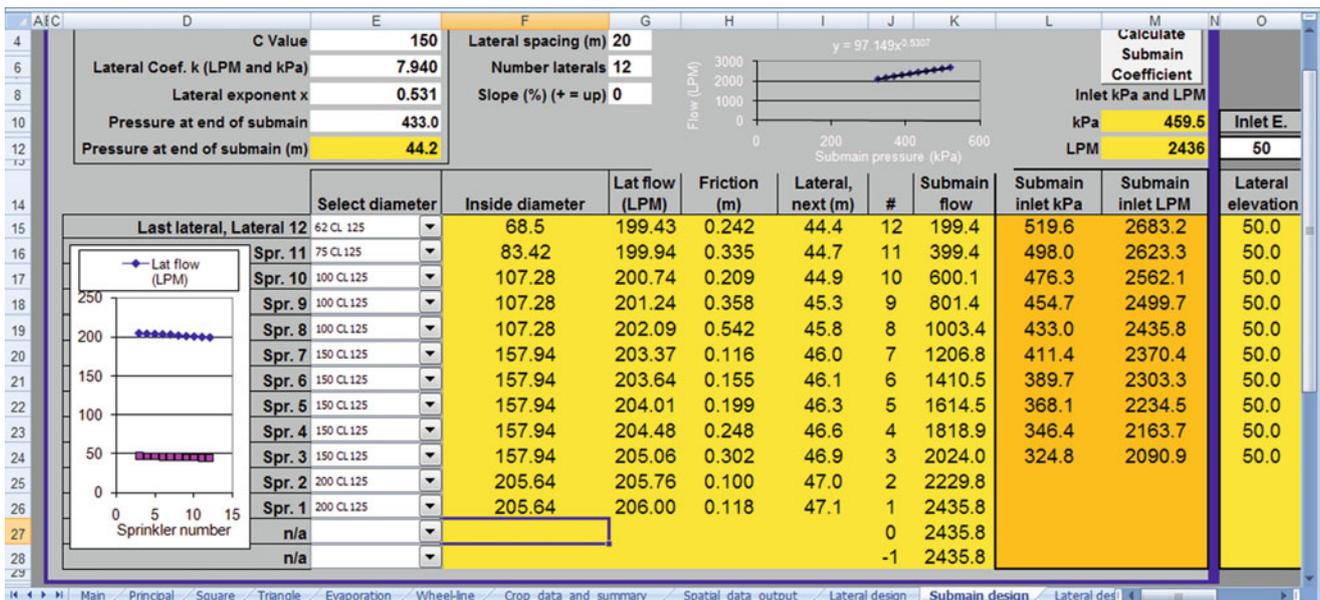
The submain exponential equation is 97.14 H $^{0.531}$

The pump and submain equations are now solved for pump flow rate. (Use Solver in Excel)

$$0 = (97.14)\left(-5.18*10^{-5}Q^2 + 0.00828*10^{-3}Q + 900\right)^{0.531} - Q$$
$$Q = 2,670 \ LPM.$$

Solve for the head.

$$H = (Q/97.14)^{1/0.531} = (2670/97.14)^{1/0.631} = 513 \ kPa.$$

Chapter 15: Solution

1. Discuss the questions presented in Exercise 15.1. How would the scientific method change the results and people's perceptions? (Write at least 1 page, double-spaced).

Answers will vary.

2. Describe the components in a landscape irrigation control zone and the function of each part.

The components of a landscape irrigation control zone are a manual ball valve, a solenoid valve and a pressure regulator.

- The solenoid valve, filter, and pressure regulator assembly are typically placed below the soil surface in a valve box.
- A ball valve should be placed before the components, thus if any repair or modification is required, the system can be turned off.
- The solenoid valve is connected to the controller and turns the zone on and off.
- The filter prevents solids from reaching and plugging the emitters.
- The pressure regulator reduces pressure to the operating range of the emitters.

3. Describe how a controller is wired and how it controls the valves.

Irrigation controllers are powered by standard 110 V AC current. A hole can be drilled in the wall of the building in order to bring wires by conduit from an electrical socket or other location to the controller. The controller outputs 24 V power to the solenoid valves. One common wire (usually white) from the controller is connected to all solenoid valves and the controller. One 24 V "hot" wire is connected to each

valve. Protection of electrical wiring is important. Metal conduit should be used to protect 110 V wire from the building to the controller. The 24 V valve wires should also be encased above ground. However, once the wires (i.e., #14 AWG) are in the ground they can buried without a conduit. The wires should be placed below the water pipes in the trench in order to protect them; thus, they are laid in the trench before the water pipes.

4. Compare the advantages and disadvantages of barbed fitting emitters, line source drip irrigation and bubbler irrigation.

One of the problems with using barbed fittings is that the connections are not as secure as PVC with glued or screwed fittings. When emitters pop out of distribution tubing or tubing is damaged, a stream of water sprays onto the landscape like a fountain. When single emitters have plugging problems, and they often do, the plant may receive no water.

There are several advantages of inline emitters: (1) inline emitters have a lower cost per wetted area than single or multiport emitters, (2) it is easy to replace the entire inline lateral when the emitters or tubing wear out, (3) inline drip irrigation tubing lasts longer than point source drip emitters, (4) even if one or two emitters go bad, there are many other emitters, and (5) many inline drip emitters are self-flushing and pressure compensating.

Another advantages of inline tubing is that it creates a line source of water, and plants will grow roots along the tube. The increased root development is better for the plant than the restricted root development around a single point source emitter.

Bubblers operate at a much higher flow rate (0.5-, 1-, or 2-GPM; 2-, 4-, or 8-LPM) than drip irrigation systems; thus, they have larger orifices and don't require filtration. The disadvantage is that more zones are needed. They are installed on black flexible PVC pipe with glued and screwed connections. Thus, the bubblers and pipe systems are more durable than typical drip systems and are not as readily broken by landscape tools, degraded in heat, or consumed by animals or insects. However, bubblers are more difficult to install because trenched PVC pipe must be routed to each bubbler.

5. Describe how a pressure compensating in-line emitter works.

One inlet to the emitter provides backpressure behind a pressure compensating diaphragm, and the other is the entrance to the turbulent flow path. As pressure increases, the diaphragm closes down and restricts flow.

6. Answer in-class Exercise 15.2. Using Table 15.2, determine the maximum distance between 4 LPH emitters in order to create a line source wetting pattern in a sandy soil? Would you select 30, 45, or 60 cm spacing?

The wetted diameter is 0.6 m; thus, ¾ of this distance would be 45 cm spacing.

7. Draw out a yard that you know about or can imagine and lay out the location of sprinklers and drip emitters. You can do this on a piece of graph paper where 1 inch = 10 ft or some other appropriate scale. You could also draw it out in a computer program. Locate positions of valves and pipes as well as define zones. For bubblers, let flow rate be 2 GPM, and for emitters let flow rate be 2 GPH. Use PVC or polyethylene tubing where appropriate. Make sure to group similar emitters in zones. Select pipe and calculate pipe friction losses.

Answers will vary

8. Evaluate the economic costs and benefits of a landscape irrigation system. Rate of return is 8 % and project life is 8 years.
   – Water costs for irrigation are $500/yr
   – Capital cost for installation is $1,500
   – Home selling price is $200,000 and landscaping adds 17 % to the value of home. Home will be sold in 8 years and home price is expected to decrease in value by 10 % over the 8 year period.
   – Irrigation system maintenance is $250/yr
   – Plant replacement costs is $100/yr

Annual costs are sum of water, maintenance, and plants: $500 + $250 + $100 = $850.
The present value of $850 payments for 8 years at an 8 % rate of return is $4,885.
Total present value of costs is $4,885 + $1,500 = $6,385.

Benefits
The value of the house in 8 years will be $200,000(1.1) = $220,000
Landscaping will add 17 % to the selling price $220,000(0.17) = $37,400.
Present value of benefits is $37,400(1 + 0.08)^{-8} = $20,200
The present value of benefits is 3 times greater than the present value of costs.

9. Which types of irrigation devices would be appropriate for four 5 m diameter, widely spaced, trees?

Either bubbler or inline emitters would cover a large wetted area and would provide sufficient water for the trees

10. Which types of irrigation devices would be appropriate for 10 × 50 ft planter with ground cover?

Inline emitters would cover a large ground surface area and could extend along the length of the planter.

Chapter 16: Solution

1. List the 5 steps in turf and landscape irrigation system design.
   • Owner interview.
   • Site survey.
   • Determine maximum flow rate and working pressure.
   • Plant water requirements and application rates.
   • Zoning and hydraulics.

2. What issues should be discussed with the property owner before designing the irrigation system?

The designer should explain to the owner the most suitable irrigation system alternatives and discuss installation, operation and maintenance costs, life expectancy, safety features (backflow and master valve), operation and design parameters (irrigation scheduling), distribution uniformity and, if a pump is required, energy consumption and flow metering. Some optional features like chemical injection, filtration and pressure regulations should be also discussed depending on owner's level of expertise and willingness to invest time or money into system management.

3. What aspects of the landscape should be included in the site plan?

The site plan should include a map of the area featuring water source, including static pressure and flow meter diameter, buildings and constructions, relevant landscape elements, like plants, turf areas, rocks, etc., existing irrigation elements, wind direction and speed.

4. What is the pressure loss in a 5/8″ municipal water meter at 12 GPM? Use the *Service line friction loss* worksheet. Is it acceptable?

Select 5/8" water meter in cell E15. Convert from GPM to LPM in cell N8 and enter flow rate in cell J15. Friction loss is found in cell L15 (3.58 m). Use cell N10 to convert value to **5.1 psi**. The water meter is acceptable.

Rules of thumb			
10	Maximum pipe velocity (m/sec)	**2.30**	
100	Percent friction loss / water main pressure	**12%** NOT OK	
764	Percent of water meter safe flow	**60%** OK	
78.0			

		GPM	12
		LPM	45.4
		m	3.58
		PSI	5.1

Select pipe D. or fitting	Pipe ID (mm) or valve L/D	Valve/fitting select dimension	Fitting ID (mm)	HW C	Flow (LPM)	Length (m)	Friction loss (m)	Discharge elevation (m)	Head after fitting (m)	#
5/8" (15) water meter	k01	1 1/2" (41)	40.94	140	45.40		3.583	100.0	74.4	1
1 1/2" copper pipe	37.6	n/a	"n/a"	140	38.70	2.00	0.024	100.0	74.4	2

5. Redo Example 16.1 but increase flow rate to 45.5 LPM. Use 1¼ inch copper pipe and fittings prior to the valves and water meter. Then use the 5/8 inch water meter and 5/8 inch valve and 5/8 inch copper in the last section.

Use the *Service line friction loss* worksheet. Is the design acceptable?

The design is not acceptable because the friction loss is too high, 19 %.

	Inlet elevation (m) 100				Percent friction loss / water main pressure	**19%** NOT OK		
	Pressure at city main (kPa) 764				Percent of water meter safe flow	**60%** OK		
	Pressure at city main (m) 78.0							

	Select pipe D. or fitting	Pipe ID (mm) or valve L/D	Valve/fitting select dimension	Fitting ID (mm)	HW C	Flow (LPM)	Length (m)	Friction loss (m)
1 Sudden contraction		28	1 1/4" (35)	35.08	140	45.40		0.037
2 1 1/4" copper pipe		31.6	n/a	"n/a"	140	45.40	2.00	0.077
3 90 degree standard elbow		25	1 1/4" (35)	35.08	140	45.40		0.037
4 1 1/4" copper pipe		31.6	n/a	"n/a"	140	45.40	1.00	0.038
5 90 degree standard elbow		25	1 1/4" (35)	35.08	140	45.40		0.037
6 1 1/4" copper pipe		31.6	n/a	"n/a"	140	45.40	1.00	0.038
7 Sudden contraction		28	5/8" (16)	16	140	45.40		0.767
8 Gate valves, ¾ open		35	5/8" (16)	16	140	45.40		0.767
9 5/8" (15) water meter		k01	5/8" (16)	16	140	45.40		3.583
10 5/8" copper pipe		16.8	n/a	"n/a"	140	45.40	11.00	9.154
11 1 1/2" (37) CL 160 PVC			n/a					

6. Define the species factor, microclimate factor, and density factor.
   – Species factor (K_s): This factor accounts for the characteristics of a particular plant species.
   – Microclimate factor (K_{mc}): This factor accounts for the specific site conditions (wind, surrounding heat-absorbing surfaces or reflective surfaces, etc.).
   – Plant density factor (K_d): This factor accounts for the collective leaf area of all plants in the landscape.

7. Look in the WUCOLS guide and determine the species factor for oleander in Blythe, California. Use the low desert classification.

The classification is moderate. In the user manual, the percentage of reference ET is 40–60 %.

8. Calculate the LPD requirement for a 2 m diameter oleander in Tucson, AZ Reference ET is 12 mm/day. The microclimate and density factors are 1.0. Irrigation efficiency is 85 %

Multiplying Eq. 16.2 by K_L, which in this case is 0.5 (0.5*1*1), and assuming an efficiency fraction of 0.85, one gets:

$$Requirement = \frac{12*(1*1*0.5)(2^2\pi)}{0.85*4} = 22 \; LPD$$

9. Calculate the LPD requirement for a 5 m diameter orange tree in Blythe, CA. The landscape, microclimate, and density coefficients are 1.0. Reference ET is 14 mm/day. Irrigation efficiency is 85 %.

$$Requirement = \frac{14*(1*1*1)(2.5^2\pi)}{0.85} = 323LPD$$

10. Calculate S under an emitter that has a 1.0 meter diameter wetted area with a 1.0 m deep root zone. The MAD is 0.5. Field capacity is 20 % and permanent wilting point is 10 %.

   Use Eq. 16.4.

$$S = \frac{\pi*1^2}{4}*1*0.1*0.5*1000 = 39L$$

11. The orange tree in problem 9 has 6 emitters with the water storage per emitter as calculated in problem 10. The reference ET rate is 10 mm/day. Calculate a watering schedule for the orange tree. Emitter flow rates are 4 LPH. Note: this problem demonstrates the problem with having few emitters on a large tree.

   Six emitters will have a water storage = 234 L. Because the storage volume is less than the daily plant requirement (323 LPD), the system will need to run every day to prevent water stress.

$$Irrigation\ time = \frac{LPD}{LPH} = \frac{323LPD}{24LPH} = 13.5hr/day$$

12. Calculate the watering schedule for an oleander hedge with 2 m width. Reference ET rate is 10 mm/day. Wetted width is 0.6 m. Rooting depth is 2 m. Emitter flow rate is 2 LPH. Use a landscape coefficient of 0.5 and MAD = 0.5. Distance between emitters = 0.3 m. Root depth is 2 m. Soil is sandy loam with AWC = 0.12.

Microclimate and density factors are 1.0. Irrigation efficiency is 80 %.

$$ET_L = 10\ mm/day*0.5*1*1 = 5\ mm/day$$

Calculate the LPD requirement per emitter

$$LPD = \frac{5\frac{mm}{day}*2*0.3}{0.80} = 3.75LPD$$

$$S = 1000*2*0.6*0.3*0.12*0.5 = 21.6L$$

$$Irrigation\ frequency = \frac{21.6L}{3.75LPD} = 5.8days$$

Thus, irrigation should take place every 5 days.

$$Irrigation\ run\ time = (LPD*Irrigation\ interval)/$$
$$Emitter\ flow\ rate$$
$$= (3.75\ LPD*5Days)/2\ LPH$$
$$= 9.4\ hr$$

13. Use Landscape Irrigation program to calculate number of screw turns for bubblers irrigating 4 orange trees with 5, 6, 7, and 8 m diameter canopy. There is one bubbler per tree. The pressure is 280 kPa (adjusted in Device data page). Determine the irrigation schedule. Soil is loamy sand, density factor is 1.0, microclimate factor (exposure) is 1.2. Leaching fraction is 0.15. There is no overlap in wetting patterns. Application efficiency is 95 %.

   Using the landscape irrigation worksheet, the following screw adjustments were calculated

Canopy diameter	Name	Type	Flow (LPM) Bub (LPH) Em	Line space (m)	Wetted Diam (m)	Tubing length (m)	Number of screw turns
8	HunterB	Bubbler kx	8.57		2.000		1.25
7	HunterB	Bubbler kx	6.56		2.000		0.71
6	HunterB	Bubbler kx	4.82		2.000		0.44
5	HunterB	Bubbler kx	3.34		2.000		0.32

Using the Step 4, Calculate schedule button, the following output is produced. Because the wetted area is small in comparison to the size of the tree, there are 7 irrigations per day of approximately 15 minutes per irrigation.

Statistics

Scheduling coefficient	1.00
Distribution uniformity	100.0%
Statistical uniformity	99.0%
Allowable % underirrigated	0%
Daily applied volume (L)	2382.00
Daily wasted volume (L)	0.00

	Step 4 Calculate schedule
Precipitation (mm/day)	0
Reference ET (mm/day)	12
MAD	50%
Days between irrigations	0
Irrigation run time (min)	14.66
Vol. App. per irrigation (L)	341.62
Number of irrigations/day	6.97

14. Calculate the number of bubblers per plant for 20 orange trees laid out in a 5 (NS) $\times$ 4 (EW) grid. Tree diameters are shown in meters. Then redo with spiral inline emitter configuration. Compare pipe sizes and number of valves. Application efficiency is 90 %. Leaching fraction is 0.15. There is no overlap in wetting patterns. Maximum number of bubblers per plant is five. Microclimate and density factors are 1.0. For the same soil and weather parameters as in Example 13, calculate the irrigation schedule.

$$
\begin{array}{cccc}
5 & 4 & 3.4 & 6 \\
2 & 4 & 6 & 3 \\
3 & 4 & 6 & 4 \\
1 & 3 & 4 & 4 \\
4 & 4 & 4 & 6
\end{array}
$$

Number of emitters per plant is shown in the following table.

Plant number	Plant name	Diam. or width (m)	Root depth (m)	Length (m)	Foliage area (m)	Water use (0.2-desert, 1 -high)	Plant type H, P, A	Number emitters/ plant
1	Orange	1.00	1		0.785	1	Plant	1
2	Orange	2.00	1		3.142	1	Plant	1
3	Orange	3.00	1		7.069	1	Plant	1
4	Orange	3.40	1		9.079	1	Plant	2
5	Orange	4.00	1		12.57	1	Plant	2
6	Orange	5.00	1		19.63	1	Plant	3
7	Orange	6.00	1		28.27	1	Plant	5

Slightly more than one irrigation is needed per day. The run time is 15.7 minutes.

Scheduling coefficient	1.22
Distribution uniformity	84.2%
Statistical uniformity	37.0%
Allowable % underirrigated	0%
Daily applied volume (L)	5723.00
Daily wasted volume (L)	1298.00
▼	**Step 4 Calculate schedule**
Precipitation (mm/day)	0
Reference ET (mm/day)	12
MAD	50%
Days between irrigations	0
Irrigation run time (min)	15.71
Vol. App. per irrigation (L)	6030.65
Number of irrigations/day	1.16

Chapter 17: Solution

1. How many 4 ft (1.22 m) diameter sand filters are needed for a 260 ha (640 ac) drip irrigated farm? Crop ET is 11 mm/day. Irrigation efficiency is 90 %.

Approximate the irrigation requirement as 11 mm/day/ 0.9 = 12 mm/day.

$$Q = 2,600,000 \text{ m}^2*0.012 \text{ m/day}*(1 \text{ hr}/3,600 \text{ sec})* (1 \text{ day}/24 \text{ hrs})$$
$$Q = 0.36 \text{ m}^3/\text{s} = (0.36 \text{ m}^3/\text{s})(1\text{m}^3/1000 \text{ L}) = 360 \text{ LPS}$$

Maximum flow rate through sand filters should be between 10 and 18 LPS per square meter of tank cross-sectional area.

$$D_{filter} = 1.22 \text{ m}$$
$$A = \pi D^2/4 = 3.1416*(1.22 \text{ m})^2/4 = 1.17 \text{ m}^2$$

At 18 LPS, the number of filters is calculated.

Number of filters = (360 LPS*1.17 m²)/18 LPS = 23.3 filters
Number of filters = 24

Because this is the upper range, and flow might vary, it is probably wise to increase the number of filters to 30.

2. Design particle size for a settling basin is 25 microns. Irrigation system flow rate is 1,000 GPM. What are the dimensions of the settling basin?

$$V_p = 3.43*10^{-5}D^2(SG - 1) = 3.43*10^{-5}*25^2*1.65 = 0.035 \text{ m/min}$$

$$Area = 0.001*F*\left(\frac{Q}{V_p}\right) = 0.001*2.0*\left(\frac{1,000}{0.035}\right) = 57 \ m^2$$

$$W = \sqrt{\frac{Area}{5}} = \sqrt{\frac{57}{5}} = 3.4 \ m \quad L = 3.4*5 = 17 \text{ m}$$

3. Calculate head loss and emission uniformity in a 120 m length of 18 mm ID tubing. x = 0.57 and k = 0.15. Inlet pressure is 200 kPa. Emitters are spaced at 0.2 m. The crop is carrots. Determine if the design is acceptable based on a criteria of 90 % emission uniformity. Use the analytic solution method and check your answer with the

Single feed lateral spreadsheet. The manufacturer's coefficient of variation is 0.07 or 7 %, and there are 2 emitters per plant. There is no slope.

200 kPa and 120 m length

Make an initial guess for lateral flow rate is based on the flow from the first emitter.

$$Q = 0.15*(200 \text{ kPa})^{0.57} = 3.07 \text{ LPH.}$$

There are 5 emitters per m and the length of tubing is 120 m. Thus, there are 600 emitters and the total flow rate per lateral is (3.07 LPH) (120 m) (5 em/m) = 1,842 LPH. Calculate friction loss in fully flowing pipe

$$v = \frac{Q}{A} = \left(\frac{1,842 \ Lph}{\pi(9/1000)^2 \ m^2}\right)\left(\frac{m^3}{1,000 \ L}\right)\left(\frac{hr}{3,600 \ \sec}\right)$$
$$= 2 \ m/\sec$$

$$\text{Re} = \frac{vD}{\nu} = \frac{2*18/1,000}{1*10^{-6}} = 36,000$$

$$f = \frac{0.316}{\text{Re}^{1/4}} = \frac{0.316}{36,000^{1/4}} = 0.023$$

$$h_f = 6.377fL\left[\frac{Q^2}{D^5}\right] = 6.377*0.030*120 \ m\left[\frac{1842^2}{18^5}\right]$$
$$= 31.6 \ m$$

$$h_{ac} = h_f F = 31.6*0.338 = 10.7 \text{ m.}$$

$$H_o = H_a + 0.74 \ h_{ac} + \frac{S_e L}{2}$$
$$H_a = H_0 - 0.74 \ h_{ac} = 20 - 0.74(10.7) = 12 \ m$$

I am going to adjust upward to 15 m because the initial estimate of average pressure made the estimate of friction loss too high.

$$Q = 0.15*(150 \text{ kPa})^{0.57} = 2.61 \text{ LPH}$$

Using the same calculation procedure as above, the average pressure is 14.1 m.

$$Q = 0.15*(141 \text{ kPa})^{0.57} = 2.52 \text{ LPH}$$

Using the same calculation procedure as above, the average pressure is 14.43 m.

$$Q = 0.15*(14.43/0.102 \text{ kPa})^{0.57} = 2.52 \text{ LPH}$$

Thus, the flow does not change and the iteration stops. Find the end pressure.

$$H_d = 14.43/0.102 + (0.26)(7.55) = 12.45$$

Inserting 12.45 as the distal end pressure in the Single Feed Lateral spreadsheet results in an inlet pressure of 20 m. See following screen copy. Make sure to press the Make Calcs button in order to find the terms for the emission uniformity.
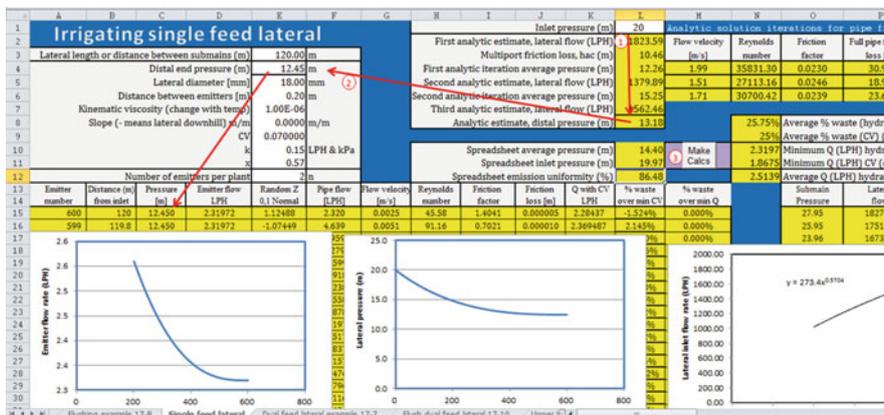
Spreadsheet

$q_{min} = 0.15*(12.45/0.102)^{0.57} = 2.32$ LPH
$q_{ave} = 0.15(14.4) = 0.15*(14.4/0.102)^{0.57} = 2.51$ LPH

$$U_e = 100\left[1 - \left(\frac{1.27}{\sqrt{2}}\right)0.07\right]\frac{2.32}{2.51} = 86.5\%$$

This design is not acceptable according to the criterion of 90 % emission uniformity. It is quite surprising that the emission uniformity is so high given the high pressure loss in the system.

4. Calculate head loss and emission uniformity in an 80 m length of 18 mm ID tubing. $x = 0.57$ and $k = 0.15$. Inlet pressure is 50 kPa. Emitters are spaced at 0.2 m. The crop is carrots. Determine if the design is acceptable based on a criteria of 90 % emission uniformity. Use the analytic solution method and check your answer with the *Single feed lateral* spreadsheet. The manufacturer's coefficient of variation is 0.07 or 7 %, and there are 2 emitters per plant. There is no slope.

50 kPa and 80 m length

Make an initial guess for lateral flow rate is based on the flow from the first emitter.

$$Q = 0.15*(50 \text{ kPa})^{0.57} = 1.38 \text{ LPH}.$$

There are 5 emitters per m and the length of tubing is 80 m. After a few iterations, the average pressure is 4.43 and flow is 1.29 (80 m) (5 em/m) = 515 LPH. Calculate friction loss in fully flowing pipe

$$v = \frac{Q}{A} = \left(\frac{515\ Lph}{\pi(9/1000)^2\ m^2}\right)\left(\frac{m^3}{1,000\ L}\right)\left(\frac{hr}{3,600\ sec}\right)$$
$$= 0.56\ m/\sec$$

$$Re = \frac{vD}{\nu} = \frac{0.9*18/1,000}{1*10^{-6}} = 10,100$$

$$f = \frac{0.316}{Re^{1/4}} = \frac{0.316}{10,100^{1/4}} = 0.0315$$

$$h_f = 6.377fL\left[\frac{Q^2}{D^5}\right] = 6.377*0.0315*80\ m\left[\frac{515^2}{18^5}\right] = 2.25\ m$$

$$h_{ac} = h_f F = 2.25*0.338 = 0.76 \text{ m.}$$

$$H_o = H_a + 0.74\ h_{ac} + \frac{S_e L}{2}$$
$$H_a = H_0 - 0.74\ h_{ac} = 5 - 0.74(0.76) = 4.43\ m$$

New average flow calculation

$$Q = 0.15*(4.43/0.102 \text{ kPa})^{0.57} = 1.28 \text{ LPH}$$

Find the end pressure.

$$H_d = 4.43 - (0.26)(76) = 4.24$$

Inserting 4.24 as the distal end pressure in the Single Feed Lateral spreadsheet results in an inlet pressure of 20 m. See following screen copy.
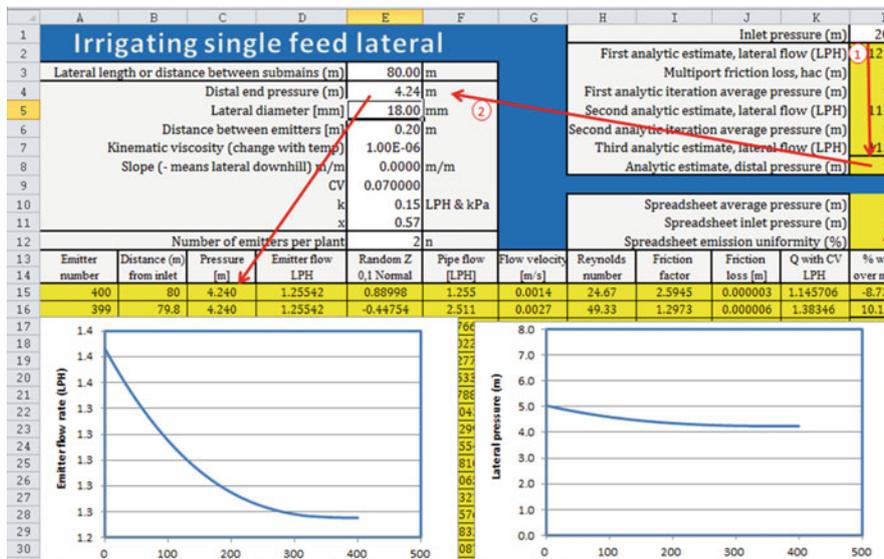
Spreadsheet

$$U_e = 100\left[1 - \left(\frac{1.27}{\sqrt{2}}\right)0.07\right]\frac{1.25}{1.29} = 91\%$$

This design is acceptable according to the criterion of 90 % emission uniformity. Just over half of the variability in this system is due to manufacturers coefficient of variation.

5. Calculate head loss and emission uniformity in a 120 m length of 18 mm ID tubing. x = 0.57 and k = 0.15.

Inlet pressure is 200 kPa. Emitters are spaced at 0.2 m. The crop is carrots. Determine if the design is acceptable based on a criteria of 90 % emission uniformity. Just use the *Single feed lateral* spreadsheet for the calculation. The manufacturer's coefficient of variation is 0.07 or 7 %, and there are 2 emitters per plant. Slope is 5 % downhill.

50 kPa and 80 m length, 5 % downhill slope
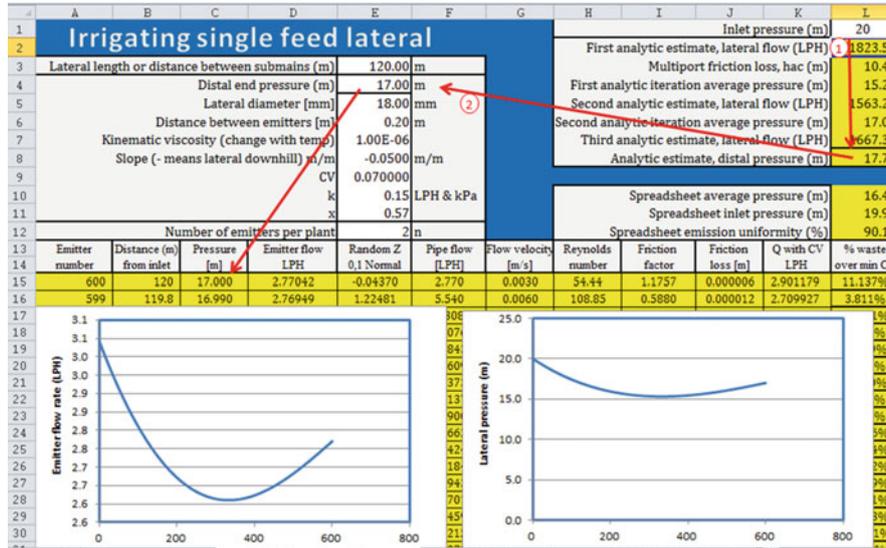
The emission uniformity is 90.2 % so the design is acceptable. The slope reduced the amount of pressure variation.

6. For the parameters in problem 3, calculate the inflow rate and pressure needed to flush the 120 m length tube.

Setting the distal end pressure at 2 m and flow at 200 LPH in order to obtain a velocity of 0.5 m. The following flow and pressure curves are obtained. The flow is 20 % less and the pressure is 20 % higher so this would probably be posible with the same pump.
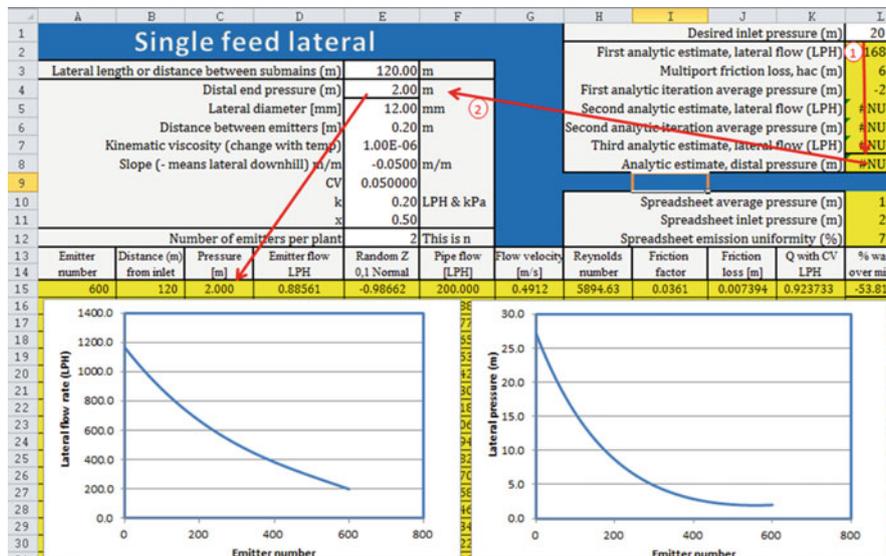
7. For the parameters in problem 5, calculate the inflow rate and pressure needed to flush the 120 m length tube.
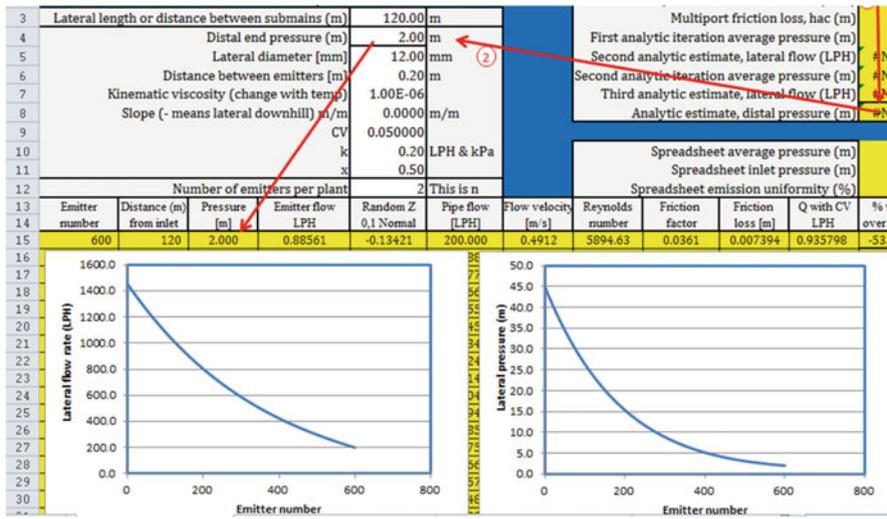
The pressure is very high in this case, and the flow rate to the lateral is not much less than the normal flow rate so it may be difficult to flush this lateral. A large booster pump would be needed.

8. Emitters are spaced at 1 m along the plant row and 1 m between plant rows, and emitter flow rate is 2 lph. For a daily plant water requirement of 12 mm/day, calculate the application rate and the application time if plants are watered on a daily basis. Assume 85 % efficiency.

$$(di/dt)_g = \left(\frac{Emitter\ flow\ rate}{area\ per\ emitter}\right) = \left(\frac{Q_e}{s_l * s_d}\right) = \left(\frac{2}{1*1}\right)$$
$$= 2\ mm/hr$$

The net application rate is the product of the gross application and the system efficiency:

$$(di/dt)_a = (di/dt)_g * Eff. = 2\ mm/hr*0.85 = 1.70\ mm/hr$$

Divide ET by the application rate to find required hours of application per day:

$$hr/day = 12\ mm/day/1.7\ mm/hr = 7.06\ hr/day$$

9. Two submains are 200 m apart and supply a dual feed lateral. Tubing diameter is 12 mm ID. x = 0.5 and k = 0.2. Inlet pressure is 100 kPa. Emitters are spaced at 0.5 m. There is no slope. Use the *upper lateral* worksheet to plot the hydraulic and flow variation. Make sure to press the Make calcs button.
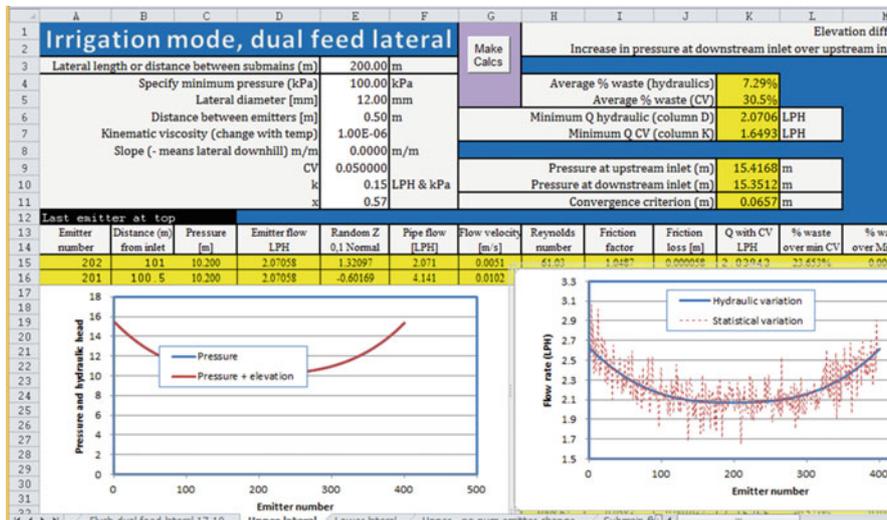
10. Two submains are 200 m apart and supply a dual feed lateral. Tubing diameter is 12 mm ID. x = 0.5 and k = 0.2. Inlet pressure is 100 kPa. Emitters are spaced at 0.5 m. There is 1 % slope. Use the *upper lateral* worksheet to plot the hydraulic and flow variation.

There is no pressure difference between the uphill and downhill inlets. Explain the difference between the red and blue lines in the pressure graph. Which line is the hydraulic head?
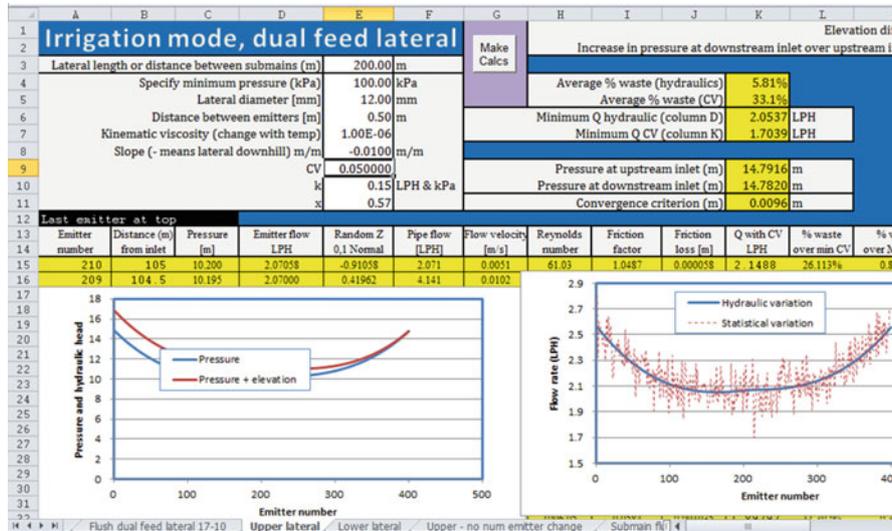
The blue line is the pressure line. The red line is the pressure + elevation. The upper end is higher so it has greater hydraulic head. The red line is the hydraulic head.

11. Design problem, answers will vary.

Chapter 18: Solution

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.

The following data was entered into the *Downslope lateral* worksheet.
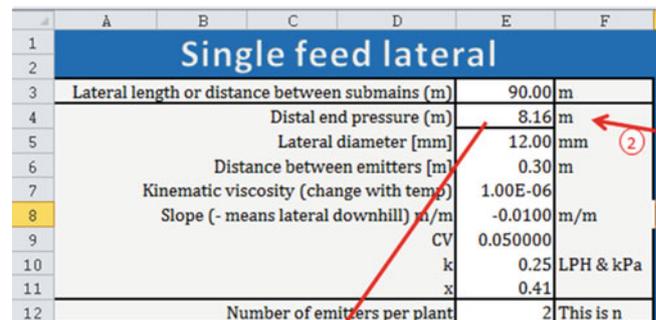
The *Make calcs* button was pressed, and the equation was developed as the program varied distal end pressure.
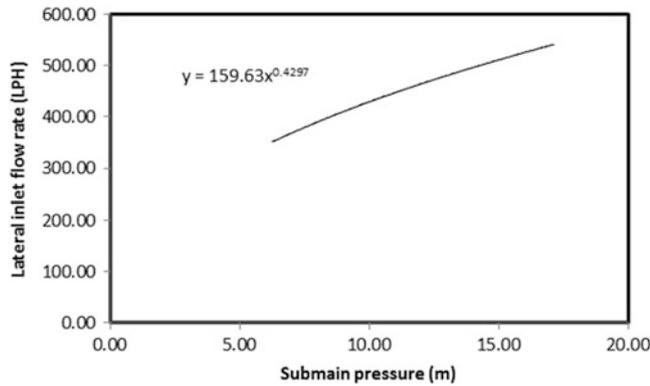
The required submain inlet pressure in order to maintain at least 8.16 m pressure at the distal end of the lateral is reported in cell L11, 12.43 m. Thus, this is the distal end pressure for the submain. The emission uniformity is 91.1 %.

$$U_e = 100\left[1 - \left(\frac{1.27}{\sqrt{2}}\right)0.05\right]\frac{1.50}{1.57} = 91.1\%$$

Spreadsheet average pressure (m)	9.07
Spreadsheet inlet pressure (m)	12.43
Spreadsheet emission uniformity (%)	91.10

The lateral flow pressure equation was entered into the *submain irrigation upper* worksheet, and 100 mm diameter pipe was entered in column E.

	A	B	C	D	E	F
1						
2			**Submain**			
3			Length of submain (m)		100.00	m
4		Lateral inlet pressure at end of submain (m)			12.43	m
5						
6			Distance between laterals [m]		1.00	m
7		Kinematic viscosity (change with temp)			1.00E-06	
8		Slope (- means submain downhill) m/m			0.0000	m/m
9				CV		
10				k	159.63	LPH & kPa
11				x	0.43	
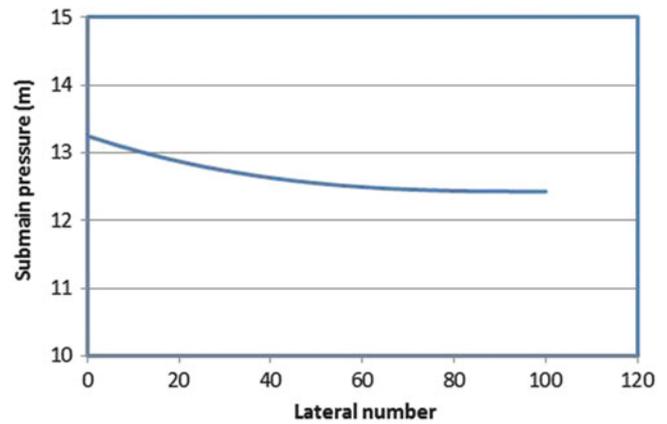
The required pressure at the submain inlet is 13.2 m. The average pressure in the submain is 12.64 m, which is 0.2 m higher than the distal end pressure. Thus the average pressure in the emission uniformity equation should be raised by 0.2 m. The average pressure in the last lateral was 9.07 m. Thus, the average pressure in the zone is approximately 9.27 m. Flow at this average pressure is calculated as follows.

$$Qave = 0.25(9.27/0.102)^{\wedge}0.41 = 1.59$$

Substitute this flow into the emission uniformity equation. The emission uniformity of the entire zone is barely above 90 %.

$$U_e = 100\left[1 - \left(\frac{1.27}{\sqrt{2}}\right)0.05\right]\frac{1.50}{1.59} = 90.1\%$$

2. Repeat problem 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 problem 1. Explain the differences and similarities.

	A	B	C	D	E	F	G	H	I	J	K	L
1		**Single feed lateral**							Desired inlet pressure (m)			14.6
2									First analytic estimate, lateral flow (LPH) ①			574.01
3		Lateral length or distance between submains (m)			90.00	m			Multiport friction loss, hac (m)			7.12
4				Distal end pressure (m)	8.16	m			First analytic iteration average pressure (m)			9.33
5				Lateral diameter [mm]	12.00	mm	②		Second analytic estimate, lateral flow (LPH)			477.80
6			Distance between emitters [m]		0.30	m			Second analytic iteration average pressure (m)			10.78
7		Kinematic viscosity (change with temp)			1.00E-06				Third analytic estimate, lateral flow (LPH)			506.88
8			Slope (- means lateral downhill) m/m		0.0000	m/m			Analytic estimate, distal pressure (m)			9.29
9				CV	0.050000							
10				k	0.25	LPH & kPa			Spreadsheet average pressure (m)			9.55
11				x	0.41				Spreadsheet inlet pressure (m)			13.47
12			Number of emitters per plant		2	This is n			Spreadsheet emission uniformity (%)			89.81
13	Emitter	Distance (m)	Pressure	Emitter flow	Random Z	Pipe flow	Flow velocity	Reynolds	Friction	Friction	Q with CV	% waste
14	number	from inlet	[m]	LPH	0,1 Normal	[LPH]	[m/s]	number	factor	loss [m]	LPH	over min CV

The emission uniformity on the single lateral is 89.91, slightly less than 90 %.

The lateral flow pressure coefficient (150) is approximately 7 % lower than 159, but the exponent has little change. The decreased coefficient reflects the fact that the average pressure in less with no slope so the flow is less. The exponent is reflective of the emitter exponent and turbulent pipe flow equation exponent (0.5), which are both in the range of the lateral exponent.
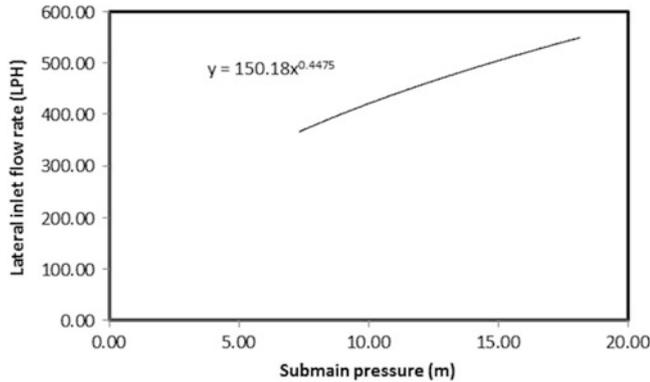
The required pressure at the lateral inlet is 13.47. The average pressure in the submain is 13.69. Thus, the average pressure in the zone should be increased by 0.22 m above the lateral average. The lateral average pressure is 9.55 so the average zone pressure should be 9.77

$$Qave = 0.25(9.77/0.102)^{\wedge}0.41 = 1.62$$

Substitute this flow into the emission uniformity equation. The emission uniformity of the entire zone is 88.4 %, which is below the 90 % criterion.

$$U_e = 100\left[1 - \left(\frac{1.27}{\sqrt{2}}\right)0.05\right]\frac{1.50}{1.62} = 88.4\%$$

The inlet pressure to the submain is 14.3 m.

Submain								
Length of submain (m)	100.00 m					Make Calcs		
al inlet pressure at end of submain (m)	13.47 m							
Distance between laterals [m]	1.00 m				13.69586			
nematic viscosity (change with temp)	1.00E-06							
ope (- means submain downhill) m/m	0.0000 m/m							
				Pressure at submain inlet from solenoid (m)			14.3077 m	
k	150.18 LPH & kPa			Flow at submain inlet from solenoid (LPS)			13.5443 LPS	
x	0.45							

al at top

Distance (m) from inlet	Pressure m	Lateral flow LPH	Pipe diameter mm	Pipe flow LPH	Flow velocity m/s	Reynolds number	Friction factor	Friction loss [m]
100	13.470	483.98011	100.0	483.980	0.0171	1711.73	0.0374	0.000006
99	13.470	483.98020	100.0	967.960	0.0342	3423.46	0.0413	0.000025

Lateral number

Lateral number

| 82 | 13.473 | 484.11172 | 100.0 | 9196.996 | | | | |

3. Repeat problem 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.

Because of symmetry (no slope), we can use the single feed lateral worksheet that was used in the previous problems. Changing the diameter from 12 to 14 increases the emission uniformity to 92.6 %. Thus, the emission uniformity is high enough that the zone emission uniformity does not need to be checked. It is probably about 92 %.

4. Based on the parameters in problems 2 and 3, calculate the inlet pressure needed for the submains. Find the equation for submain inlet flow vs. pressure.

The required lateral inlet pressure is 10.64 (cell L11)
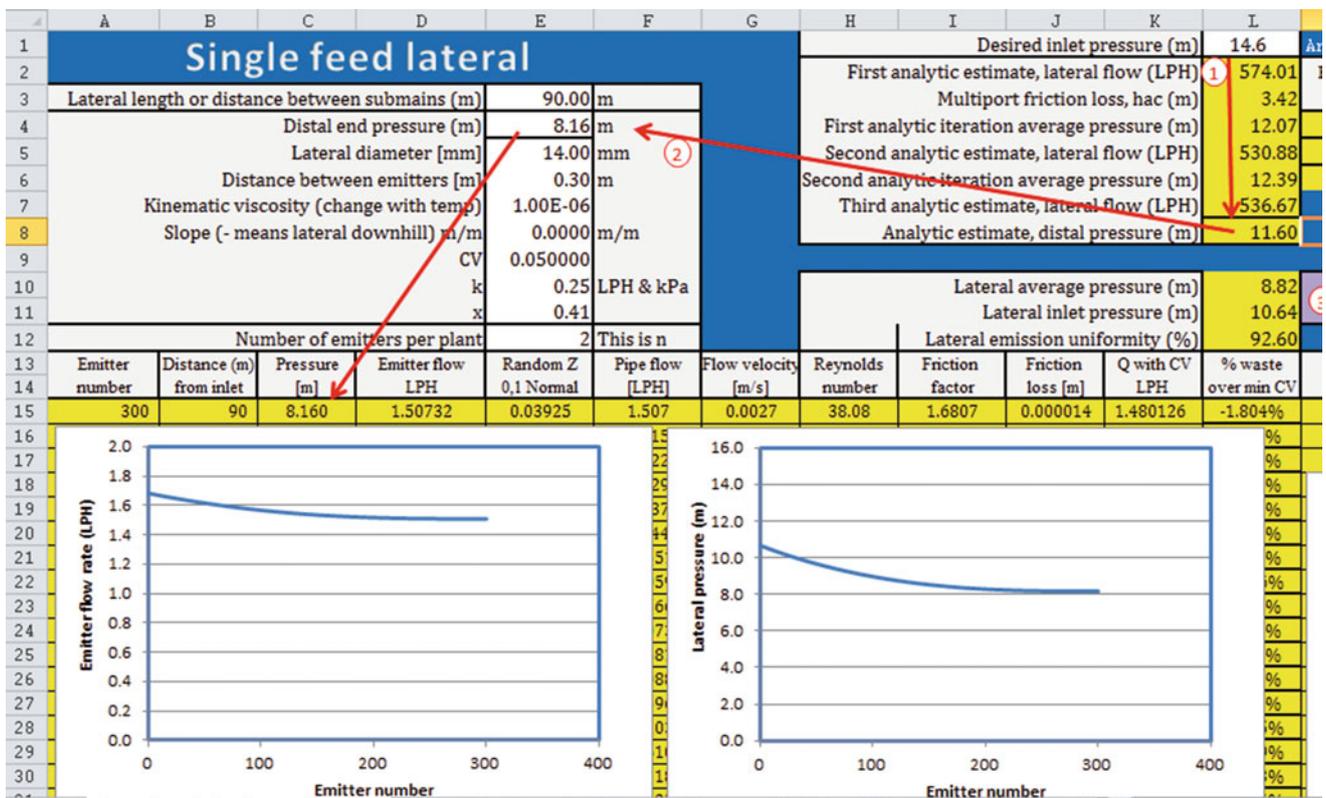
The submain inlet pressure requirement is 11.33, and the flow rate is 12.18 LPS. The flow pressure equation at the submain inlet is $4.04H^{0.455}$.

	B	C	D	E	F	G	H	I	J	K	L
1											
2	**Submain**					Make					
3		Length of submain (m)		100.00	m	Calcs					
4	al inlet pressure at end of submain (m)			10.64	m						
5											
6		Distance between laterals [m]		1.00	m		10.82761				
7	nematic viscosity (change with temp)			1.00E-06							
8	ope (- means submain downhill) m/m			0.0000	m/m						
9							Pressure at submain inlet from solenoid (m)			11.3359	m
10			k		150.18	LPH & kPa	Flow at submain inlet from solenoid (LPS)			12.1851	LPS
11			x		0.45						
12	al at top										
13	Distance (m)	Pressure	Lateral flow	Pipe diameter	Pipe flow	Flow velocity	Reynolds	Friction	Friction		
14	from inlet	m	LPH	mm	LPH	m/s	number	factor	loss [m]		
15	100	10.640	435.24705	100.0	435.247	0.0154	1539.37	0.0416	0.000005		
16	99	10.640	435.24714	100.0	870.494	0.0308	3078.74	0.0424	0.000020		

Long Submain irrigation (upper) — Submain irrigation (upper) — Submain irrigation (lower)

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5. Based on the parameters in problems 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.

End pressure and flow should be set at 0.5 m and 280 LPH in order to generate sufficiency flow velocity for scouring (0.5 m/sec).

The equation for lateral flow rate vs. inlet pressure is $242H^{0.473}$ Inlet pressure to the lateral is 24.3 m.
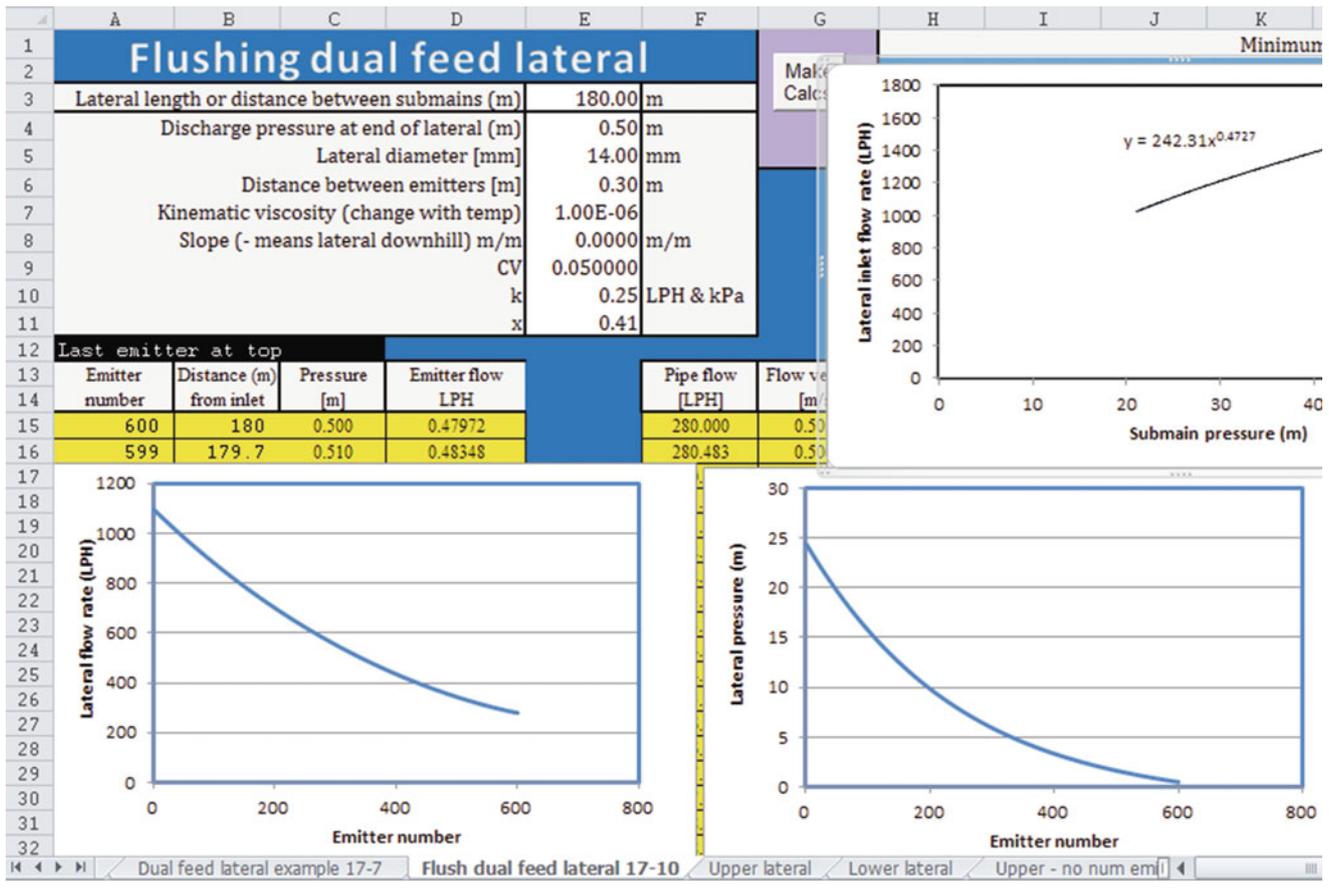
6. Based on the parameters in problems 2–5, evaluate flushing in the submain. There are 100 laterals spaced 1 m apart. Use the *Submain flushing* worksheet. Check that flow velocity is not excessive. Pipe flow velocity restrictions (normally < 1.5 m/sec) can be relaxed for flushing mode, as long as the owner slowly closes valves during the flushing process, keep the velocity below 2 m/sec in this problem. Find the required inlet flow velocity and pressure. Find the equation for inlet pressure vs. flow rate.

In order to keep flow velocity below 2 m/sec, pipe size is 150 mm (6 inch) on the first half of the submain, and 100 mm (4 inch) on the second half of the submain. Required inlet pressure is 25.2 m and flow is 30.36 LPS. The equation (CFS and m) is $6.6H^{0.47}$
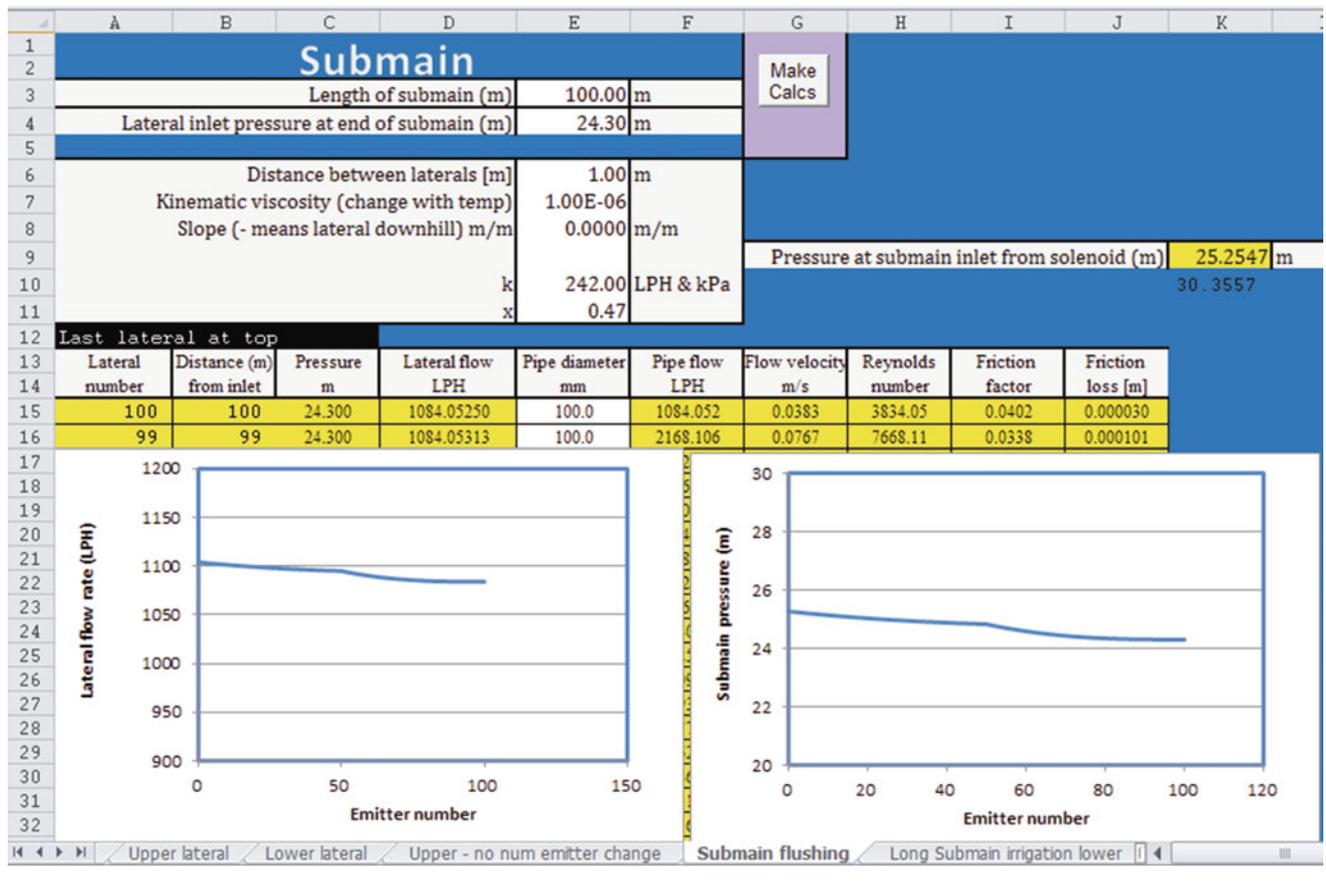
7. Using the information compiled in problems 1–6, design a pump, filter, and mainline system for a level field that has dimensions 400 m × 400 m. Allow 20 m for a central road so the length of laterals (distance between submains) is 180 m. Use the 100 m × 180 m zones that you have already designed. 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). Zero 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.
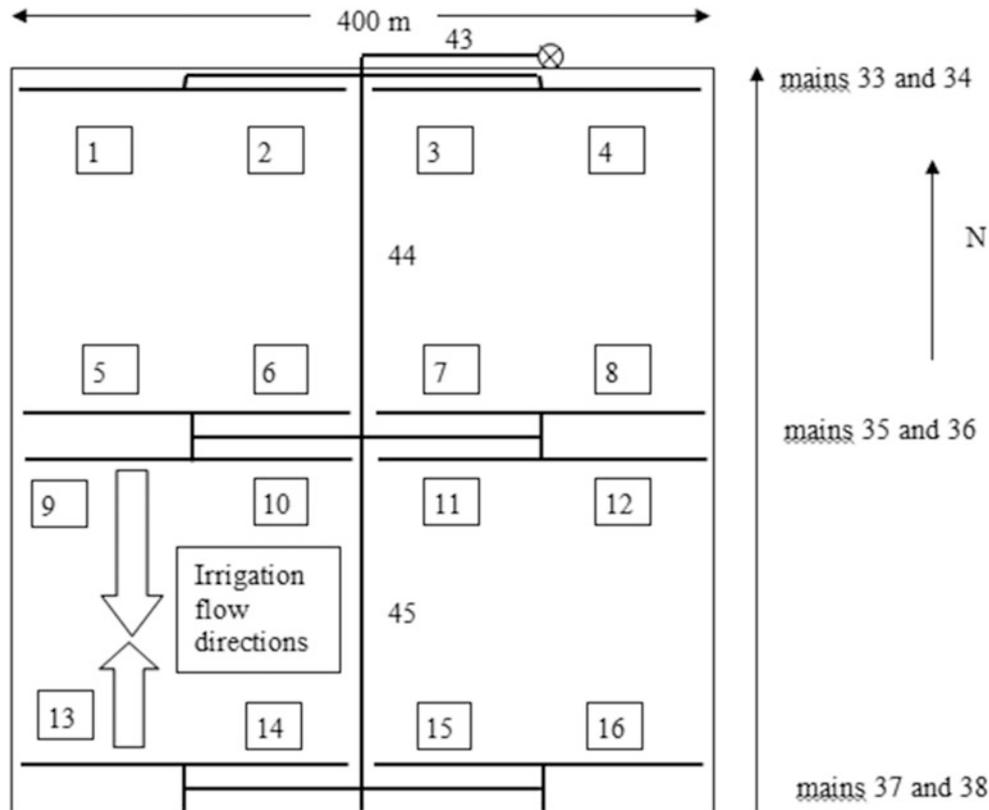
Mainlines are constrained to the 1.5 m/sec maximum velocity. Mains 43, 44, 33, 34, 35, and 36 must supply the flushing velocity, which is 30 LPS. Mains 45, 37, and 38 only supply the normal submain flow, which is 12.1 LPS.

Six inch (150 mm) flow velocity at 30 LPS is greater than 1.5 ft/sec. However, mains 37, 38 and 45 only carry 12.1 LPS, so they are suitable for 6 inch pipe. Designate the 300 m distance with mains 45 and 14 as 6 inch.

Flow velocity is 0.9 m/sec in 8 inch class 125. Because all pipes must carry the same volume, the entire mainline system is uses 8 inch class 125. The longest distance from pump to solenoid valve is 600 m. This distance and value are entered into the *Chapter 18 Mainline* workbook. During the flushing process, the head loss in 8 inch (200 mm) class 125 is 2.294 m, and the head loss in 10 inch (250 mm) class 125 is 0.785 m.

Select pipe D. or fitting	Pipe ID (mm) or valve L/D	Valve/fitting select dimension	Fitting ID (mm)	HW C	Flow (LPM)	Length (m)	Friction loss (m)	Discharge elevation (m)
8" (200) CL 125 PVC ▼	205.64	n/a ▼	"n/a"	140	1800.00	600.00	2.294	100.0
10" (250) CL 125 PVC ▼	256.28	n/a ▼	"n/a"	140	1800.00	600.00	0.785	100.0

During normal operation, the flow rate is 24.2 LPS, with each of two EW mains receiving 12.1 LPS. Because EW mains receive such a small flow in comparison to the flushing design flow, it is obvious, that all of the EW mains will use 8 inch pipe. In addition, main 45 will only carry a maximum of 12.1 LPS, so it is also an 8 in (200 mm) pipe. The only pipes that should possibly be 10 in (250 mm) are 44 and 43.

	Pipe	12.1 LPS		24.2 LPS		
Pipe size	cost	h_f (m)	ΔP (m)	h_f (m)	ΔP (m)	Cost for 300 m
6 (158 mm)	$5.87/m	.772	0.772			$1761
8 (206 mm)	$9.71/m	.213	.213	.771	.771	$2913
10 (256 mm)	$18.6/m			.264	.264	$5580

There is an increase of 0.5 m pressure in each comparison.

$$E = \frac{0.0272(1,110\ mm)(0.5\ m)}{0.8} = 18.9\ kW - hr/ha$$

$$(\$/ha) = \left(\frac{18.9\ kW - hr}{ha}\right)\left(\frac{\$0.10}{kW - hr}\right) = \$1.89/ha$$

The area of the field is 400*380/10000 = 15.2 ha

Total yearly cost for 15.2 ha = $1.89/ha * 15.2 = $28.7/yr.

Present value of energy saving with 206 mm (8 in. pipe (20 year, 8 %) is $282

The increased cost of pipe is over $1,000 to increase from 6 to 8 and from 8 to 10. Thus, larger pipe is not justified.

Use 6 in (200 mm) for sections 45, 37, and 38, and use 8 in (250 mm) for sections 43,44, and 33–36.

Calculate the total energy required at the pump for normal operation. Total pressure required at the pump is 24.9 m. Flow rate is 1452 LPM.

Number of pipe sections 2		Sand filter losses (m) 7					GPM	12
Inlet elevation (m) 100		Pump station losses (m) 3					LPM	45.4
Solenoid valve losses (m) 2.0		Head at mainline inlet 14.9					m	3.58
ired at end of last main (m) 11.3		Required pump pressure (m) 24.9					PSI	5.1

	Select pipe D. or fitting	Pipe ID (mm) or valve L/D	Valve/fitting select dimension	Fitting ID (mm)	HW C	Flow (LPM)	Length (m)	Friction loss (m)	Discharge elevation (m)	Head after fitting (m)
1	6" (150) CL 125 PVC	157.94	n/a	"n/a"	140	726.00	300.00	0.772	100.0	14.1
2	8" (200) CL 125 PVC	205.64	n/a	"n/a"	140	1452.00	300.00	0.771	100.0	14.9

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.

Some values are less than 40 because the random number generator in column B is used to randomize the depths, and half of these values are negative.
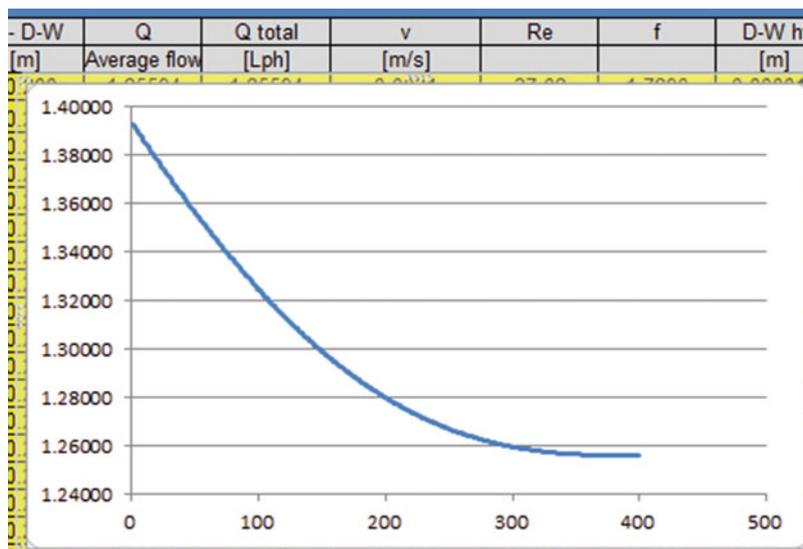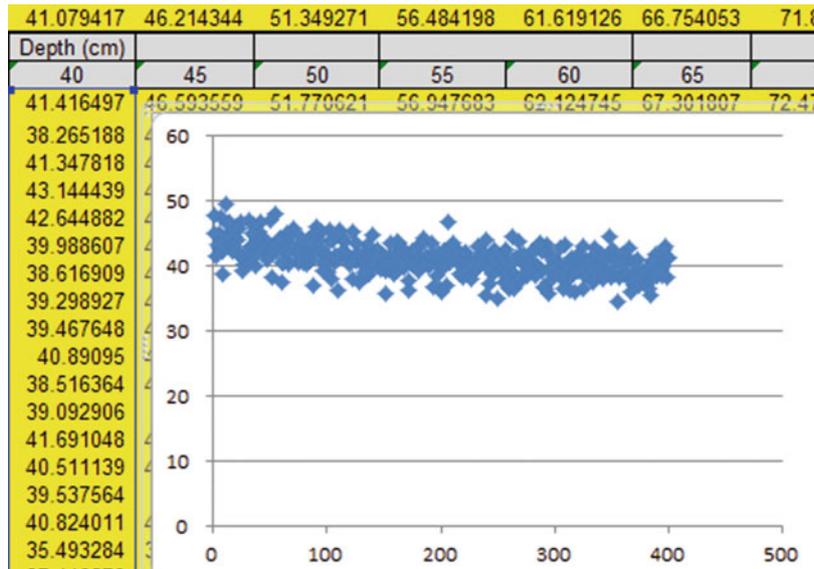
The upper yield curve is at 75 cm minimum. There is less variation than the 50 cm curve because it is near the peak of the yield curve and yield is not as sensitive to change in depth as in the 50 cm range. Yield decreases with distance in the 50 cm curve because yield is sensitive to decreased water application caused by hydraulics at the lower part of the curve.
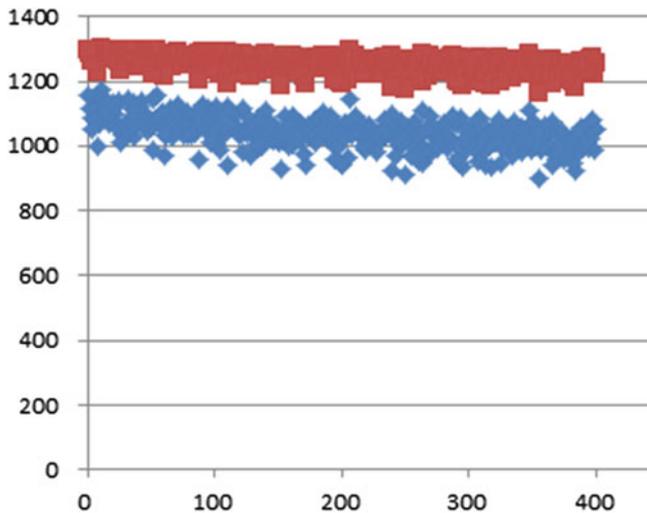
9. Open the *Chapter 18 Economic analysis* workbook and *Cotton Drip lateral CV analysis* worksheet. Move the graph away from table T5:X13. Clear cells T5:X13. Click the Monte Carlo Cotton button in cell P1. Watch what happens in cells H2:W13. Then click the Monte Carlo Cotton button in cell A1 and watch 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)?

The VBA program changes the values in column E. Each time that a change is made, the random number generator changes all the values. The value in cell O9 is the maximum value from column N. This value is then placed in the corresponding CV and tubing category in table T1:X13.

The program runs each condition 10 times, with the random number generator changing the values for each run. This is Monte Carlo analysis.

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.

⟋	AJ	AK	AL	AM	AN	AO	AP	AQ	AR	AS	AT
1											
2											
3			Type	Cost ($/m)	Repl. (yr)	diam (mm)	k	x	spacing	Min Press (kPa)	type
4		1	8 mil tape	0.09	2	16	0.1	0.5	0.25	50	Turbulent
5		2	8 mil tape,	0.07	2	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
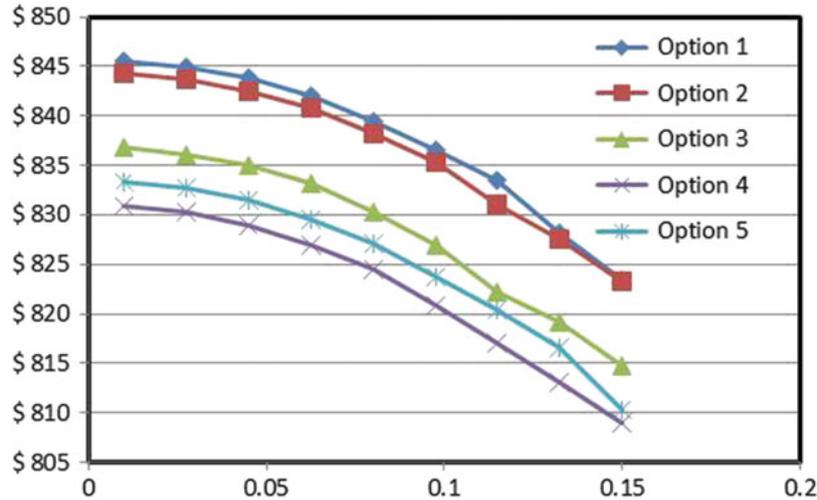
The equations are different; however, observation of the curves indicates that the difference in equations is just due to statistical differences in the Monte Carlo analysis and that the curves are in basically the same positions in both cases. The reason that there is no difference is that the replacement period does not change the relationship between CV and profit during each year.

Options 1–2 have higher profit than 3–5 because the tubing cost is lower. Option 3 has higher profit than option 4 because tubing cost is lower.

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 problem 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

Replacing the tubing every other year improves the annual benefit from the crop; however, the cost of installation makes it prohibitive. The only option with a positive cash flow is option 3.

Chapter 19: Solution

ABE/CE 456/556 Chapter 19 homework solutions.

1. **Determine a fertilizer injection schedule for N,P, and K for bell peppers. Make same irrigation and soil assumptions as for cantaloupe example. The bell pepper nutrient curves and coefficients are shown below.**
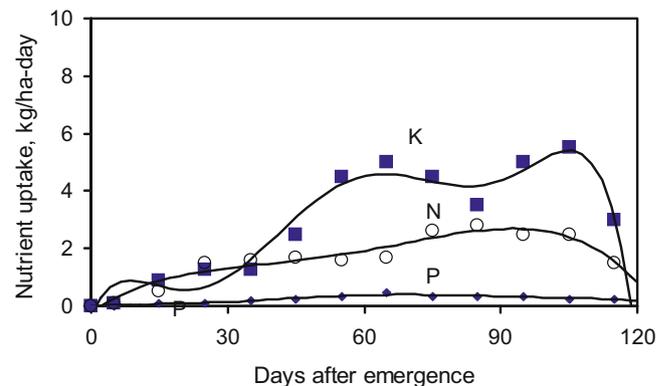
Nutrient uptake rate of N, P, and K as related to days after emergence for bell pepper. Data from Bar-Yosef (1999).

Calculated fertilizer requirements and fertilizer application times are shown below. Assume that 28 kg/ha N and 7 kg/ha P are available and that potassium is not limiting.

Table HW11-1. Nutrient application times for Bell Peppers.

Stage	Nitrogen N (Kg/ha)		Phosphorus (kg/ha)		Poassium 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	
	206	178	30	23	389	0
		28		7		389

Multiply nutrient application rates in table HW11-1 by 15 to find nutrient application rates per block per stage. Assume that 20 kg/ha Ca is applied during the last 2 stages.

Table HW11-1. Nutrient application rates per block.

Stage	Nutrients -kg/block/stage				Water –			
	N	P	K	Ca	Irr. events per stage	Fertigation h/stage	Irrigation h/stage	Water applied per block per stage – (L)
1 (0–25 days)	255	0	0	0	6	12	24	$1.44 * 10^7$
2 (25–50 days)	525	0	0	0	12	24	48	$2.88 * 10^7$
3 (50–75 days)	600	345	0	0	16	32	64	$3.84 * 10^7$
4 (75–100 days)	750	0	0	300	16	32	64	$3.84 * 10^7$
5 (100–120 days)	540	0	0	300	16	32	64	$3.84 * 10^7$

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. 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.

• **Stage 1**

UAN32 will supply 255 kg N per block over 12 h of fertigation (Table 27.7) during the first stage. The density of UAN32 is 1.33 kg/L and the formulation is 32-0-0 (Table 27.5).

$$Volumetric \ N \ content \ of \ UAN32$$
$$= 1.33 \ kg/L \times 0.32 = 0.425 \ kg/L \ of \ N$$
$$UAN32 \ volume \ per \ block \ during \ stage \ 1$$
$$= 255 \ kg/0.425 \ kg/L = 600 \ L \ UAN32$$

Injection rate = 600 L/12 h of fertigation = 50 L/h. of UAN32

• **Stage 2**

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

$$UAN32 \ volume \ per \ block \ during \ stage \ 2$$
$$= 525 \ kg/0.425 \ kg/L = 1,235 \ L \ UAN32$$

Injection rate = 1,235 L/24 h of fertigation = 51.5 L/h. of UAN32

• **Stage 3**

Ammonium polyphosphate will supply 345 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 27.5). Thus, 34 % of the mass of the fertilizer is phosphorous as P_2O_5. P_2O_5 is multiplied by 0.44 (Table 27.4) to convert to elemental P (PO_4-P).

Volumetric P content of APP
    $= 1.37 \ kg/L \times 0.34 \times 0.44 = 0.205 \ kg/L \ of \ P$
APP volume per block during stage 3
    $= 345 \ kg/0.205 \ kg/L = 1,683 \ L \ of \ APP$

APP Injection rate $= 1,683$ L/(32 h of fertigation) $= 53$ L/h of APP

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

Volumetric N content of APP
    $= 1.37 \ kg/L \times 0.10 = 0.137 \ kg/L \ of \ N$
Mass N applied as APP
    $= 1,683 \ L \times 0.137 \ kg/L = 231 \ kg \ of \ N$

If 231 kg N is applied as ammonium phosphate, then the remainder of the nitrogen requirement (600–231 $= 370$ kg/block) during stage 3 must be supplied by UAN32.

*UAN*32 *volume per block during stage* 3
    $= 370 \ kg/(0.425 \ kg/L) = 870 \ L \ of \ UAN$32

Injection rate $= 870$ L/(32 h of fertigation) $= 27$ L/h of UAN32

• **Stage 4**

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 calcium fertilizer is 1.55 and the formulation is 17-0-0-8.8 Ca (Table 19.6). Thus, 8.8 % of the mass of the fertilizer is calcium.

*Volumetric Ca content for CAN*17
    $= 1.55 \ kg/L \times 0.088 = 0.136 \ kg/L \ of \ Ca$
CAN 17 *volume per block during stage* 4
    $= 300 \ kg/(0.136 \ kg/L) = 2,205 \ L \ of \ CAN$17

Injection rate of CAN17 $= 2,205$ L/(32 h of fertigation) $= 69$ L/h of CAN17

The amount of nitrogen supplied by CAN17 during stage 4 is calculated as follows.

*Volumetric N Content of CAN*17
    $= 1.55 \ kg/L \times 0.17 = 0.264 \ kg/L \ of \ N$
*Mass N applied as CAN*17
    $= 2,205 \ L \ CAN17 \times 0.264 \ kg/L = 582 \ kg \ of \ N$

If 600 kg N is applied as CAN17, then the remainder of the nitrogen requirement

(750–582 $= 168$ kg/block) during stage 4 must be supplied by ammonium nitrate.

Volumetric N content for Ammonium nitrate $= 1.29$ kg/L $\times 0.2 = 0.26$ kg/L of N

Ammonium nitrate volume per block during stage 4 $= 168$ kg/(0.26 kg/L) $= 646$ L of Ammonium nitrate

Injection rate $= 646$ L/(32 h of fertigation) $= 20$ L/h of Ammonium nitrate

• **Stage 5**

*Volumetric Ca content for CAN*17
    $= 1.55 \ kg/L \times 0.088 = 0.136 \ kg/L \ of \ Ca$
CAN 17 *volume per block during stage* 5
    $= 300 \ kg \ / \ (0.136 \ kg/L) = 2,205 \ L \ of \ CAN$17

Injection rate of CAN17 $= 2,205$ L/(32 h of fertigation) $= 69$ L/h of CAN17

The amount of nitrogen supplied by CAN17 during stage 4 is calculated as follows.

*Volumetric N Content of CAN*17
    $= 1.55 \ kg/L \times 0.17 = 0.264 \ kg/L \ of \ N$
*Mass N applied as CAN*17
    $= 2,205 \ L \ CAN17 \times 0.264 \ kg/L = 582 \ kg \ of \ N$

In this stage the plants only need 540 kg. Thus, no excess fertilizer is required.

2. **Plot carbonate, bicarbonate, and carbonic acid concentration as a function of pH for alkalinity as calcium carbonate equal to 120 mg/L.**

Molecular weight $CaCO_3 = 100.1$ g/mol

Then: 120 mg/l $= 0.12$ g/l; we have $\dfrac{0.12 g/l}{100.1 g/mol} = 0.0012 mol/l$
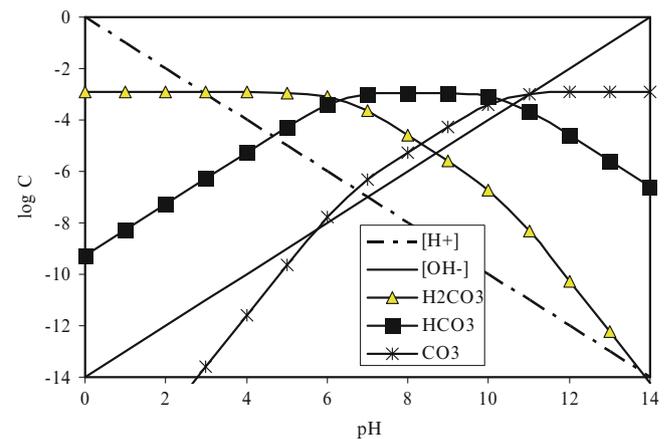
Figure HW11-2. Carbonate species vs. pH.

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.**

Water has $CaCO_3$ of approximately 120 mg/L. This is the same as 60 mg/L CO_3^{-2}. The molecular weight of carbonate (CO_3^{-2}) is 60 g/mole. The calculation of carbonate molarity is as follows.

$$\left(\frac{120 \ mg \ CaCO_3}{L \ CAP \ water}\right)\left(\frac{0.6 \ mg \ CO_3^{-2}}{1 \ mg \ CaCO_3}\right)\left(\frac{g \ CO_3^{-2}}{1,000 \ mg \ CO_3^{-2}}\right)$$

$$\left(\frac{1 \ mole \ CO_3^{-2}}{60 \ g \ CO_3^{-2}}\right) = 0.0012 \ mole/L$$

Hydroxyl ion concentration at $pH(7.9) = 10^{-(14 \ - \ 7.9)} = 2*10^{-6} mole/L$.

Calculate initial HCO_3^- molarity at pH (7.9).

$$[HCO_3^-] = \frac{[C][K_1][H^+]}{[H^+]([H^+] + K_1) + K_1K_2} =$$
$$= \frac{[0.0012]\left[4.47*10^{-7}\right]\left[1.26*10^{-8}\right]}{[1.26*10^{-8}]\left([1.26*10^{-8}] + 4.47*10^{-7}\right) + 4.47*10^{-7}*4.68*10^{-11}} = 1.16*10^{-3}mol/L$$

Calculate the initial CO_3^{-2} molarity at pH (7.9)

$$[CO_3^{-2}] = \frac{[C][K_1][K_2]}{[H^+]([H^+] + K_1) + K_1K_2} =$$
$$== \frac{[0.0012]\left[4.47*10^{-7}\right]\left[4.68*10^{-11}\right]}{[1.26*10^{-8}]\left([1.26*10^{-8}] + 4.47*10^{-7}\right) + 4.47*10^{-7}*4.68*10^{-11}} = 4.32*10^{-6} \ mol/L$$

Calculate the total alkalinity at pH (7.9)

$$\sum \left(HCO_3^- + CO_3^{2-} + OH^-\right) = 1.16*10^{-3} + 2*4.32*10^{-6} + 2*10^{-6} = 0.00117 \ eq/L$$

Now calculate the alkalinity at the final pH (6.8).
Hydroxyl ion concentration at pH (6.8) $= 10^{-(14–6.8)} = 1.58 * 10^{-7}$ mole/L.
Calculate final HCO_3^- molarity at pH (6.8).

$$[HCO_3^-] = \frac{[C][K_1][H^+]}{[H^+]([H^+] + K_1) + K_1K_2} =$$
$$= \frac{[0.0012]\left[4.47*10^{-7}\right]\left[1.58*10^{-7}\right]}{[1.58*10^{-7}]\left([3.16*10^{-7}] + 4.47*10^{-7}\right) + 4.47*10^{-7}*4.68*10^{-11}} = 8.86*10^{-4} \ mol/L$$

Calculate final CO_3^{-2} molarity at pH (6.8)

$$[CO_3^{-2}] = \frac{[C][K_1][K_2]}{[H^+]([H^+] + K_1) + K_1K_2} =$$
$$== \frac{[0.001]\left[4.47*10^{-7}\right]\left[4.68*10^{-11}\right]}{[1.58*10^{-7}]\left([1.58*10^{-7}] + 4.47*10^{-7}\right) + 4.47*10^{-7}*4.68*10^{-11}} = 2.62*10^{-7} \ mol/L$$

Calculate final total alkalinity at pH (6.5)

$$\sum \left(HCO_3^- + CO_3^{2-} + OH^-\right) = 8.86*10^{-4} + 2*2.62*10^{-7} + 1.58*10^{-7} = 0.000886 \text{ eq/L}$$

Change in alkalinity = initial alkalinity − final alkalinity

$= 0.00117 \text{ eq/L} - 0.000886 \text{ eq/L} = 2.84*10^{-4}$

$Q_a C_a = Q_w C_w \rightarrow 37,560 \text{ meq/L} : *$ acid flow rate $= 0.284 \text{ meq/L}*44 \text{ L/sec}$

Acid flow rate $= 0.284*44/37,560 = 0.0003327 \text{ L/sec} = 1.2 \text{ L/hr}$

---

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

   Calculate for 25 °C

   $A = (Log10[1000] - 1)/10 = 0.2$
   $B = -13.12 \times Log10(25^oC + 273) + 34.55 = 2.088$
   $C = Log10[65] - 0.4 = 1.41$
   $D = Log10[120] = 2.1$
   $pH_s = (9.3 + A + B) - (C + D)$
   $pHs = (9.3 + 0.2 + 2.088) - (1.41 + 2.1) = 8.08$

$LSI = pH - pH_s = 7.96 - 8.08 = -0.12$ (The LSI is close to zero, so precipitation may occur).

   Calculate for 35 °C

   $A = (Log10[1000] - 1)/10 = 0.2$
   $B = -13.12 \times Log10(35^oC + 273) + 34.55 = 1.9$
   $C = Log10[65] - 0.4 = 1.41$
   $D = Log10[120] = 2.1$
   $pH_s = (9.3 + A + B) - (C + D)$
   $pHs = (9.3 + 0.2 + 1.9) - (1.41 + 2.1) = 7.9$

$LSI = pH - pH_s = 7.96 - 7.9 = 0.06$ (The LSI is very close to zero: add acid).

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.**

$$200 \, LPM = 3.33 \, LPS$$

Liquid (liquid flow rate, use 10 % chlorine)

$$\left(\frac{3.34 \, L \, water}{sec}\right)\left(\frac{3 \, mg \, Cl_2}{L \, water}\right)\left(\frac{100 \, mg \, bleach}{10.1 \, mg \, Cl_2}\right)$$
$$\left(\frac{kg}{1*10^6 \, mg}\right)\left(\frac{L}{1.15 \, kg}\right)\left(\frac{3,600 \, sec}{hr}\right) = 0.31 \, L/hr$$

Chapter 20: Solution

1. Describe the three phases of surface irrigation

Surface irrigation events have 3 phases: advance, storage, and recession. During advance, the wetting front (Fig. 20.1) moves down the channel. The second phase of surface irrigation is the storage phase (Fig. 20.2). After the advance reaches the end of the field, the water must remain ponded for a sufficient length of time for the end of the field to receive the required depth of water. The length of the storage phase depends on the required depth of infiltration, and the soil infiltration rate. It may last from several hours to 24 hours. If the storage phase is long, then a significant quantity of water may run off the end of the field. Also, significant leaching may occur at the upstream end. After irrigation water is turned off at the time of cutoff, recession begins: ponded water infiltrates or moves down the furrow and the upper end dries (Fig. 20.2). In furrow irrigation systems, the upper end of the furrow dries immediately after the time of cutoff, and then the dried section increases as the water infiltrates and moves off the end of the field. However, recession does not begin immediately for border and level basin systems because there is a much greater ratio of water on the field surface to wetted soil area than in furrows.

2. Answer the following questions true or false.
   (a) Uniformity is generally high if the storage phase is relatively small in comparison to the advance phase. false
   (b) The advantage of the two-point method is that the infiltration rate during the storage phase can be extrapolated from the infiltration rate calculated during the advance phase. false
   (c) The Kostiakov equation includes steady state infiltration. false
   (d) The two-point volume balance method can be expanded to find the coefficient b in the steady state term by using another point. false
   (e) The vertical infiltration rate as calculated from a double ring infiltrometer can be adjusted for furrow

irrigation by taking the width of the furrow divided by the distance between furrows. False

3. Using the Merriam and Clemmens approach, calculate k and a if the time to infiltrate 100 mm is 8 hours. Make the calculation by hand and in the *Infiltration* worksheet. Compare to the closest NRCS (SCS) curve number: the curve that is closest to 100 mm over 8 hours.

$$a = 0.675 - 0.2125 \ \mathrm{LOG}_{10}(\mathrm{T}_{100})$$
$$= 0.675 - 0.2125 \ \mathrm{LOG}_{10}(8) = 0.483$$
$$k = 100/8^{0.483} = 36.6$$

The closest NRCS curve number is the 0.35 intake family.
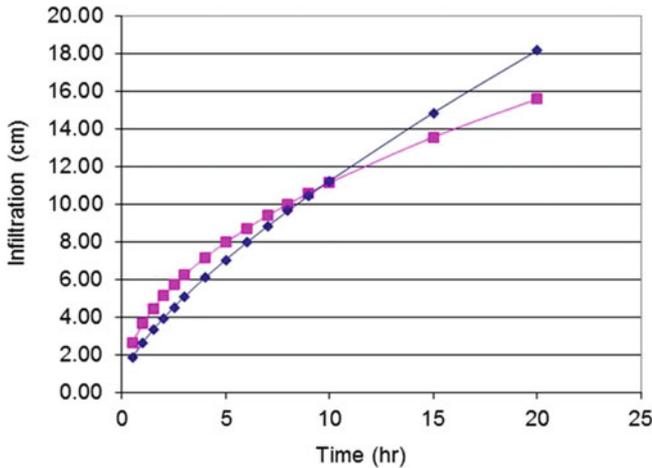
4. Flow rate $= 2.0$ L/s, $z = 1.7$, $b = 0.2$ m, Manning's $n = 0.05$, furrow slope $= 0.001$ m/m. Calculate the depth of flow by hand and with the *Furrow* worksheet. Using the Clemmens k and a values from problem 6, adjust the k value for the wetted perimeter and a furrow spacing of 1 m. Make calculations by hand and in furrow worksheet.

Calculate the section factor (Chap. 10)

$$\frac{Qn}{S_f^{1/2}} = \frac{(0.002 \ m^3/\sec)\,(0.05)}{0.001^{1/2}} = Section \ factor$$

$$= 0.003162$$
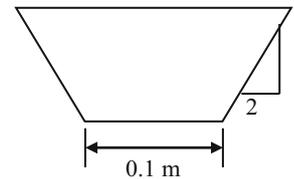
$AR^{2/3}$ is calculated with the following equation.

$$AR^{2/3} = A(A/P)^{2/3}$$
$$= (b + zy)y\left(((b+zy)y)/\left(b + 2y(1+z^2)^{\wedge 0.5}\right)\right)^{2/3}$$

Make an initial guess, $y = 0.04$ m.

$$AR^{2/3} = \left(0.2 + (1.7)(0.04)(0.04)\left(\left(0.2 + (1.7)(0.04)\right)(0.04)/\left(0.2 + (2)(0.04)\left(1 + 1.7^2\right)^{\wedge 0.5}\right)\right)\right)^{2/3}$$

Iterate by inputting the required section factor (0.003612) and the first guess for a section factor into the following equation. This equation is designed for rapid convergence for this iteration.

$$y = initial \ y\left(SF/AR^{2/3}\right)^{0.5} = 0.04(0.003162/0.00103)^{0.5} = 0.07 \ m.$$

$$AR^{2/3} = \left(0.2 + (1.7)(0.07)(0.04)\left(\left(0.2 + (1.7)(0.07)\right)(0.07)/\left(0.2 + (2)(0.07)\left(1 + 1.7^2\right)^{0.5}\right)\right)\right)^{2/3} = 0.0029$$

0.003162 and $0.0029 \rightarrow y = 0.0730$.

$$AR^{2/3} = \left(0.2 + (1.7)(0.073)(0.04)\left((0.2 + (1.7)(0.073))(0.073)/\left(0.2 + (2)(0.073)\left(1 + 1.7^2\right)^{\wedge 0.5}\right)\right)\right)^{2/3} = 0.00315$$

$$0.003162 = 0.00315 \rightarrow y = 0.0732.$$

Calculate wetted perimeter

$$P = b + 2\ y(1+z^2)^{0.5} = 0.1 + (2)(0.0732)(1+1.7^2)^{0.5}$$
$$= 0.488\ m$$

Adjust the infiltration rate for the equivalent furrow infiltration width.

$$\frac{0.488\ m + 0.213\ m}{1.0\ m}36.6 = 25.7$$

5. Using the information from problem 4, calculate s and h and plot the advance curve for a 500 m long furrow with 1 m spacing between furrows. Inflow rate is 2.0 L/s. Use a convergence criterion of less than 1 min difference for advance time between iterations. Make calculations by hand and with the furrow worksheet.

Calculate cross-sectional area at the furrow inlet, A_0.

$$A_0 = (b + z\ y)y$$
$$= (0.1\ m + (1.7)(0.0732\ m))(0.0732\ m)$$
$$= 0.0237\ m^2$$

The design procedure starts with a guess for the advance time to ½ the field length and to the end of the field. For this example, we arbitrarily guess 100 and 250 minutes, respectively. For a flow rate of 1.0 L/s, calculate inflow volumes during these two periods.

$$V_{L/2} = Qt = 100\ min(60\ sec/min)(0.001\ m^3/sec)$$
$$= 6\ m^3$$

$$V_L = Qt = 250\ min(60\ sec/min)(0.001\ m^3/sec)$$
$$= 15\ m^3$$

$$h = \log(t_{L/2}/t_L)/\log(1/2) = \log(100/250)/\log(1/2)$$
$$= 1.32$$

The next step is to calculate the subsurface shape factor.

$$\sigma_z = \frac{h + a(h-1)+1}{(1+a)(1+h)} = \frac{1.32 + 0.483(1.32-1)+1}{(1+0.483)(1+1.32)}$$
$$= 0.72$$

The next step is to calculate subsurface storage. The infiltrated depths at the upper end of the field at 100 and 250 minutes are calculated.

$$d_{L/2} = kt^a = 25.7(100/60)^{0.46} = 32.9\ mm\ infiltrated.$$
$$d_L = kt^a = 25.7(250/60)^{0.46} = 51.2\ mm\ infiltrated.$$

Calculate subsurface storage at $t_{L/2}$ (time to reach L/2) and t_L

$$Vz_{L/2} = d_0\sigma_zWx = 32.9/1,000\ mm)(0.72)(1.0\ m)(250\ m)$$
$$= 5.9\ m^3$$
$$Vz_L = d_0\sigma_zWx = (51.2/1,000\ mm)(0.72)(1.0\ m)(500\ m)$$
$$= 18.4\ m^3$$

Calculate surface storage at $t_{L/2}$ and t_L.

$$V_{s\ L/2} = \sigma_yA_0x = (0.75)(0.0237\ m^2)(250\ m) = 4.45\ m^3.$$
$$V_{s\ L} = \sigma_yA_0x = (0.75)(0.0237\ m^2)(500\ m) = 8.9\ m^3.$$

Calculate total storage at $t_{L/2}$ and t_L.

$$V_{T\ L/2} = 5.9 + 4.45 = 10.36\ m^3$$
$$V_{T\ L} = 18.4 + 8.9 = 27.31\ m^3$$

The advance times are adjusted with Eq. 20.16

$$t_{m+1} = t_m\left(\frac{V_T}{Q\ t_m}\right)^{1.4} = 100\left(\frac{10.36}{12}\right)^{1.4} = 81\ min$$

$$t_{m+1} = t_m\left(\frac{V_T}{Q\ t_m}\right)^{1.4} = 250\left(\frac{27.31}{30}\right)^{1.4} = 219\ min$$

The procedure is then repeated for the next iteration with $t_{L/2} = 81$ min, and $t_L = 219$ min.

These times are close to the actual value. The next iteration leads to the final times 83 and 221

Iteration steps for two point volume balance method.

	t_1	t_2	h	σ_z	$V_{in-t\ L/2}$	$V_{in-t\ L}$	$V_{TL/2}$	V_{TL}
Initial guess	100	250	1.32	0.72	12	30	10.4	27.3
Iteration 1	81	219	1.43	0.73	9.77	26.3	9.90	26.5
Iteration 2	83	221	1.42	0.73	9.95	26.4	9.93	26.5

$$t = sx^h \quad s = t/x^h \quad s = 221/500^{1.42} = 0.0332$$

$$t = 0.03332\ x^{1.42}$$

The advance curve is shown below
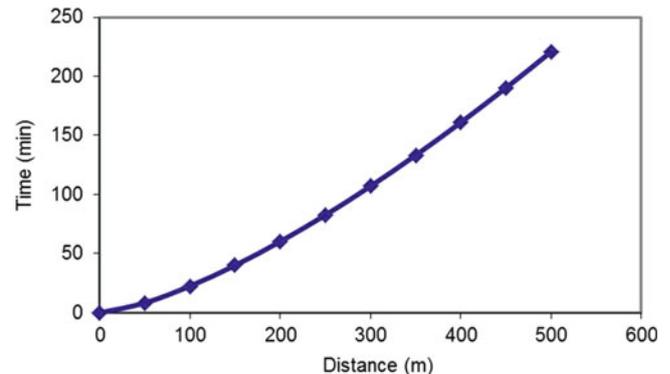
6. Find the time of cutoff for the parameters in problem 5. The depth required is 76 mm. You should calculate a total irrigation time of approximately 12 hr.

Calculate the required intake opportunity time.

$$d = kt^a$$
$$t = (d/k)^{1/a} = (76/25.7)^{1/0.483} = 9.45 \ hr = 567 min$$

Calculate the recession time.

$$t_{rec} = V/Q = (0.0237 \ m^2)(500 \ m)(0.8)/(0.12 \ m^3/min)$$
$$= 79 min = 1.32 \ hr$$

The advance time was already calculated as 220 min

$$t_{co} = t_{adv} + IOT_{req} - t_{rec}$$
$$= (567 min + 220 min - 79 min)/60 = 11.8 \ hr$$

7. Use the Furrow times worksheet to find the depth of infiltration every 50 m down the furrow for the parameters in problems 5–6. Calculate the depth of infiltration at 150 m by hand and compare to the worksheet. Calculate the DU LQ by hand and compare to the value in cell G33. By hand, calculate the DP%, RO %, and efficiency based on applied volume and infiltrated volume reported in the worksheet. In this problem, do not use cutback irrigation. Adequately irrigate the entire field (minimum required depth is applied to end of furrow).

Find the intake opportunity time at 150 m

$$\text{Advance time to 150 } m = sx_j^h = (0.0332*150^{1.42})$$
$$= 40 \ min$$

$$\text{Time that water recedes from 150 } m = t_{co} + x_j/L \ t_{rec}$$
$$= (10.8 + 150/500*1.32)*60 = 733 \ min$$

$$IOT = 733 \ min - 40 \ min = 693 \ min = 11.55 \ hr$$

$$d_{120} = kt^a = 25.7(11.52)^{0.483} = 83.7 \ mm$$

Same calculation in one equation:

$$d_{120} = k(t_{co} + x_j/L \ t_{rec} - sx_j^h)^a = 25.7((10.8 \ h + (150/500)(1.32 \ h))(60) - (0.0332*150^{1.42})/60)^{0.483}$$
$$= 83.7 \ mm$$

Calculate the DU LQ and compare to the value in the *Furrow times* worksheet

Total volume $= 40.8 \ m^3$ (from cell G30)
Field average $= (40.8/500 \ m/1 \ m)*1000 \ mm/m = 81.7 \ mm$
Low quarter average $= (78.8 + 77.5 + 76*0.5)/2.5 = 77.7 \ mm$
DU LQ $= 77.7/81.7(100\%) = 95\%$

Calculate the DP% and RO%

Applied volume $= 10.8 \ hr(2 \ LPS)(1 \ L/1000 \ m^3)(3600 \ sec/hr) = 85.07 \ m^3$
RO% $= $ (Applied volume $-$ infiltrated volume)/(applied volume) $= (85.1 \ m^3 - 40.8 \ m^3)/85.1 \ m^3) \ (100\%) = 52\%$

Required volume $= 500 \ m(76 \ mm)/(1000 \ mm/m)(1 \ m \ furrow \ width) = 38 \ m^3$
DP% $= $ (Infiltrated volume $-$ required volume)/Applied volume $= ((40.8 \ m^3 - 38 \ m^3)/85.1 \ m^3) \ (100 \ \%) = 3.3\%$

Efficiency $= $ Water used/(water applied)(100\%) $= 38 \ m^3/(85 \ m^3)(100\%) = 45\%$

8. For the parameters in problems 5–7, observe how the parameters for cutback irrigation are calculated in the cutback worksheet. Can cutback take place as soon as water reaches the end of the furrow? What will be the cutback flow rate (half of initial flow rate). Find the following parameters and report the cell number in which they are found: the average infiltration at the end of the furrow when water reaches the end of the furrow, the volume infiltration rate when water reaches the end of the furrow (LPS), the average infiltration rate (mm/hr) 10 minutes after water reaches the end of the furrow, and the time when cutback can take place. Compare the total

depth applied to the depth applied without cutback, and the RO%, DP%, and efficiency

Cutback cannot take place as soon as water reaches the end of the furrow. The cutback flow rate will be 1 LPS.

- the average infiltration at the end of the furrow when water reaches the end of the furrow
  – cell F13, 10.36 mm/hr
- the total infiltration in the field when water reaches the end of the furrow (LPS)
  – cell F16, 1.44 LPS (exceeds the average infiltration 10 minutes after water reaches the end of the furrow)
  – cell G13, 9.35 mm/hr
- the time when cutback can take place
  – cell S1, 33 minutes after advance reaches the end of the field

The total depth applied is 54.5 m^3, which is far less than the 85 m^3 applied without cutback. The RO% is 25 % instead of 52 %. The DP% is higher (4.75 %), but this is just due to less total water applied. The efficiency is 70 % compared to 45 %.

9. Calculate an irrigation schedule for the parameters in previous problems for peak ETc 10 mm/day. Leaching fraction is 10 %.

The entire soil profile is filled during the irrigation; however, 10 % of the water is used for leaching. Thus, only 90 % is available for crop water uptake.

Infiltration is 76 mm. The depth left after leaching for crop uptake is 76 mm * 0.9 = 68.4 mm.

The crop could survive for approximately 7 days between irrigations so irrigate weekly.

10. Design a runoff-recovery system for the parameters in problems 3–7 and 9. Do not worry about economic analysis or comparison to cutback irrigation unless asked by instructor. Determine the required supply flow rate, Q$_s$, to the head ditch. The field width is 800 m wide. The delivery efficiency of the head ditch is 90 %. The collection system efficiency of the runoff recovery system, prior to water reentering the head ditch, is 87 % (3 % lost to evaporation and 10 % lost to seepage in the tailwater ditch and reservoir). Assume that the reservoir is full at the beginning and end of the irrigation cycle.

Supply source water is pumped from a well with a dynamic water table depth of 50 m, and the well pump efficiency is 80 %. Reuse water is pumped a distance of

1,300 m (800 + 500), and the difference in elevation between the head ditch inlet and the reuse reservoir water surface is 3 m.

Part 1 solution: Design of reuse system.

The furrow is designed to apply 76 mm, d$_{req}$ at end of furrow, per irrigation. The interval between irrigation events is 7 days, and the field should be divided as shown in Fig. 20.18, except that all of the zones would be the same size. The number of zones is

$$N = (70 \text{ mm})/(10 \text{ mm/day}) = 7 \text{ sets}$$

The reuse delivery efficiency, Eff$_{dr}$, is the same as the pumped water delivery system efficiency since reuse water is added to the head ditch at the same point, 0.9. The reuse collection system efficiency, Eff$_{rcs}$, is 0.87. The required system flow rate, Q$_s$, with the reuse system is found by rearranging Eq. 20.33.

$$Q_s = \frac{FQ_f}{N\left(Eff_{ds}/_{100}\right)\left(1 + \left(\frac{RO\%}{100}\right)\left(Eff_{dr}/_{100}\right)\left(Eff_{rcs}/_{100}\right)\right)}$$

$$Q_s = \frac{800*2.0 \ L/s}{7(0.9)(1 + (0.52)(0.9)(0.87))} = 180 \ L/s$$

$$Q_r = Q_s(Eff_{ds}/100\%)(Eff_{rcs}/100\%)(RO\%/100\%)$$
$$= 180(0.9)(0.87)(0.52) = 74 \ L/s$$

Check results with Eq. 20.31

$$F = 7\left(\frac{180(0.9)}{2} + \frac{74(0.9)}{2}\right) = 800 \ furrows$$

Number of furrows irrigated per day is 800 furrows/7 sets = 114 furrows per irrigation. Supply system flow rate, Q$_s$, without reuse is 114 furrows (1 L/s-furrow)/ 0.9 = 254 L/s.

Let the reservoir hold a 1-day water supply.

$$(73.6/0.87 \ L/s)(24 \ hr)(3,600 \ sec/hr)/1,000 \ L/m^3$$
$$= 7305 \ m^3$$

If the reservoir is 2 m deep, then the average reservoir storage area is 2,000 m^2. Average dimensions of 200 m × 36 m would be adequate. If the side slopes are 2:1, and the bottom width is 32 m, then the top (water surface) width would be 40 m, for an average width of 36 m. Likewise, the bottom length should be 193 m and the top length (water surface) should be 207 m for an average length of 100 m. The top of the reservoir should be 0.3 m higher to account for filling of the bottom and an additional 0.3 m for

freeboard. Thus, the width of the reservoir with a 2:1 side slope would increase by 1.2 m to 41.2 m. The length would increase by 0.3 m (2) + 0.3 m (5) = 2.1 m. Thus, the length of the reservoir is 209.1 m.

11. The required intake opportunity time is 17 hours, advance is 2 hours, and recession time is 1 hour. What is the t_{co}?

$$t_{co} = t_{adv} + IOT_{req} - t_{rec}$$
$$tco = 2 + 17 - 1$$
$$\textbf{tco} = \textbf{18 hr}$$

12. Volume of deep percolation is 20 m³, volume of runoff is 25 m³, and volume used in the soil profile is 60 m³. What is the irrigation efficiency, inflow volume, deep percolation percentage, and runoff percentage.

Irrigation Efficiency = **(60) / 105** = **57%**
Inflow Volume = **60 + 20 + 25** = **105m³**
Deep Percolation % = **20 / 60 * 100** = **33%**
Runoff % = **25 / 60 * 100** = **42%**

13. The average depth of infiltration in a field is 100 mm, and the average depth of infiltration over the last 25 % of the field is 90 mm. What is the DU?

Low quarter / Furrow Average
90 / 100 = **90%**

14. Why can't one just increase the flow rate to any velocity in order to get water across the field as quickly as possible?

High runoff percentage will lead to wasted water. Erosion may take place

15. Why does surge irrigation improve irrigation efficiency in some soils?

In medium to coarse textured soils, the surface tends to consolidate and seal up once the water is turned off. Then when water is reintroduced in the furrow, infiltration is very low, and the advance phase is very fast. With surge irrigation, the advance time can be nearly as fast as continuous flow, but use half as much water. Surge valves can also be effective because they give the farmer more control over the irrigation event.

16. Download WinSRFR onto your computer and copy a screen showing that it is open on your computer.
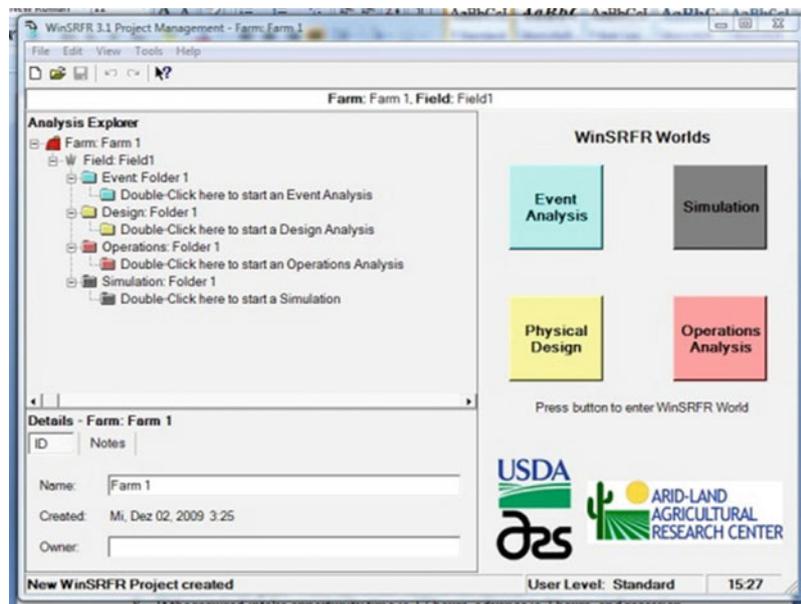
17. Put the data in Figs. 20.16, 20.17, 20.18, 20.19, 20.20, 20.21 and 20.22 into WinSRFR and get the same result shown in the chapter. Copy the data from the Estimated Function page and paste to this document. Include Two point advance per furrow data and Kostiakov a and b data.
    - WinSRFR 3.1 – Arid-Land Agricultural Research Center, Maricopa, AZ
    - Event Analysis Results – Mittwoch, 2. Dezember 2009 16:04
        - Farm: Farm 1, Field: Field1
        - Folder: Folder 1, Analysis: Analysis 1
    - *Two-Point Advance* per Furrow

Parameter	Point 1	Point 2
Distance (X)	200 m	400 m
Time (T)	1,35 hr	3,85 hr
Flow Rate (Qavg)	1 l/s	1 l/s
Upstream Depth (Y0)	52 mm	53 mm
Average Depth (Yavg)	42 mm	42 mm
Upstream Wetted Perimeter (WP0)	335 mm	336 mm
Average Wetted Perimeter (WPavg)	288 mm	290 mm
Upstream Flow Area (A0)	0,01075 m^2	0,01086 m^2
Average Flow Area (Aavg)	0,00798 m^2	0,00803 m^2
Surface Shape Factor (sy)		
User Entered	0,76	0,76
Calculated	0,743	0,739
Inflow Volume (Vin)	4,86 m^3	13,86 m^3
Surface Volume (Vy)	1,63 m^3	3,3 m^3
Vy/Vin (%)	33,6 %	23,8 %
Infiltrated Volume (Vz)	3,23 m^3	10,56 m^3
Power Advance Exponent	(r) = 0,66142	
Power Advance Constant (p) = 10,93252 m/min^r		
Estimates for Kostiakov k, a & b		
k: 18,791 mm/hr^a		
a: 0,46996		
b: 0 mm/hr		

18. Modify the previous problem by putting in an advance time to 2 hours to the midpoint in the field and 5 hours to the end of the field. Copy the data from the Estimated Function page.
    - WinSRFR 3.1 – Arid-Land Agricultural Research Center, Maricopa, AZ
    - Event Analysis Results – Mittwoch, 2. Dezember 2009 16:10
        - Farm: Farm 1, Field: Field1
        - Folder: Folder 1, Analysis: Analysis 1
    - *Two-Point Advance* per Furrow

Parameter	Point 1	Point 2
Distance (X)	200 m	400 m
Time (T)	2 hr	5 hr
Flow Rate (Qavg)	1 l/s	1 l/s
Upstream Depth (Y0)	52 mm	53 mm
Average Depth (Yavg)	45 mm	46 mm
Upstream Wetted Perimeter (WP0)	335 mm	336 mm
Average Wetted Perimeter (WPavg)	300 mm	304 mm
Upstream Flow Area (A0)	0,01075 m^2 0,01086 m^2	
Average Flow Area (Aavg)	0,00867 m^2 0,00885 m^2	
Surface Shape Factor (sy)		
User Entered	0,76	0,76
Calculated	0,806	0,815
Inflow Volume (Vin)	7,2 m^3	18 m^3
Surface Volume (Vy)	1,63 m^3	3,3 m^3
Vy/Vin (%)	22,7 %	18,3 %
Infiltrated Volume (Vz)	5,57 m^3	14,7 m^3
Power Advance Exponent	(r) = 0,75647	
Power Advance Constant	(p) = 5,34798 m/min^r	
Estimates for Kostiakov k, a & b		
k: 28,207 mm/hr^a		
a: 0,30328		
b: 0 mm/hr		

19. Modify the previous problems by changing the furrow bottom width to 200 mm and the slope to 0.003. Copy the data from the Estimated Function page.
    - WinSRFR 3.1 – Arid-Land Agricultural Research Center, Maricopa, AZ
    - Event Analysis Results – Mittwoch, 2. Dezember 2009 19:07
    - Farm: Farm 1, Field: Field1
    - Folder: Folder 1, Analysis: Analysis 1
    - Two-Point Advance per Furrow

Parameter	Point 1	Point 2
Distance (X)	200 m	400 m
Time (T)	2 hr	5 hr
Flow Rate (Qavg)	1 l/s	1 l/s
Upstream Depth (Y0)	36 mm	37 mm
Average Depth (Yavg)	31 mm	31 mm
Upstream Wetted Perimeter (WP0)	363 mm	363 mm
Average Wetted Perimeter (WPavg)	337 mm	339 mm

Parameter	Point 1	Point 2
Upstream Flow Area (A0)	0,00992 m^2	0,00997 m^2
Average Flow Area (Aavg)	0,00808 m^2	0,00822 m^2
Surface Shape Factor (sy)		
User Entered	0,76	0,76
Calculated	0,815	0,825
Inflow Volume (Vin)	7,2 m^3	18 m^3
Surface Volume (Vy)	1,51 m^3	3,03 m^3
Vy/Vin (%)	20,9 %	16,8 %
Infiltrated Volume (Vz)	5,69 m^3	14,97 m^3
Power Advance Exponent	(r) = 0,75647	
Power Advance Constant	(p) = 5,34798 m/ min^r	

Estimates for Kostiakov k, a & b

k: 28,854 mm/hr^a

a: 0,29884

b: 0 mm/hr

Note: make the following modifications, but don't run the program for problems 5–7 (it won't work)

20. Modify the furrow side slope to 1 and do a screen capture of the System geometry page, showing the modified furrow shape.
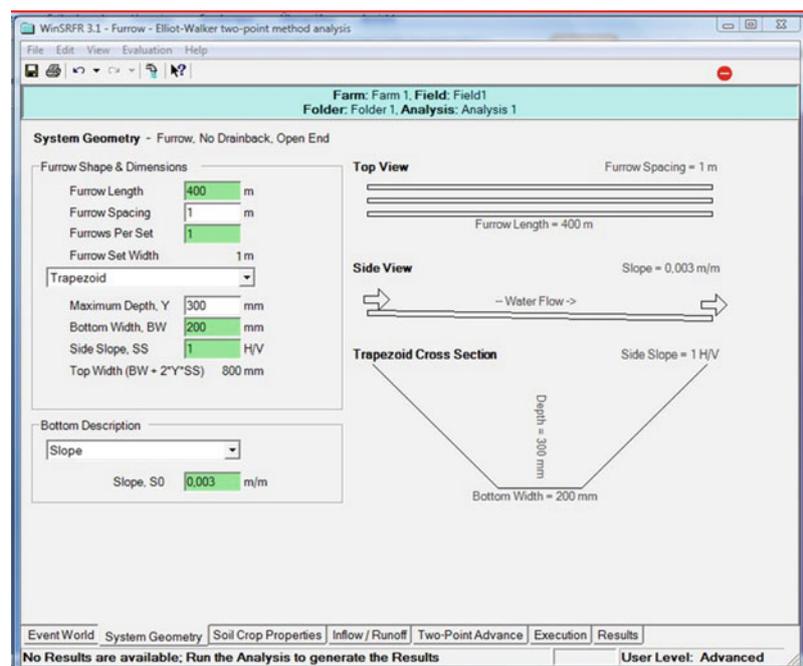
21. Change the furrow shape to the Power Law shape and use exponent M = 0.4. Do a screen capture of the System Geometry page, showing the modified furrow shape.
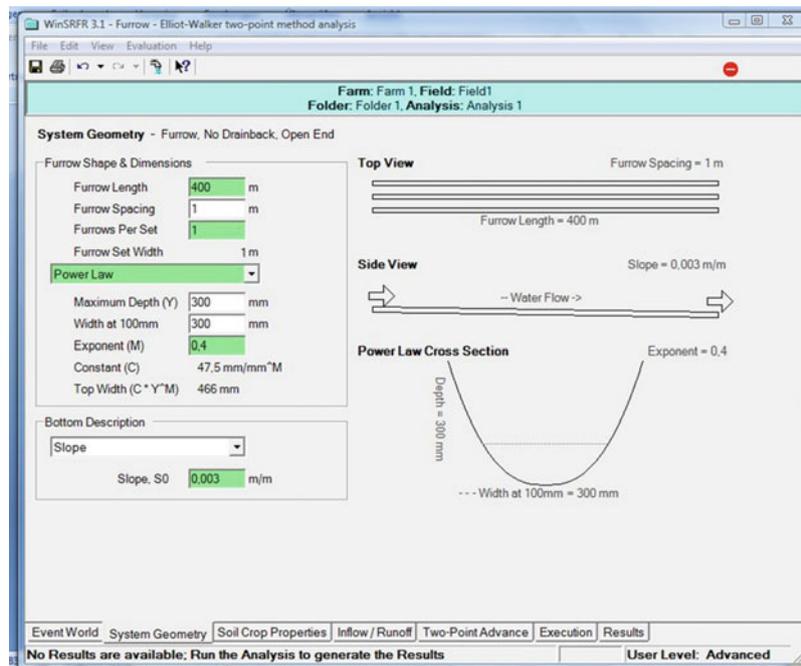
22. Change the Manning n on the Soil/Crop Properties page to that for alfalfa, mint, or broadcast small grain. Write down this value as the answer.
    – n = 0.15

Chapter 21: Solutions

1. Turbulent flow emitters are cheaper than pressure compensating emitters. The emitter flow rate flow rate is 2 L/hr, and emitter spacing is 0.17 m. The emitter k is 0.2 and × is 0.5. Tubing diameter is 12 mm. Manufacturer's CV is 3 %. Barbed fittings reduce the cross-sectional area of the tube to 95 mm^2. There is no slope. Include minor losses due to emitter barbs. Inlet pressure to the lateral is 120 kPa. Calculate whether the emission uniformity exceeds a 95 % threshold for hydroponic drip irrigation. Should the grower switch to pressure compensating emitters? Use the Drip lateral worksheet to make the calculation.

The emission uniformity is 93 %. Thus, the grower should switch to pressure compensating emitters.

2. For the parameters in problem 1, switch to pressure compensating emitters with 2 LPH flow rate. In order to do this, change the values in cells E10:E11. Calculate the emission uniformity. Make a screen copy of the worksheet.

The emission uniformity is 97.3 %, which is acceptable.
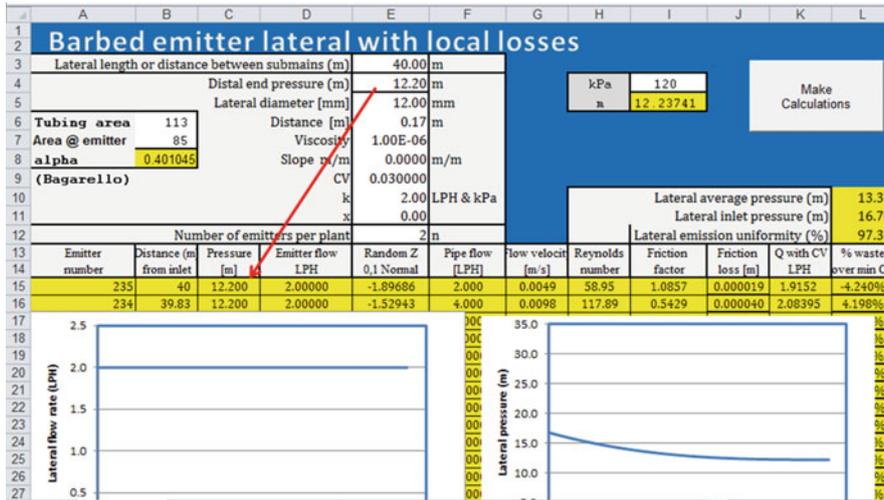
3. A 12 mm diameter irrigation lateral has pressure compensating inline emitters that reduce the internal diameter of the pipe to 10 mm. Flow velocity is 1.2 m/sec. Calculate the friction loss due to 1 emitter by hand. Use the *Inline emitter local losses* worksheet to calculate the friction loss due to 100 emitters, where flow is reduced proportionally vs. distance along the lateral. Compare to the loss calculated in Example 21.2. Make a screen copy of the worksheet.

$$\alpha = 0.116\left[\left(\frac{D}{d}\right)^{13.87} - 1\right] = 0.116\left[\left(\frac{12}{10}\right)^{13.87} - 1\right] = 1.33$$

$$\Delta H_s = \alpha\frac{V^2}{2g}$$

$$= 1.33\frac{1.5^2}{2g} = 0.15 \; m$$

Friction loss due to 1 emitter at 1 m/sec flow rate is 0.15 m, which is 10 times greater than the head loss in Example 21.1.

The total head loss due to minor losses is 5.2 m, which is more than 10 times the loss calculated in Example 21.1.

The calculation for 100 emitters is made in the *Inline emitter local losses* worksheet.
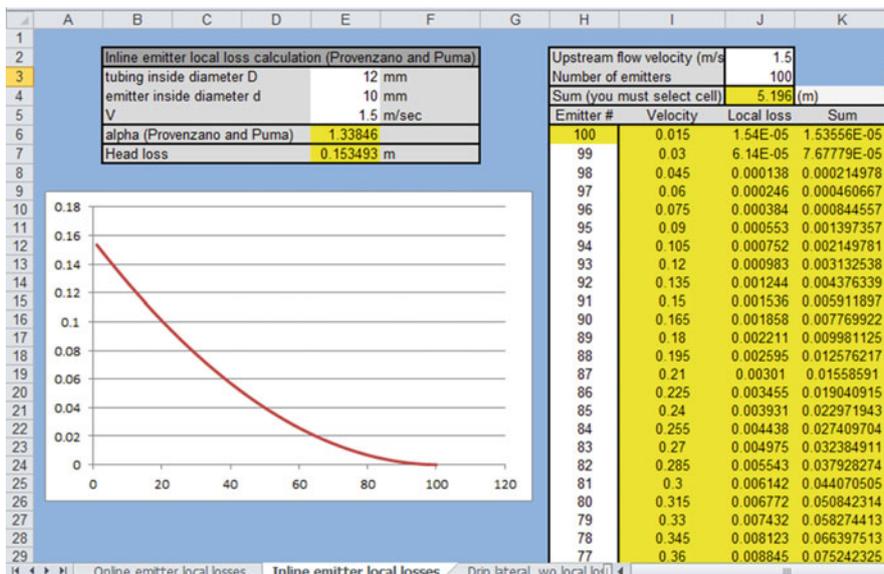
4. A 12 mm diameter irrigation lateral has pressure compensating online emitters that reduce the internal diameter of the pipe to 90 mm². Flow velocity is 0.5 m/sec. Calculate the friction loss due to 1 emitter by hand. Use the *Online emitter local losses* worksheet to calculate the friction loss due to 100 emitters, where flow is reduced proportionally vs. distance along the lateral. Compare to the loss calculated in Example 21.2. Make a screen copy of the worksheet.

$$\alpha = 1.68\left[\left(\frac{A_p}{A_g}\right) - 1\right]^{1.29} = 1.68\left[\left(\frac{113}{90}\right) - 1\right]^{1.29} = 0.29$$

$$\Delta H_s = \alpha \frac{V^2}{2g}$$

$$= 0.29\frac{0.5^2}{2g} = 0.0037 \ m$$

Friction loss due to 1 emitter at 1 m/sec flow rate is 0.0037, which is 37 % of the value in Example 21.2: 0.010 m.

The calculation for 100 emitters is made in the *Online emitter local losses* worksheet. Total loss due to local losses is 0.125 m, which is approximately 37 % of the losses in the example. Thus, the total loss for the entire lateral and the loss for one emitter are both 37 % less than for Example 21.2. This shows that the percent difference for a single emitter is approximately the same as the percent difference for the lateral.
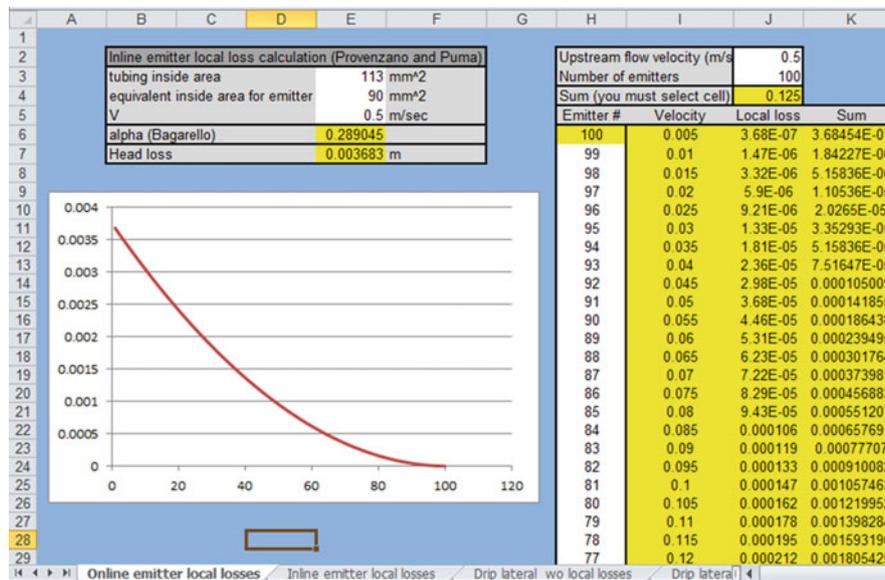
5. Emitters (4 LPH) are spaced 0.34 m in a 12 mm pipe that is 50 m long. Emitters are turbulent with k = 0.4 and x = 0.5. Slope is zero. Coefficient of variation is 5 %. Full tubing area without emitters is 113 mm² and tubing area at the emitters is 85 mm². Calculate emission uniformity and head loss. Include one calculation with local losses and one calculation without local losses. Compare to the friction loss due to local losses in Example 21.3. Make sure to press the *Make calculations* button. Make a screen copy of the worksheet with local losses.

The pressure loss in the pipe without considering local losses is 14.84 m and with local losses is 17.15 m. Thus, the head loss increases from 4.6 to 7 m with local losses. The head loss due to local losses is 2.4 m, which is half of that calculated in Example 21.3.

The emission uniformity drops from 90.4 % to 88.4 % with local losses.
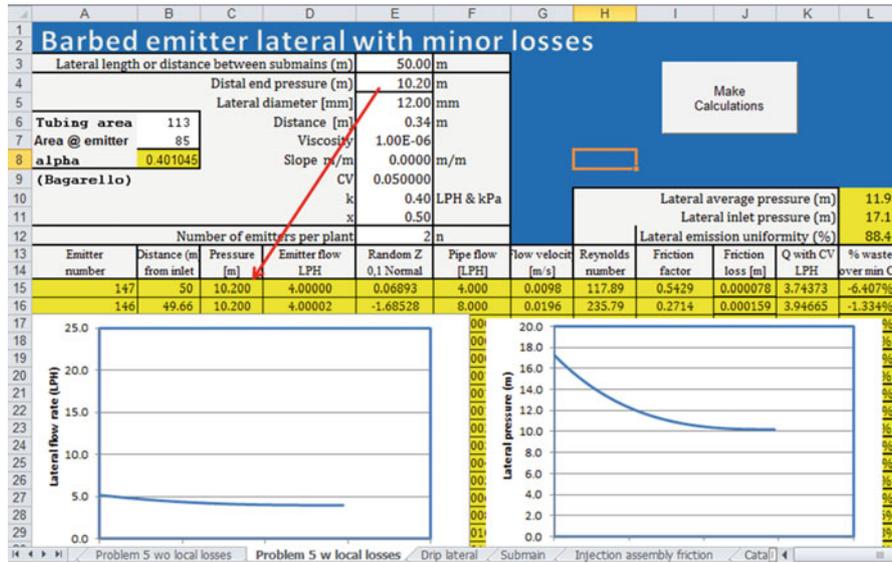
6. A submain supplies the lateral described in problem 5. The submain is 100 m long and laterals are spaced every 1.5 m. The inside diameter of the submain is 100 mm. Using the *Submain* worksheet, find the pressure loss in the submain and make a screen copy of the worksheet. Make sure to press the *Make calcs* button.

The required inlet pressure to the submain is 17.7 m. The pressure loss is 17.7 m − 17.2 m = 0.5 m.
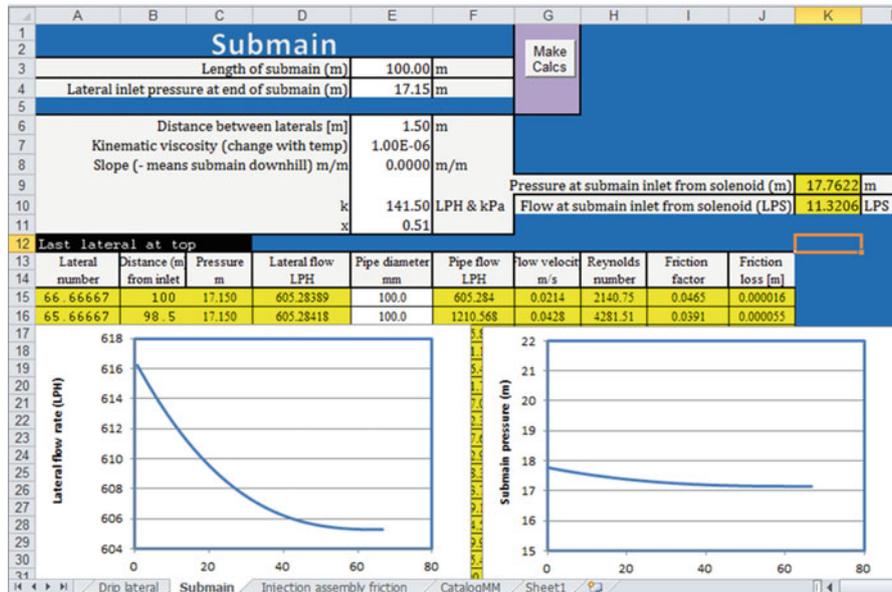
7. For the parameters in problem 6, calculate the required pump pressure and flow rate. Chemical injection is from diaphragm pumps, which cause no pressure loss in the irrigation pipeline. Ring filters are used to filter the water, which have 4 m maximum pressure drop. A large pressure regulator controls pressure to the system and has 4 m pressure drop across the regulator. Total fittings losses at the pump station are 5 m. Solenoid valves to each submain have a 3 m pressure drop.

Valve and injection assembly

Submain pressure loss	0.0		Solenoid valve losses (m)	3.0			GPM	12
Number of fittings or pipes	1		Large filter losses (m)	4			LPM	45.4
Inlet elevation (m)	100		Pump station losses (m)	5			m	3.58
			Head at board inlet	21.8	Req. end pres. (m) 17.8		PSI	5.1
			Required pump pressure (m)	33.8	Act. end pres. (m) 17.8			

	Select pipe D. or fitting	Pipe ID (mm) or valve L/D	Valve/fitting select dimension	Fitting ID (mm)	HW C	Flow (LPM)	Length (m)	Friction loss (m)	Discharge elevation (m)	Head after fitting (m)
1	Ball valve open	13	3/4" (20)	20.96	140	0.00		4.000	100.0	17.8
2	Swing check valves, fully open		3/4" (20)	20.96	140	0.00			100.0	

8. Determine whether the lateral shown in Fig. 21.15 will flush with the required 0.5 m/sec flow velocity at the end of the lateral.

The required inlet pressure is 5.51 so the lateral will flush. Emitters should be checked to make sure that the flushing mode at low pressure will not disrupt the process.
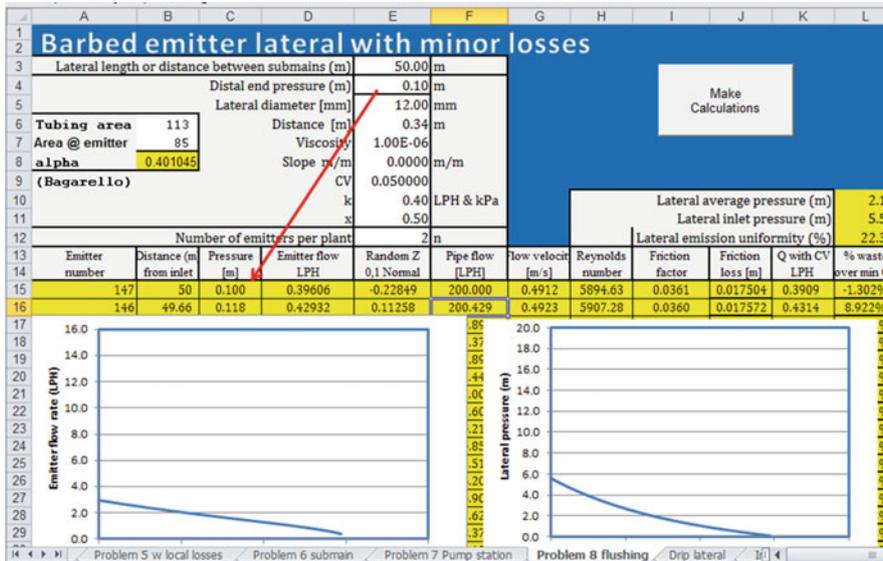
9. List the maintenance procedures for hydroponic drip irrigation.
   1. Injection of biocides
   2. Injection of acids to prevent precipitation of salts
   3. Flush drip laterals regularly
   4. Filtration
   5. Daily check of pump station pressure and operation
   6. Weekly or monthly check of uniformity and flow rates of drip emitters

10. Why is it desirable to have water from a deep well for irrigation of greenhouse crops?

Water from wells that are deeper than 60 m (200 ft) will probably not have appreciable amounts of bacteria or organic carbon, and disinfection is probably not necessary

11. Describe typical irrigation practices at dawn and dusk in a tomato greenhouse.

For tomatoes, there is normally no irrigation for the first 1½ to 2 hours after sunrise and the last 1½ to 2 hours before sunset in order to prevent fruit cracking.

12. Develop an irrigation schedule for the following solar radiation intensity. The units for energy are those given by the Arizona agricultural weather network. You will need to convert to J/cm^2.

Time (hours)	Solar radiation (MJ/m^2)
7	0.15
8	0.41
9	0.94
10	1.61
11	2.99
12	3.33
13	3.4
14	3.3
15	2.7
16	2.44
17	0.65
18	0.5
19	0.06

Hour	MJ/m^2	J/cm^2	Number of irrigations
7	0.15	15	
8	0.41	41	
9	0.94	94	1
10	1.61	161	2
11	2.99	299	4
12	3.33	333	4
13	3.4	340	4
14	3.3	330	4
15	2.7	270	4
16	2.44	244	4
17	0.65	65	1
18	0.5	50	
19	0.06	6	

13. Calculate daily depth applied for the irrigation schedule in question 8. Each water application volume is 100 ml. The area represented by each plant/emitter is 0.27 m^2.

Each irrigation supplies 100 ml to the plant. There are 27 irrigations. Thus, 2,700 ml is supplied to the plant.

$$Depth = volume/area = 0.0027/0.25 = 0.01 \text{ m/day}$$
$$= 10 \text{ mm/day}$$

14. List the macronutrients and micronutrients

- Macronutrients: N, P, K, Ca, Mg, S
- Micronutrients: Fe, Mn, B, Zn, Cu, Mo, Cl.

15. Why were the Sachs and Knopf nutrient experiments unsuccessful? Why or why not?

They were not successful because they did not supply oxygen to the roots.

16. Who was the first plant nutritionist in the United States, and where did he work?

Dennis Hoagland from UC Berkeley.

17. Based on molarity, which three nutrients in the Hoagland solution (Table 21.2) are required in the greatest amount? Does this agree with Table 21.3? Does this agree with Table 21.4?

Nitrogen is included in the first three fertilizers so it is required in the greatest amount. Based on Table 21.3, nitrogen, potassium, and calcium have approximately the same concentration; however, nitrogen has a lighter molecular weight so a greater number of moles of nitrogen are required in comparison to potassium and calcium. In Table 21.4, potassium and calcium are required in much higher concentration than nitrogen during the early part of the season; however, the greater molecular weights indicate that the molar amounts are approximately the same.

18. T/F. Testing water for nutrients prior to determining a fertigation regime in the greenhouse is not necessary because greenhouse plants require so much fertilizer anyway?

False, you need to subtract the nutrients in the source water from the fertigation requirement.

19. Calculate the amount of manganese chelate in the B tank (Table 21.3) if the injection rate is 1/50th of the greenhouse irrigation flow rate.

$$5.8 * 50 = 290 \text{ mg/L}$$

20. T/F. Adding too much of one cation can decrease the uptake of other cations.

True

21. Calculate the concentrations of the fertilizers required to formulate the nutrient mix shown in the "Week 6–12" column in Table 21.4. Mix enough fertilizer to dissolve in a 500 L tank when the water flow rate is 200 X greater than the fertilizer injection rate. The source water contains 20 mg/L Ca. Perform calculations by hand and check answer with fertigation calculator.

Chapter 21 Fertigation calculator

	Fertilizer	Grams	Kilograms	Pounds
1	Fertilizer	Grams	Kilograms	Pounds
2	KH2PO4	20632.13	20.63	45.49
3	K2SO4	61076.12	61.08	134.65
4	MgSO4-7H2O	61224.49	61.22	134.98
5	Ca(NO3)2	89473.68	89.47	197.26
6	KNO3	4560.14	4.56	10.05

	Macro Nutrients Required	PPM
16	Macro Nutrients Required	PPM
17	Nitrogen	145
18	Phosphorous	47
19	Potassium	351
20	Calcium	170.0
21	Magnesium	60
22	Sulfur	121.4

Standard Recipe

Personal Recipe

90

24	Calcium in water source (mg/L)	20.0

Developed by former U of A student Sarah Cook

Chapter 22: Solutions

1. What are the advantages and disadvantages of low-head gravity bubbler system?

Answer:
Advantage:

Works with minimum head as low as one meter
Low energy requirement i.e., no pumping required
Surface systems can easily be converted
No filtration required as the delivery tubes are larger in diameter to let small particles pass through them.

Disadvantages:

Initial cost is somewhat high mainly due to the pipe distribution system.
Airlock in the system can affect the efficiency
Limited to orchard crops, vines and tree crops
Requires basins around the trees in heavy soils
Rodents sometimes eat the delivery tube

2. What is the cause of airlocks in low-head gravity bubbler systems

Answer:
Airlocks are caused by air accumulation at the crest of undulating pipes.

3. What are the effects of airlocks?

Answer:
Airlocks absorb the flow energy and may partially or entirely block the flow of water

4. How do you avoid airlocks?

Answer:
By minimizing undulation of the flexible pipe components of the system such as the delivery hoses.
Keep the hydraulic gradient above the pipeline
Installation of air relief valves downstream of the crest (not applicable for bubbler systems)
Putting pipe stands at the crest
Proper installation of the system

5. What is the main cause of non-uniformity of flow along the lateral in bubbler systems?

Answer:
The delivery hose elevation not following the hydraulic gradient line. This happens mainly during installation and as time goes by the delivery hoses move.

6. The Hazen-Williams empirical equation for flow in pipes is given by

$$Q = 0.849 CAR^{0.63}\left(\frac{h_f}{L}\right)^{0.54}$$ metric system

Where Q is flow rate, A is cross-sectional area, R is hydraulic radius, L is length of pipe, and h_f is the friction head loss. The friction head loss h_f can be written from the above relationship as $h_f = K \left[\frac{Q}{C}\right]^{1.852} D^{-4.87} L$

For h_f in meter, D in meter, L in meter, and Q in cubic meters per second determine the value of K.

Solution:

$$Q = 0.84 C A R^{0.63} \left[\frac{h}{L}\right]^{0.54}$$

$$A = \pi \frac{D^2}{4}$$

$$R = \frac{D}{4}$$

Then

$$Q = 0.849 C \pi \frac{D^2}{4} \left[\frac{D}{4}\right]^{0.63} \left[\frac{h_f}{L}\right]^{0.54}$$

$$Q = 0.849 \frac{\pi}{4} \left[\frac{1}{4}\right]^{0.63} C D^{2.63} \left[\frac{h_f}{L}\right]^{0.54}$$

$$Q = 0.2784 C D^{2.63} \left[\frac{h_f}{L}\right]^{0.54}$$

$$\frac{h_f^{0.54}}{L^{0.54}} = \frac{Q}{0.2784 C D^{2.63}}$$

Or

$$h_f = \frac{Q^{1/0.54} L}{(0.2784)^{1/0.54} C^{1/0.54} \left(D^{2.63}\right)^{1/0.54}}$$

$$h_f = \frac{Q^{1.852} L}{(0.2784)^{1.852} C^{1.852} D^{4.87}}$$

$$h_f = \frac{Q^{1.852} L}{0.9365 C^{1.852} D^{4.87}}$$

$$h_f = 10.7 \left[\frac{Q}{C}\right]^{1.852} L D^{-4.87}$$

Thus K = 10.7
Rearranging and solving for h_f

7. For microirrigation design we use the Hazen-Williams equation more commonly than the Darcy-Wiesbach equation even though the later is more accurate for different fluid and flow conditions and the Hazen-Wiliams equation is easier to use for water. (a) Develop a relationship between Darcy-Wiesbach resistance coefficient (f) in Equation – and the Hazen-Williams (C) in Equation – and (b) develop a relationship between C and Reynolds number. Assume water at 20 °C.

Solution

Part (a)

The Hazen-Williams and Darcy-Wiesbach equations can be written, respectively as:

$$h_f = k_1 L \frac{\left(\frac{Q}{C}\right)^{1.852}}{D^{4.87}} \tag{1}$$

$$h_f = k_2 f L \frac{Q^2}{D^5} \tag{2}$$

To develop the relationship between f and C equate Eq. 1 to Eq. 2 and solve for f or C

Then

$$k_1 L \frac{\left(\frac{Q}{C}\right)^{1.852}}{D^{4.87}} = k_2 f L \frac{Q^2}{D^5} \tag{3}$$

Or

$$k_1 \frac{\left(\frac{Q}{C}\right)^{1.852}}{D^{4.87}} = k_2 f \frac{Q^2}{D^5} \tag{4}$$

Then

$$\frac{k_1}{k_2 C^{1.852}} \frac{1}{} = f \frac{Q^{(2-1.852)}}{D^{(5-4.87)}} = f \frac{Q^{0.148}}{D^{0.13}} \tag{5}$$

Or

$$f = \frac{k_1}{k_2} \frac{D^{0.13}}{Q^{0.148} C^{1.852}} \tag{6}$$

In equations 1 and 2 k_1 and k_2 for water at 20 °C, Q in Liters/second (L/s), D in millimeters (mm) and L in meters (m) are

$$k_1 = 1.22 \times 10^{10}$$

And

$$K_2 = 8.27 \times 10^7$$

Thus substituting these values Eq. 6 gives

$$f = 147.65 \frac{D^{0.13}}{Q^{0.148} C^{1.852}} \tag{7}$$

Or
Solving for C

$$C = \frac{D^{0.072}}{f^{0.54} Q^{0.08}} \tag{8}$$

Part (b)

Using Eq. 8 and rearranging it

$$C = \frac{14.84}{f^{0.54}} \left(\frac{D}{Q}\right)^{0.08} D^{-0.008} \quad (9)$$

For water at 20 °C the Reynolds number can be computed as

$$R_n = 1.26 \times 10^6 \frac{Q}{D} \quad (10)$$

Or

$$\frac{D}{Q} = \frac{1.26 \times 10^6}{R_n} \quad (11)$$

Substituting Eq. 11 into Eq. 9 for D/Q and solving for C we have

$$C = \frac{14.84}{f^{0.54}} \left(\frac{1.26 \times 10^6}{R_n}\right) D^{-0.008} \quad (12)$$

Or

$$C = 45.64 \frac{D^{-0.008}}{f^{0.54} R_n^{0.08}} \quad (13)$$

The term $D^{-0.008}$ varies from 0.982 to 0.962 for D ranging from 10 to 125 mm. If we are to be conservative and take 0.962 for the term and use it in Equation 13 we will have a simple relationship between C and Reynolds number, R_n, as

$$C = 43.9 f^{-0.54} R_n^{-0.08} \quad (14)$$

8. The friction drop ratio a for a microirrigation lateral can be given by

$$R_x = \frac{h_{fx}}{h_{fL}}$$

where h_{fx} is the head loss due to friction from the head end to any point x along the lateral and h_{fL} is the head loss for the entire length of the lateral. It can also be shown that R_x can be calculated by

$R_x = 1 - \left(1 - \frac{x}{L}\right)^{m+1}$ where x is the distance from the head end to any point along the lateral, L is the length of the lateral, and m is the exponent for the velocity or flow varying in the friction loss equation Ex. m = 2 for Darcy-Wiesbach equation and 1.852 for Hazen-Williams equation. The pressure head, H_x at any given point x on the lateral neglecting the velocity head term can be computed as

$$H_x = H_o - h_{fx} - h_{Zx}$$

where H_x is the pressure head at a point located at a distance x from the pipeline inlet

H_0 is pressure head at the pipeline inlet and

H_{Zx} is difference in elevation between point x, and pipeline inlet

Using these relationships show that the average pressure head, H_a, can be calculated using $H_{av} = H_0 - \frac{m+1}{m+2} h_{fL} - \frac{H_{ZL}}{2}$ and

Solution:

The average pressure head in a lateral can be obtained by integrating $H_x = H_o - h_{fx} - h_{Zx}$ **and dividing by the total length L.**

then,

$$\frac{1}{L}\int_0^L H_x dx = \frac{1}{L}\left(\int_0^L H_0 dx - \int_0^L h_{fx} dx - \int_0^L H_{Zx} dx\right)$$

but h_{fx} can be substituted using the pressure drop ratio, R_x and the total head loss in the lateral h_{fL} as

$$H_{av} = H_0 - \frac{1}{L}\left\{h_{fL}\int \left[1 - \left(1 - \frac{x}{L}\right)\right]^{m+1} dx - \int S_0 x \, dx\right\}$$

$$H_{av} = H_0 - \frac{h_{fL}}{L}\left[\int_0^L dx + L\int \left(1 - \frac{x}{L}\right)^{m+1}\left(-\frac{1}{L} dx\right)\right] - \frac{S_0 L}{2}$$

$$H_{av} = H_0 - \frac{h_{fL}}{L}\left[L - \frac{L}{m+2}\left(1 - \frac{x}{L}\right)^{m+2}\right] - \frac{H_{ZL}}{2}$$

$$H_{av} = H_0 - \left[L - \frac{L}{m+2}(1)^{m+2}\right] - \frac{H_{ZL}}{2}$$

Note:

$$\left(1 - \frac{1}{m+2}\right) = \frac{m+1}{m+2}$$

Therefore the average pressure in a lateral can be expressed by

$$H_{av} = H_0 - \frac{m+1}{m+2} h_{fL} - \frac{H_{ZL}}{2}$$

9. Determine the size of a PVC manifold for low-head gravity bubbler system with each lateral to carry a flow of with 2 l/s flow to meet the crop demand and is to be laid in a field 100 m wide and 200 m long. The field is going to be used to grow orchard with tree spacing is 5 m by 5 m. The standpipe is to be at the middle of the manifold. The allowable head loss in the manifold is 0.2 meters.

Solution:

The length of the manifold is 50 m-5 m = 45 m

The Christiansen F factor for 5 outlet = 0.40

The energy gradient is $h_f/L_m = h_{fa}/FL_m = 0.2/(0.4 \times 45) = 0.011 \, m/m$

The flow in the manifold is $5 \times 2 \, L/s = 10 \, L/s$

From figure – for a head loss gradient of 0.011/m/m and a flow rate of 10 L/s the size will be 102 mm or 4 inches.

10. Design a bubbler system to irrigate a citrus orchard with tree spacing of 6 m by 6 m. The field is level and has a dimension of 120 m by 96 m. The water source is a low-head pipeline located at the edge of the field. Assume the design head at the constant head device is 1.2 m and the maximum and minimum delivery hose elevations are 1 m and 0.3 m respectively. Also assume the laterals are laid midway between two rows of trees. To prevent air locks, assume the delivery hose flow rate of 0.047 L/s.

Solution:

Refer to field layout in the figure below.

Given:

Field length, L = 120 m

Field Width, W = 96.0 m

Field Slopes, $S_L = S_W = 0$ S_W is the slope along the width of the field

The design head, H_d, is given as 1.2 m.

Tree plant and row spacing, $S_p = S_r = 6$ m

Maximum delivery hose elevation, $H_{max} = 1.0$ m

Minimum delivery hose elevation, $H_{min} = 0.3$ m

Assuming the lateral is laid mid-way between two rows of trees and that two delivery hoses are installed per row spacing

Delivery hose spacing, $S_e = S_p = 6$ m

Lateral spacing, $S_l = 2S_r = 12$ m

Depth of lateral, $d_l = 0.46$ m

Length and number of pipes

Length of mainline = not needed

Length of manifold, L_m = (Width, W/2) – S_r = (96/2)-6 = 42 m

Length of lateral, $L_l = L - (S_p/2) = 120 - (6/2) = 117 \, m$

Number of delivery hoses per lateral, $N_e = 2 \, L/S_e = 240$ m/6 m =40 delivery hoses

Total number of trees, $N_t = N_e \times N_l = 40 \times 8 = 320 \, trees$

Design flow rates

Flow per lateral, $q_l = q_{dh} \times N_e = 0.0473(40) = 1.893 \, L/s$

Flow in Manifold, $q_m = q_l \times N_l = 1.893(4) = 7.572 \, L/s$

Flow in mainline, $Q_s = q_{dh} \times N_t = 0.047(320) = 15.0 \, L/s$

Sizing Pipelines

Manifold Diameter

Total allowable head loss $h_{fa} = H_d - H_{min} = 1.2 - 0.3 \, 0.9 \, m$

Assume 50 % of the total allowable head loss is within the manifold

Then

$$h_{fam} = 0.5(h_{fta}) = 0.5(0.9m) = 0.45 \, m$$

The Christiansen reduction factor, F, is equal 0.41 for 4 outlets with the first outlet spaced one-half the spacing from the lateral inlet

The manifold head loss gradient is then

$H_f/L = h_{fam}/(FL_m) = 0.45/(0.41(42m)) = 0.026$ From Figure – with a head loss gradient of 0.026 m/m and flow of 7.6 L/s, gives a manifold diameter of 102 mm (4 inches) PVC pipe.

Size of laterals

Assuming minor losses to be zero the manifold friction losses between laterals are calculated using Equation – and are 0.047 m, 0.057 m, 0.028 m and 0.008 m respectively. The lateral inlet pressures are thus as follows

Laterals 4 and 5 (center of field) = $H_d - h_{fm}$
  = 1.20 - 0.047 - 1.15 m
Laterals 3 and 6 (next to center) = 1.15 - 0 057 = 1.10 m
Laterals 2 and 7 (next to the edges) = 1.10 - 0.028 = 1.07 m
Laterals 1 and 8 (edges of the field) = 1.07 - 0.008 = 1.06 m

The allowable head loss within the laterals and delivery hoses are calculated as the difference between the lateral inlet and the minimum delivery hose elevation, H_{min}

For lateral number 1

$$h_{fal} = h_{fal} + h_{fadh} = (H_u - H_{do}) - \Delta Z = H_u - H_{min}$$
$$= 1.06 - 0.3 \, 0.76 \, m$$

For sizing the laterals and delivery hoses use 50 % of the allowable head loss within both laterals and delivery hoses. Thus,

$$h_{fal} = h_{fadh} 0.50(0.76 \, m) = 0.38 \, m$$

The Christiansen reduction coefficient, F, for 20 multiple outlets with one-half spacing for the first outlet is 0.36

The head loss gradient for laterals and delivery hoses are then,

$h_f/L = h_{fal}/FL_l = 0.38 \, m/(0.36(117m))$
    $= 0.009 \, m/m \, laterals$
$h_f/L = h_{fadh}/L_{dh} = 0.38m/4.46m = 0.085, delivery \, hoses$

Using the design flow rates for laterals of 1.89 L/s and 0.047 L/s for delivery hoses and using the design chart (see below) we get 63 mm for the lateral and 10 mm for the delivery hose

After the lateral and the delivery hose diameters are decided, the elevation of the delivery hoses can be calculated as presented in the table below.
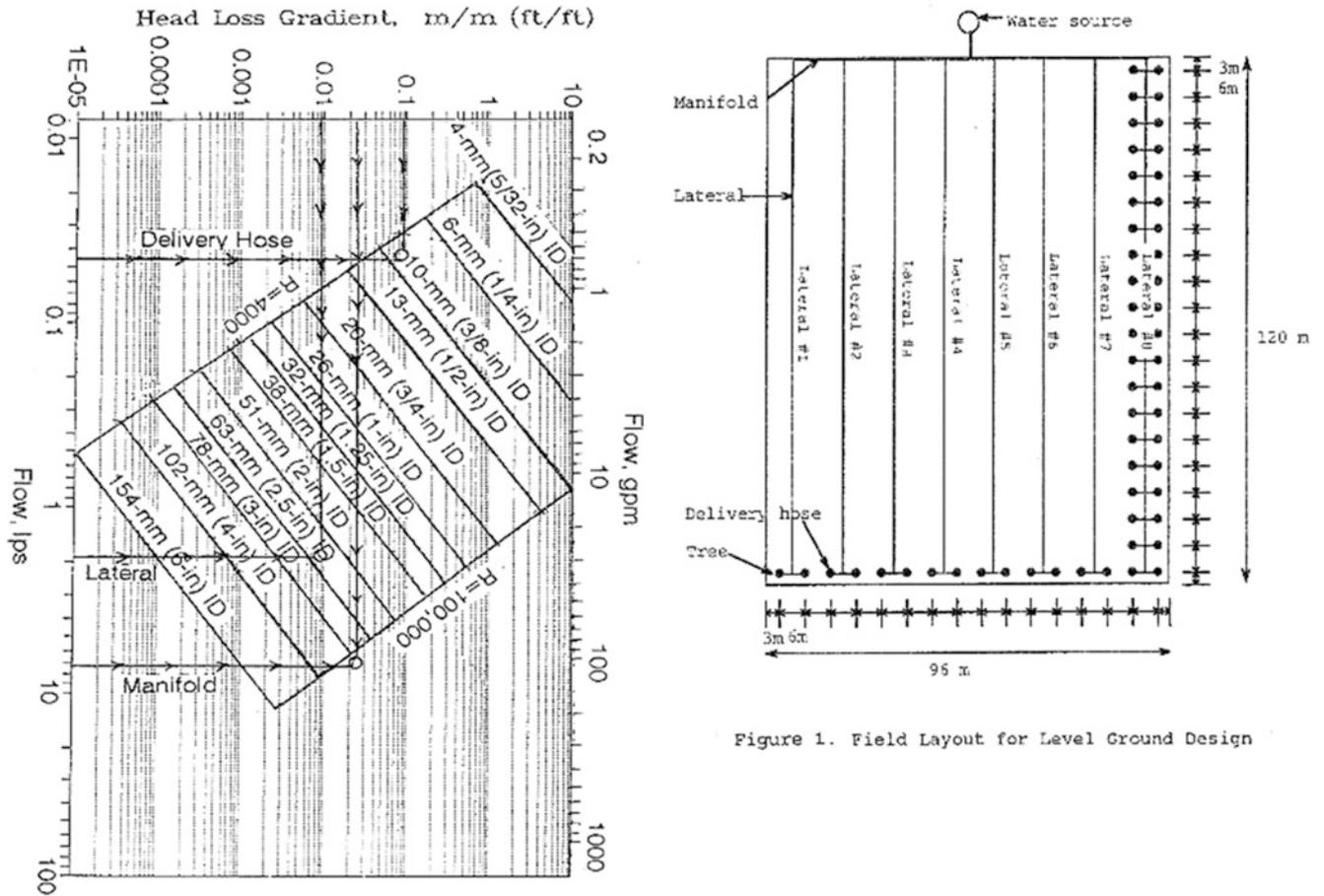
Figure 1. Field Layout for Level Ground Design

Table 2. Delivery Hose Elevation Tabulation (Level Field Design)

Lateral #1

Lateral diameter	=	63	mm
Lateral diameter length	=	117	m
Lateral pipe flow range	=	7.54-0.095	lps
Delivery hose diamater	=	10	mm
Delivery hose length	=	4.5	m

Out/ Sect.	Flow	Section Length	Total Length	Ground Elev.	Lateral Friction Losses	Lateral HGL	Hose Friction Losses	V/Head +Minor Losses	Total Losses	Hose HGL	Hose Elev.	Refer Datum
	(lps)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
0			0.0	0.00		1.040				0.72		0.00
1	1.890	3.0	3.0	0.00	0.020	1.020	0.30	0.00	0.320	0.70	0.72	-0.50
2	1.796	6.0	9.0	0.00	0.037	0.982	0.30	0.00	0.337	0.67	0.68	-0.53
3	1.701	6.0	15.0	0.00	0.034	0.948	0.30	0.00	0.334	0.63	0.65	-0.57
4	1.607	6.0	21.0	0.00	0.031	0.917	0.30	0.00	0.330	0.60	0.62	-0.60
5	1.512	6.0	27.0	0.00	0.028	0.890	0.30	0.00	0.327	0.57	0.59	-0.63
6	1.418	6.0	33.0	0.00	0.025	0.865	0.30	0.00	0.324	0.55	0.57	-0.65
7	1.323	6.0	39.0	0.00	0.022	0.843	0.30	0.00	0.322	0.53	0.54	-0.67
8	1.229	6.0	45.0	0.00	0.019	0.824	0.30	0.00	0.319	0.51	0.52	-0.69
9	1.134	6.0	51.0	0.00	0.017	0.807	0.30	0.00	0.316	0.49	0.51	-0.71
10	1.040	6.0	57.0	0.00	0.014	0.792	0.30	0.00	0.314	0.48	0.49	-0.72
11	0.945	6.0	63.0	0.00	0.012	0.780	0.30	0.00	0.312	0.46	0.48	-0.74
12	0.851	6.0	69.0	0.00	0.010	0.770	0.30	0.00	0.310	0.45	0.47	-0.75
13	0.756	6.0	75.0	0.00	0.008	0.762	0.30	0.00	0.308	0.45	0.46	-0.75
14	0.662	6.0	81.0	0.00	0.007	0.755	0.30	0.00	0.306	0.44	0.46	-0.76
15	0.567	6.0	87.0	0.00	0.005	0.750	0.30	0.00	0.305	0.43	0.45	-0.77
16	0.473	6.0	93.0	0.00	0.004	0.747	0.30	0.00	0.303	0.43	0.45	-0.77
17	0.378	6.0	99.0	0.00	0.002	0.744	0.30	0.00	0.302	0.43	0.44	-0.77
18	0.284	6.0	105.0	0.00	0.001	0.743	0.30	0.00	0.301	0.43	0.44	-0.77
19	0.189	6.0	111.0	0.00	0.001	0.742	0.30	0.00	0.300	0.43	0.44	-0.77
20	0.095	6.0	117.0	0.00	0.000	0.742	0.30	0.00	0.300	0.43	0.44	-0.77

Total lateral friction loss =   0.298 m
Est. lateral friction loss =   0.330 m

Chapter 23: Solutions

1. What is the fecal-oral pathway of disease transmission?

Pathogens are spread through wastewater by the fecal-oral route. They multiply in the intestinal systems of humans and animals, and are then excreted. When pathogens from humans and livestock enter the water system, they are transmitted through water systems to drinking water or food unless wastewater treatment blocks their transmission.

The process of disease causing organisms entering into a water supply as human waste from which they are ingested by others through drinking is called fecal-oral transmission. Wastewater and water treatment systems are designed limit the possibility of fecal-oral transmission.

2. Pathogens come from four kingdoms of life: list and describe them.
   - Monera/bacteria (Prokaryote). All pathogens labeled as bacteria are part of the monera kingdom. The monera kingdom also includes organisms that are important components of wastewater treatment. They reduce or oxidize waste, decrease biological oxygen demand, convert ammonia to nitrate and ultimately nitrogen gas, and kill harmful pathogens in wastewater.
   - Protista (Eukaryote). All of the eukaryotes that don't fit in the animal, plant, or fungi kingdoms. This kingdom includes the protozoa, some of which consume bacteria in latter phases of wastewater treatment, and others that cause many waterborne diseases.
   - Fungi (Eukaryote). Responsible for primary decomposition of organic waste. Fungi grow roots into organic matter and suck out the nutrients. Some waterborne diseases are caused by fungi.
   - Animalia (Eukaryote) – helminth worms are carried in wastewater and cause disease.

3. List viruses that cause waterborne disease.
   - Poliovirus
   - Coxsackie virus
   - Echovirus
   - Enteroviruses
   - Hepatitis A
   - Hepatitis E
   - Caliciviruses
   - Rotaviruses
   - Reoviruses

4. List bacteria that cause waterborne disease.
   - Salmonella
   - Campylobacter
   - Shigella
   - E. coli O157:H7
   - Vibrio cholera

5. Describe the story of Typhoid Mary.

The most famous case (of Typhoid infection) was Typhoid Mary in New York: Mary Mallon was a cook for rich families. One of the families, which contracted typhoid fever, hired a private investigator to determine the cause of the typhoid fever in their family. The private investigator found that 22 people contracted typhoid fever at 7 different jobs where Mary worked from 1900 to 1906. Mary refused to believe that she was the source of typhoid fever. In fact, when officials asked to take urine and stool samples, Mary attacked them with a carving knife. Eventually, public health authorities confined her to Brother Island. She was released after 2 years with the understanding that she would give up cooking. However, an outbreak of typhoid fever (25 people) occurred 5 years later at a location where a Mrs. Brown was the cook. Mrs. Brown turned out to be Mary Mallon. New York authorities then confined her to Brother Island for the last 23 years of her life.

"North Brother Island is an island in the East River situated between the Bronx and Riker's Island. Its companion, South Brother Island, is a short distance away. The island was uninhabited until 1885, when Riverside Hospital moved there from the island now known as Roosevelt Island. Riverside Hospital was founded in the 1850s as the Smallpox Hospital to treat and isolate victims of that disease; its mission eventually expanded to other quarantinable diseases. Typhoid Mary was confined to the island for over two decades until she died there in 1938. The hospital closed shortly thereafter." ~ Wikipedia

6. List protozoan parasites that cause waterborne disease.

   Protozoans fed off of the Human Gut.

   - Giardia lambia
   - Cryptosporidium
   - Cyclospora
   - Microsporidia
   - Toxoplasma gondii

7. Why are indicator organisms used and how do they distinguish between different sources of disease?

Rather than test for specific pathogens in wastewater, it is much cheaper to test for the presence of indicator organisms or surrogates that are produced in large quantities by humans or animals. It is assumed that if an indicator organism such

as fecal coliform is absent, then other pathogens are absent. The ratio of different coliforms can indicate the source of water pollution (animal or human) because the ratio of fecal coliform to fecal streptococcus varies between animals and humans

8. List the factors that determine wastewater treatment plant discharge pathogen concentration.

The concentration of pathogens in the incoming wastewater stream is one factor that determines the effluent pathogen concentration. In general, developing countries have much higher pathogen counts in raw wastewater because there is a higher incidence of disease. Other factors that influence pathogen concentrations in wastewater are socioeconomic status, per capita water use, and time of year.

9. Calculate the required contact time in order to remove 99.9 % of remaining *E-coli* at a

chlorine concentration of 3 mg/L.
Typically C T Values for E coli range between 0.001 and 0.01.

$$C\ T\ =\ 0.001$$

$$T\ =\ 0.001\ /\ 3\,mg/L\ =\ 0.00033\ minutes$$

10. What was the key factor that reduced typhoid fever in the United States.

The introduction of chlorine as a disinfectant in 1910 was the key factor that resulted in major declines in typhoid fever outbreaks.
Historically, waterborne diseases were common until the introduction of chlorine as a disinfectant for public water systems; the incidence of typhoid fever in the United States dropped from an average of 25 incidences per 100,000 people per year to approximately 400–500 cases per year (less than 0.2 incidences per 100,000 people). Thus, the per capita disease frequency dropped by 100 times due to the introduction of chlorine into public water supplies.

11. Why aren't ozone and chlorine used together?

Ozone oxidizes chlorine.

12. What environmental factors influence pathogen fate in the environment?

Environmental factors that decrease pathogen survival time are high temperature, low water content in soils, antagonistic microflora, and extreme pH (<3 or >9). Soil or organic matter that adsorbs organisms increases survival time but also decreases transport, which may decrease the hazard to the environment since organisms are not leached to transported to groundwater or surface water.

13. Give a brief summary (one paragraph) of how the body fights pathogens.

The human immune system is responsible for fighting off harmful pathogens. The key weapon for the human immune system is the ability to recognize self and non-self molecules. This allows the body to differentiate between good and bad cells (pathogens) in the body. One the bad cells are found, immune cells (primarily lymphoid and myeloid cells) create antibodies that attack the antigen (in this case considered the pathogen cells although an antigen can be bacteria, viruses or foreign cells). Once these antibodies attach to the antigen, the antigen is destroyed by the antibody complement system.

14. How do vaccines help the body fight disease?

The body builds up immunity to disease because some of the T cells and B cells used in the initial defense remain after the battle as memory cells. The next time that an individual encounters that same antigen, the immune system is primed to destroy it quickly. Long-term immunity can be stimulated not only by infection but also by vaccines made from infectious agents that have been inactivated or, more commonly, from minute portions of the microbe.

15. Why must acid be injected at the same time as chlorine during disinfection?

"Chlorine exists in two forms within water, hypochlorous acid (HOCl) and hypochlorite (OCl-)."
The hypochlorous acid and hypochlorite, OCl-, equilibrium in water is HOCl ⇔H+ + OCl-.
Hypochlorous acid (free chlorine) is 80 times more effective at killing bacteria than hypochlorite because the hypochlorite has a charge and is repelled from the cell. Hypochlorous acid is the primary form of chlorine in acidic waters, pH <6.5. Thus, if the initial pH is high, acid must often be added in concert with chlorine in order to drop the pH to 6.5.

16. Redo the risk assessment problem. The expected number of salmonella bacteria in wastewater is 10^5 MPN/100 ml, and 200 children are expected to play for 16 hours in the landscaped area.
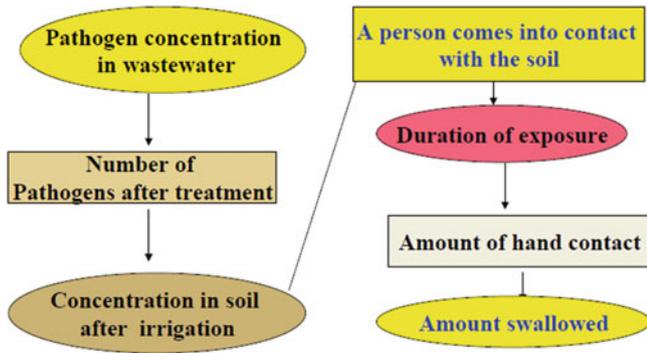
100,000 MPN/100 ml water * 15 ml water/100 ml soil = 15,000 MPN/100 ml of soil.

If children ingest 500 mg of soil every 8 hours, then they will ingest 1000 mg of soil in 16 hours.

Assume that the soil bulk density is 1.15 mg/ml.

1,000 mg soil ingested/1.15 mg/ml soil = 870 ml soil

870 ml soil * 15,000 MPN/100 ml soil = $1.31 \times 10^5 \approx$ 1,300,000 Salmonella bacteria

This number is in the range of 70–80 % infection. Thus, approximately 150 children will become sick.
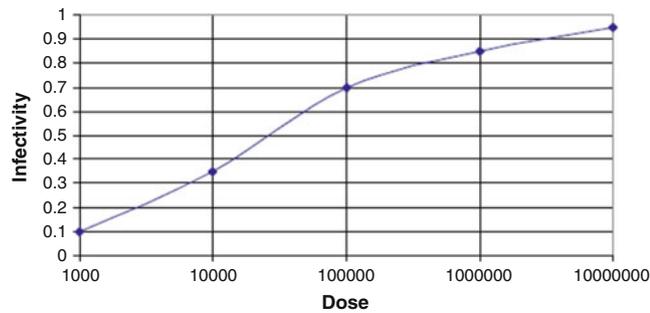
17. What are the 3 steps of Risk Analysis?

The process of Risk analysis involves three steps: Risk Assessment – determining the probability that an adverse event will occur and its magnitude, Risk Management – considers various regulatory options to minimize the risk, and Risk Communication – transfer of risk information to experts and non-experts.

18. What are the 4 steps of Risk Assessment?

Risk Assessment has four basic steps:

1. Hazard Identification – identifying the contaminant (i.e. Salmonella)
2. Dose–response Assessment – relationship between the number of organisms ingested and the probability of becoming infected (i.e. how many does it take to make you sick)

3. Exposure Assessment – Determining the concentration of a pathogen in the water and estimating amount of contact and possibly ingestion.
4. Risk Characterization – Estimating the potential impact (infection, disease) of a pathogen based on the severity of its effects.

19. What is BOD and why is high BOD detrimental when wastewater is discharged to streams?

Biochemical Oxygen Demand (BOD) is defined as the amount of oxygen required for the bacterial decomposition (oxidation) of organic matter under aerobic conditions at a standard temperature and incubation time.

If wastewater with a heavy organic load is added to surface waters, the dissolved oxygen concentration can decrease from the normal 5 to 7 mg/L to 2 mg/L or less, a point at which fish die.

20. Describe the difference between oxidation and synthesis and endogenous respiration.

Oxidation Synthesis

$$COHNS + O_2 + Nutrients \rightarrow CO_2 + NH_3 + C_5H_7NO_2 + Other\ End\ Products \qquad (2--1)$$

Endogenous Respiration

$$C_5H_7NO_2 + 5O_2 \rightarrow 5CO_2 + 2H_2O + NH_3 + Energy \qquad (2--2)$$
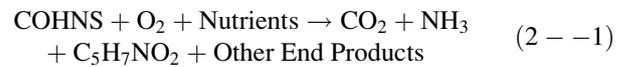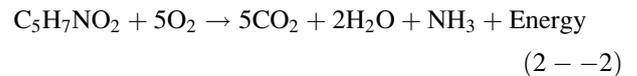
Organic matter (CHONS) is oxidized and the resulting bacterial cells have the formula: C5H7NO2. Dead bacterial cells are then consumed by protozoa in a process called endogenous respiration. The result of endogenous respiration is stable, nontoxic, byproducts.

21. Calculate the BOD5 if the dilution factor is 20–1, the initial dissolved oxygen concentration is 6 mg/L, and the final dissolved oxygen concentration is 2 mg/L.

$$BOD = (DO_i - DO_f)\frac{V_b}{V_s} = \Delta DO(DF) \qquad (2--3)$$

where

DO_i = initial dissolved oxygen concentration, mg/L,
DO_f = final dissolved oxygen concentration, mg/L,
DF = dilution factor : volume of the bottle divided by volume of the sample,
V_b = volume of the bottle, ml,
V_s = volume of sample added to the bottle, ml,

(Pg. 21)

$$BOD_5 = (DO_i - DO_f)(DF)$$
$$= (6 - 2)(20/1)$$
$$= \mathbf{80mg/L}$$

22. List the steps in the nitrogen cycle in soils.

Bacteria sequentially transform nitrogen from one form to another in soils and wetlands. The nitrogen cycle includes anaerobic (no oxygen) bacteria, aerobic (oxygen) bacteria and facultative (anaerobic or aerobic) bacteria: ammonification, followed by nitrification, and denitrification. The steps from conversion of organic N to NO3 – are called mineralization.

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organic matter → amines	→	ammonium → nitrate	→	nitrate	→	nitrous oxide or nitrogen gas
	anaerobic		aerobic	anaerobic or aerobic		
	ammonification		nitrification	denitrification		

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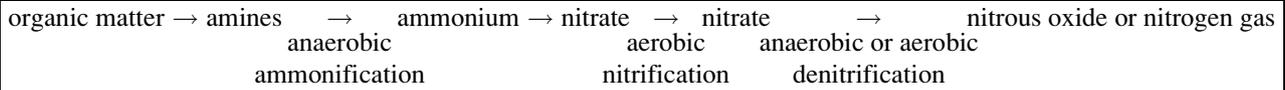
23. How is the nitrogen cycle carried to completion in wetlands with herbaceous aquatic plants?

Herbaceous aquatic plants that pump oxygen into the water facilitate nitrification and denitrification. Aerobic nitrification takes place near cattail and bulrush roots that add oxygen to the water and provide an aerobic zone for aerobic bacteria. Anaerobic denitrification takes place in water that is not close to plant roots and in the deep zones of wetlands that do not include plant material.

Chapter 24: Solutions

1. Explain the meaning of Eq. 24.1 in a sentence.

The rate of change of concentration is directly proportional to the concentration.

2. Integrate Eq. 4.1 and derive Eq. 4.2.

$$\frac{dC}{dt} = -kC$$
$$\frac{dC}{C} = -kdt$$
$$\int_{C_1}^{C_2} \frac{dC}{dt} = \int_0^t -kC$$
$$\ln(C_2) - \ln(C_1) = -kt \quad \ln\left(\frac{C_2}{C_1}\right) = -kt$$
$$\frac{C_2}{C_1} = e^{-kt} \quad C_2 = C_1 e^{-kt}$$

3. Explain the similarity between Eqs. 24.2 and 24.3, and explain the justification for using Eq. 24.2 for calculating effluent concentration from a wetland (Eq. 24.3).

Free water surface and subsurface flow wetlands can be modeled as plug flow systems. Thus, the outlet concentration can be modeled with the same equation as is used for a batch reactor with time equal to the length of time that water remains in the wetlands. It is like a batch reactor is moving through the wetlands.

4. Show how Eq. 24.5 is derived from Eq. 24.4.

$$T = V/Q$$

$$V = A*d$$

$$T = A*d/Q$$

5. Explain the meaning of Eq. 24.6.

The equation calculates the microbial activity with a baseline of 20 °C and microbial activity varies exponentially with temperature from the baseline.

6. Repeat the area based calculations of Example 24.1 but use 25 °C and 10 °C instead of 20 °C and 4 °C

Effluent is discharged from septic tanks into a subsurface flow system wetland. Assume that total nitrogen in septic tank effluent is 36 mg/L and that water temperature in a subsurface flow system wetland is 25 °C; calculate the total nitrogen, TN, in wetlands effluent if the wetlands hydraulic loading rate is 25,000 m³/yr and the wetlands surface area is 1,071 m². Recalculate for 4 °C. Assume that the void fraction in the gravel is 0.33 and the depth of flow is 0.4 m. The maximum acceptable total nitrogen discharge concentration is 10 mg/L. Calculate a time-based coefficient based on the wetland volume and the area-based rate coefficient. Then, determine whether the wetland has an adequate size with a 5 day detention time at 10 °C.

Calculation of effluent concentration at 25 °C

The irreducible background concentration for total nitrogen is not temperature dependant and is a constant, 1.5 mg/L. The area-based rate constant, k_{20}, is 27 m/yr (Table 4.1).

$$k = k_{20}\, \theta_k^{(T-20)} = 27*1.05^{(25-20)} = 34 \ \ m/yr$$

$$C_{out} = C^* + e^{\left(\frac{-kA}{Q}\right)}\left(C_{in} - C^*\right) = 1.5 + e^{\left(\frac{-34*1,070}{25,000}\right)}(36 - 1.5)$$
$$= 9.5 \ \ mg/L \ \ TN$$

The wetland is adequate at this because the treatment goal of 10 mg/L of total nitrogen is met.

Calculation of effluent concentration at 10 °C

$$k = k_{20}\theta_k^{(T-20)} = 27*1.05^{(10-20)} = 16.6 \ \ m/yr$$

$$C_{out} = C^* + e^{\left(\frac{-kA}{Q}\right)}\left(C_{in} - C^*\right) = 1.5 + e^{\left(\frac{-16.6*1,070}{25,000}\right)}(36 - 1.5)$$
$$= 18.4 \ \ mg/L \ \ TN$$

The wetland is even more inadequate at 10 °C.

Calculate an equivalent time-based rate constant (e^{-kT}). Volume of water in wetland

$$V_{cv} = d*A*q = 0.4 \ \ m*1,071 \ \ m^2*0.33 = 141 \ \ m^3$$

Hydraulic detention time

$$T = V/Q = 141 \ \ m^3/25,011 \ \ m^3/yr(365 \ \ day/yr) = 2 \ \ days$$

Calculate time based k based on hydraulic detention time

$$\frac{-k_{area}A}{Q} = -k_{time}T = \frac{-k_{time}V_{cv}}{Q}$$

$$k_{time} = \frac{k_{area}A}{V_{cv}} = \frac{k_{area}}{d\theta} = \frac{(27 \ \ m/yr)}{0.4*0.33}\left(\frac{1}{365 \ \ day/yr}\right)$$
$$= 0.56 \ \ d^{-1}$$

Calculate effluent TN with 5-day detention time and 25 °C $(A = 1,071 * 5/2 = 2,678 \ m^2)$

$$k = k_{20}\theta_k^{(T-20)} = 0.56*1.05^{(25-20)} = 0.91/day$$

$$C_{out} = C^* + e^{(-kT)}\left(C_{in} - C^*\right) = 1.5 + e^{(-5*0.91)}(36 - 1.5)$$
$$= 1.9 \ \ mg/L \ \ TN$$

Calculate effluent TN with 5-day detention time and 10 °C $(A = 2,678 \ m^2)$

$$k = k_{20}\theta_k^{(T-20)} = 0.56*1.05^{(10-20)} = 0.34/day$$

$$C_{out} = C^* + e^{(-kT)}\left(C_{in} - C^*\right) = 1.5 + e^{(-5*0.34)}(36 - 1.5)$$
$$= 8 \ \ mg/L \ \ TN$$

7. Treated wastewater has a BOD_5 of 100 mg/L, and flow rate is 200 L/min. What is the required area of a FWS wetland? Calculate based BOD load and hydraulic load. Design for an effluent BOD of 12 mg/L.

Calculation of effluent concentration at 20 °C
There is no change with temperature. k is 35 and C^* is 6. Convert flow rate to m^3/yr.

$$200 \ \ L/min = 0.001 \ \ m^3/L*60min/hr*24 \ \ hr/day*$$
$$365 \ \ days/year = 105,000 \ \ m^3/yr.$$

The irreducible background concentration for total nitrogen is not temperature dependant and is a constant, 1.5 mg/L. The area-based rate constant, k_{20}, is 27 m/yr (Table 4.1).

$$C_{out} = C^* + e^{\left(\frac{-kA}{Q}\right)}\left(C_{in} - C^*\right) = 6 + e^{\left(\frac{-36*A}{105,000}\right)}(100 - 6)$$
$$= 12 \ \ mg/L \ \ TN$$

With respect to BOD, the wetlands would be adequate with a surface area of 8,000 m^2.

The optimal hydraulic loading rate is 200 $m^3/ha/day$.
At 105,000 m^3/yr, the hydraulic loading rate is

$$105,000 \ \ m^3/yr/(0.8 \ \ ha)/365 = 360 \ \ m^3/day$$

This is within the recommended hydraulic loading rate of 150–500 m^3/day.

8. Why is there a minimum acceptable BOD_5 loading rate for wetlands?

BOD (organic matter) provides carbon for denitrification.

9. Calculate the size of a wetland required to treat an animal waste effluent stream. The desired TN concentration on the discharge side of the wetland is 30 mg/L, the waste flow rate is 50 m^3/day, and the TN concentration in the dairy waste effluent is 200 mg/L.

The daily load of nitrogen is 200 mg/L * 1000 L/m^3 * 50 m^3/day * 10^{-6} kg/mg = 10 kg/day.

The Loading Rate is calculated as follows for an effluent concentration of 30 mg/L.

$$LR(kg/ha/day) = 0.68(C_{out}) - 7.88 = (0.68)*30 - 7.88$$
$$= 12.5 \ \ kg/ha/day.$$

$$A = TN/LR = 10/12.5 = 0.8 \ \ ha.$$

10. A storage pond is expected to receive 10,000 m^3 of manure, clean water, and wastewater during a 6 month storage period (winter) (50 m^3/day * 200 days). The pond is only pumped once every 2 years and is expected to have settling of 600 m^3 of solids during the 2 year

interval. The normal depth of evaporation during the winter is 0.5 m, and the expected precipitation during the winter is 0.25 m. The depth of the 25-year 24-hour storm is 10 cm. The dimensions of the base of the pond are 20 m × 20 m. The side slope of the pond is 2.5: 1. (2.5 run × 1 rise). Calculate the depth of the pond.

$$A_{base} = \text{Area of base} = 20*20 = 400 \text{ m}^2$$
$$A_{top} = \text{Area of top} = (20 + 5*D)*(20 + 5*D)$$
$$V_{Pond} = \text{Volume pond} = (A_{base} + A_{top})/2*D$$
$$V_{Freeboard} = (A_{top} + ((20 + 5*(D - 1))*(20 + 5*(D - 1)))/2*0.3 \text{ m}$$
$$V_{PE} = \text{Volume precipitation} - \text{evaporation} = (\text{Area of top})*(0.25 - 0.5)$$
$$V_{WW} = 10,000 \text{ m}^3$$
$$V_{Solids} = 600 \text{ m}^3$$
$$V_{Storm} = 0.1 \text{ m}*A_{top}$$
$$V_{Pond} = V_{Solids} + V_{WW} + V_{PE} + V_{Freeboard} + V_{Storm}$$

A depth of 6.9 m results in the volume of the pond equal to the required volume.

Total slope	5	run over rise
D	6.9	m
Base W	20	m
Base L	20	m
Abase	400	m^2
Atop	2970.25	m^2
Vpond	11627.36	m^3
Vfreeboard	813.075	m^3
P – ET	−0.25	m
Vpe	0	m^3
Vww	10000	m^3
Vsolids	600	m^3
V required	11413.08	m^3

11. A dairy farm has 500 lactating dairy cows in Central Arizona (Maricopa County). Average mass/cow is 500 kg. Cows are kept in open lots, and 95 % of manure is dried. Five percent of manure from the milking parlor is washed into an anaerobic waste storage pond with 6 L water/day/cow. The maximum pond operating depth is 4 m. Side slopes are 2.5:1 (2 horizontal by 1 vertical). The 25 year – 24 hour storm is 7 cm. Annual precipitation is 15 cm, and mean annual evaporation is 200 cm.

Soils on the sites for waste application are well drained sandy loams and have a leaching index of 6 (6 inches (15 cm) percolates below the root zone). The organic matter content is <2 %. The soils are flood irrigated. Soil slopes are close to dead level. Crop is cotton. Required annual nitrogen addition is 150 kg/ha nitrogen (N). Assume that no extra phosphorous or potassium are required, and that there is no environmental hazard associated with overapplication of phosphorous or potassium in these soils and in this hydrologic setting with no adjacent surface water bodies. Manure is applied by truck in spring just before planting when soil is warm and dry. Assume that the storage period is 365 days in order to account for the average evaporation rate during the year. Manure has been applied for several years every spring and is incorporated into the soil by plowing within 1 day of application. Calculate application rates for truck application of dried manure and for sprinkler application of liquid manure from the waste storage pond. Assume that 150 m^3/yr remain on the bottom of the pond each year.

Partition of liquid and solid manure and N load:
Step 1. Manure load and washwater volume/day

Total manure mass/day is 80 kg/day/1,000 kg*500 cows*500 kg/cow = 20,000 kg manure/day
Total manure volume/day is 81 L/day/1,000 kg*500*500 = 20,000 L manure/day

Total volume of manure in the milking parlor is 20,000 L manure*0.05 = 1,000 L/day

Assume that 3,000 L is used to wash the milking parlor at 6 L/day/cow.

Thus, a total of 4,000 L/day (1,500 m^3/year) is washed into the waste storage pond.

An Excel spreadsheet is set up to calculate the dimensions of the pond. The required dimensions are a base width of 6 m, base length of 10 m, and depth of 3.5 m. At this depth, the evaporation volume is 700 m^3/year. Because 1,500 L is added per year in washwater, and the volume of manure is 500 m^3/year, the dilution volume is 1,500–500 = 1,000 m^3/year.

Total slope	5	run over rise
D	3.5	m
Base W	6	m
Base L	10	m
Depth ET	200	cm
Depth precipitation	15	cm
Vww	1500	m^3
Vsolids	150	m^3
Abase	60	m^2
Atop	646.25	m^2
Vfreeboard	159	m^3
Vevaporation	706	m^3
Vprecipitation	96.9375	m^3
Vpond	1235.938	m^3
V required	1200	m^3

The dilution ratio is volume of water over volume of manure (1,000/500) = 2. Thus, there is greater than 50 % dilution for nitrogen reduction calculation.

Estimate the total nitrogen (N) in the excreted manure. Phosphorous and potassium are not calculated since the application rate is only calculated based on the nitrogen content.

Nutrients per storage period = Number of animals × mass (kg) × daily nutrient production (kg/day/1,000 kg) x storage period (days).

Yearly nutrient values for as excreted dairy cow manure (use Table 2.6 for kg/d/1,000 kg)

$$N = \frac{500*500*0.45*365}{1,000} = 41,050 \ kg$$

Of this mass, 95 % is dried, 41,050–2,050 = 39,000 kg is dried, and 2,050 kg of N is added to the waste storage pond.

Step 3. Subtract nutrients lost during storage.

Dried manure retains 75 % of nitrogen. Thus, 9,750 kg remains.

Manure in a storage pond with greater than 50 % dilution retains 30 % nitrogen. Thus, 600 kg remains.

Step 4. Determine the plant available nutrients by mineralization in the soil.

The N mineralization rate after 3 years for waste stored in an open lot in a hot arid region is 53 %. Thus, 5,000 kg N is available as plant nutrients.

The N mineralization rate after 3 years for waste stored in a pond with greater than 50 % dilution is 49 %. Thus, 300 kg is available as plant nutrients

Step 5. Compute the plant nitrogen requirement.

$$N_{-plant} = 150 \ kg/ha$$

Adjust the plant N requirement based on denitrification, leaching, and volatilization.

Add denitrification losses to the plant nitrogen requirement.

From Table 24.8, a well drained soil with an organic matter content of 0 % has an annual denitrification rate of 3–9 %. Because arid soils with low organic matter have very low denitrification rate, estimate the lowpoint of this range, 3 %. The values in Table 24.8 must be doubled for manure application so estimate the denitrification rate as 6 %. The plant nitrogen requirement is 150 kg/ha so the field nitrogen required is

$$N_{-required-denitrification} = 150 \ kg/ha/0.94 = 160 \ kg/ha$$

Add leaching losses to the plant nitrogen requirement

The plant nitrogen requirement must be increased to replace anticipated leaching losses. As stated above, a leaching index of 6 (6 inches of annual percolation below the root zone), results in an annual nitrate loss of 10 percent.

$$N_{-required-denitrification \ and \ leaching} = 160 \ kg/ha/0.9$$
$$= 177 \ kg/ha$$

Add application (volatilization) losses to plant nitrogen requirement.

Dry manure will be incorporated so there is no volatilization of ammonia.

The answer to question 1 is that the required application rate is

$$N_{-plant} = 177 \ kg/ha$$

Step 6. Compute the area on which dry manure can be applied.

$$Area = (5,000 \ kg/year \ N)/(177 \ kg/ha \ N) = 28 \ ha$$

Step 6. Solution for application of storage pond water by irrigation:

For application of waste by sprinklers, the nitrogen requirement should be recalculated based on surface volatilization expected from sprinkler application (Table 24.7).

$$N_{-required-denitrification, \ leaching, \ and \ volatilization}$$
$$= 177 \ kg/ha/0.75 = 236 \ kg/ha$$

Area for full nitrogen application
$$= (300 \ kg/year \ N)/(236 \ kg/ha \ N) = 1 \ ha = 2 \ acres$$

It isn't worth setting up a sprinkler system for one ha so just dilute the manure in surface irrigation canal and apply to a large field. If the field is 10 ha, then the application rate would be 30 kg/ha. The total volume to be applied is 1,500–700 = 700 m^3.

For a 10 ha area, this would be a depth of 700/100,000 = 0.007 m = 0.7 cm depth. If the total irrigation is 4 cm depth, then approximately 0.7/4 = 17 % would come from wastewater and 83 % would come from the normal surface irrigation source.

12. Calculate the dry manure salinity application rate (kg/ha) for problem 11.

    20,000 kg manure per day
    20 tons fresh manure per day
    7,200 + 100 = 7,300 tons fresh manure per year
    95 % of manure is dried 7300 * 0.95 = 6935 tons fresh manure per year
    Applied to 28 ha
    6935/28 = 247 tons fresh manure per ha
    EC = 18.8 dS/m
    18.8(640) = 11,500 mg/L = 1.15 % salt in dried manure
    0.0155 (250) = 3.87 tons /ha = 3,870 kg/ha

13. Calculate the salinity application rate if 20 t/ha poultry manure (dry weight basis) is applied to a field.

    There is 25 % solids in chicken manure.
    23.7 ds/m(640 mg/L/ds/m) = 15168 mg/L = 1.517 % by weight salts in fresh manure
    .01517/.25 kg dry manure/ kg wet manure = 0.06067 kg salts/kg dry manure
    App rate = (20 ton manure/ha) (1000 kg/ton) (0.06067 kg salt/kg d. manure) = 1213 kg/ha
    % salts = 2(3.9 + .91 + 9.6 + .72) = 30 % salts in dry manure = .30 kg salts/kg dry manure
    .30(.25) = .075 kg salts/kg manure
    App rate = (20 ton/ha) (1000 kg/ton) (.075 kg/kg) = 1,500 kg/ha

14. Calculate the required blend of groundwater/wastewater to provide 200 kg/ha nitrogen to the field. The municipal wastewater concentration after secondary treatment is 15 mg/L N with 75 % ammonia in an arid region. The crop requires 1.2 m depth of water. Groundwater has 6 mg/L nitrate.

    Assume all ammonia in wastewater is converted to nitrate within 1 day.

$$1.2 \text{ m depth}*10,000 \text{ m}^2/\text{ha} = 12,000 \text{ m}^3/\text{ha}$$

$$200 \text{ kg/ha}/12000 \text{ m}^3/\text{ha} = 17 \text{ g/m}^3 = 17 \text{ mg/L}$$

$$C_T = C_{WW}F_{WW} + C_{GW}(1 - F_{WW})$$

$$17 = 15 \ F_{WW} + 6(1 - F_{WW})$$

$$F_{WW} = 11/9 = 1.2.$$

Actually, supplemental nitrogen from fertilizer will be needed since there is not enough nitrogen in the wastewater. This is why the fraction is greater than 1.0.

Chapter 25: Solutions

1. An application of 100 kg/ha of NO$_3$-N is incorporated to a depth of 0.15 m. The 100 refers to only the N portion of nitrate. All of the fertilizer is dissolved on the day that it is incorporated. Calculate the change in the concentration of fertilizer in the upper 0.15 m per soil volume and in soil water. Water content is 0.3 L/L.

$$\Gamma_{fer} = K_{fer}\frac{A_{fer}}{10D_{fer}} = \frac{1.0}{10}\left(\frac{100 \ kg/ha}{0.15 \ m}\right) = 67 \ mg/L$$

If water content is 30 %, then concentration of nitrate in water in the upper 0.15 m of soil is 67/0.3 = 222 mg/L.

2. Annual Tucson temperature data at 10 and 50 cm depth is available in the Chapter 25 WINDS salinity and nitrogen workbook. Develop an annual sin wave Eq. 25.16 based on this data, and plot temperatures at 5, 10, 50, and 100 cm.
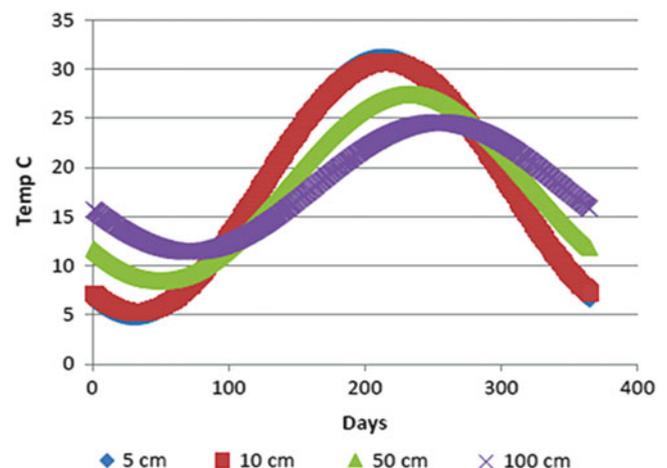
3. Hourly data is available in the *Chapter 25 WINDS salinity and nitrogen* workbook for 3 days in January and 2 days in June. Develop a diurnal sin wave Eq. 25.16 based on this data, and plot temperatures at the surface and at 5, 10, 50, and 100 cm for January and June. Compare the lag times calculated with the diffusivity to the lag times observed in the figures. Compare the equations that were derived based on data for the two different seasons.
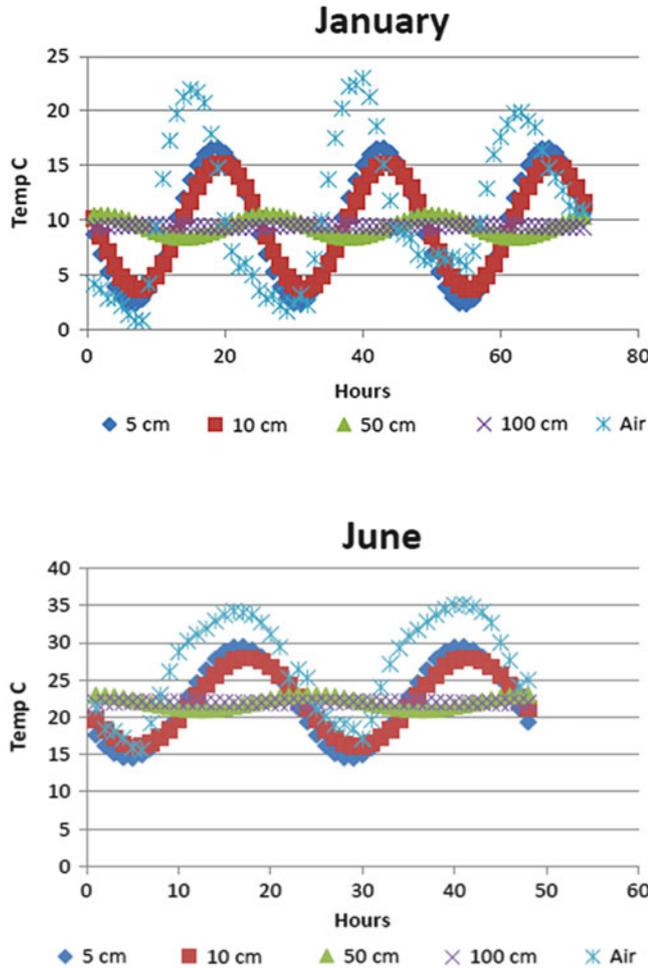
January

June

In January, the lag time appears to be about 4 hours based on the graphs. This is quite a bit longer than the predicted value of 0.21 hours. In June, however, the graph's lag time appears to be much shorter (about 1 hour). This is closer to the predicted lag time of 0.22 hours.

4. Find the mineralization over a 2 day period in a sandy loam soil with θ_{pwp} θ_{low}, θ_{high}, and θ_{sat} are equal to 0.1, 0.17, 0.26, and 0.42, respectively. Find the final concentration of nitrate in soil water if the initial concentrations are 15, 8, and 3 mg/L in layers 1, 2, and 3 respectively assuming no water content changes and no other sources or sinks of nitrate. Surface organic matter content is

2,000 µg/g, K_{mnl} = 0.00005 d^{-1}, α = 0.021. The average water contents and temperatures in the top three layers are

Water content		Cell elevations	Temperature
Layer 1	0.16	0–40 cm,	27 °C
Layer 2	0.28	40–80 cm,	22 °C
Layer 3	0.25	80–120 cm,	20 °C

Surface organic matter content is 2,000 µg/g, K_{mnl} = 0.00005 d^{-1}, α = 0.021.

Find the water content adjustment factors.

Water content is between θ_{pwp} and θ_{low} in the 0–40 cm depth increment:

$$f_{mnl\theta} = \left(\frac{\theta - \theta_{pwp}}{\theta_{low} - \theta_{pwp}}\right) = \left(\frac{0.16 - 0.10}{0.17 - 0.1}\right) = 0.86$$

Water content is between θ_{high} and θ_{sat} in the 40–80 cm increment

$$f_{mnl\theta} = 0.6 + 0.4\left(\frac{\theta_{sat} - \theta}{\theta_{sat} - \theta_{high}}\right)$$

$$= 0.6 + 0.4\left(\frac{0.42 - 0.28}{0.42 - 0.26}\right) = 0.95$$

Water content is between θ_{low} and θ_{high} 80–120 cm increment

$$f_{mnl\theta} = 1.0$$

Find the temperature adjustment factors

The temperature adjustment factor in the upper layer, with average temperature equal to 27 °C, is

$$f_{temp} = Q_{10}^{\left(\frac{T-t_b}{10}\right)} = 3^{\left(\frac{27-20}{10}\right)} = 2.16$$

The temperature adjustment factor in the 40–80 cm increment, with average temperature equal to 22 °C, is

$$f_{temp} = Q_{10}^{\left(\frac{T-t_b}{10}\right)} = 3^{\left(\frac{22-20}{10}\right)} = 1.25$$

The temperature adjustment factor in the 80–120 cm increment, at 20 °C, is 1.0

Find the average organic matter concentration in each cell.

Layer   1

$$O_n = O_{n_{max}}e^{-0.021z} = 2,000 \; e^{-0.021 \; *20} = 1,314 \; \mu g/g$$

Layer   2

$$O_n = O_{n_{max}}e^{-0.021z} = 2,000 \; e^{-0.021 \; *60} = 567 \; \mu g/g$$

Layer   3

$$O_n = O_{n_{max}}e^{-0.021z} = 2,000 \; e^{-0.021 \; *100} = 245 \; \mu g/g$$

Find the mineralization rate in each of the cells and the change in concentration in cell water

The saturated water content is 0.42. Thus, the porosity is approximately 0.42. Soil bulk density is.

$$\rho = \rho_p(1 - \phi) = 2.65(1 - 0.42) = 1.54.$$

Mineralization rate and change in nitrate concentration in water in layer 1 are calculated below. The change in nitrate concentration in the soil solution is the change in nitrate concentration in the soil volume divided by the water content.

$$\Gamma_{mnl} = K_{mnl}f_{mnl\theta}f_{temp}\rho O_n = 0.00005*0.86*2.16*1.54*1,314 = 0.188 \text{ mg/L soil/d}$$
$$dN_1 = \Gamma_{mnl}/\theta = 0.188/0.16 = 1.18 \text{ mg/L water/day}$$

Total mineralization over 2 days in the upper layer is 2.35 mg/L water

Layer 2

$$\Gamma_{mnl} = K_{mnl}f_{mnl\theta}f_{temp}\rho O_n = 0.00005*0.95*1.25*1.54*567 = 0.052 \text{ mg/L soil/d}$$
$$dN_1 = \Gamma_{mnl}/\theta = 0.052/0.28 = 0.19 \text{ mg/L water/day}$$

Total mineralization over 2 days is 0.38 mg/L water.

Layer 3

$$\Gamma_{mnl} = K_{mnl}f_{mnl\theta}f_{temp}\rho O_n = 0.00005*1.0*1.0*1.54*245 = 0.019 \text{ mg/L soil/d}$$
$$dN_1 = \Gamma_{mnl}/\theta = 0.052/0.28 = 0.038 \text{ mg/L/day}$$

Total mineralization over 2 days is 0.076 mg/L water

Change in nitrate concentration in soil water.

	$\Gamma * 2$	$N_{initial}$ (mg/L$_{water}$/day)	Final concentration (mg/L water)
Layer 1	2.35	15	17.35
Layer 2	0.38	8	8.38
Layer 3	0.038	3	3.038

5. Calculate the denitrification rate in the sandy loam soil described in problem 14 at 60 cm depth. Assume that initial nitrate concentration in soil water is 8 mg/L, and that the denitrification rate constant is 0.002 d^{-1}. Let the depth adjustment factor equal 0.021. Calculate the change in concentration within the soil volume and change in concentration within the soil water. Consider both the denitrification and mineralization to calculate the final concentration in layer 2 after 2 days.

$$\theta_{den} = 0.6*\theta_{sat} = 0.6*0.42 = 0.25$$

Calculate the water content adjustment factor.

$$f_{den\theta} = \left(\frac{\theta - \theta_{den}}{\theta_{sat} - \theta_{den}}\right)^2 = \left(\frac{0.28 - 0.25}{0.42 - 0.25}\right)^2 = 0.031$$

Calculate the temperature adjustment factor:

$$f_{temp} = Q_{10}^{\left(\frac{T=t_h}{10}\right)} = 3^{\left(\frac{22=20}{10}\right)} = 1.25$$

Calculate depth adjustment factor, f_z.

$$f_z = e^{-0.021*60} = 0.28$$

Calculate net loss of nitrate due to denitrification in layer 2.

$$\Gamma_{den} = K_{den}f_{den\theta}f_{temp}f_z\theta N$$
$$= 0.002*0.031*1.25*0.28*0.28*8$$
$$= 4.9*10^{-6} \ mg/L_{soil}/day$$

Calculate change in concentration within soil water

$$dN = mg/L_{soil}/day/\theta = 4.9*10^{-6}/0.28$$
$$= 0.000017 \ mg/L/day$$

The amount of denitrification is trivial compared to the amount of mineralization so the final concentration is still 8.38 mg/L water

6. Determine the seasonal removal of nitrate from the root zone (mg/L_{soil}) for a crop that has a yield of 8,000 kg/ha and has a nitrogen percentage of 1.6 %. Root zone depth is 1.5 m.

$$\Gamma_{upt} = \frac{Y}{10} \frac{fN}{dz} = \frac{8,000*0.016}{10*1.5}$$
$$= 8.53 \ mg/L_{soil}/season$$

7. $N_{req} = 1.4$ kg/ha, $N_{min} = 2$ mg/kg soil, and $N_{max} = 1.8$ kg/ha. The fraction of nitrogen taken up as nitrate is 1.0. The optimal level of nitrate in the soil is 30 mg/kg. Find Km, plot the uptake rate vs. soil nitrogen concentration, and calculate the uptake of nitrate at a soil nitrate concentration of 20 mg/kg.
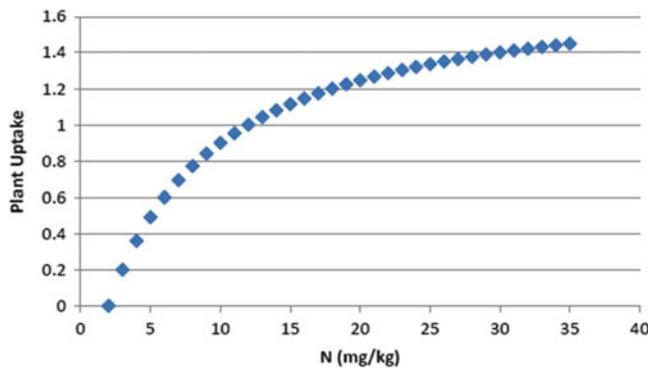
Plant uptake at 20 mg/kg = 1.25 kg/ha (from the figure)

Chapter 26: Solutions

1. **Repeat Example 26.1, but change the infiltration from the first storm to 3 cm, and the field capacity to 0.25. As before, infiltration from the second storm is 4 cm.**

$$d_{initial} = \theta \ \Delta z = 0.17*1.2 = 0.204 \ m$$

Calculate the maximum depth of water that the soil profile can hold

$$d_{cv-max} = \theta_{fc}\Delta z = 0.25*1.2 = 0.3 \ m$$

Find final depth of water in cell after the 3 cm storm.

$$d_{final} = d_{initial} + i = 0.204 + 0.03 = 0.234 \ m$$

d_{final} does not exceed d_{cv-max}, thus, there is no deep seepage and $d_{final} = 0.234$ m. Water content after the first storm is $\theta_{cv} = d_{cv}/dz = 0.234/1.2 = 0.195$

Now, repeat the calculation for the second storm. Initial depth of water in the soil (before the second storm) is

$$d_{initial} = 1.2 \ m*0.195 = 0.234 \ m$$

Depth of water added by second storm = 4 cm = 0.04 m.

$$d_{initial} + \Delta d_{cv} = 0.234 + 0.04 = 0.274 \ m$$

Thus, there is no deep seepage since the final water content is less than field capacity

Final water content after the second storm

$$\theta_{cv} = d_{cv}/dz = 0.274/1.2 = 0.228$$

2. **Redo question 1, but divide the soil into three layers of 0.4 m depth.**

For all cells, the initial depth of water is

$$d_{cv} = \theta \ \Delta z = 0.17*0.4 = 0.068 \ m$$

The maximum water depth held by each cell is

$$d_{cv-max} = \theta_{fc} \ \Delta z = 0.25*0.4 = 0.1 \ m$$

Infiltrated depth during the first storm is 3 cm (0.03 m).
For the first cell

$$d_{final-1} = d_{initial-1} + i_1 = 0.068 + 0.03 = 0.098 \ m$$

$$\theta_1 = d_{final-1}/dz = 0.098/0.4 = 0.245$$

Because the final depth does not exceed the maximum depth, no water is leached below the first cell. Water content in cells 2 and 3 remains the same.

The second storm infiltration is 4 cm (0.04 m). The first cell can hold 0.002 m, so 0.038 m drains to the second cell, and water content in the first cell is 0.25. The second cell can hold 0.032 m so the final water depth in cell 2 is 0.1 m, and water content is 0.25. Finally, the third cell receives 0.06 m so the final water depth in cell 3 is 0.074 m.

The final water content in cell 3 is

$$\theta_3 = d_{final-3}/dz = 0.074/0.4 = 0.185$$

3. **Redo Example 26.3, but change the upper layer FC to 0.26, and the lower layer FC to 0.24. Change the percent of ET removed from the upper layer to 70 % and the percent of ET removed from the lower layer to 30 %.**

Upper layer : $\theta_{FC} = 0.26, \theta_{PWP} = 0.1$, cell thickness, dz
$= 60$ cm, TAW $= (0.26 - 0.1)*60 = 9.6$ cm

Lower layer : $\theta_{FC} = 0.24, \theta_{PWP} = 0.11$, cell thickness, dz,
$= 40$ cm, TAW $= (0.24 - 0.11)*40$
$= 5.2$ cm

Water content before second storm.

Upper layer, $D_r = 4$ days*0.7 cm/day $= 2.8$ cm $\quad \Delta\theta$
$= -2.8/60 = -0.0467$

$\theta_{final} = 0.26 - 0.0467 = 0.213$

Lower layer, $D_r = 4$ days*0.3 cm/day $= 1.2$ cm $\quad \Delta\theta$
$= -1.2/40 = -0.03 \quad \theta_{final} = 0.24 - 0.03$
$= 0.21$

Water content after second storm.

Upper layer, storm adds 3 cm, which exceeds the 2.8cm depletion : $\theta_{final} = 0.26$

Lower layer, 0.2 cm leaches to the lower layer. $\Delta\theta = 0.2/40 = 0.005 : \theta_{final} = 0.21 + 0.005 = 0.215$

What is the percent depletion before and after the second storm in each layer?

$D_{r \; upperl \; ayer-before \; storm} = 2.8$ cm %depletion $= 2.8$ cm/9.6 cm*100 $= 29\%$
$D_{r \; lower \; layer-before \; storm} = 1.2$ cm %depletion $= 1.2$ cm/5.2 cm*100 $= 23\%$
$D_{r \; upper \; layer-after \; storm} = (0.2 - 0.2)60 = 0$ cm %depletion $= 0$ cm/9.6 cm*100 $= 0\%$
$D_{r \; lower \; layer-after \; storm} = (0.24 - 0.215)40 = 1$ cm %depletion $= 1$ cm/5.2 cm*100 $= 19\%$

4. **Redo Example 26.4 with the WINDS model and by hand, but lower the leaching fraction to 0.05. Make calculations for the irrigation on the third day for the upper two layers by hand. Next, use the WINDS model to calculate EC for 100 days. There are only two field sections in the *WINDS Chapter 26* workbook. The sections are organized with respect to their irrigation zones in the *spatial data* worksheet. Add another G01 section in column C and write "3" in the same row in column. In cell K7, specify that the number of cells is 3 and click the *Make new sections* button. This process adds the C_3 worksheet to the end of the workbook. The next step is to populate the date in the *Crop_data* worksheet for section 3. You can do this in the A*ctive Data* worksheet or just copy the cells from section 2 (column C) to section 3 (column D) in the *Crop_data* worksheet. If you use the *Active_data* worksheet, then the copy the information from section 2, "Copy data from crop data," and then copy rows 3–450 to section 3 (specified in cells G13:G16) and click the "Copy data to crop data" button. After calculating the required application depth for 0.05 leaching fraction, add the**

calculated fraction of baseline irrigation to the section 3 column in the G01 worksheet. Go to the Main worksheet. In cell G2, specify that three sections will be evaluated. After clicking Run, select position 3 in the Get Data combo box (upper right side of the worksheet). Find the "Water content" graph and the "Irrigation, rain depth, and leaching" graph with the Selection form. If rainfall appears in the graph, remove the rainfall from the *Active year weather* page for the first 100 days. Find the soil water salinity graph in the *Salinity* worksheet. Compare to the salinity levels in Example 26.4. Copy and paste the worksheets or graphs into this document. Use the graphs to assess the processes.

The depth of irrigation is 7 cm/0.95 $= 7.371$ cm (0.074 m) /irrigation for the 0.05 LF. Available water capacity is (0.2–0.184)(0.5) $=$ so Eq. 26.38 is not valid.

Layer 4, irrigation day salinity calculation for 0.05 LF

$$EC_{final} = \frac{d_{in}EC_{in} + EC_{initial}\Delta z \theta_{initial}}{d_{in} - ET_{layer} + \Delta z \theta i_{initial}{}^{initial}}$$

$$EC_{final} = \frac{(0.0737 \text{ m})(1) + 2.17 \ (0.49) \ (0.184)}{0.0737m - 10 \ mm*0.4/1000 + 0.49 \ m(0.184)}$$

$$= 1.68 \ dS/m$$

Layer 3, irrigation day salinity calculation for 0.05 LF

The initial moisture content in the upper layer is 0.184. Thus, the storage depth during the irrigation is calculated as (0.2–0.184) (0.5) +0.004 = 0.012 m. This means that 0.0737–0.012 = 0.0617 m passes through layer 4 and into layer 3.

$$EC_{final} = \frac{(0.0617 \text{ m})(1.68 \ dS/m) + 2.13(0.5)(0.188)}{0.0617 \ m - 10 \ mm(0.3)/(1000 \ mm/m) + 0.5(0.188)}$$

$$= 1.99 \ dS/m.$$

Solution with WINDS model for 100 days

The fraction of baseline irrigation is 1/0.95 = 1.053. Thus, the seasonal depth applied is 1,053 mm for leaching fraction equal to 0.05.

$$LF = \frac{i - ET}{i} = \frac{1,053 - 1,000}{1,053} = 0.05$$

Change the irrigation depths in the G01 worksheet to 1.053, and run the model from the Main page.

	A	B	C	D	E	F
1	DOY	Ref (mm)	Sec_1	Sec_2	Sec_3	Sec_4
2	1					
3	2					
4	3	70	1	1.053	1.053	
5	4					
6	5					
7	6					
8	7					
9	8					
10	9					
11	10	70	1	1.053	1.053	
12	11					
13	12					
14	13					
15	14					
16	15					
17	16					
18	17	70	1	1.176	1.053	
19	18					
20	19					
21	20					
22	21					
23	22					
24	23					
25	24	70	1	1.176	1.053	
26	25					

Get Data from section 3 in the Main worksheet. Then click the *View water content data* button. Select the water content graph and the irrigation and leaching graph from the *Water graphs* form.
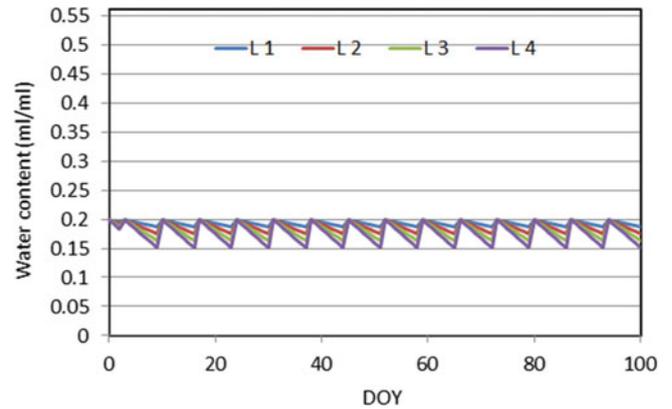
Water content vs. DOY graph
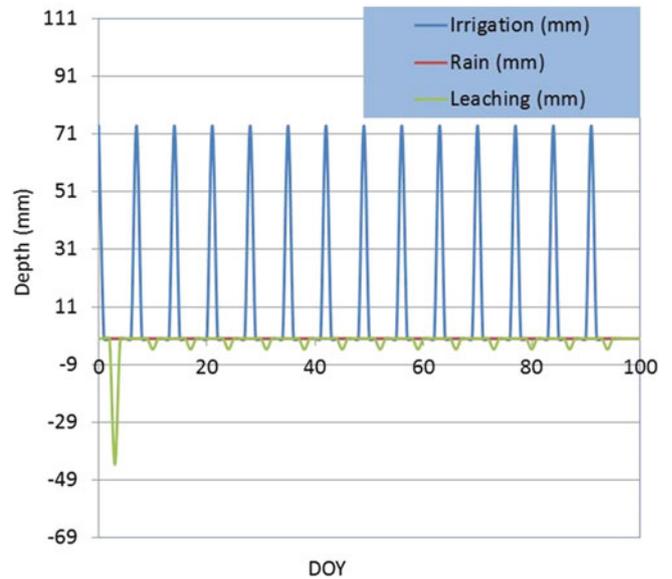
Irrigation, rain depth, and deep leaching graph from Water Content worksheet.

Go back to the Main worksheet and click the *View salinity data* button.
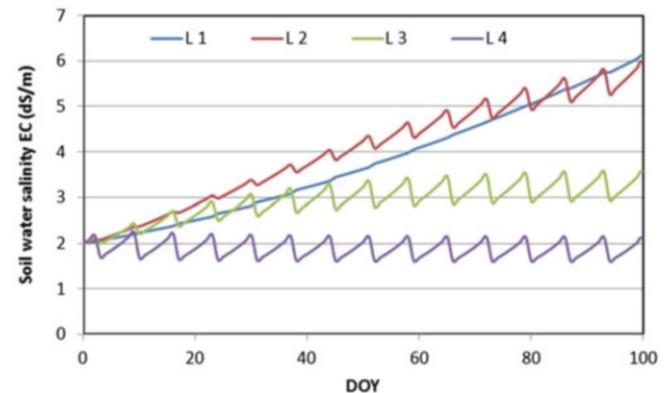
Soil water salinity graph.

Assessment:

The irrigation and leaching graph shows that leaching was excessive on day 3 so irrigation was not needed. The soil water content graph shows that irrigations returned the soil to field capacity after each irrigation. A small excess was applied, which resulted in the leaching events seen in the irrigation and leaching graph. The salinities are in between the no leaching and 15 % leaching cases in Example 26.4. Salinity built up in the lower part of the root zone, but the upper part of the root zone was leached. There is no jagged line for salinity in the lower layer because water content change was minimal between irrigation events; thus, the jagged change between irrigation events for the upper layers was due to water content change and resultant concentration of the existing salinity in less water.

5. **Calculate leaching fraction for irrigation water salinity 2 dS/m and required EC_e 1.5 dS/m?**

$$LF = \frac{EC_{iw}}{5*EC_e - EC_{iw}} = \frac{2}{5*1.5 - 2} = 0.36$$

6. **What are the ratios EC_e/EC_{ave}, and EC_e/EC_{dw} in Example 26.4? EC_{dw} is the leachate salinity. Discuss the importance of understanding these ratios with respect to crop management decisions?**

The ratio of $EC_e/EC_{ave} = 0.5$

The ratio of $EC_e/EC_{dw} = 1.6/6.7 = 0.24$

If one assumed that the drainage water salinity was the same as the ECe defined for crop management, then using the drainage water salinity as ECe would result in a much higher leaching fraction than necessary for the health of the crop. Similarly, using the model for salinity management would be incorrect if the ECave was used as the ECe.

7. **Redo Example 26.5, but change the fertilizer application to 40 kg/ha on the first day application and change nitrate concentration in the irrigation water to 20 mg/L. Make a new hand calculation of the changes due to fertilizer application and irrigation during the first three days in the upper cell. Run the WINDS simulation for 100 days with the higher irrigation water nitrate concentration and higher fertilization rate on day 3. The irrigation rate will be the same as problem 4. You can change the nitrogen data in the Active_data worksheet and copy it to section 3 in the *Crop_data* worksheet. Make sure that cell G5 in *Main* worksheet is marked True. Run the simulation from the *Main* worksheet. Select 3 in the *Get_data* combobox in the Main worksheet. Click the *View Nitrogen* data button. Copy the following graphs into your homework document: *Nitrate* (mg/kg) in layers, *Irrigation and drainage nitrate* (you might need to update both x and y axes from the selection form or from the axes), *Reactions*, and *Cumulative leaching, nitrate and reactions*. Assess the processes by looking at the graphs.**

Calculate the change in nitrate concentration due to fertilizer application (day 2, 1 day after application) on day 2

$$m_{fer} = \frac{App\ rate(kg/ha)}{10} = \frac{40\ kg/ha}{10} = 4\ mg/L_{soil}\ m$$

Calculate new nitrate concentration on day two with 40 kg/ha fertilizer with Eq. 26.39

$$N_{final} = \frac{d_{in}N_{in} - d_{out}N_{initial} + m_{min} - m_{den} + m_{fer} - m_{upt} + \square \times \square_{initial}\ \Delta z\ \theta_{initial}}{\Delta z\ \theta_{final}}$$

$$N_{final} = \frac{(0)N_{in} - (0)N_{initial} + 0.0455 - 0 + 4 - 0 + 296\ (0.49)\ (0.192)}{0.49\ (0.184)} = 354\ mg/L$$

Next, calculate the concentration in the upper cell after application of irrigation water on the third day. In this case, the complete mixing equation must be used because water passes through the layer.

$$N_{final} = \frac{d_{in}N_{in} + m_{min} - m_{den} + m_{fer} - m_{upt} + {}_{initial}\Delta z\ \theta_{initial}}{d_{in} - ET_{layer} + \Delta z\ \theta i_{initial}{}^{initial}}$$

$$N_{final} = \frac{(0.0737\ m)(20\ mg/L) + 0.0455 - 0 + 0 - 0 + 354(0.49)\ (0.184)}{0.0737\ m - 10\ mm*0.4/1000 + 0.49\ m\ (0.184)} = 209\ mg/L$$

There is no change in cell 3.

Data for section 3 is copied back into the *Active data* worksheet. Fertilization and irrigation parameters are changed in the lower left part of the *Nitrogen* form, which is accessed in the *Active Data* worksheet. Data is then copied back to the *Crop_data* worksheet.

Nitrogen form

Nitrate in layers graph
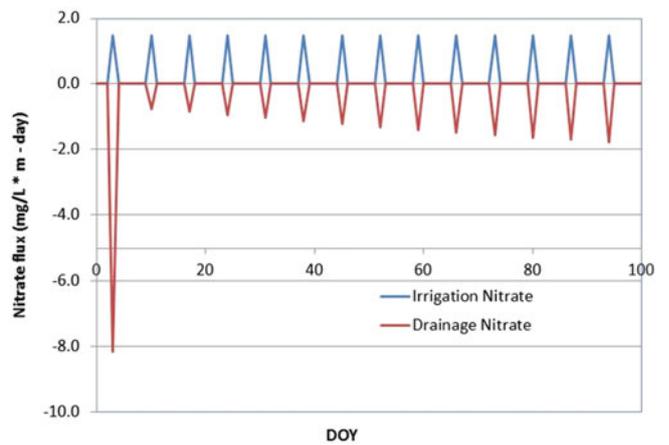
Irrigation and drainage nitrate graph
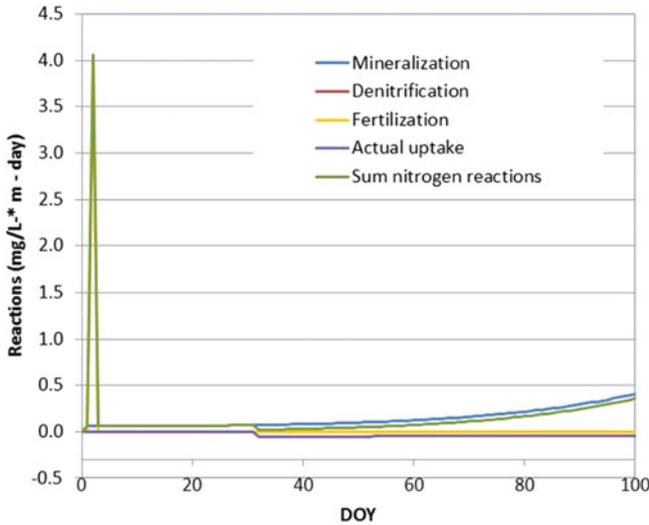
Mineralization, denitrification, fertilization, and uptake graph
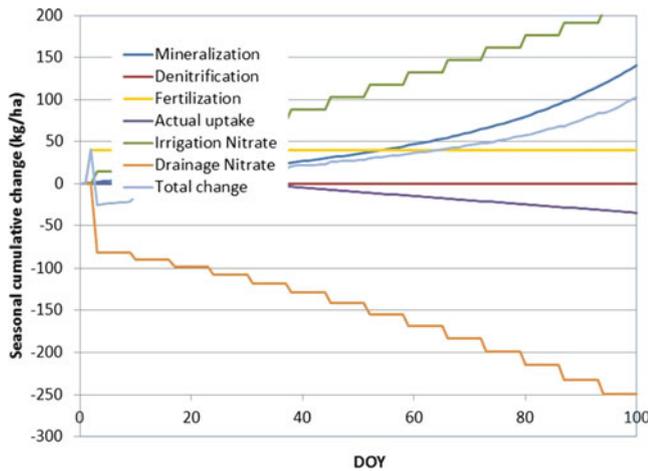
Cumulative mineralization, denitrification, fertilization, and uptake graph

Assessment:

There was heavy leaching during the first irrigation event; however, unavoidable leaching took place after every irrigation event since nitrate was concentrated in the lower part of the soil profile. The primary source of nitrogen was irrigation water. Nitrate concentration was low in the upper part of the soil profile, even below the optimal 30 mg/kg concentration. However, it reached the 50–60 mg/kg range in the lower part of the soil profile. Mineralization was a significant part of the total nitrogen mass balance during the season; however, denitrification was insignificant.

8. **A soil has three 0.4 m layers, numbered 1, 2, and 3 from the bottom, with field capacity in all layers equal to 0.25. The initial water salinity in layers 1, 2, and 3 is, 23-, 7-, and 5-dS/m, respectively. ET is 10 mm/day with 20 %, 30 %, and 50 % of ET in layers 1, 2, and 3 respectively. Irrigation water salinity is 2 dS/m. The initial water content on the previous day in layers 1, 2, and 3 is 0.18, 0.15, and 0.10, respectively. Soil porosity is 0.4. An irrigation event adds 11 cm water to the soil in the morning. Compare to the final water content, actual salinity, and saturated paste extract salinity before the morning irrigation event. Compare the changes in water salinity and saturated paste extract salinity.**

Available water capacity before irrigation (to select between equations).

$$\text{Layer } 3 = (0.25 - 0.1)*0.4 = 0.06 \text{ m}$$
$$\text{Layer } 2 = (0.25 - 0.15)*0.4 = 0.04 \text{ m}$$
$$\text{Layer } 3 = (0.25 - 0.18)*0.4 = 0.028 \text{ m}$$

The available water capacity is less than the storm depth so final water content in the upper layers after storm is field capacity

$$\text{Layer } 3, \theta = 0.25$$
$$\text{Layer } 2, \theta = 0.25$$

10 mm is added to layer 1 by irrigation, and 2 mm is lost by ET $\theta = 0.18 + 0.01/0.4 - 0.002/0.4 = 0.2$

Salinity calculations. Must use equation that accounts for irrigation water passing through the layer for the upper 2 layers. No water passes through layer 1. The final salinity calculation must include the ET water that is lost from the soil during the day.

$$EC_{\text{final}} = \frac{d_{\text{in}}EC_{\text{in}} + EC_{initial}\Delta z \theta_{initial}}{d_{in} - ET_{layer} + \Delta z \theta i_{initial}^{initial}}$$

$$EC_{\text{final}-3} = \frac{(0.11\text{m})(2) + 5(0.4)\ (0.1)}{0.11\ m - 10\ mm*0.5/1000 + 0.4\ (0.1)}$$
$$= 2.90\ dS/m$$

$$EC_{\text{final}-2} = \frac{(0.05\ m)(2.90) + 7(0.4)\ (0.15)}{0.05\ m - 10\ mm*0.3/1000 + 0.4\ (0.15)}$$
$$= 5.28\ dS/m$$

$$EC_{final} = \frac{i\ EC_{iw} - d_{seepage}EC_{initial} + EC_{initial}\Delta z\ \theta_{initial}}{\Delta z\ \theta_{final}}$$

$$EC_{final-1} = \frac{0.01*5.28 - 0 + 23*0.4*0.2}{0.4*0.2} = 23.7\ dS/m$$

$$EC_e = EC\frac{\theta}{\theta_{Sat}}$$

$$ECe_{3-initial} = 5*(0.1/0.4) = 1.25\ dS/m$$
$$ECe_{2-initial} = 7*(0.15/0.4) = 2.62\ dS/m$$
$$ECe_{1-initial} = 23*(0.18/0.4) = 10.35\ dS/m$$

$$ECe_{3-final} = 2.90*(0.25/0.4) = 1.81\ dS/m$$
$$ECe_{2-final} = 5.28*(0.25/0.4) = 3.30\ dS/m$$
$$ECe_{1-final} = 23.7*(0.2/0.4) = 11.8\ dS/m$$

The water salinity changed most in the upper layer. The saturated paste extract salinity increased in all layers, most dramatically in the upper layer. The reason for the increase in saturated paste extract salinity is that salt was added to all layers. The reason for the decrease in water salinity in the upper layer is that water in the layer was diluted by irrigation water with lower salinity.

9. **During a 1 day period, the upper layer of soil, 0.4 m depth, has a mineralization rate of 0.1 mg/L * m, a denitrification rate of 0.05 mg/L*m, and plant uptake of 1 *kg/ha*. One cm (average for the field) depth of water is added to the layer by drip irrigation and the irrigation water has a nitrate concentration of 20 mg/L. Transpiration removes 1.4 cm from the layer. No water leaches to the next layer. The initial water content is 0.18, and the initial nitrate concentration in the soil water is 15 mg/L. Calculate the final water content and nitrate concentration in the water. Calculate the kg/ha nitrate in the layer at the end of the day.**

Final water content is $0.18 + (0.01 - 0.014)/0.4 = 0.179$

Plant uptake $- 1\ kg/ha = 0.1\ mg/L*m$

$$N_{final} = \frac{d_{in}N_{in} - d_{out}N_{initial} + m_{min} - m_{den} + m_{fer} - m_{upt} + {}_{initial}\Delta z\ \theta_{initial}}{\Delta z\ \theta_{final}}$$

$$N_{final} = \frac{0.01*20 - 0 + 0.1 - 0.05 + 0 - 0.1 + 15*0.4*0.18}{0.4*0.179} = 17.2\ mg/L$$

Final kg/ha $= (17.2\ mg/L)\ (0.4\ m)*10\ kg/ha/(mg/L*m) = 172\ kg/ha$

Chapter 27: Solutions

1. How is energy lost as water flows through pipelines, soils, and channels?

In soils, heat is generated and energy is lost as water molecules slide past pore walls and slide past each other. As water moves through pipelines and channels, turbulent eddies in the flow cause water molecules to move past each other and release heat.

2. Convert 20 m water hydraulic head to units of kPa, atmospheres, bars, J/kg, ft head, and PSI. Approximate values are acceptable. Try to memorize the approximate relationships.

$$20\ m = 2\ atm = 2\ bar = 200\ kPa = 200\ J/kg$$
$$= 20/0.3048 = 66\ ft\ /2.31 = 28\ PSI$$

3. Water flows through a 1 m long column at a rate of 2 m/d and the pressure differential from one end of the column to the other is 1 m. Calculate the hydraulic conductivity of the media in the column. What would the flow rate be if the pressure differential was 100 kPa?

The energy difference, ΔH, is 1.0

$$L = 1.0 \quad Darcy\ velocity = 2\ m/d \quad k = vL/DH = 2\ m/d$$

Part 2.

$$100 \, kPa = 10 \, m \quad v = k\Delta H/L = 2 \, m/d(10/1) = 20 \, m/day$$

4. Calculate the kinetic energy of the water in problem 4 for the case of 1 m pressure differential. Is calculation of kinetic energy necessary in soil water calculations?

$$E = v^{\wedge 2}/2g = (2m/day/60/60/24)^2/(2*9.8)$$
$$= 2.73e - 11 \, Joules$$

Calculation of kinetic energy is not necessary in soils calculations.

5. Draw the energy diagram for Example 27.2 (part 1)
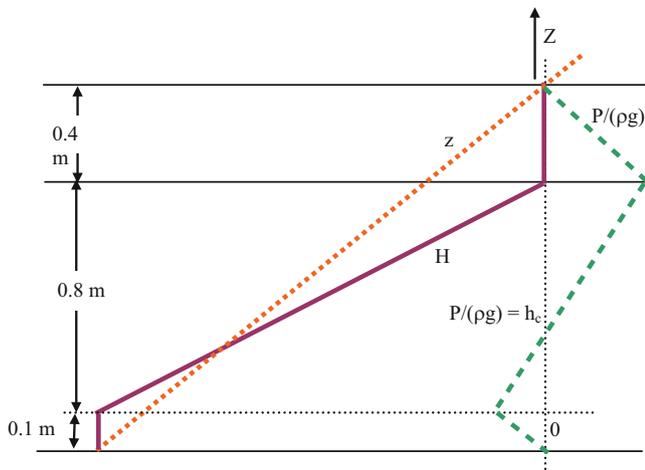
6. For Example 27.2 (part 1), place the lower water surface at the same elevation as the upper boundary of the sand (0.4 m below the elevation of the upper tank water surface). Draw the energy diagram.

$$H_f = 0.4 \, m$$

Calculate the velocity of flow with Darcy's law.

$$v = k\frac{H_f}{L} = 5 \, cm/hr\frac{0.4 \, m}{0.8 \, m} = 2.5 \, cm/hr$$

Calculate the flow rate Q through the sand filter.

$$Q = vA = v\left(pd^2/4\right)$$
$$= (2.5 \, cm/hr)(1 \, m/100 \, cm)\,p\left(0.7^2/4\right)\left(1000L/m^3\right)$$
$$= 9.6 \, L/hr.$$

If the porosity of sand is 0.38, then calculate the actual velocity of water through the filter.

$$v_{actual} = v_{Darcy}/porosity = 2.5 \, cm/hr/0.38 = 6.6 \, cm/hr.$$
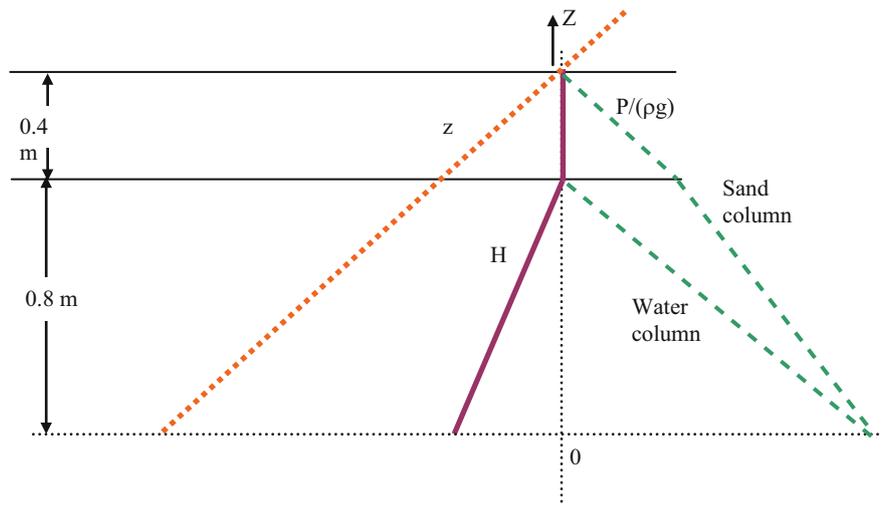
7. For Example 27.5, change the conductivities in cells 1, 2, and 3 to 5-, 4-, and 3-cm/hr, and change the heights of the cells to 0.3, 0.4, and 0.5-m, respectively. Draw the energy diagram.

Calculate the flow velocity (Darcy velocity) in the column and energy loss in each layer?

$$K_e = \frac{1.2}{\frac{0.3}{5} + \frac{0.4}{4} + \frac{0.5}{3}} = 3.67 \ cm/hr \quad v = K_e \frac{H_f}{L} = 3.67 \ cm/hr \frac{1.5 \ m}{1.2 \ m} = 4.59 \ cm/hr$$

$$H_{f1} = \frac{vL}{K} = \frac{4.59*0.3}{5} = 0.28 \ m \quad H_{f3} = \frac{vL}{K} = \frac{4.59*0.4}{4} = 0.46 \ m$$

$$H_{f2} = \frac{vL}{K} = \frac{4.59*0.5}{3} = 0.77 \ m$$

Start with known energy at position A and work downwards through the column.

Position	Total energy (H)	Elevation energy (z)	Matric potential (h or P)
A	1.6 m	1.2 m	1.6–1.2 = 0.4 m
B	1.6–0.28 = 1.32 m	0.9 m	1.32–0.9 = 0.42 m
C	1.32–0.46 = 0.86 m	0.5 m	0.86–0.5 = 0.36 m
D	0.86–0.77 = 0.1 m	0 m	0.1–0.0 = 0.1 m
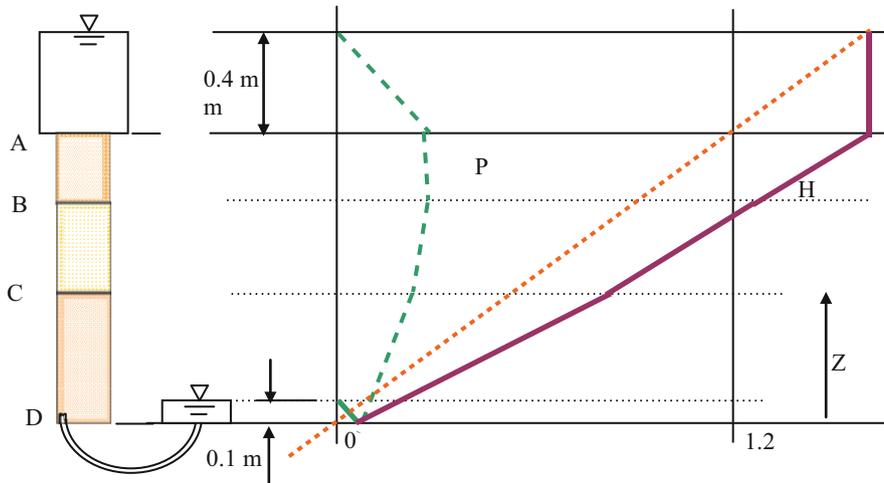
8. For Example 27.6, change the conductivities in cells 1, 2, and 3 to 5-, 4-, and 3-cm/hr, and change the heights of the cells to 0.3, 0.4, and 0.5-m, respectively. Draw the energy diagrams at the midelevation for each of the three cells in the direction parallel to flow (rotate the axes).

$$K_e = \frac{5*0.3 + 4*0.4 + 3*0.5}{1.2} = 3.83 \ cm/hr \quad v = K_e \frac{H_f}{L} = 3.83 \ cm/hr \frac{1.5 \ m}{1.2 \ m} = 4.8 \ cm/hr$$

$$v_1 = K_1 \frac{H_f}{L} = 5 \ cm/hr \frac{1.5 \ m}{1.2 \ m} = 6.25 \ cm/hr$$

$$v_2 = 4 \ cm/hr \frac{1.5 \ m}{1.2 \ m} = 5 \ cm/hr \quad v_3 = 3 \ cm/hr \frac{1.5 \ m}{1.2 \ m} = 3.75 \ cm/hr$$
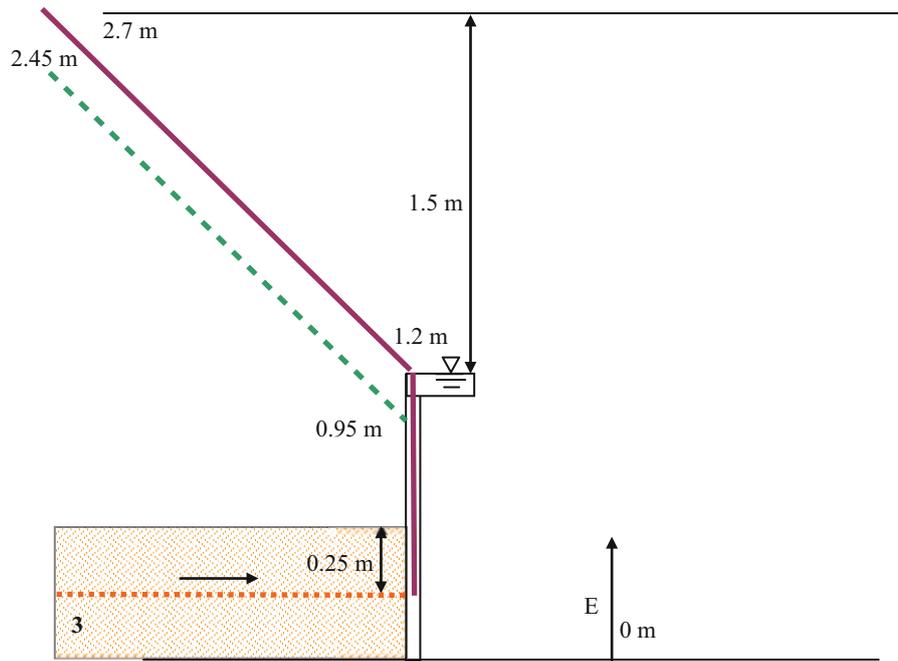
9. A column has two soil layers. Layers 1 and 2 have saturated hydraulic conductivities of 1 and 2 cm/hr, respectively. The datum is at the bottom of the column. Calculate the energy, elevation, and pressure potential at points A, B, and C. Draw the energy potential lines. You do not need to draw any lines below the datum. Calculate the flow velocity (Darcy velocity) in the column and energy loss in each layer?
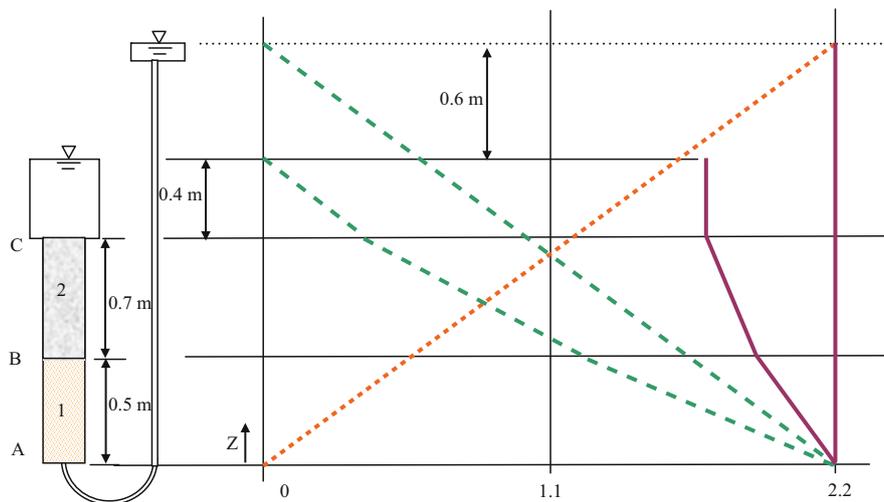
$$K_e = \frac{1.2}{0.5/1 + 0.7/2} = 1.41 \;\; cm/hr$$

$$v = K_e\frac{H_f}{L} = 1.41 \;\; cm/hr\,\frac{0.6 \;\; m}{1.2 \;\; m} = 0.705 \;\; cm/hr$$

$$H_{f1} = v_1\frac{L}{K_1} = 0.705 \;\; cm/hr\,\frac{0.5 \;\; m}{1 \;\; cm/hr} = 0.352 \;\; m$$

$$H_{f2} = v_1\frac{L}{K_1} = 0.705 \;\; cm/hr\,\frac{0.7 \;\; m}{2 \;\; cm/hr} = 0.247 \;\; m$$

Position	Total energy (H)	Elevation energy (z)	Matric potential (h or P)
A	2.2 m	0 m	2.2 m
B	2.2–0.35 = 1.85 m	0.5 m	1.85–0.5 = 1.35 m
C	1.85–0.25 = 1.6 m	1.2 m	1.6–1.2 = 0.4 m

10. Draw the energy potential lines for this soil column, and calculate the total and matric potential energy at points A, B, and C. The conductivity of layer 1 is 2 cm/day, and the conductivity of layer 2 is 0.5 cm/day.
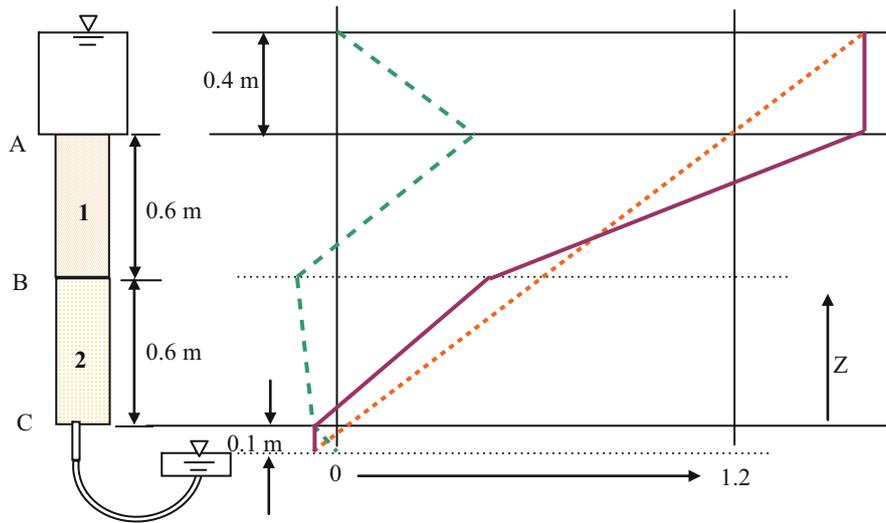
$$K_e = \frac{1.2}{0.6/1 + 0.6/2} = 1.33 \;\; cm/hr$$

$$v = K_e\frac{H_f}{L} = 1.33 \;\; cm/hr\,\frac{1.7 \;\; m}{1.2 \;\; m} = 1.88 \;\; cm/hr$$

$$H_{f1} = v_1\frac{L}{K_1} = 1.88 \;\; cm/hr\,\frac{0.6 \;\; m}{1 \;\; cm/hr} = 1.13 \;\; m$$

$$H_{f2} = v_1\frac{L}{K_1} = 1.88 \;\; cm/hr\,\frac{0.6 \;\; m}{2 \;\; cm/hr} = 0.57 \;\; m$$

Position	Total energy (H)	Elevation energy (z)	Matric potential (h or P)
A	1.6 m	1.2 m	0.4 m
B	1.6–1.13 = 0.47 m	0.6 m	0.47–0.6 = −0.13 m
C	0.47–0.57 = −0.1 m	0 m	−0.1–0 = −0.1 m

11. Using Eq. 27.25, calculate the change in mass in cell 2, which has an energy of 4 J, For this example, E (meters) = 2 * mass (kg). Cell 1 E = 2 J and Cell 3 E = 3 J. The conductivity between cells is 6 m/sec, and the cross-sectional area of cells, A, is 0.1 m². The length of cells is 0.4 m. The length of time steps is 1 second. Calculate final mass and energy.

$$m_{initial} = mass = E/2 = 2 \; J.$$

$$m_{2=final} = m_{2=initial} - AK\frac{E_2 - E_1}{gL}\Delta t + AK\frac{E_3 - E_2}{gL}\Delta t$$

$$m_{2=final} = 2 - (0.1)(6)\frac{4-2}{9.8*0.4}(1) + (0.1)(6)\frac{5-4}{(9.8)(0.4)}(1)$$

$$= 2 - (0.1)(6)\frac{-1}{(9.8)(0.4)}$$

$$m_{2=final} = 2 + 0.15 = 2.15$$

$$\text{Final energy} = 4.3 \; J$$

12. Redo Example 27.7 except let the initial masses be equal to 1-, 4-, 5-, 6-, 8-, and 10-kg. Print out the energy graph and discuss results.
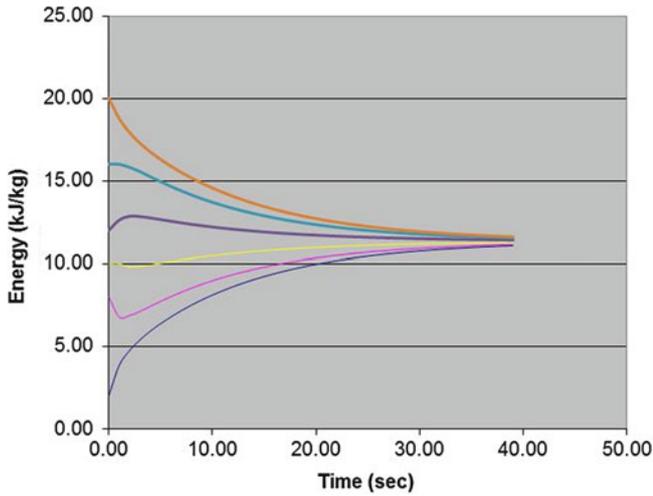
Because the energy gradient is not even, flow is initially in the direction of cells that have a relatively low mass.

13. Repeat problem 12, but change the time step to 10 seconds. Print out the energy graph and discuss results.
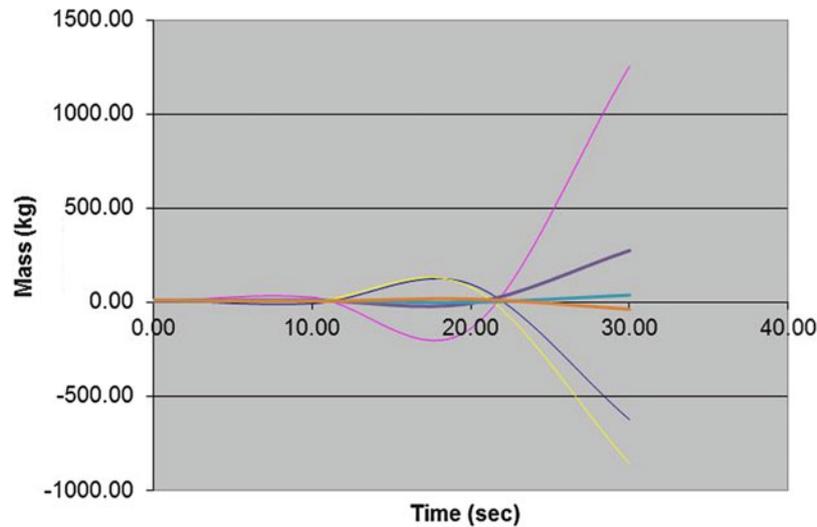
The solution is unstable because the time steps are too large relative to the space steps.

14. Change the *Calculations in worksheet* so that 1 kg mass is continually added each second to the left of the control volume (cell 1). Make the time step 0.2 seconds. Then make a second modification so that 0.4 kg is removed from the right side whenever the mass on the left side is greater than 8. Simulate for 60 seconds and show in a graph. Show the equations that you used. Make sure that the A,K, and L values are the same as those in the Mass and Energy worksheet: $(A = 0.1, k = 6, \text{ and } L = 0.4)$.
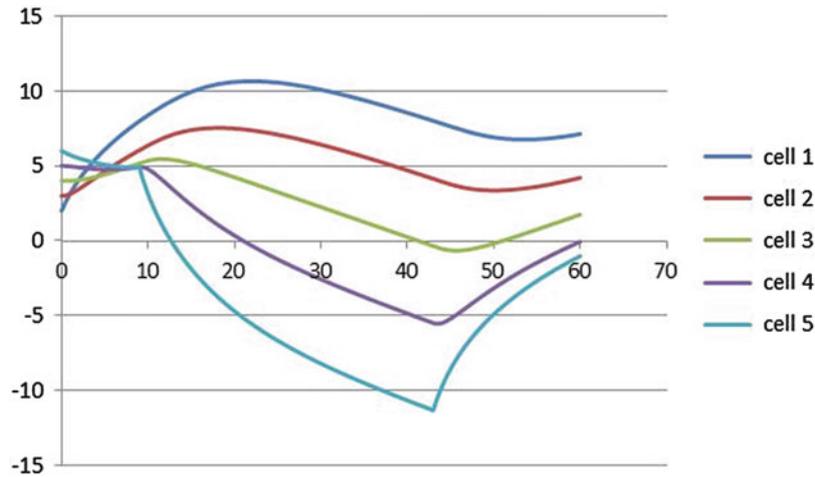
Left side equation Column C

$$= (K9 - J9)^*K^*A/L/9.806^*T + C9 + Added\_mass$$

Right side equation in Column G

$$= -(N9 - M9)^*K^*A/L/9.806^*T + G9$$
$$+ IF(C10 > 8, -0.4, 0)$$

15. Repeat Problem 14 in *Functions in Worksheet*. Show the equations/functions as well as the graph. You will need to add the Right_mass() function as well as make the modification on removed mass. Also, let the criteria be that the left mass must be greater than 10.
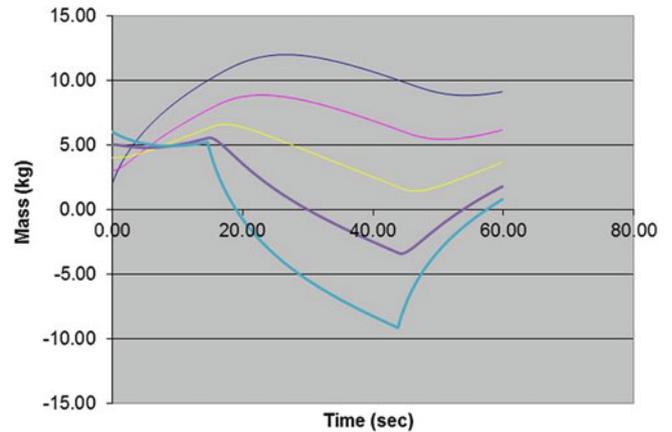
Left side equation Column C

$$= Left\_mass(K9, J9, K, A, L, T, C9) + 0.2$$

Right side equation in Column G

$$= Right\_mass(M10, N10, K, A, L, T, G10)$$
$$- if(C10 > 8, 0.4, 0)$$

16. Repeat Problem 14 but make the changes in the VBA Mass_Energy subroutine so that the results are shown in the Mass and Energy worksheet. Show the parts of the code that you changed. The graph should have the same pattern as the previous graphs.

Code:

```
Final_time = 60
   Num_Cells = Range("D1")
   T = 0.2
   Num_Times = Final_time / T

   For i = 1 To Num_Times
      For j = 1 To Num_Cells
       If j = 1 Then
          Mass(i, j)  =  Left_mass(Energy(i -
          1, j + 1), Energy(i - 1, j), K, A, L, T,
          Mass(i - 1, j)) + 0.2
       ElseIf j < Num_Cells Then
```

```
      Mass(i, j)  =  Middle_mass(Energy(i - 1,
      j - 1), Energy(i - 1, j), Energy(i - 1,
      j + 1), K, A, L, T, Mass(i - 1, j))
       Else
          Mass(i, j) = Right_mass(Energy(i - 1, j
          - 1), Energy(i - 1, j), K, A, L, T, Mass
          (i - 1, j))
          If Mass(i, 1) > 10 Then
             Mass(i, j) = Mass(i, j) - 0.4
          End If
       End If
       Energy(i, j) = 2 * Mass(i, j)
     Next j
   Next i
```

17. A SSF wetland is run at 0.3 m depth, 10 m wide, and
    20 m long. The hydraulic conductivity of the gravel in
    the wetland is 10^{-3} m/sec (360 cm/hr), and the poros-
    ity is 0.38. The impermeable liner has a 0.5 % slope in
    the direction of flow. What are the Darcy velocity,
    flow rate, pore volume, and hydraulic detention time
    within the wetland? Calculate the percent reduction
    in flow from that of the wetland described in
    Example 27.6.

The difference in impermeable liner elevation between
the beginning and end of the wetland is 0.005 * 20 m = 0.1
m. Calculate Darcy velocity,

$$v = K\frac{\Delta H}{L} = 360\frac{0.1}{20} = 1.8 \ cm/hr$$
$$Q = vA = (1.8cm/hr)(0.01 \ m/cm)(10 \ m)(0.3 \ m)$$
$$(1000 \ L/m^3) = 54 \ L/hr$$
$$V_{cv} = A \ L \ f = 10*0.3*20*0.38 = 23 \ m^3$$
$$HDT = \frac{V}{Q} = \frac{23 \ m^3}{54 \ L/h}\left(\frac{1,000 \ L}{m^3}\right)\left(\frac{day}{24 \ hr}\right) = 18 \ days$$

Percent reduction in flow capacity
$$= (1 - (168 - 54)/168)*100 = 68\%$$

18. Evaluate your answer in problem 17 with the SSF work-
    book. Determine whether 54 L/hr (0.054 m³/hr) results
    in steady 0.3 m depth flow. Inlet flow rate is specified in
    cell B5. Set all cells at an initial depth of 0.3 m. Set
    discharge depth (cell L4) equal to 0.3 m. Inlet bot.
    difference (cell G3) is 0.1 m.

    Parameters are set as shown below

	A	B	C	D	E	F	G	H	I	J	K	L
1	Wetland width	10	Num_Cells	5			Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
2	K (m/hr)	3.6	Time_step	0.1	Initial surface		0.39	0.37	0.35	0.33	0.31	
3	Wetland length	20	Time_unit	hours	Inlet bot. diff (m)		0.1					
4	Length unit	m	Final time	100	Porosity		0.38		Discharge depth (m)		0.3	
5	Inlet flow rate	0.054	m3/hr		Water depth in cell (m)					Water surface elevation (r		
6		hours	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5			Cell 1	Cell 2	Cell 3
7	Click to run	0.00	0.3000	0.3000	0.3000	0.3000	0.3000		0.00	0.3900	0.3700	0.3500
8	SSF Macro	0.10	0.3000	0.3000	0.3000	0.3000	0.3000		0.10	0.3900	0.3700	0.3500
9		0.20	0.3000	0.3000	0.3000	0.3000	0.3000		0.20	0.3900	0.3700	0.3500

All cells remain at 0.3 m depth so the SSF model is
verified by the problem 16.
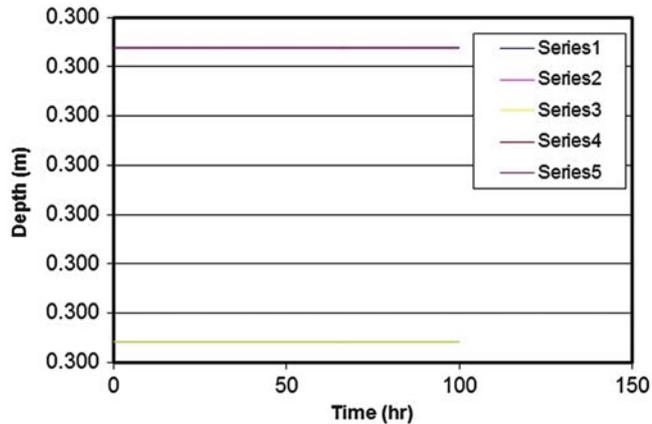
19. With initial conditions described in problem 17, investi-
    gate the effect of increasing the discharge depth to 0.5 m
    and increasing the flow rate to 90 L/hr with the *SSF*
    model. Run for 200 hours. Verify with the equations in
    problem 16 that this flow depth results in steady state
    depth = 0.5 m.

	A	B	C	D	E	F	G	H	I	J	K	L	M	
1	Wetland width	10	Num_Cells	5			Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	Cell 7	
2	K (m/hr)	3.6	Time_step	0.1		Initial surface	0.39	0.37	0.35	0.33	0.31			
3	Wetland length	20	Time_unit	hours		Inlet bot. diff (m)	0.1							
4	Length unit	m	Final time	200		Porosity	0.38		Discharge depth (m)		0.5		Hid	
5	Inlet flow rate	0.09	m3/hr			Water depth in cell (m)			Water surface elevation (m)					
6		hours	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5		Cell 1	Cell 2	Cell 3	Cell 4		

20. With the initial conditions described in problem 17, investigate the effect of keeping the discharge depth at 0.3 m and increasing the flow rate to 90 L/hr with the *SSF* model. Run for 200 hours. Show the graph and describe the final conditions after 200 hours. Look at the hydraulic gradient and discuss its effect on flow rate. Discuss the ability of SSF wetlands to handle variations in flow rate.

The upper end of the raceway is only 0.4 m deeper than at the 0.54 flow rate. The lower end remains at 0.3 m depth.

This increased depth at the upper end results in a greater hydraulic gradient across the raceway, which drives the increased flow. An increase of almost 100 % flow rate results in very little change in depth in the raceway, which shows that the raceway is able to handle large differences in flow rate due to increasing the hydraulic gradient.

21. Plot the water characteristic curves for sandy loam and clay soils with the van Genuchten equation for the terms in Table 27.2. Make three graphs for each soil. 0–50 cm matric potential with linear scale, 0–15 bar matric potential with linear scale, and 0–15 bar matric potential with logarithmic scale on the x-axis. For logarithmic scale, the matric potentials must be expressed as positive values. Describe the differences in the curves. Make sure that the water content scale on all graphs begins at zero in order to make the comparison.

The clay soil has very little decrease in water content over the first 50 cm; however, the sandy loam soil drops significantly over the first 50 cm. The clay soil retains significantly more moisture, even at a matric potential of 15 bar. The logarithmic curves have the same shape for both soils.
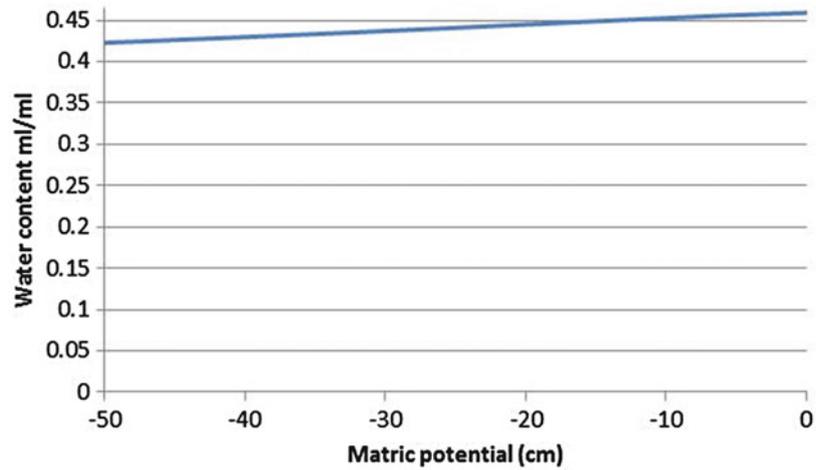
Clay soil (0 to −50 cm)
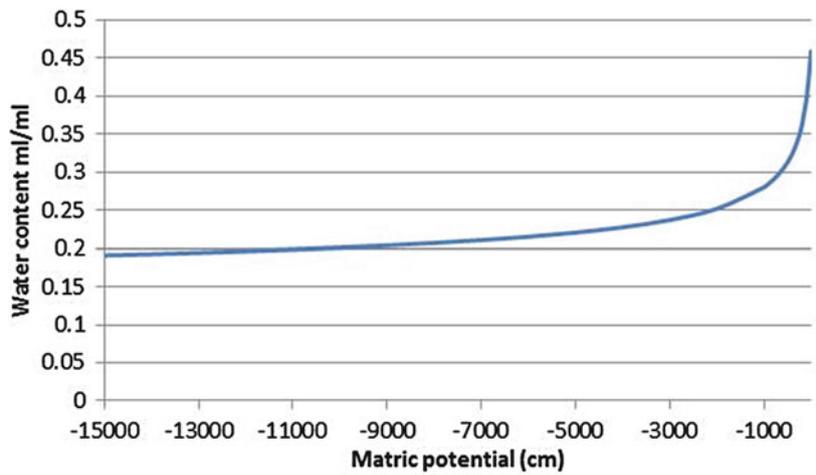
Clay soil (0 to −15000 cm)
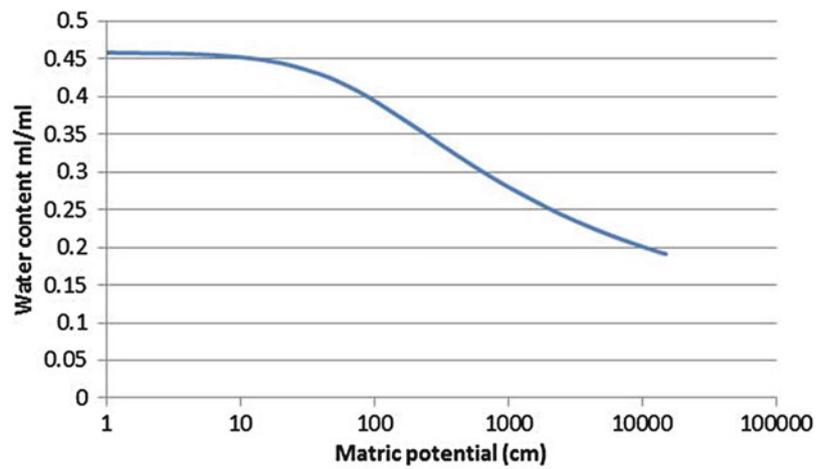
Clay soil (logarithmic axis)
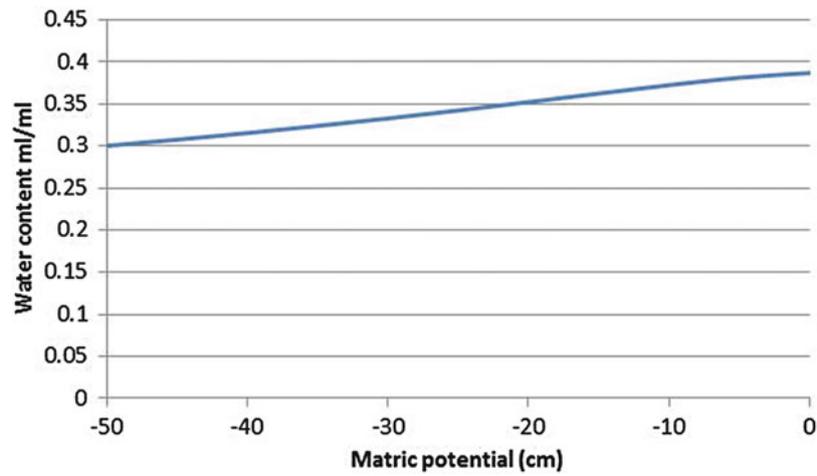
Sandy loam soil (0 to −50 cm)
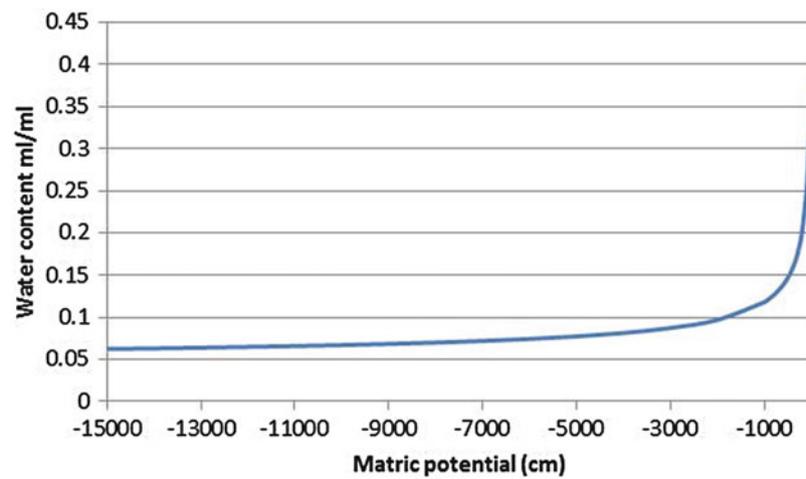
Sandy loam soil (0 to −15000 cm)
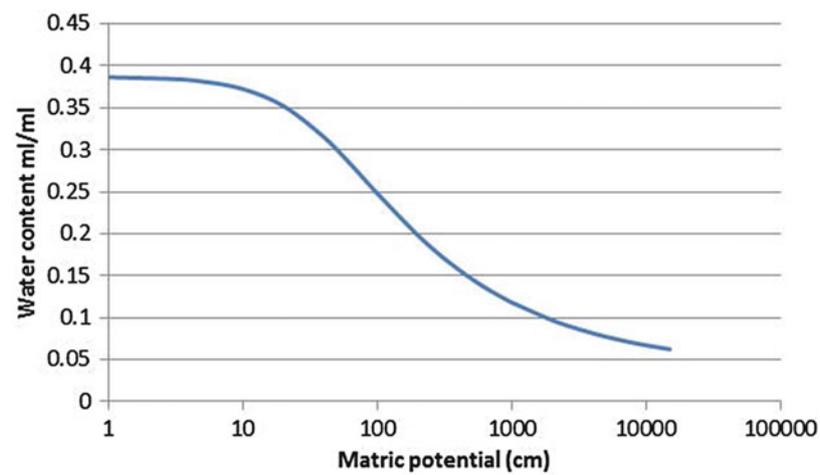
Sandy loam soil (logarithmic axis)

22. Find λ and hb for the Goldsboro Sandy Loam water content vs. matric potential in the table below. Show initial log-log plot, adjusted log-log plot, and show final graph with a comparison of the experimental water characteristic curve and the Brooks-Corey water characteristic curve. (Note: the graph does not align quite as well as the example in the book).

Ψm (m)	$-\Psi$m (m)	θ
0.00	0.00	0.365
− 0.10	0.10	0.355
− 0.30	0.30	0.320
− 0.50	0.50	0.275
− 0.60	0.60	0.260
− 0.80	0.80	0.235
− 2.00	2.00	0.188
− 2.50	2.50	0.182
− 3.00	3.00	0.178
− 3.50	3.50	0.170

Ψm (m)	$-\Psi$m (m)	θ	θ_e	S	S_e	B-C Eq.
0.00	0.00	0.365	1.000	1.000	1.000	1.000
− 0.10	0.10	0.355	0.953	0.973	0.953	1.000
− 0.30	0.30	0.320	0.791	0.877	0.791	1.000
− 0.50	0.50	0.275	0.581	0.753	0.581	0.635
− 0.60	0.60	0.260	0.512	0.712	0.512	0.571
− 0.80	0.80	0.235	0.395	0.644	0.395	0.482
− 2.00	2.00	0.188	0.177	0.515	0.177	0.282
− 2.50	2.50	0.182	0.149	0.499	0.149	0.247
− 3.00	3.00	0.178	0.130	0.488	0.130	0.222
− 3.50	3.50	0.170	0.093	0.466	0.093	0.203

Numbers in yellow were used for calculation of pore size distribution index.
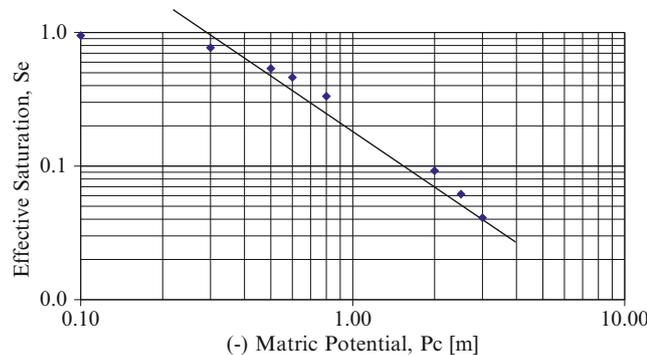
Initial log-log plot with $\theta_r = 0.17$
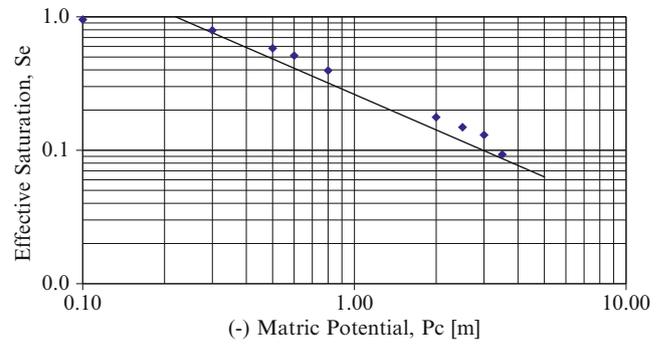
Adjusted log − log plot with $\theta_r = 0.15$

The Goldsboro soil does not fit the Brooks-Corey model very well. The Wagram loamy sand Brooks-Corey curve had a very close match with the experimental curve; however, the Goldsboro soil is not so close.
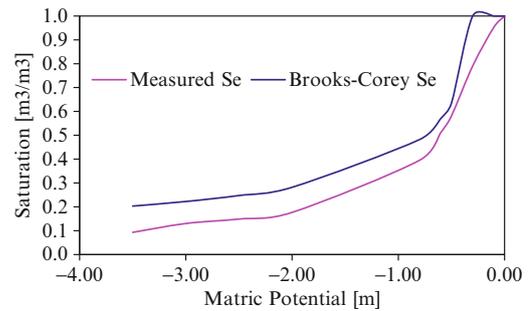
The values in yellow were selected for calculation of the pore size distribution index.

$$\lambda = \frac{\log(0.953) - \log(0.130)}{\log(0.10) - \log(3.00)} = 0.585$$

The bubbling pressure is the intersection of the slope of the pore size distribution index on log-log paper and the $S_e = 1.0$ line, −23 cm.

$h_b =$	−0.230
λ =	0.585
θs =	0.365
θr =	0.150
S_r	0.411

23. Replace the simplistic relationship between mass and energy in the Mass and Energy worksheet VBA code with the Van Genuchten equation for water content (mass) and matric potential (energy) relationship. Also, include the Van Genuchten relationship between matric potential (energy) and conductivity instead of the constant conductivity that is included in the problem. In order to simplify the problem, you can assume that the cells are horizontal in order to avoid the calculation of elevation energy. The solution is basically the VBA code used in the next chapters, but without the vertical change in elevation energy.

Chapter 28: Solution

1. **Derive Eq. 28.3 from Eq. 27.20**

$$\Delta V_2 = -AK\frac{H_2 - H_1}{L}\Delta t + AK\frac{H_3 - H_2}{L}\Delta t$$

$$\frac{\Delta V_2}{A} = \frac{-AK\dfrac{H_2 - H_1}{L}\Delta t + AK\dfrac{H_3 - H_2}{L}\Delta t}{A}$$

$$\Delta d = \left(-K\frac{H_2 - H_1}{L} + K\frac{H_3 - H_2}{L}\right)\Delta t$$

$$\Delta d = \Delta\theta\Delta x$$

$$\Delta\theta\ \Delta x = \left(-K\frac{H_2 - H_1}{L} + K\frac{H_3 - H_2}{L}\right)\Delta t$$

2. **Define H in terms of matric potential and elevation, and then rearrange Eq. 28.3 so that it has the same format as Eq. 28.2.**

$$\Delta\theta_j\Delta z = \left(-K_{e(j\&j-1)}\frac{H_j - H_{j-1}}{\Delta z} + K_{e(j\&j+1)}\frac{H_{j+1} - H_j}{\Delta z}\right)\Delta t$$

$$\frac{\Delta\theta_j}{\Delta t} = \frac{1}{\Delta z}\left(-K_{e(j\&j-1)}\frac{h_j - h_{j-1} + z_j - z_{j-1}}{\Delta z} + K_{e(j\&j+1)}\frac{h_{j+1} - h_j + z_{j+1} - z_j}{\Delta z}\right)$$

$$\frac{\Delta\theta_j}{\Delta t} = \frac{1}{\Delta z}\left(-K_{e(j\&j-1)}\left(\frac{h_j - h_{j-1}}{\Delta z} + \frac{z_j - z_{j-1}}{\Delta z}\right) + K_{e(j\&j+1)}\left(\frac{h_{j+1} - h_j}{\Delta z} + \frac{z_{j+1} - z_j}{\Delta z}\right)\right)$$

$$\frac{\Delta\theta_j}{\Delta t} = \frac{1}{\Delta z}\left(-K_{e(j\&j-1)}\left(\frac{h_j - h_{j-1}}{\Delta z} + 1\right) + K_{e(j\&j+1)}\left(\frac{h_{j+1} - h_j}{\Delta z} + 1\right)\right)$$

3. **Include osmotic potential as a function of soil water EC in Eq. 8.5. Leave only the change in water content ($\Delta\theta$) on the left side of the equation. Use Eq. 5.2 to calculate osmotic potential based on soil water EC.**

The osmotic potential, $\psi_s = -3.6 * EC$ in units of meters. Because the other terms are in units of meters, the equation can be substituted directly into the equation. Use the equation derived in question 1.

$$\Delta\theta_j = \frac{\Delta t}{\Delta z}\left(\begin{array}{l} -K_{e(j\&j-1)}\left(\dfrac{h_j - h_{j-1}}{\Delta z} + \dfrac{-3.6*\left(EC_j - EC_{j-1}\right)}{\Delta z} + 1\right) \\ +K_{e(j\&j+1)}\left(\dfrac{h_{j+1} - h_j}{\Delta z} + \dfrac{-3.6*\left(EC_{j+1} - EC_j\right)}{\Delta z} + 1\right) \end{array}\right)$$

The EC in this equation is soil water EC and not ECe.

4. **Data on three cells (3, 4, 5) is listed below. Write the equation derived in question 3 in terms of cell 4.**

Calculate the change in water content in cell 4 with and without the influence of salinity. Use a 1 day time step.

$z_3 = 1.0$ m	$h_3 =$	-2 m	EC_{w-3}	$= 4$ dS/m
$z_4 = 1.4$ m	$h_4 =$	-3 m	EC_{w-4}	$= 3$ dS/m
$z_5 = 1.8$ m	$h_5 =$	-5 m	EC_{w-5}	$= 6$ dS/m

The effective hydraulic conductivity between cells 3 and 4 is 0.01 m/day

The effective hydraulic conductivity between cells 4 and 5 is 0.001 m/day

Equation written for cell 4.

$$\Delta\theta_4 = \frac{\Delta t}{\Delta z}\left(\begin{array}{c} -K_{e(3,4)}\left(\frac{h_4 - h_3}{\Delta z} + \frac{-3.6*(EC_4 - EC_3)}{\Delta z} + 1\right) \\ +K_{e(4,5)}\left(\frac{h_5 - h_4}{\Delta z} + \frac{-3.6*(EC_5 - EC_4)}{\Delta z} + 1\right) \end{array}\right)$$

Calculation with salinity

$$\Delta\theta_4 = \frac{1}{0.4}\left(\begin{array}{c} -0.01\left(\frac{-3-(-2)}{0.4} + \frac{-3.6*(3-4)}{0.4} + 1\right) \\ +0.001\left(\frac{-4-(-5)}{0.4} + \frac{-3.6*(6-3)}{0.4} + 1\right) \end{array}\right)$$

$$\Delta\theta_4 = \frac{1}{0.4}\left(\begin{array}{c} -0.01\left(\frac{-1}{0.4} + \frac{3.6}{0.4} + 1\right) \\ +0.001\left(\frac{1}{0.4} + \frac{-10.8}{0.4} + 1\right) \end{array}\right)$$

$$= \frac{1}{0.4}\left(-0.01(3) + 0.001\left(\frac{-9.4}{0.4}\right)\right) = -0.133$$

Calculation without salinity

$$\Delta\theta_4 = \frac{1}{0.4}\left(\begin{array}{c} -0.01\left(\frac{-3-(-2)}{0.4} + 1\right) \\ +0.001\left(\frac{-4-(-5)}{0.4} + 1\right) \end{array}\right)$$

$$\Delta\theta_4 = \frac{1}{0.4}\left(\begin{array}{c} -0.01\left(\frac{-1}{0.4} + 1\right) \\ +0.001\left(\frac{1}{0.4} + 1\right) \end{array}\right)$$

$$= \frac{1}{0.4}(-0.01(-1.5) + 0.001(3.5)) = 0.046$$

5. **Calculate the water content, effective water content, effective saturation and hydraulic conductivity of Wagram loamy sand at -1 bar matric potential.**

$$1 \text{ bar } = 1{,}000 \text{ cm.}$$

$$K_{rw} = \left(\frac{-30}{-1{,}000}\right)^{2+3(1.27)} = 1.42*10^{-9}$$

$$S_e = \theta_e = \left(\frac{h_b}{h_c}\right)^\lambda = \left(\frac{-30}{-1{,}000}\right)^{1.27} = 0.012$$

$$\theta = (\theta_s - \theta_r)\left(\frac{h_b}{h_c}\right)^\lambda + \theta_r$$

$$= (0.31 - 0.044)\left(\frac{-30}{-1{,}000}\right)^{1.27} + 0.044 = 0.047$$

6. **Calculate the Darcy velocity between two points in unsaturated Wagram loamy sand with matric potential values of $-1{,}000$ cm (point 1) and $-2{,}000$ cm (point 2) and elevations of 10 cm (point 1) and 20 cm (point 2), respectively. Assume that the saturated hydraulic conductivity of Wagram loamy sand is 0.6 cm/hr. The distance between the two points is 50 cm. Use the Brooks Corey model for hydraulic conductivity. Use the geometric mean to calculate effective hydraulic conductivity.**

$$K_{rw} = \left(\frac{-30}{-1{,}000}\right)^{2+3(1.27)} = 1.42*10^{-9}$$

$$K_{rw} = \left(\frac{-30}{-2{,}000}\right)^{2+3(1.27)} = 2.53*10^{-11}$$

$$K(h_{1000}) = K_S K_{rw\ 1000} = 0.6 \text{ cm/hr}*1.4*10^{-9} = 8.5*10^{-10} \text{cm/hr}$$

$$K(h_{2000}) = K_S K_{rw\ 2000} = 0.6 \text{ cm/hr}*2.5*10^{-11} = 1.5*10^{-11} \text{cm/hr}$$

$$K_e = \frac{L_1 + L_2}{\frac{L_1}{K_1} + \frac{L_2}{K_2}} = \frac{25 + 25}{\frac{25}{8.5*10^{-10}} + \frac{25}{1.5*10^{-11}}} = 3.0*10^{-11} \ cm/hr$$

$$h_f = \Delta H = h_2 + z_2 - h_1 - z_1$$
$$= -2{,}000 + 20 - (-1000) - 10 = -990 \text{ cm}$$

The fact that the energy gradient is negative means that water flows from point 1–2.

$$v = -K_e\frac{\Delta H}{L} = -3*10^{-11}\frac{-990}{50} = 5.9*10^{-10} \ cm/hr$$

7. **Three cells numbered 1 through 3 from bottom to top have 0.5 m depth. Use the van Genuchten equations to calculate water contents after 1 day and 2 days. Initial water content in all cells is 37 %. $n = 1.31$, $\theta_r = 0.095$, $\theta_S = 0.41$, $\alpha = 0.019$, $L = 0.5$, and $K_0 = 6.24$ cm/day. There is no infiltration and no seepage of water below the control volume. Calculate effective conductivity between two cells with the geometric mean. Calculate water contents after the first day and after the second day. It is impossible for any cell to have greater than the saturated water content.**

The middle cell water content will remain the same after the first day since the input from above equals the drainage below. The upper cell water content is calculated as follows.

$$\theta_{n-final} = \theta_{n-initial} + \frac{\Delta t}{\Delta z^2}\left(-K_{e(n\,\&\,n-1)}(H_n - H_{n-1})\right) + \frac{i}{\Delta z}$$

$$\theta_{3-final} = \theta_{3-initial} + \frac{\Delta t}{\Delta z^2}\left(-K_{e(3\,\&\,2)}(h_3 - h_2 + \Delta z)\right) + \frac{i}{\Delta z}$$

$$\theta_{3-final} = 0.37 + \frac{1}{0.5^2}(-0.0018(0.5)) + 0 = 0.3663$$

The lower cell water content is calculated as follows.

$$\theta_{1-final} = \theta_{1-initial} + \frac{\Delta t}{\Delta z^2}\left(K_{e(1\&2)}(h_2 - h_1 + \Delta z)\right)$$

$$\theta_{1-final} = 0.37 + \frac{1}{0.5^2}(0.0018(0.5)) = 0.3737$$

Day 2

Calculate initial effective water content in each cell

$$\theta_{e-1} = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{0.3737 - 0.095}{0.41 - 0.095} = 0.885$$

$$\theta_{e-2} = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{0.37 - 0.095}{0.41 - 0.095} = 0.873$$

$$\theta_{e-3} = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{0.3663 - 0.095}{0.41 - 0.095} = 0.861$$

Calculate matric potential in each cell

$$h_{c-1} = -\frac{\left(\theta_e^{-1/m} - 1\right)^{1/n}}{\alpha} = -\frac{\left(0.885^{-1/0.236} - 1\right)^{1/1,31}}{0.019}$$

$$= -39.1\ cm\, h_{c-2}$$

$$= -\frac{\left(\theta_e^{-1/m} - 1\right)^{1/n}}{\alpha}$$

$$= -\frac{\left(0.873^{-1/0.236} - 1\right)^{1/1,31}}{0.019}$$

$$= -43.3\ cm\, h_{c-3}$$

$$= -\frac{\left(\theta_e^{-1/m} - 1\right)^{1/n}}{\alpha}$$

$$= -\frac{\left(0.861^{-1/0.236} - 1\right)^{1/1,31}}{0.019}$$

$$= -47.7\ cm$$

Calculate hydraulic conductivity in each cell

$$K(\theta)_1 = K_0\theta_e^{1/2}\left[1 - \left(1 - \theta_e^{1/m}\right)^m\right]^2 = 6.24*0.885^{0.5}\left[1 - \left(1 - 0.885^{1/0.236}\right)^{0.236}\right]^2 = 0.218\ cm/d$$

$$K(\theta)_2 = K_0\theta_e^{1/2}\left[1 - \left(1 - \theta_e^{1/m}\right)^m\right]^2 = 6.24*0.873^{0.5}\left[1 - \left(1 - 0.873^{1/0.236}\right)^{0.236}\right]^2 = 0.18\ cm/d$$

$$K(\theta)_3 = K_0\theta_e^{1/2}\left[1 - \left(1 - \theta_e^{1/m}\right)^m\right]^2 = 6.24*0.77^{0.5}\left[1 - \left(1 - 0.77^{1/0.236}\right)^{0.236}\right]^2 = 0.157\ cm/d$$

Calculate effective hydraulic conductivities with the geometric mean

$$K_{e-2-3} = \frac{2}{\dfrac{1}{K_j} + \dfrac{1}{K_{j+1}}} = \frac{2}{\dfrac{1}{0.18} + \dfrac{1}{0.157}} = 0.17\ cm/day = 0.00170\ m/day$$

$$K_{e-1-2} = \frac{2}{\dfrac{1}{K_j} + \dfrac{1}{K_{j+1}}} = \frac{2}{\dfrac{1}{0.18} + \dfrac{1}{0.219}} = 0.20\ cm/day = 0.0020\ m/day$$

Calculate final water contents in each cell

$$\theta_{3-final} = \theta_{3-initial} + \frac{\Delta t}{\Delta z^2}\left(-K_{e(3\,\&\,2)}(h_3 - h_2 + \Delta z)\right) + \frac{i}{\Delta z}$$

$$\theta_{3-final} = 0.3663 + \frac{1}{0.5^2}\left(-0.001696(-0.477 - (-0.433) + 0.5)\right) + 0 = 0.3632$$

$$\theta_{1-final} = 0.3737 + \frac{1}{0.5^2}(0.002004*(-0.433 - (-0.391) + 0.5)) = 0.3774$$

$$\theta_{2-final} = \theta_{2-initial} + \frac{\Delta t}{\Delta z^2}\left(-K_{e(2\,\&\,1)}(h_2 - h_1 + \Delta z) + K_{e(2\,\&\,3)}(h_3 - h_2 + \Delta z)\right)$$

$$\theta_{2-final} = 0.37$$

$$+\frac{1}{0.5^2}(-0.0020*(-0.433 - (-0.391) + 0.5) + 0.0017(-0.477 - (-0.443) + 0.5)) = 0.3694$$

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8. **Repeat problem 7 but allow water to drain below the lower cell. There is no water table. Use Eq. 28.27 for cell 1.**

$$\theta_{final} = \theta_{initial} + \frac{\Delta t}{\Delta z^2}\left(K_{e(1\,\&\,2)}(h_2 - h_1 + \Delta z) - K_1\Delta z\right)$$

$$\theta_{1-final} = 0.37 + \frac{1}{0.5^2}(0.0018(0.5) - 0.0018*0.5) = 0.37$$

Day 1
Other calculations remain the same as in question 7 except for the final water content in cell 1.

Day 2

$$\theta_{2-final} = \theta_{2-initial} + \frac{\Delta t}{\Delta z^2}\left(-K_{e(2\,\&\,1)}(h_2 - h_1 + \Delta z) + K_{e(2\,\&\,3)}(h_3 - h_2 + \Delta z)\right)$$

$$\theta_{2-final} = 0.37$$

$$+\frac{1}{0.5^2}(-0.0018*(-0.433 - (-0.433) + 0.5) + 0.0017(-0.477 - (-0.443) + 0.5)) = 0.3694$$

The water content in cell 1 will remain the same (0.37) at the end of the second time step since the water content in cell 2 is still 0.37 at the end of the first time step; however, the water content in cell 2 will change.

$$\theta_{2-final} = \theta_{2-initial} + \frac{\Delta t}{\Delta z^2}\left(-K_{e(2\,\&\,1)}(h_2 - h_1 + \Delta z) + K_{e(2\,\&\,3)}(h_3 - h_2 + \Delta z)\right)$$

$$\theta_{2-final} = \theta_{2-initial}$$

$$+\frac{1}{0.5^2}(-0.0020*(-0.433 - (-0.391) + 0.5) + 0.0017(-0.477 - (-0.443) + 0.5)) = 0.3694$$

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9. Repeat problem 7 but restrict the downward movement of water to 0.1 cm/day from layer 1 (as with subsurface drainage and a water table).

$$\theta_{final} = \theta_{initial} + \frac{\Delta t}{\Delta z^2}\left(K_{e(1\,\&\,2)}(h_2 - h_1 + \Delta z) - \Delta z*d_{seepage}\right)$$

$$\theta_{1-final} = 0.37 + \frac{1}{0.5^2}(0.0018(0.5) - 0.5*0.001) = 0.3716$$

Day 1
Other calculations remain the same as in question 7 except for the final water content in cell 1.

Day 2
Calculate the new effective water content, matric potential and hydraulic conductivity for cell 1.

$$\theta_{e-1} = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{0.3716 - 0.095}{0.41 - 0.095} = 0.878$$

$$h_{c-1} = -\frac{\left(\theta_e^{-1/m} - 1\right)^{1/n}}{\alpha}$$

$$= -\frac{\left(0.878^{-1/0.236} - 1\right)^{1/1.31}}{0.019} = -41.5 \ cm \, K(\theta)_1$$

$$= K_0 \theta_e^{1/2} \left[1 - \left(1 - \theta_e^{1/m}\right)^m\right]^2$$

$$= 6.24 * 0.878^{0.5} \left[1 - \left(1 - 0.878^{1/0.236}\right)^{0.236}\right]^2$$

$$= 0.199 \ cm/d$$

Calculate effective hydraulic conductivities with the geometric mean

$$K_{e-1-2} = \frac{2}{\dfrac{1}{K_j} + \dfrac{1}{K_{j+1}}} = \frac{2}{\dfrac{1}{0.1848} + \dfrac{1}{0.199}} = 0.1915 \ cm/day = 0.001915 \ m/day$$

$$\theta_{2-final} = \theta_{2-initial} + \frac{\Delta t}{\Delta z^2} \left(-K_{e(2\&1)}(h_2 - h_1 + \Delta z) + K_{e(2\&3)}(h_3 - h_2 + \Delta z)\right)$$

$$\theta_{2-final} = 0.37$$

$$+ \frac{1}{0.5^2}(-0.001915 * (-0.433 - (-0.415) + 0.5) + 0.0017(-0.477 - (-0.443) + 0.5)) = 0.3694$$

The water content in cell 1 will remain the same (0.37) at the end of the second time step since the water content in cell 2 is still 0.37 at the end of the first time step; however, the water content in cell 2 will change.

$$\theta_{2-final} = \theta_{2-initial} + \frac{\Delta t}{\Delta z^2} \left(-K_{e(2\&1)}(h_2 - h_1 + \Delta z) + K_{e(2\&3)}(h_3 - h_2 + \Delta z)\right)$$

$$\theta_{2-final} = \theta_{2-initial}$$

$$+ \frac{1}{0.5^2}(-0.001915 * (-0.433 - (-0.391) + 0.5) + 0.0017(-0.477 - (-0.443) + 0.5)) = 0.3694$$

$$\theta_{1-final} = 0.3716 + \frac{1}{0.5^2}(0.001915(0.5) - 0.001 * 0.5) = 0.3734$$

10. **Thirty cm is removed from the soil as the water table is lowered from 2.5 to 0.5 m. Calculate the incremental specific yield between 0.5 and 2.5 m.**

$$SY = \frac{\Delta d_d}{\Delta DTWT} = \frac{0.3}{2} = 0.15 = 15\%$$

11. **The water table drops from 1.0 to 1.5 m below the ground surface, and the specific yield of the soil is 10 %. Calculate the depth of water removed from the soil profile.**

$$\Delta z_{WT} = -\Delta DTWT = -(1.5 \ m - 1.0 \ m) = -0.5 \ m$$
$$d_d = -SY * \Delta z_{WT} = -0.1 * (-0.5) = 0.05 \ m = 5 \ cm$$

12. What do the right and left terms on the right side of Eq. 28.17 represent? What is the hatched area in Fig. 28.8? What does $\theta(z)$ represent in the Eq. 28.17? Why is the Brooks-Corey calculation of $\theta(z)$, which is based on matric potential substituted into the equation derivation? Explain why the upper limit of integration is $z_t - z_{WT}$ and the lower limit is h_{ba}.

The left term represents the depth of water in the soil when the soil is saturated. The right term represents the depth of water at each elevation based on the matric potential at that elevation. The hatched area in Fig. 8.7 is the difference between the two. The equation solves for water content at each elevation which is θ_z. The Brooks-Corey equation for water content as a function of matric potential is substituted into the equation because matric potential is directly proportional to elevation. The upper limit of integration represents the matric potential at the soil surface and the lower limit of integration represents the matric potential at the bubbling pressure elevation.

13. **Calculate the depth of water drained and specific yield for a water table that drops from the soil surface to 0.8 m above the datum in Wagram loamy sand. Place the datum 1.5 m below the soil surface.**

The bubbling pressure elevation is 0.8 m + 0.3 m = 1.1 m.

$$d_d = (\theta_s - \theta_r)\left(z_t - z_{hb} - \frac{h_{ba}^\lambda}{-\lambda+1}\left((z_t - z_{hb} + h_{ba})^{-\lambda+1} - (h_{ba})^{-\lambda+1}\right)\right)$$

$$d_d = (0.305 - 0.044)\left(1.5 - 1.1 - \frac{0.3^{1.27}}{-1.27+1}\left((1.5 - 0.8)^{-1,27+1} - (0.3)^{-1,27+1}\right)\right) = 0.045 \ m$$

$$SY = \frac{\Delta d_d}{\Delta DTWT} = \frac{0.045}{0.7 \ m} = 0.064 = 6.4\%$$

14. If the problem 13 water table dropped from 0.7 m below the surface to 0.8 m below the surface, then how much water would you expect would be drained from the soil during this 0.1 m drop in water table elevation? Calculate the depth drained in two ways: use the specific yield that you calculated in problem 13 and also calculate the actual depth drained at 0.8 m depth with Eq. 28.18. Then use the two drained depths to calculate the incremental specific yield between 0.7 m and 0.8 m depth below the soil surface.

At 6.4 % specific yield, the depth drained would be 0.1 m * 0.064 m/m = 0.0064 m = 0.64 cm

The actual drained depth at 0.8 m depth below the surface is calculated as follows

$$d_d = (\theta_s - \theta_r)\left(z_t - z_{hb} - \frac{h_{ba}^\lambda}{-\lambda+1}\left((z_t - z_{WT})^{-\lambda+1} - (h_{ba})^{-\lambda+1}\right)\right)$$

$$d_d = (0.305 - 0.044)\left(1.5 - 1.0 - \frac{0.3^{1.27}}{-1.27+1}\left((1.5 - 0.7)^{-1,27+1} - (0.3)^{-1,27+1}\right)\right) = 0.063 \ m$$

Thus, the actual drained depth between 0.7 and 0.8 m is

$$0.063 - 0.045 = 0.018 \text{ m} = 1.8 \text{ cm}.$$

This drained depth is much greater than that calculated based on the specific yield in question 13. The low specific yield in the upper soil region is caused by the fact that there isn't very much water lost during the initial drop in water table elevation because the bubbling pressure is still near the soil surface.

Thus, the incremental specific yield between 0.7 m and 0.8 m is 0.018/0.1 = 0.18 = 18 %.

15. **Use Eq. 28.19 to find the incremental specific yield at 0.75 m depth below the soil surface for Wagram loamy sand and compare to the incremental specific yield that was calculated in problem 14.**

$$SY = \frac{d(d_d)}{d(z_{WT})} = -(\theta_s - \theta_r)\left[-1 + \left(\frac{h_{ba}}{DTWT}\right)^\lambda\right]$$

$$= -(0.305 - 0.044)\left[-1 + \left(\frac{0.3}{0.75}\right)^{1.27}\right] = 18\%$$

The incremental specific yields calculated with the two methods are exactly the same.

16. **Find the depth drained if the water table drops from the soil surface to 50 cm depth, from the soil surface**

to 100 cm depth, and from the soil surface to 150 cm depth. Use the Brooks-Corey Goldsboro sandy loam parameters that you calculated question 27–23. Set the datum at 3 m. Find the specific yield associated with the water table drop from the surface to each depth

The volume drained with the water table at 50 cm below the soil surface is calculated as follows.

$$d_d = (0.365 - 0.15)\left(3 - 2.73 - \frac{0.23^{1.27}}{-0.59 + 1}\left((3 - 2.5)^{-0.59+1} - (0.23)^{-0.59+1}\right)\right) = 0.013 \; m$$

The volume drained with the water table at 100 cm below the soil surface is calculated as follows.

$$d_d = (0.365 - 0.15)\left(3 - 2.23 - \frac{0.23^{1.27}}{-0.59 + 1}\left((3 - 2)^{-0.59+1} - (0.23)^{-0.59+1}\right)\right) = 0.0658 \; m$$

The volume drained with the water table at 150 cm below the soil surface is calculated as follows.

$$d_d = (0.365 - 0.15)\left(3 - 1.73 - \frac{0.23^{1.27}}{-0.59 + 1}\left((3 - 1.5)^{-0.59+1} - (0.23)^{-0.59+1}\right)\right) = 0.133 \; m$$

$$SY - 50 = 1.3/50*100\% = 2.6 \; \%$$
$$SY - 100 = 6.5/100*100\% = 6.5 \; \%$$
$$SY - 150 = 13.2/150*100\% = 8.8 \; \%$$

17. **Derive Eq. 28.31 from Eq. 28.20**

$$d_{total} = \theta_s(z_{hb}) + \int_{h_ba}^{Zt-ZWT} \theta(z)dz$$

$$\theta(z) = \theta_r + (\theta_s - \theta_r)\left(\frac{h_b \, c}{h_c}\right)^\lambda = \theta_r + (\theta_s - \theta_r)\left(\frac{h_{ba}}{z}\right)^\lambda$$

$$d_{total} = \theta_s(z_{hb}) + \left(\int_{h_{ba}}^{Zt-ZWT}\left(\theta_r + (\theta_s - \theta_r)\left(\frac{h_{ba}}{z}\right)^\lambda\right)dz\right)$$

$$d_d = \theta_s(z_{hb}) + (z_t - z_{hb})\theta_r + \frac{(\theta_s - \theta_r)h_{ba}^\lambda}{-\lambda + 1}$$
$$\left((z_t - z_{WT})^{-\lambda+1} - (h_{ba})^{-\lambda+1}\right)$$

18. **Use the integrator at http://integrals.wolfram.com/index.jsp to integrate the left hand side of Eq. 28.24.**

The answer should be the right side of Eq. 8.37.

19. **Find the hypergeometric function page at the Wolfram website listed in question 18 and find the transformation shown between Eqs. 28.24 and 28.25. List the line number of the transform on the Wolfram page to prove that you found the transform. Find the series solution to the hypergeometric function on the same page and list the line number. Explain how you would implement the series solution in a computer code or spreadsheet.**

Line 35. Transformation

Line 7. Series solution. Each term in the series includes an extra term that is multiplied by the previous term and then added to the series. The series solution is implemented in the hg function as follows within the *van Genuchten* Excel/VBA program.

```
Function hg(a, b, c, z) As Single
 Dim i As Integer
 Dim value As Single
 value = 1
 hg = value
 For i = 1 To 40
    value = value * (a + i - 1) * (b + i - 1) / (c + i - 1) /
    i * z
    hg = hg + value
 Next i
```

20. **A soil has the following parameters: n = 1.5, α = 0.06, z_t = 2 m, z_{WT} = 1 m, θ_s = 0.45, and θ_r = 0.08. Calculate the a, b, c, and w terms for the transformed Gauss hypergeomtric function in Eqs. 28.25. A function is included in the Van Genuchten Excel/VBA program called hg that calculates the hypergeometric series solution. Calculate the series solution with the function hg by calling it from a worksheet with the following: "=hg(a,b,c,w/(w-1))". Make sure to write z in units of cm in the calculation of w since α has units of 1/cm. Finally, calculate the total depth of water in the soil profile from the datum to the soil surface.**

$a = 1,$
$b = 1 - 1/n = 1 - 1/1.5 = 0.333$
$c = 1 + 1/n = 1 + 1/1.5 = 1.667$
$w = -((a(z_t - z_{WT}))^n) = -\left((0.06*(200 - 100))^{1.5}\right)$
$\quad = -\left(6^{1.5}\right) = -14.7$
$hg(a, b, c, w/(w - 1)) = 1.49$

$d_{total} = \theta_s(z_{WT}) + \theta_r(z_t - z_{WT}) + (\theta_s - \theta_r)$
$(z_t - z_{WT})(1 - w)^{1/n-1}{}_2F_1\left(1, 1 - \frac{1}{n}; 1 + \frac{1}{n}, \frac{w}{w - 1}\right)$
$d_{total} = 0.45(1) + 0.08(2 - 1) + (0.45 - 0.08)$
$(2 - 1)(1 - (-14.7))^{-0.33}*1.49 = 0.75 \ m$

21. **Redo problem 20, but place the water table at 0.1 m above the datum. Calculate the specific yield if the water table drops from 1 m to 0.1 m above the datum.**

$w = -((a(z_t - z_{WT}))^n) = -\left((0.06*(200 - 10))^{1.5}\right) = -38.5$
$hg(a, b, c, w/(w - 1)) = 1.60$

$d_{total} = 0.45(1) + 0.08(2 - 1) + (0.45 - 0.08)(2 - 1)$
$\quad (1 - (-38.5))^{-0.33}*1.60 = 0.53 \ m$
$SY = (0.75 - 0.53)/0.9 = 25\%$

22. **Find the average water content in two layers. The upper cell has lower and upper boundaries that are 1 and 1.2 m above the datum. The lower cell has lower and upper boundaries that are 0.8 and 1.0 m above the datum. Both cells are in hydraulic equilibrium with the water table. The matric potential, h_c, at the center of the upper cell is – 0.5 m. Use the Brooks-Corey parameters for Wagram loamy sand.**

The water table elevation is 1.0 m below the center of the cell. The center of the cell is 1.1 m above the datum so the water table is located 0.6 m above the datum.

The bubbling pressure is 0.3 m so the bubbling pressure elevation is 0.9 m above the datum.

The cell is above the bubbling pressure elevation so Eq. 27.27 can be used to estimate the average water content in the cell.

$$\theta = (\theta_s - \theta_r)\left(\frac{h_b}{h_c}\right)^\lambda + \theta_r$$

$$= (0.305 - 0.044)\left(\frac{0.3}{0.5}\right)^{1.27} + 0.044 = 0.18$$

The cell below contains the bubbling pressure elevation so calculate as follows.

$$d_{cell} = \theta_s(z_{hb} - z_L) + \theta_r(z_u - z_{hb}) + \frac{(\theta_s - \theta_r)h_{ba}^\lambda}{-\lambda + 1}\left((z_u - z_{WT})^{-\lambda+1} - (h_{ba})^{-\lambda+1}\right)$$

$$d_{cell} = 0.305(0.9 - 0.8) + 0.044(1.0 - 0.9) + \frac{(0.261)0.3^{1.27}}{-1.27 + 1}\left((1 - 0.6)^{-0.27} - (0.3)^{-0.27}\right)$$

$$d_{cell} = 0.0566 \ m$$

$$\theta = d_{cell}/\Delta z = 0.0566/0.2 = 0.28$$

23. **Calculate the average water content in a cell that has upper and lower limits that are 1.4 m and 1.2 m** **above the datum. Use the parameters listed in question 20.**

$$a = 1,$$
$$b = 1 - 1/n = 1 - 1/1.5 = 0.333$$
$$c = 1 + 1/n = 1 + 1/1.5 = 1.667$$
$$w_L = -((a(z_L - z_{WT}))^n) = -\left((0.06(1.2 - 1.0)*100)^{1.5}\right) = -1.31$$
$$w_u = -((a(z_u - z_{WT}))^n) = -\left((0.06(1.4 - 1.0)*100)^{1.5}\right) = -3.72$$

$$hg(a, b, c, wl/(wl - 1)) = 1.661$$
$$hg(a, b, c, wu/(wu - 1)) = 1.299$$

$$d_{cell} = \theta_r(z_u - z_L) + (\theta_s - \theta_r)(z_u - z_{WT})(1 - w_u)^{1/n-1} {}_2F_1\left(1, 1 - \frac{1}{n}; 1 + \frac{1}{n}, \frac{w_u}{w_u - 1}\right)$$
$$-(\theta_s - \theta_r)(z_L - z_{WT})(1 - w_L)^{1/n-1} {}_2F_1\left(1, 1 - \frac{1}{n}; 1 + \frac{1}{n}, \frac{w_L}{w_L - 1}\right),$$
$$d_{cell} = 0.08(1.4 - 1.2) + (0.45 - 0.08)(1.4 - 1)(1 - (-3.72))^{1/1.5-1}*1.299$$
$$-(0.45 - 0.08)(1.2 - 1)(1 - (-1.31))^{1/1.5-1}*1.661 = 0.0654 \ m$$

$$\theta = d_{cell}/\Delta z = 0.0654/0.2 = 0.327$$

24. **A crop requires 0.006 m/day evapotranspiration. Calculate the maximum distance between the water table and the bottom of the root zone for sub irrigation without water stress. Use Wagram loamy sand parameters. Compare the discretized solution (Eq. 28.32) to Anat's Eq. (28.31). The saturated hydraulic conductivity of Wagram loamy sand is 0nnnn144 s**

Based on the discretized solution, if the water table is set at 0.52 m depth below the root zone, then the matric potential is zero at the water table.

The Anat equation calculation is between 0.54 m and 0.55 m below the root zone for an upward flux rate of 0.006 m/day.

25. Repeat Example 28.3; however, use the parameters for sandy loam in the *WINDS* model. Make sure to change the initial water content in the Active Data page to field capacity (0.21) before copying the data to Crop_data. Make sure that the final DOY is set to 200 days (cell E3) in order to run the simulation for the entire period. Show the water content, matric potential, and matric potential + elevation graphs. The Matric potential graph is in the *Matric potential* worksheet. Discuss results.

As with Example 28.3, redistribution takes a long time at field capacity. The reason for this is that the matric potential is approximately -2 m. The hydraulic conductivity at the low matric potential is very low. The redistribution ceases when the matric potential + elevation is the same in all cells.

26. Repeat Example 28.3; however, use the parameters for sand in the *WINDS* model. Make sure to change the initial water content in the Active Data page to field capacity (0.1) before copying the data to Crop_data. Show the water content, matric potential, and matric potential + elevation graphs. The Matric potential graph is in the *Matric potential* worksheet. Discuss results. Is there reason to believe that the field capacity estimate may be too high?
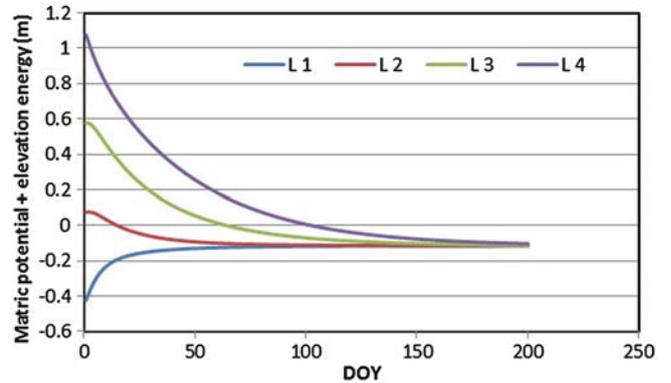
Although more water drained to the lower cells in this example, the field capacity estimate may be reasonable. The drainage did not occur immediately, and field capacity is the amount of water held by the soil 2 days after irrigation. Redistribution ceased after equilibrium.

27. Repeat Example 28.10; however, use the parameters for sand in the *WINDS* model. Show the water table graph and the water content graph. Evaluate drainage rate multipliers 0.01 and 0.02. The multiplier can be changed in the *Drainage* form, which is accessed from the *Active Data* worksheet.

The first two graphs are for the 0.01 multiplier. The change in water table elevation vs. time is approximately the same as Example 28.10. However, the soil drains to a much lower water content once the water table moves downward.

The drainage rate is much faster for the 0.02 multiplier (following pages).
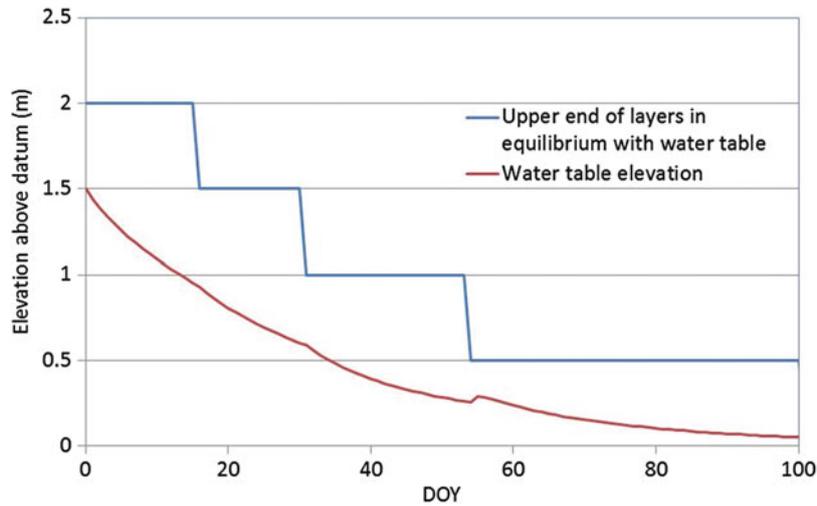
The following graphs are for the 0.02 multiplier
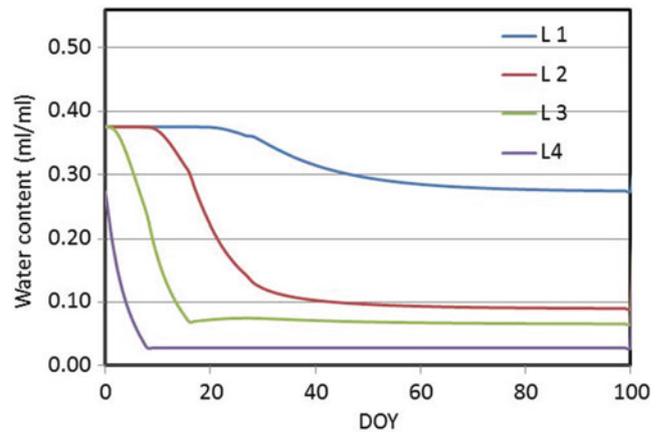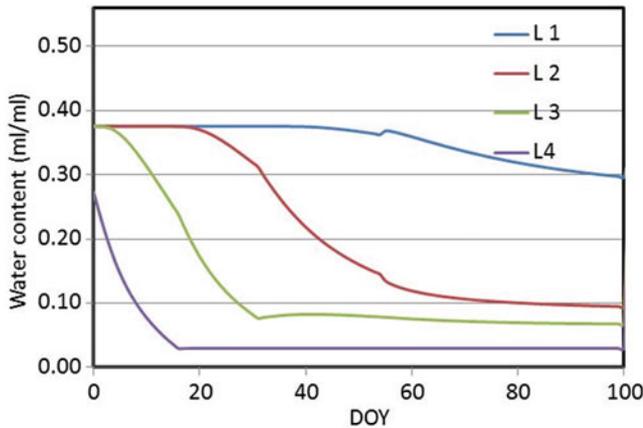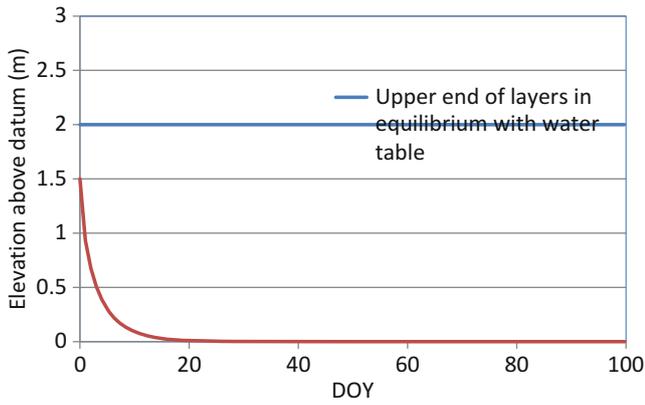
28. Repeat Example 28.10; however, use the parameters for clay in the *WINDS* model. Show the water table graph and the water content graph. Evaluate drainage rate multiplier 0.02. The multiplier can be changed in the *Drainage* form, which is accessed from the *Active Data* worksheet. Explain the results.

The clay soil did not release water as the water drained. Thus, the water table was lowered quickly, but the soils remained saturated.

29. Repeat Example 28.12; however, use the parameters for sandy loam in the *WINDS* model. Increase the drainage rate multiplier to 0.03. Set the initial elevation of the water table at 0.2 m. Show the water content graph and the water table elevation graph.
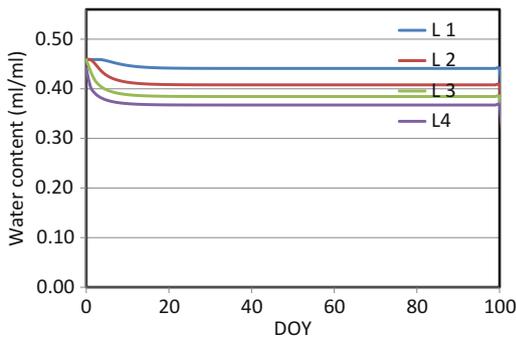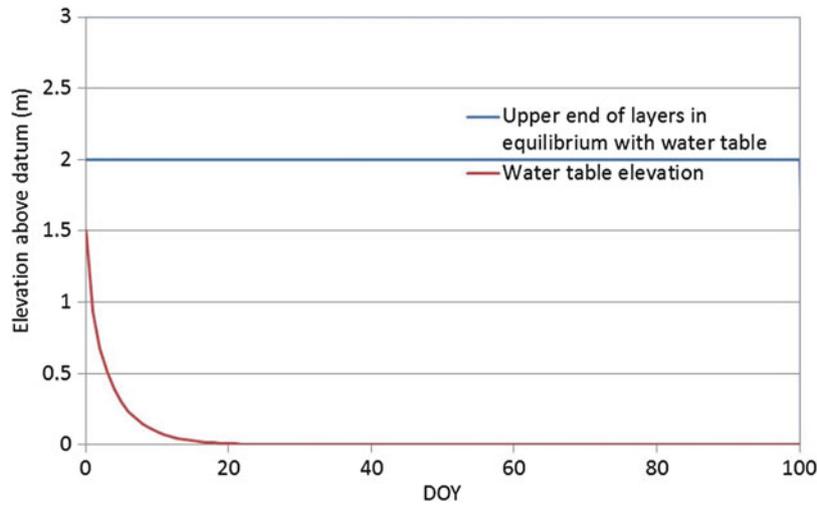
The high drainage rate keeps the soil dry. If not for the high rate, the model would bomb due to the water table being at the soil surface. Just being honest.
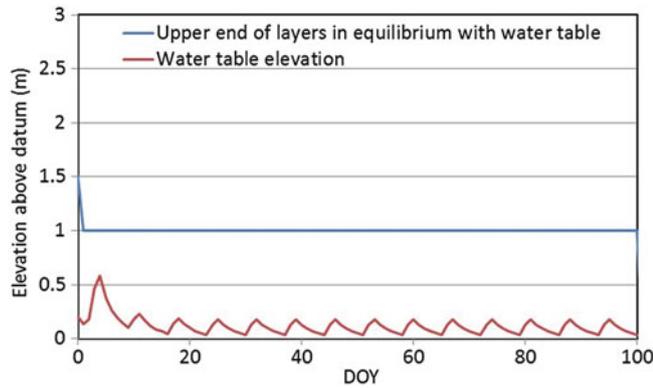
Chapter 29: Solutions

1. Based on Fig. 29.8, estimate the midseason crop coefficient (around DOY 200). Also estimate the maximum soil evaporation coefficient early in the season and during the midseason.

The crop coefficient is 1.0 on DOY 200 since the ET is the same as reference ET.

2. Why would the dual crop coefficient provide a better comparison between two irrigation methods such as infrequent surface irrigation of a crop and frequent minisprinkler irrigation?

The dual crop coefficient accounts for surface wetting. Frequent wetting leads to greater evaporation.

3. Based on Fig. 29.8, when would the use of a dual crop coefficient be superior to a single crop coefficient, during early season or midseason? How could you adjust a single crop coefficient to reflect the frequency of rainfall and irrigation events during the early season?

The dual crop coefficient is superior during the early season. FAO56 accounts for frequency of irrigation in the surface crop coefficient.

4. Calculate crop evapotranspiration. Reference evapotranspiration is 10 mm/day. The basal crop coefficient is 0.8 and the soil evaporation coefficient is 0.1. The water stress factor 0.9.

$ET_0 = 10$ mm/day
$ET = 10*0.8*0.9 + 0.1*10 = 7.2 + 1 = 8.2$ mm/day

5. Use the following data to calculate the percent of maximum potential yield due to water stress. There is no salinity stress. The sum of Ky values during the season is 150.

DOY	Actual transpiration (mm/day)	Potential transpiration (mm/day)	Crop sensitivity to water stress	
185	8	8	1.5	(1–8/8) = 0
186	7	8	1.5	(1–7/8) 1.5 = 0.1875
187	6	8	1.5	(1–6/8) 1.5 = 0.375
188	5	9	1.5	(1–5/9) 1.5 = 0.67
189	4	9	1.5	(1–4/9) 1.5 = 0.83
190	3	10	1.5	(1–3/10) 1.5 = 1.05
191	7	9	1.5	(1–7/9) 1.5 = 0.33
192	8	8	1.5	(1–8/8) 1.5 = 0

Total potential transpiration during this period is 69 mm. Total reduction = 3.44

$(1 - 3.44/150) = .977 \rightarrow 97.7\%$ of maximum yield

6. Calculate the depths of water extracted and the final water content for the four layers in the table. MAD is 0.4, ET_0 is 6 mm, K_{cb} is 0.6, and K_w is 0.05. Field capacity is 0.19 and permanent wilting point is 0.10. Assume that there is no evaporation due to full canopy cover.

Layer number	Lower boundary (m)	Initial water content	Fraction transpiration
4	0.1	0.13	0.05
3	0.4	0.17	0.6
2	0.8	0.18	0.3
1	1.2	0.22	0.05

Calculate the threshold water content

$\theta_t = \theta_{FC} - (\theta_{FC} - \theta_{PWP})\,p = 0.19 - (0.19 - 0.10)*0.4$
$= 0.154$

Layer	Nominal fraction	Adjustment	First estimate	Final fraction
4	0.05	(0.13–0.10)/ (0.154–0.10) =0.55	0	0
3	0.6	(0.17–0.10)/ (0.154–0.10) > 1	0.6	0.6/ 0.95 = 0.632
2	0.3	(0.18–0.10)/ (0.154–0.10) > 1	0.3	0.3/ 0.95 = 0.316
1	0.05	(0.22–0.10)/ (0.22–0.10) > 1	0.05	0.05/ 0.95 = 0.052
			Sum 0.95	Sum 1.0

The average percent depletion is less than p so there is no reduction in ET

$$\text{Transpiration} = ET_0 K_{s-water} K_{cb} = 6 \text{ mm/day}*1*0.6$$
$$= 3.6 \text{ mm}$$

Layer	Fraction	Transpiration (mm)	Final water content (ml/ml)
4	0	3.6(0) = 0 mm	0.13–(0/1000)/0.1 = 0.13
3	0.632	3.6(0.632) = 2.28 mm	0.17–(2.28/1000)/0.3 = 0.162
2	0.316	3.6(0.316) = 1.14 mm	0.18–(1.14/1000)/0.4 = 0.177
1	0.052	3.6(0.052) = 0.18 mm	0.22–(0.18/1000)/0.4 = 0.2196

7. Run the *WINDS Chapter 29 surface irrigation model*. Use the data from Example 29.3, but redo the irrigation schedule (IRR_01 worksheet) and depths such that no more than 14 mm water is lost to leaching after each irrigation (use the irrigation leaching graph in the Water Content worksheet or column CX) and no stress occurs (MAD is 0.5, percent depletions are listed in column DF and the *percent depletion* graph) before DOY 240. Let the fraction wetted (*ET_fractions worksheet*) be 1.0 for the entire growing season. Print out the *ETc*, *irrigation and leaching*, and *water content* graphs from the *Water_content* worksheet. Discuss how you might automate this adjustment process in the computer program. Discuss whether the required number of irrigations is practical. Consider whether the stress is overestimated in the early season. Also consider the effect of frequent irrigations on ETc (see ETc graph).
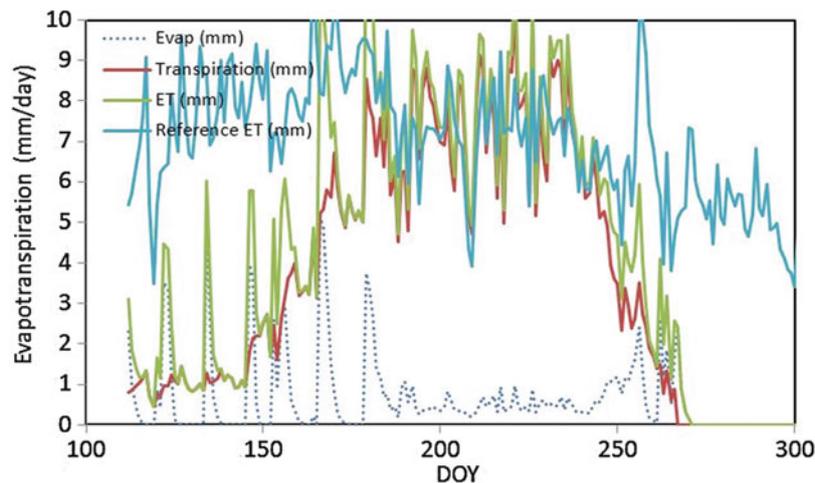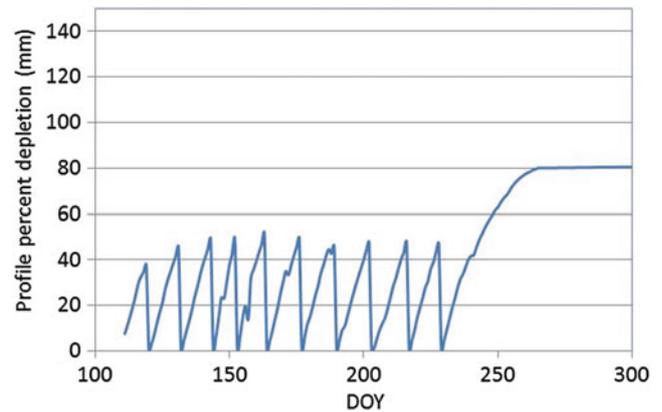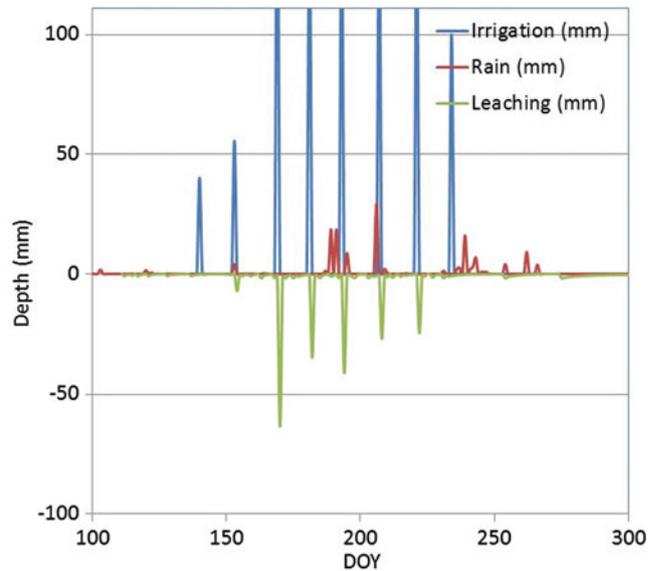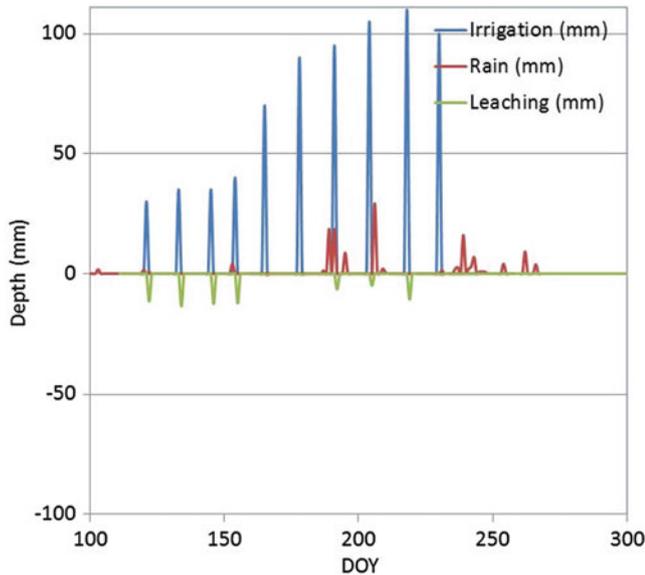
The program could be adjusted by requiring irrigation every time that depletion reaches 50 %. Depths could be adjusted based on the calculated leaching depth.

Ten irrigation events would require extra labor. It may not be economically practical. Also efficiency might be reduced with frequent shallow irrigation events.

It is possible that roots would just grow down to water and the plant would not experience any stress early in the season with the original irrigation schedule.

Frequent irrigations in the early season does lead to increased evaporation loss.

8. Run the *WINDS Chapter 29 surface model*. Change the soil type to clay loam. Print out the percent depletion graph from the *Water_content* worksheet. Compare to problem 7 and discuss the effect of soil type on irrigation scheduling and deep leaching. How could the deep leaching have been prevented with the same large irrigation depths?

The irrigation schedule had no stress, but the problem is that the soil water was not depleted before the large irrigation events so a similar amount of wasted water is observed. The irrigation events should have been spaced further apart to prevent deep leaching.
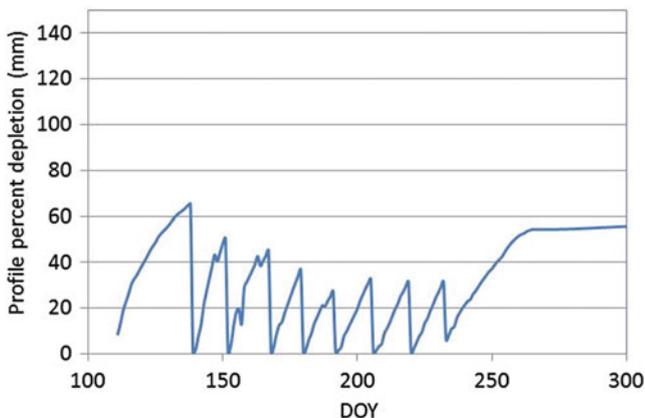
9. Initial water content in the soil profile before flood irrigation is 0.15, Ks = 0.2 cm/hr, and depth of ponded water is 10 cm. Plot the infiltration rate vs. time curve for ponded infiltration. Calculate infiltration rate every 0.1 hours with a spreadsheet. Calculate the infiltration rate and depth for 3 hours. Also plot the cumulative infiltration.

10. An irrigation event is 12 hours long. The depth of ponded water is 5 cm. Bubbling pressure = 0.3 m and saturated water content = 0.305. The antecedent water content is 15 %. Saturated hydraulic conductivity = 0.2 cm/hr. Calculate by hand for the first two time steps, Use time steps = 0.1 hr. Run the *1 layer ponded* worksheet to find the depth infiltrated after 12 hours. You may need to adjust the columns in order to make it work correctly. One of the challenges of Green-Ampt infiltration is to find an assumed depth of infiltration before the first time step, which results in a smooth overall curve. Adjust the initial infiltrated depth until the curve is smooth. Investigate the sensitivity of the estimate of total infiltration over the entire irrigation event to the initial assumed depth of infiltration. Print out the infiltration rate in cumulative infiltration curves. Based on the graph, what term in the Green-Ampt equation does the final rate of infiltration approach.

$$v_{Darcy} = K_s \frac{h_f}{L_f} = K_s \frac{H_0 + S_{av} + L_f}{L_f} = \frac{(H_0 + S_{av})K_s}{L_f} + K_s$$
$$\theta_S - \theta_I = M = 0.305 - 0.15 = 0.155$$
$$S_{av} = 0.76*h_b = 0.76*0.30 \ m = 0.23 \ m = 23 \ cm$$
$$H_0 = 5 \ cm$$

Initial depth of infiltration (before the first calculation) equals Ks, 0.2, resulting in a smooth curve. With M = 0.15, to the initial depth of the wetting front is 1.33.

$$\frac{di}{dt} = \frac{(H_0 + S_{av})K_s}{L_f} + K_s$$

$$= \frac{(5 + 23)0.2 \; cm/hr}{1.33 \; cm} + 0.2 \; cm/hr = 0.83 \; cm/hr$$

Depth of infiltration

$$i = 0.83 \; cm/hr * 0.1 \; hr = 0.083 \; cm$$

Total depth of infiltration after first time step

$$i = 0.2 \; cm + 0.083 \; cm = 0.283 \; cm$$

Depth of wetting front

$$L = i/M = 0.283/0.15 = 1.89 \; cm$$

Next time step. Calculation of infiltration rate in the second time step.

$$\frac{di}{dt} = \frac{(H_0 + S_{av})K_s}{L_f} + K_s$$

$$= \frac{(5 + 23)0.2 \; cm/hr}{1.89 \; cm} + 0.2 \; cm/hr = 0.65 \; cm/hr$$

Depth of infiltration

$$i = 0.65 \; cm/hr * 0.1 \; hr = 0.065 \; cm$$

Total depth of infiltration after first time step

$$i = 0.283 \; cm + 0.065 \; cm = 0.35 \; cm$$

Depth of wetting front

$$L = i/M = 0.35/0.15 = 2.31 \; cm$$
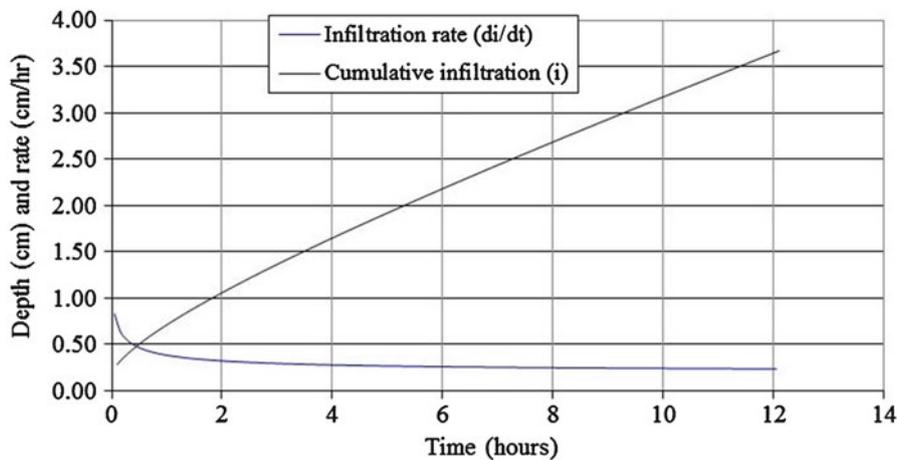
Investigation of sensitivity

Initial infiltration (cm)	Total infiltration (cm)
0.2	3.67
0.5	3.79
1	4.09

There is about a 10 % change in total infiltration with an increase of 5 times in the initial depth estimate.

The final rate of infiltration approaches the saturated hydraulic conductivity.

11. For the parameters in question 10, change the depth of ponding to 10 cm. Evaluate whether increasing the

depth of ponding plays a significant role in infiltration in the case of typical depths used in surface irrigation events.

The infiltration increased from 3.67 to 3.80. Thus, depth of ponding has very little effect in the range of typical surface irrigation depths.

12. For the parameters in question 10, change the initial water content to 10 % and 20 %, and 25 %. Evaluate whether antecedent water content plays a significant role in infiltrated depth and depth of the wetting front.

Changing antecedent water content has a significant effect on infiltration and even more on depth to the wetting front.

Antecedent water content	M	Depth infiltrated (cm)	Depth to wetting front (cm)
10 %	0.205	4.25	20
15 %	0.155	3.72	24
20 %	0.105	3.23	31
25 %	0.055	2.82	52

13. A soil has two layers, both 20 cm depth. The upper layer (0–20 cm) has a drainable porosity equal to 0.2. The lower layer (20–40 cm) has a drainable porosity equal to 0.10. The suction at the wetting front in both layers is 20 cm, and the depth of ponding is 10 cm. The saturated hydraulic conductivity in both layers is 0.6 cm/hr. Plot the infiltration rate and cumulative infiltration for 12 hours of ponding. Compare to a uniform drainable porosity in the entire soil profile of 0.2. Is there a significant different in infiltration rate once the wetting front reaches the 2nd layer due to the changed drainable porosity?

Use the *Two layers* worksheet but set the storm intensity to a high number so there was no limitation on water.

There is little change due to the changed drainable porosity in the lower layer. Infiltration with M = 0.1 in lower layers is 13.67 cm. Infiltration with M = 0.2 is 14.85 cm
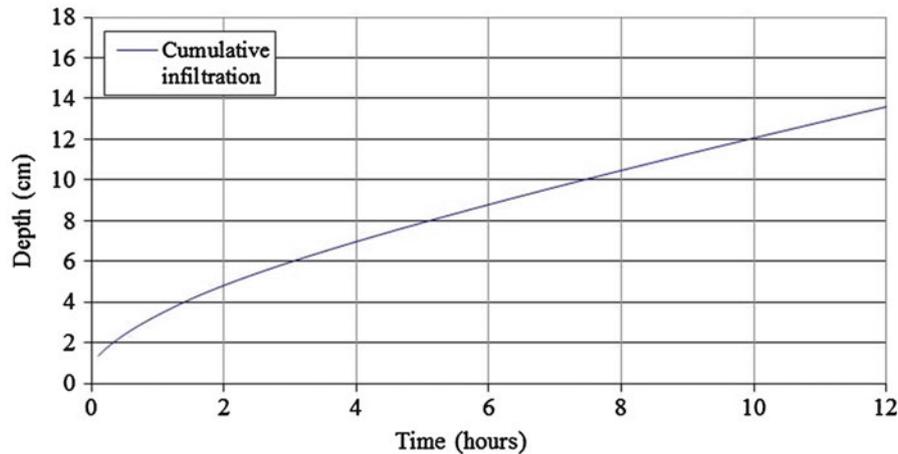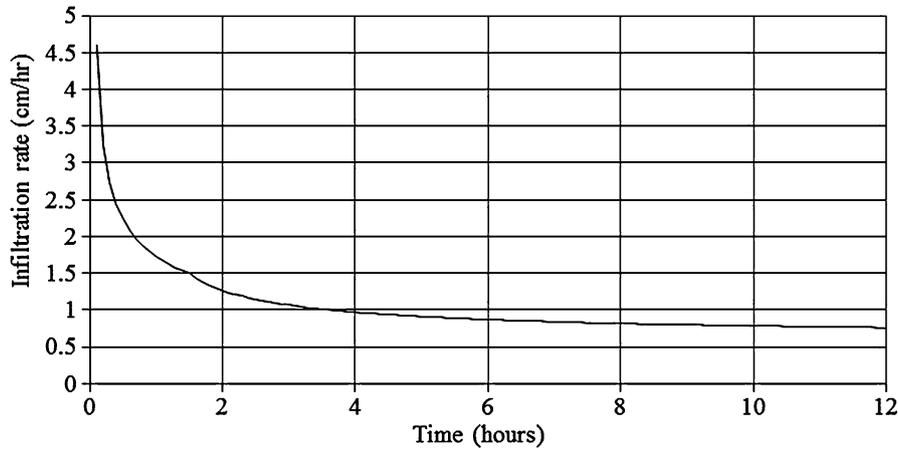
14. Redo problem 13, but let the conductivity of the lower layer equal 0.3 cm/hr and M = 0.1. Calculate effective hydraulic conductivity as the geometric mean and show a sample calculation of the weighted conductivity. Plot the infiltration rate and the depth of the wetting front vs. time. Evaluate the effect of decreased conductivity in the lower layer on cumulative infiltration and how this might influence irrigation practices.

This if statement calculates the weighted conductivity.

UBtwo is depth of top of lower layer

L13 is depth of the wetting front

Ks is saturated hydraulic conductivity of upper layer

Kstwo is saturated hydraulic conductivity of lower layer

$$= IF(L13 < UBtwo, Ks, L13/ \\ (UBtwo/Ks + (L13 - UBtwo)/Kstwo))$$

Example, depth is the wetting front is at 39.2 cm with Ks = 0.6 and Kstwo = 0.3.

$$Keff = 39.2/(20/0.6 + (39.2 - 20)/0.3) = 0.40$$

The effect of decreased conductivity on infiltration is significant, dropping total infiltration to 10.59 cm. One possible method of dealing with a low conductivity lower layer might be to have more frequent and shallower irrigation events.

15. Redo Example 29.5 (*WINDS Chapter 29 tropical*), but use a sandy loam soil. Print the ET/transpiration graph and the water content graph. Compare the crop water stress during the season with and without water harvesting. Make sure to change the initial water content to field capacity.

With water harvesting
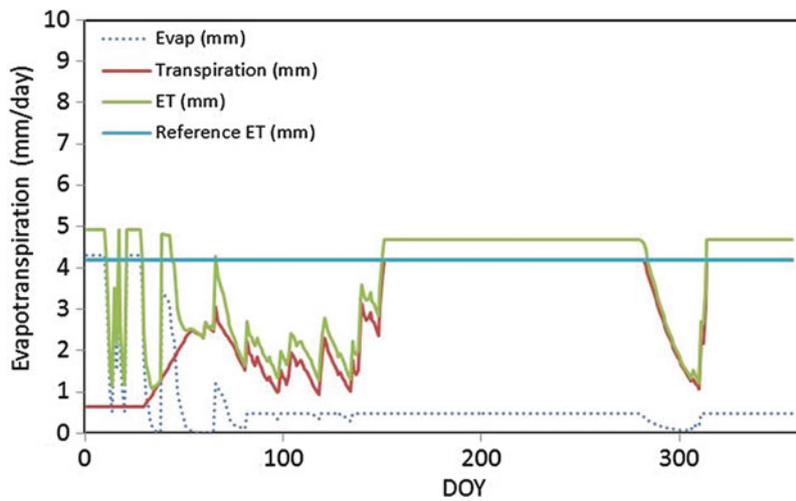
With water harvesting
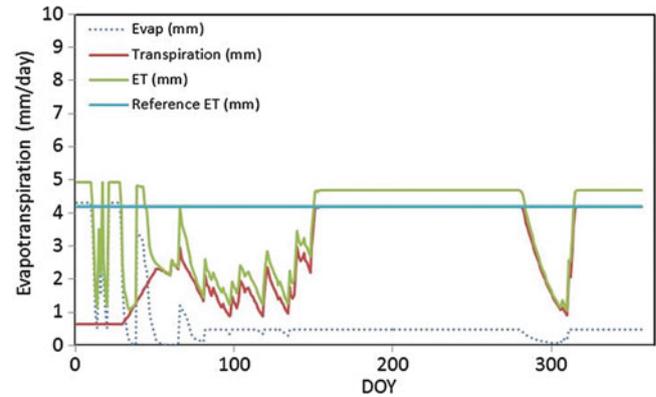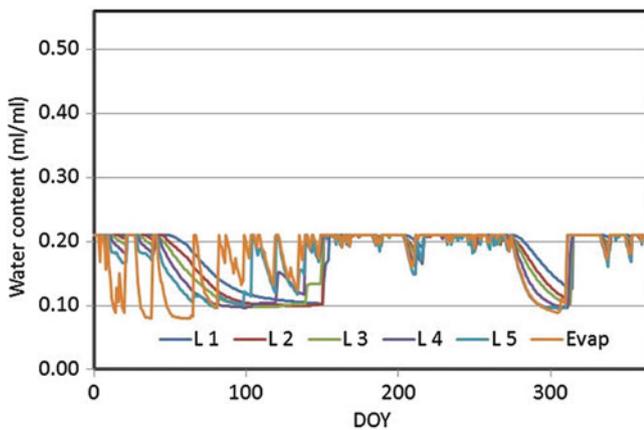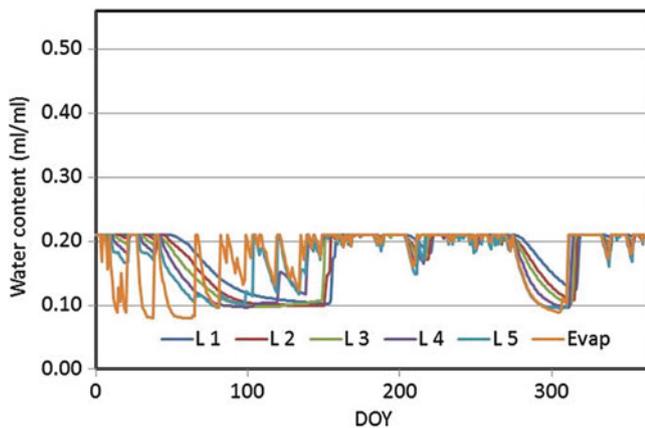
There is almost no difference in water stress with and without water harvesting in the high infiltration rate soil.

Chapter 30: Solution

1. List the positive and negative environmental aspects of subsurface drainage.

   - The impact of water table management practices is primarily on receiving surface water.
   - Subsurface drainage systems reduce erosion. Overland flow is reduced while the total surface and subsurface drainage increases at the edge of the field.
   - Subsurface drainage results in significant reduction of sediment and pollutants (transport to streams), primarily phosphorous and potassium not in solution.
   - Subsurface drainage sometimes results in increased nitrate nitrogen concentrations delivered to receiving water; however, controlling subsurface drainage can reduce the nitrate nitrogen delivered.
   - Water table management provides the capability to enhance best management practices that deal with field surface nutrient management and erosion control.
   - Subsurface drainage intercepts downward percolating water, which allows for monitoring water quality and providing treatment if needed.
   - Water table management practices can contribute to reducing nonpoint pollution alone and with other practices.

2. What measures are recommended by the NRCS recommends to reduce the impact of drained water from farmland on the environment.
   - Implement wetland restoration areas, denitrifying ponds, or managed riparian zones where drainage water could be "treated" to remove excess nitrate-N before discharge into drainage ditches or streams.
   - Design new subsurface drainage systems or retrofit existing drainage systems to manage soil water and water table levels through controlled drainage or subirrigation, lowering concentrations of nitrate-N in shallow ground water. The cost of retrofitting existing systems for subirrigation must be compared to the benefit of increased yields.
   - Use alternative cropping systems that contain perennial crops to reduce nitrate-N losses. Obtaining a market and a satisfactory economic return presents some barriers.
   - Fine tune fertilizer N management. Research shows that applying the correct rate of N at the optimum time substantially affects the reduction of nitrate-N losses.
   - Improved management of animal manure would contribute to lowering nitrate-N losses in livestock-producing areas. Knowing the nutrient content and application rate of the manure, spreading it uniformly, and incorporating it in a timely manner would all lead to better management and confidence in manure N as a nutrient source.

3. List the features that should be noted in a drainage reconnaissance survey.
   - Location and extent of any wetlands.
   - The areas in which crops show damage, as pointed out by the farmer, indicated by the aerial photograph, or noted in personal observations.
   - Personal observations of unique landscape features, ecologically significant areas, land use patterns, operation (land management) aspects, and site visibility.
   - Topography and size of the watershed area
   - Size, extent, and ownership of the area being considered for drainage.
   - Location of the drainage outlet and its condition.
   - Location, condition, and approximate size of existing waterways.
   - Presence of cultural resources.
   - Potential impacts outside the area being evaluated.
   - General character of soil throughout the area needing drainage, including land capability, land use, crops and yields, and salinity or sodicity.
   - High-water marks or damaging floods and dates of floods.
   - Utilities, such as pipelines, roads, culverts, bridges, and irrigation facilities and their possible effect on the drainage system (see NEM part 503).
   - Sources of excess water from upslope land or stream channel overflow and possible disposal areas and control methods.
   - Condition of areas contributing outside water and possible treatment needed in these areas to reduce runoff or erosion.

- Condition of any existing drainage system and reasons for failure or inadequacy. Old subsurface drainage systems that have failed because of broken or collapsed sections may well be the cause of a wet area.
- Estimate of surveys needed.
- Type and availability of construction equipment.
- Feasibility.

4. Based on the geometry of Fig. 30.1 and the derivation of Eq. 30.1, are drains designed for saturated flow over the top of the drain?

No.

5. Derive a drainage coefficient equation for flow with the water table directly over the drain. Compare the ratio of flow rates based on your equation and Eq. 30.4. Discuss why drains are not designed based on the flow rate that takes place when the water table is directly over the drain.

The cross sectional area is $2\pi D$, and the energy gradient is 1.0

$$q_{WT} = KA\frac{\Delta H}{\Delta x} = 2\pi KD$$

$$q_d = KD\pi\frac{m_o}{L/2} = \frac{2\pi K m_o D}{L} \tag{11}$$

The ratio is m/L, which can be in the range of 50 or 100. Thus, drains would need to carry flows that are 50–100 times greater if they were designed for the water table directly over the drain.

6. Derive Eq. 30.6 from Manning's equation assuming that the pipe is full and half full and determine whether the equation assumes that the drain is flowing half full of full.

$$Q = \frac{AR^{2/3}S_0^{0.5}}{n} = \frac{\pi D^2/4\left(\pi D^2/4\pi D\right)^{2/3}S_0^{0.5}}{n} = \frac{\pi D^{2.67}/4^{1.67}S_0^{0.5}}{n}$$

$$Q = AD_c$$

$$D^{2.67} = \frac{4^{1.67}nQ}{\pi S^{0.5}} = \frac{4nQ}{\pi S^{0.5}} = 3.23^{0.375}(nAD_c)^{0.375}S^{-0.1875}$$

$$= 1.55(nAD_c)^{0.375}S^{-0.1875}$$

Note: A is used both for field area and Pipe inside area. D is used for inside diameter and D_c refers to the drainage coefficient

Unit conversion

Manning's equation uses units of m/sec. Convert to mm/day

$$1.55(nAD_c)^{0.375}S^{-0.1875}$$

$$= 1.55\left[\left(\frac{m^3}{sec}\right)\left(\frac{ha}{10,000\ m^2}\right)\left(\frac{1,000\ mm}{m}\right)\left(\frac{24*60*60\ sed}{day}\right)\right]^{0.375}$$

$$ID = 1.55*29.9*(nAD_c)^{0.375} = 46.5*(nAD_c)^{0.375}S^{-0.1875}$$

The ID is slightly overpredicted by Eq. 11.6 if the pipe is flowing full as in this derivation. Thus, the pipe is not completely full.

Calculate the diameter required for a half full pipe. A half full pipe would have the following equation (area is half but wetted perimeter is unchanged). The level of pipe filling can be found by .

Section	Area, A	Wetted perimeter, P	Hydraulic radius, R	Top width, T
	$\frac{1}{8}(\theta - \sin\theta)d_0^2$	$\frac{1}{2}(\theta)d_0$	$\frac{1}{4}\left(1 - \frac{\sin\theta}{\theta}\right)d_0$	$\left(\sin\frac{\theta}{2}\right)d_0$
Culvert				
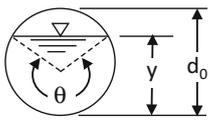
$$Q = \frac{AR^{2/3}S_0^{0.5}}{n} = \frac{\pi D^2/8\left(\pi D^2/4\pi D\right)^{2/3}S_0^{0.5}}{n} = \frac{\pi D^{2.67}/2*41.67 S_0^{0.5}}{n}$$

$$2.0(nAD_c)^{0.375}S^{-0.1875} = 2.0\left[\left(\frac{m^3}{sec}\right)\left(\frac{ha}{10,000\ m^2}\right)\left(\frac{1,000\ mm}{m}\right)\left(\frac{24*60*60\ sed}{day}\right)\right]^{0.375} \backslash$$

$$ID = 2.0*29.9*(nAD_c)^{0.375} = 59.8*(nAD_c)^{0.375}S^{-0.1875}$$

The coefficient is 51.7 which is approximately halfway between the full and half pipe coefficient. Thus, Eq. 11.6 assumes that the pipe is somewhere in the range of 3/4 full.

7. A 5 ha area has a drainage coefficient of 19.1 mm/day. The drain slope is 0.3 %. Calculate the required drain size.

$$ID = 51.7(D_c*A*n)^{0.375}s^{-0.1875}$$
$$= 51.7(19.1*5*0.015)^{0.375}0.003^{-0.1875} = 176 \ mm$$

Recalculate based on half full drain and n = 0.017 with Eq. 11.6.

$$ID = 51.7(D_c*A*n)^{0.375}s^{-0.1875}$$
$$= 51.7(19.1*5*0.015)^{0.375}0.003^{-0.1875} = 213 \ mm$$

The ID calculated based on the half full drain and slightly higher n is still slightly lower than that calculated with the figure, but it is closer than the calculation with the unmodified Eq. 11.6.

8. Calculate the required diameter of a subsurface drain based for the following parameters.

Let Manning's n	0.017
Drain elevation above impermeable layer	3 m
Drain slope	s = 0.2 m/100 m
Hydraulic conductivity	K = 2 m/day
Drain spacing	L = 60 m.
Length of drain pipe	L_d = 500 m
Maximum WT height above drains:	m_0 = 2 m - 0.48 m = 1 m.
Average depth of flow to drain	D = d + m_0/2 = 3 + 1/2 = 3.5 m.

Calculate drainage coefficient.

$$D_c = \frac{2,000\pi K m_o D}{L^2} = \frac{2,000\pi*2*2*3.5}{60^2} = 24.4 \ mm/day$$

Calculate pipe diameter

$$ID = 51.7(D_c*A*n)^{0.375}s^{-0.1875}$$
$$= 51.7(24.4*500*60/10,000*0.017)^{0.375}*0.002^{-0.1875}$$
$$= 180 \ mm$$

The next larger drain diameter is 205 mm (8 in).

9. Can a geotextile filter be used in a loam soil? What mesh is recommended ?

Either a sand and gravel or a geotextile filter is acceptable.

A loam soil has an even distribution of sand, silt, and clay with a smaller percentage of clay than the others. The Number 200 sieve only catches sand particles (Fig. 11.10). Thus, most of the particles in the soil would pass the Number 200 sieve. If this is the case, the filter mesh size should be the same as a number 50 sieve, 0.297 mm.

Chapter 31: Solution

1. Give two reasons for installing subsurface drainage in a field and discuss its importance.

Leach salts from the soil, and lower the water table. Drainage removes excess water from the soil profile. Evapotranspiration removes water and leaves much of the salts in the water in the soil, salinizing the soil. If the water table is perched, then it is impossible to leach these salts from the soil. Water logging of soils can restrict the diffusion of oxygen from the atmosphere to the roots. Lack of oxygen will decrease plant yield

2. Describe the two different types of flow to subsurface drains

Just after a storm or irrigation, water flows directly into the drains from above. After the water table intersects the drain, water flows to the drain from the side and below the drain as water flows in response to the hydraulic gradient of the water table.

3. List the water sources and sinks for drained soils.

Water Sources:

Rainfall
Irrigation
Groundwater

Water Sinks:

Evaporation
Transpiration
Drainage
Deep Seepage or leaching

4. Describe the Dupuit Forchheimer assumption and draw flow lines to a subsurface drain according to the Dupuit-Forchheimer assumption.

The Dupuit-Forchheimer assumption is that all flow is horizontal.
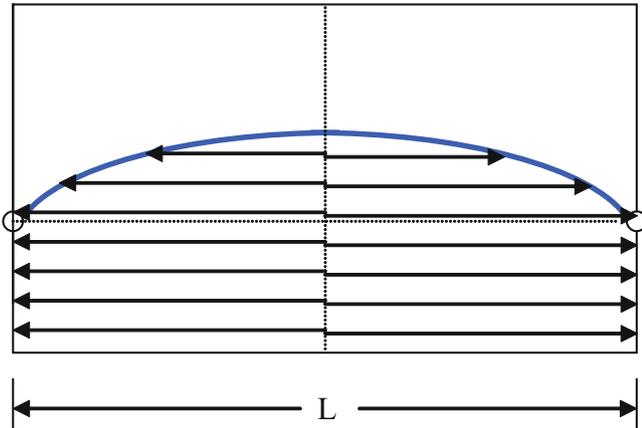
5. Discuss the following drainage systems: open parallel ditches, conventional drainage, water table control, and subirrigation.

Open ditch drainage include open ditches that drain to rivers. They can be very deep and surround the outer parts of fields or they can be shallow and installed within the field.

Conventional subsurface drainage systems are corrugated plastic perforated pipes installed between 1 and 2 m below the soil surface.

Water table control systems require additional structures in the collection system, but they can prevent excessive drainage in order to preserve water in the soil and supply the plant during dry periods.

Subirrigation systems provide water to the crop by adding water from an outside source. These systems can result in the highest crop yield because they remove water when it is not needed but add water when it is needed.

6. Calculate the yield reduction for corn with the following water table data. Assume that CS is 0.12 from DOY 135–143 and is 0.10 from DOY 144–160. YRDMAX = 102 and DSLOPE = 0.75. When does the storm occur?

DOY	DTWT	DOY	DTWT
135	5	143	5
136	15	144	15
137	24	145	24
138	32	146	32
139	39	147	39
140	44	148	44
141	46	149	46
142	0	150	47

DOY	DTWT	CS	SEW-30	CS SEW
135	5	0.12	25	3
136	15	0.12	15	1.8
137	24	0.12	6	0.72
138	32	0.12	0	0
139	39	0.12	0	0
140	44	0.12	0	0
141	46	0.12	0	0
142	0	0.12	30	3.6
143	5	0.12	25	3
144	15	0.1	15	1.5
145	24	0.1	6	0.6
146	32	0.1	0	0
147	39	0.1	0	0
148	44	0.1	0	0
149	46	0.1	0	0
150	47	0.1	0	0

The stress day index is 14.2

The percent of maximum yield is YRDMAX − DSLOPE * SDI = 102 − 0.75 * 14.2 = 91.3 %

The storm takes place on DOY 142.

7. Why does the water table elevation in Figure 31.5 increase rapidly after a rainstorm and then decrease more and more slowly over time? Discuss the influence of energy gradients.

The water table increases rapidly during a storm (can rise a meter within a matter of minutes). If the soil was recently drained, then very little water is required to fill the pores and cause the water table to rise. If the soil is dry prior to the storm, then the water table will not rise as quickly and possibly not at all. During a storm, infiltration is a vertical process; thus, infiltration is driven by a relatively large energy gradient. However, the energy gradient in the horizontal direction of an elliptical water table is low. If the water table at the midpoint between drains is 1 m higher than the drain and the drains are 100 m apart, then the gradient moving water to subsurface drains may be 1 to 50 (1/50 m/m). As the water table declines, then the gradient also decreases, and water table moves to the drains even slower.

8. Rainfall is 0.02 m / day, and drain spacing is 40 m. Calculate flow rate q_5, at a distance of 10 m from the drain. Find the flow rate into the drain per unit length of drain tubing.

$$q_x = \left(\frac{L}{2} - x\right)R = \left(\frac{40}{2} - 10\right)*0.02 \ m/day = 0.2 \ m^2/day$$

The total flow rate per unit length, q_p, into the drain is

$$q_d = LR = 40*0.02 = 0.8 \ m^2/day$$

9. A drain is placed in the field in the shape of a circle with radius 20 m. Derive equations for the flow rate to a unit length of the drain (m²/day) at any distance from the drain. Let R represent the radius of the drain circle, r = distance from the center of the circle, D = distance from the drain, and P represent the precipitation rate. Only derive an equation for the flow on the inside of the circle.

First derive an equation for the inside of the drain.
The circumference at any distance from the center of the circle
C = 2 π r
The area enclosed by the distance r is
A = π r²
The volume rate of precipitation is PA
The flow per unit area at distance r is
AP/C = π r² P / (2 π r) = rP/2
At the drain, the unit flow to the drain is RP/2

10. Calculate the required spacing between drains. The farmer wants to maintain the water table at least 0.7 m below the soil surface. Yearly rainfall is 1 m/yr. The impermeable layer is 2.5 m below the soil surface. Hydraulic conductivity of the soil is 1 m/day. The conventional practice in the region is to install drains at 1.1 m depth below the soil surface. Drains are standard 4 in (10 cm) diameter drains. Effective drain radius for the 4 in drain is 0.51 cm

Average rainfall (1.0 m/year)/(365 days/year) = 0.00274 m/day.

The drains are 1.1 m below the soil surface. Thus, the water table elevation above the drain, m, is
m = 1.1 m – 0.7 m = 0.4 m.
The elevation of the drain, d, above the impermeable layer is
d = 2.5 m – 1.1 m = 1.4 m.
Make an initial guess of L = 40 m and solve for d_e with equation 10–12 because d/L is much less than 0.3. Spreadsheet calculated values are shown below

L	c	de	new L
40	3.496	1.015	37.68
37.68	3.493	0.998	37.41
37.41	3.493	0.996	37.38

11. Set up a finite difference solution in a spreadsheet in order to solve for water table elevation vs. distance from the drain for the conditions in question 10. Solve for Δz with the finite difference solution at each position by rearranging Darcy's law and solving for Δz, and sequentially calculate the increasing drain elevation beginning at the drain and working toward the midpoint between drains. For the location close to the drain (horizontal distance from drain is less than distance from drain to impermeable layer), set up the flow to the drain as a quarter circle (or slightly more as water table increases with distance from the drain), and calculate head loss as a function of distance from the drain. Where it intersects the drain, let the water table be at the midpoint elevation of the drain. Use Dupuit-Forchheimer solution far from the drain. You should have less than 10 % difference between your solution and the 0.4 m elevation m at the midpoint between drains calculated in question 10.

For the distance from the drain to 1.1 m from the drain the following spreadsheet solution is obtained for the circular geometry.

	A	B	C	D	E	F
1	Distance to midpoint	18.69 m				
2	Precipitation	0.00274 m/day				
3	Hydraulic conductivity	1 m/day				
4	Circle zone dx	0.05 m/day				
5	Distance to impermeable layer	1.1 m				
6						
7	m		q	Water table elevation	cross section	Cross-sectional	dz = 1/K v dx
8	Distance (m)	Flow (m2/day)	above drain midpoint (m (radians)		length (m)	Head loss (m)
9	0.05	0.0510736	0	1.570796327	0.117809725	0.021676309
10	0.1	0.0509366	0.021676309	1.784257068	0.178425707	0.014273896
11	0.15	0.0507996	0.035950205	1.806027398	0.27090411	0.009375937
12	0.2	0.0506626	0.045326143	1.793662362	0.358732472	0.007061335
13	0.25	0.0505256	0.052387477	1.777357402	0.44433935	0.005685474
14	0.3	0.0503886	0.058072952	1.762007889	0.528602367	0.00476621
15	0.35	0.0502516	0.062839162	1.748444113	0.61195544	0.004105822
16	0.4	0.0501146	0.066944984	1.736621915	0.694648766	0.00360719
17	0.45	0.0499776	0.070552174	1.726312941	0.776840823	0.003216721
18	0.5	0.0498406	0.073768894	1.717277378	0.858638689	0.002902303
19	0.55	0.0497036	0.076671198	1.70930589	0.940118239	0.002643476
20	0.6	0.0495666	0.079314674	1.702225432	1.021335259	0.002426559
21	0.65	0.0494296	0.081741232	1.695895367	1.102331989	0.002242047
22	0.7	0.0492926	0.083983279	1.690201705	1.183141194	0.002083124
23	0.75	0.0491556	0.086066403	1.685051747	1.26378881	0.001944771
24	0.8	0.0490186	0.088011175	1.680369655	1.344295724	0.001823207
25	0.85	0.0488816	0.089834382	1.676092947	1.424679005	0.00171553
26	0.9	0.0487446	0.091549912	1.672169761	1.504952785	0.001619473
27	0.95	0.0486076	0.093169385	1.668556733	1.585128897	0.001533238
28	1	0.0484706	0.094702623	1.665217348	1.665217348	0.001455384
29	1.05	0.0483336	0.096158007	1.662120645	1.745226678	0.001384737
30	1.1	0.0481966	0.097542744	1.659240212	1.825164234	0.001320336

For the 1.1 m distance to the midpoint between drains, the following solution is found for the linear geometry. The elevation m is 0.428, which is within 10 % of the elevation m = 0.4.
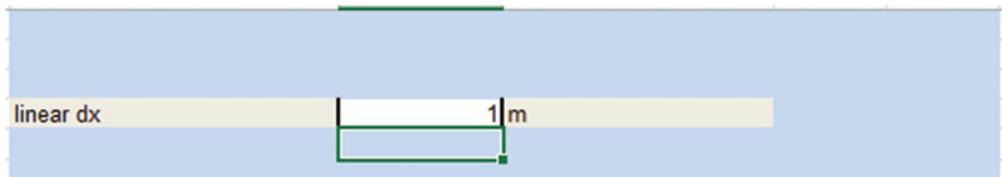
linear dx		1 m			
	q	Water table elevation	Cross-sec	dz = 1/K v	
Distance (m)	Flow (m2/day)	above drain (m)	length (m)	Head loss (	
1.1	0.0481966	0.097542744	1.197543	0.040246	
2.1	0.0454566	0.13778899	1.237789	0.036724	
3.1	0.0427166	0.17451302	1.274513	0.033516	
4.1	0.0399766	0.208029037	1.308029	0.030562	
5.1	0.0372366	0.238591508	1.338592	0.027818	
6.1	0.0344966	0.266409255	1.366409	0.025246	
7.1	0.0317566	0.291655425	1.391655	0.022819	
8.1	0.0290166	0.314474723	1.414475	0.020514	
9.1	0.0262766	0.33498877	1.434989	0.018311	
10.1	0.0235366	0.353300132	1.4533	0.016195	
11.1	0.0207966	0.369495411	1.469495	0.014152	
12.1	0.0180566	0.383647615	1.483648	0.01217	
13.1	0.0153166	0.395818026	1.495818	0.01024	
14.1	0.0125766	0.40605764	1.506058	0.008351	
15.1	0.0098366	0.414408316	1.514408	0.006495	
16.1	0.0070966	0.420903658	1.520904	0.004666	
17.1	0.0043566	0.4255697	1.52557	0.002856	
18.1	0.0016166	0.42842542	1.528425	0.001058	

12. Redo problem 11, but include a sloping geometry ($\theta = 10^0$) for the impermeable layer as shown below. Let the elevation of the drain be 1.1 m above the impermeable layer at the position of the drain. Assume Dupuit-Forchheimer flow in the region far from the drain. Compare the midpoint water table elevation to that calculated in question 11.
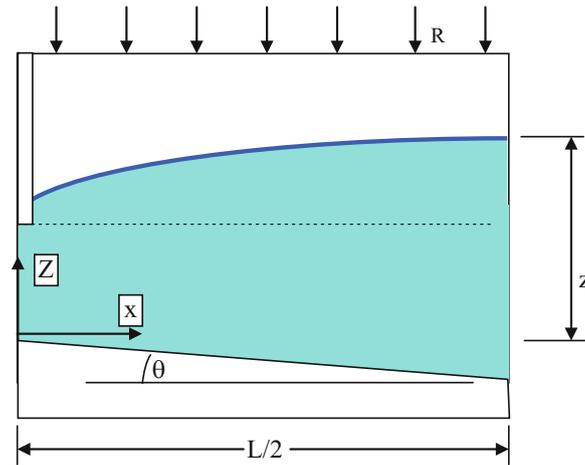
The following equation was placed in column K in order to account for the increasing cross-sectional area due to the sloping impermeable layer, where Imp refers to the depth of the impermeable layer below the drain, directly under the drain.

=J10 + Imp + TAN(2*PI()/360*10)*H10

linear dx		1 m		
theta		10 degrees		

Distance (m)	q Flow (m2/day)	Water table elevation above drain (m)	Cross-sectional length (m)	dz = 1/K v dx Head loss (m)
1.1	0.0481966	0.097542744	1.391502423	0.034636375
2.1	0.0454566	0.132179119	1.602465779	0.028366659
3.1	0.0427166	0.160545778	1.807159418	0.023637428
4.1	0.0399766	0.184183205	2.007123826	0.019917356
5.1	0.0372366	0.204100562	2.203368163	0.016899854
6.1	0.0344966	0.221000415	2.396594998	0.014394005
7.1	0.0317566	0.23539442	2.587315983	0.012273955
8.1	0.0290166	0.247668375	2.775916919	0.010452979
9.1	0.0262766	0.258121354	2.962696878	0.008869149
10.1	0.0235366	0.266990503	3.147893008	0.007476938
11.1	0.0207966	0.274467441	3.331696926	0.006242044
12.1	0.0180566	0.280709485	3.514265952	0.005138086
13.1	0.0153166	0.285847571	3.695731018	0.004144403
14.1	0.0125766	0.289991974	3.876202402	0.003244567
15.1	0.0098366	0.293236542	4.05577395	0.002425332
16.1	0.0070966	0.295661874	4.234526263	0.00167589
17.1	0.0043566	0.297337764	4.412529134	0.000987325
18.1	0.0016166	0.298325089	4.58984344	0.000352212

The midpoint water table elevation is 0.3, which is much lower than the midpoint water table elevation in question

13. Redo question 12, but let $\theta = -4^0$ which means that the impermeable layer slopes upward from the drain rather

than down. Compare to the midpoint water table elevation calculated in question 12.

The midpoint water table elevation is 0.6, which is double the elevation question 12.

| linear dx | 1 m |
| theta | -4 degrees |

Distance (m)	q Flow (m2/day)	Water table elevation above drain (m)	Cross-sectional length (m)	dz = 1/K v dx Head loss (m)
1.1	0.0481966	0.097542744	1.120623251	0.043008745
2.1	0.0454566	0.140551489	1.093705184	0.041562023
3.1	0.0427166	0.182113512	1.065340395	0.040096668
4.1	0.0399766	0.22221018	1.035510251	0.038605702
5.1	0.0372366	0.260815882	1.004189141	0.037081261
6.1	0.0344966	0.297897143	0.97134359	0.035514313
7.1	0.0317566	0.333411456	0.936931091	0.033894275
8.1	0.0290166	0.367305731	0.900898554	0.03220851
9.1	0.0262766	0.399514241	0.863180252	0.030441614
10.1	0.0235366	0.429955855	0.823695054	0.02857441
11.1	0.0207966	0.458530264	0.782342652	0.02658247
12.1	0.0180566	0.485112734	0.73899831	0.024433885
13.1	0.0153166	0.50954662	0.693505383	0.022085769
14.1	0.0125766	0.531632389	0.645664341	0.019478542
15.1	0.0098366	0.551110931	0.595216071	0.016526099
16.1	0.0070966	0.567637031	0.541815358	0.01309782
17.1	0.0043566	0.580734851	0.484986366	0.008982933
18.1	0.0016166	0.589717784	0.424042487	0.003812354

14. Redo question 10 but let hydraulic conductivity of the soil within the top 1.1 m equal 0.3 m/day and below the drain equal 1 m/day.

Find the effective conductivity. Let D_1 be equal to half of the elevation, m, above the drain, 0.3 m, in order to reflect the fact that part of the upper region is submerged and is a function of distance from the drain.

$$K_e = \frac{K_1 D_1 + K_2 D_2}{D_1 + D_2} = \frac{0.3*0.2 + 1*1.4}{0.2 + 1.4} = 0.91 \ m/day$$

Spreadsheet iterations are shown below

L	c	de	new L
40	3.496	1.015	35.44
35.44	3.490	0.981	34.86
34.86	3.489	0.976	34.78

15. With information from question 10, calculate the change in water table elevation over two weeks with the modified Hooghoudt equation. The initial elevation is 0.5 m, and the specific yield, SY_{mid}, is 15 %.

The water table falls at the rate shown in the following figure.

	A	B	C	D	E	F	G	H	I	J	K
1	L	37.38 m									
2	de	0.996 m									
3	initial m	0.5 m									
4	Sm	0.15									
5	Drain depth	1.1									
6											
7											
8		day	m	qp	ddrainage	dm		final m	DTWT		
9		0	0.5	0.133	0.0036	-0.024		0.48	0.6		
10		1	0.48	0.126	0.0034	-0.022		0.45	0.62		
11		2									
12		3									
13		4									
14		5									
15		6									
16		7									
17		8									
18		9									
19		10									
20		11									
21		12									
22		13									
23		14									

(plot: Elevation (m) vs Days, curve labeled Hooghoudt)
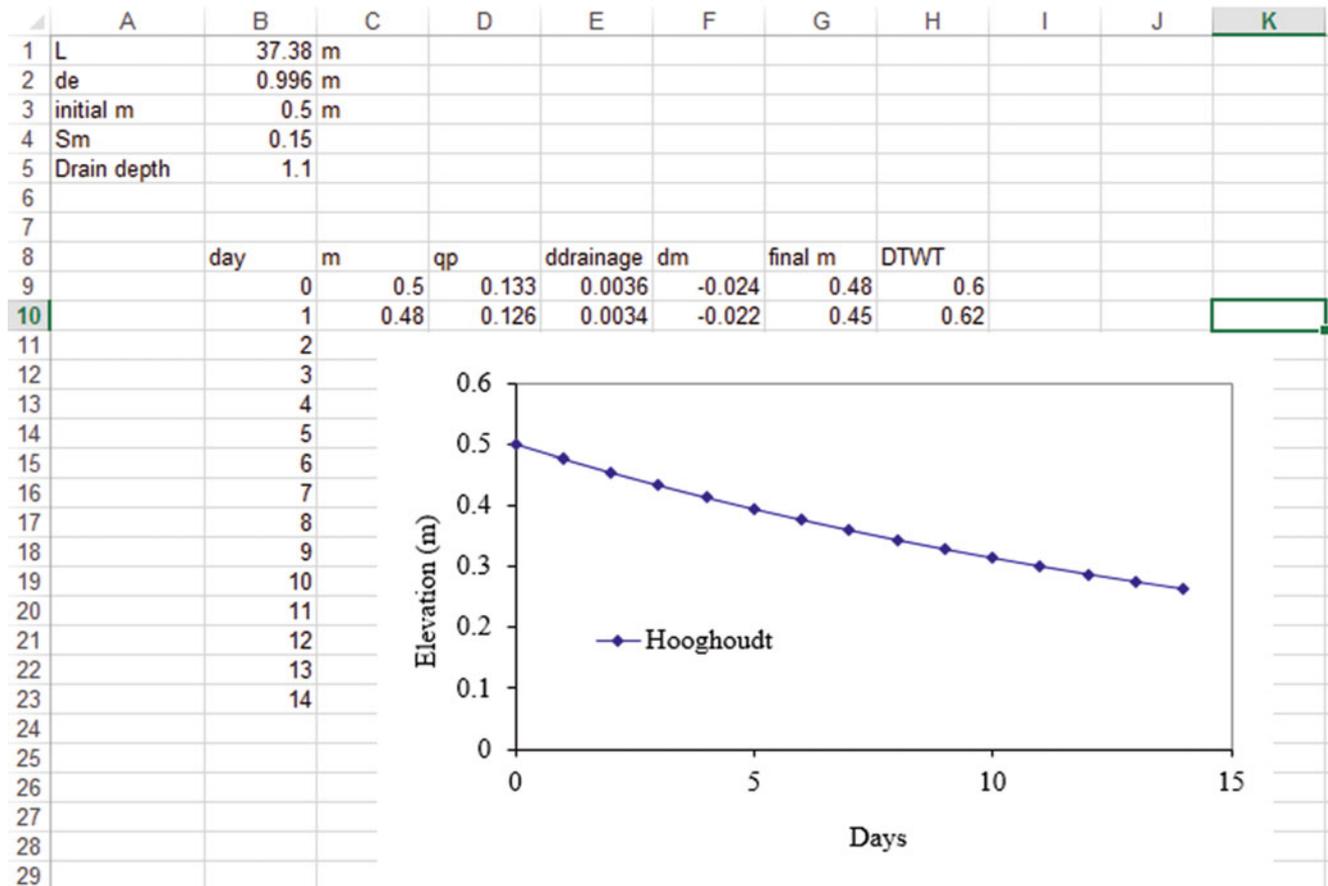
16. With parameters from question 10 and question 15 ($d_e = 1.0$), calculate the change in water table elevation over time with the USBR equation. The initial elevation is 0.5 m, and the specific yield, SY_{mid}, is 15 %. Remember to calculate D with the effective depth. Plot results and compare to the Hooghoudt transient graph from question 15. There is very little agreement because the KDt/SL^2 value is at the limit of the USBR curve from which it is derived.

(plot: Elevation (m) vs Days, curves labeled USBR and Hooghoudt)
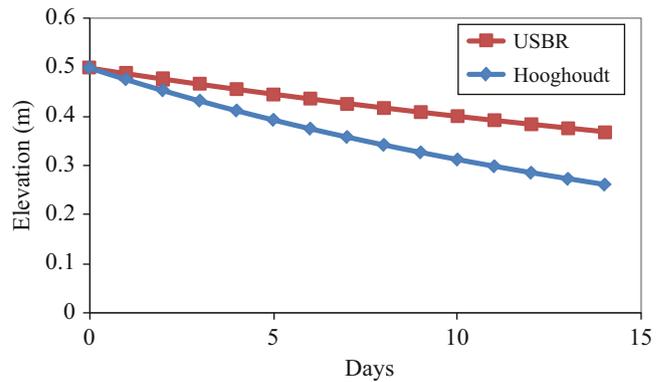
17. Redo question 16 but let the equivalent depth, de = 3 for both the Hooghoudt and USBR solutions. The solutions are close because the USBR equation is in the central part of the USBR curve.
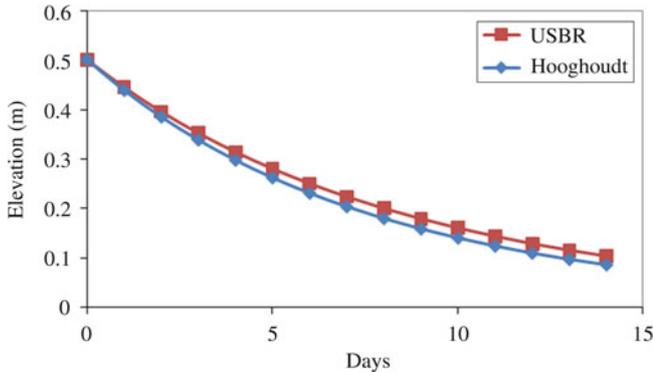
18. A field has an infiltration rate of 38 mm/hr. An irrigation with a gross application depth (volume applied divided by field area) of 10 cm is applied, and the fraction of runoff is 0.2. Calculate the change in water table elevation for a drainage system with d_e = 3.0 m and K = 0.5 m/day. Plot the water table elevation (m) vs. time for four weeks of irrigation events that take place once each week. Remember to include the specific yield in the calculation of change in water table elevation and also to include drainage on the days that irrigation water is added to the water table.

The fraction of deep percolation from Table 31.3 is 24 %
$d_{dp-i} = i$ *(1-f_{RO})*(f_{dp}) = 0.1   *   (1 − 0.2)   *
0.24 = 0.019 m = 1.9 cm
The change in water table elevation is
$\Delta m = d_{dp}$ / SY = 0.019 / 0.15 = 0.13 m = 13 cm.
The simulation of four irrigation events is shown below .
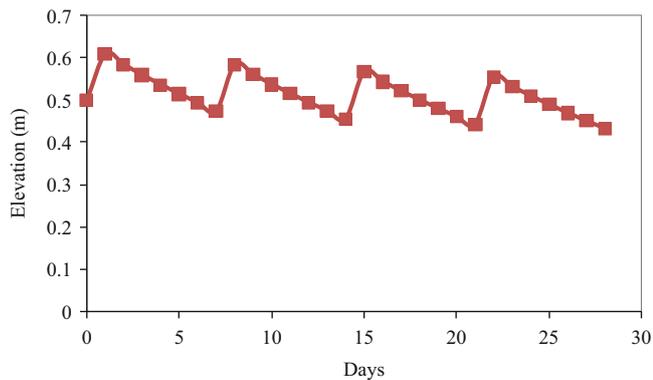
19. Redo question 18, but add 20 cm gross application depth during each irrigation event. Plot the water table elevation vs. time (m).

The water table elevation vs. time is shown below. The water table rises from irrigation to irrigation, and eventually nears the soil surface. This demonstrates that overirrigation results in waterlogging of the soil whereas the correct application depth in question 18 results in no long-term rise of the water table. In many regions with inefficient irrigation systems, the primary cause of water table rise is inefficient irrigation.
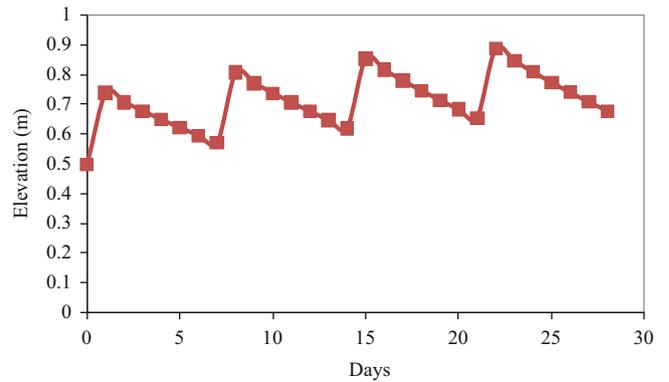
20. Redo Example 31.9, but call drainage companies for drainage alternatives and prices in your region.

Answers will vary

21. Redo Example 31.10, but evaluate a field soil and drainage scenario in your area, specified by the instructor.

Answers will vary

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