20 Surface Irrigation

Surface irrigation methods include furrow (Fig. 1.15), border, and basin irrigation. This chapter shows how to use volume balance methods in spreadsheets and the WinSRFR program, http://www.ars.usda.gov/services/software/download.htm?softwareid=250, to design furrow surface irrigation systems. The same procedures are used in the design of other surface irrigation methods. Volume balance methods compare the applied volume to surface and subsurface storage volumes in order to calculate parameters such as infiltration rate or the rate of water advance down the field. The primary design objectives in surface irrigation are to maximize application efficiency and uniformity. The primary design variables are inlet flow rate, and application time. Field length and slope are not easily changed without earthmoving equipment. Soil permeability, soil surface roughness, furrow geometry, water temperature, wind direction and speed, and surface crusting can vary during the growing season and thus change the infiltration rate and flow characteristics. Variability in these parameters and spatial variability of soil properties can make it difficult to optimize surface irrigation systems.

Surface irrigation events have three phases: advance, storage, and recession. During the advance phase, the wetting front (Fig. 20.1) moves down the field. The advance time is the length of time required for the wetting front to reach the end of the field. If the advance time is long, then the upstream end of the field receives more water than the downstream end; thus, water application is not uniform. Higher flow rates result in faster advance of the wetting front and uniform infiltration over the length of the field. However, flow velocity must be lower than the erosive flow velocity, and high flow velocity may result in excessive runoff from the end of the field if the flow rate is not reduced once the wetting front reaches the end of the field.

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. With respect to irrigation efficiency (under or over irrigation), the length of the storage phase is the most important design criterion for surface irrigation. In furrow irrigation systems, the length of the storage phase at the end of the field is the time of cutoff minus the advance time. The time of cutoff is the time when the irrigation flow to the field is shut off.

After irrigation water is turned off at the time of cutoff, the recession phase 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 (Fig. 20.3).

Surface Irrigation Infiltration

Infiltration rate determines the rate of advance, and the required length of the storage phase. Surface irrigation systems cannot be placed in certain fields because the soil infiltration rate prevents successful operation of surface irrigation systems. For example, in sandy soils, the wetting front may never reach the end of the field due to excessive infiltration. In sloping clay soils, the required storage time may be extremely long and cause excessive runoff. Thus, determination of the infiltration rate should be made before deciding to install a surface irrigation system or selecting between different surface irrigation systems.

The soil infiltration rate is a key parameter in surface irrigation models. If the soil infiltration parameters are in

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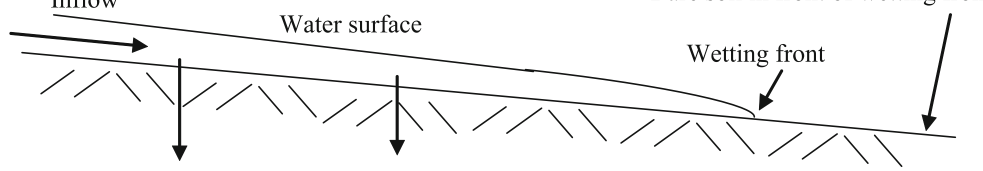

Fig. 20.1 Advance phase during surface irrigation

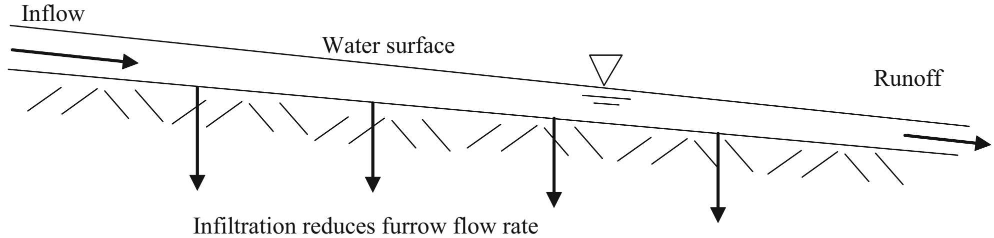

Fig. 20.2 Storage phase during surface irrigation of open-ended field

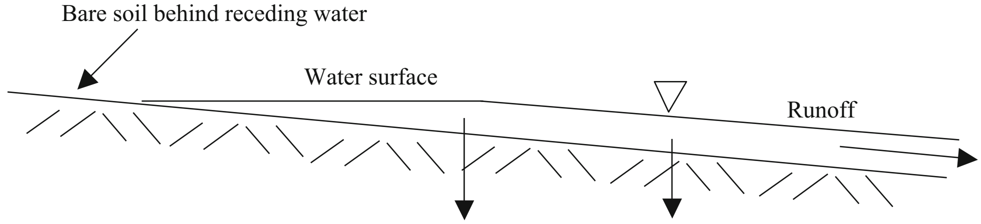

Fig. 20.3 Recession phase during surface irrigation of open-ended field

error, then no matter which model is used to design the irrigation system, the design will be in error. Many methods are used to determine average field infiltration rate. (1) Observe the rate of advance and use the two-point volume balance method to determine the infiltration parameters. (2) Observe a surface irrigation event and perform a mass balance by measuring the inflow, outflow, rate of advance, and time of recession. (3) Same as 2 with the addition of an infiltrometer test. (4) Same as 2 with the addition of measuring flow depth at intervals in the field. (5) Same as 2, except with the assumption of Phillips' infiltration equation. (6) Use several infiltrometers to measure the rate of infiltration. (7) Determine the intake family from an NRCS soils map.

Although it is preferable to use direct measurements of infiltration (observation of advance and recession times during an irrigation event or use of infiltrometers), infiltration rate can be estimated based on soils maps and NRCS intake families (method 7 listed above). The infiltration equation as typically written for surface irrigation modeling is similar to but uses different terms than the NRCS intake family equations.

$$d = at^b + c \quad \text{(NRCS form)} \tag{20.1a}$$

$$d = kt^a + bt + c \ \text{(as typically written for surface irrigation models)} \tag{20.1b}$$

where

d = infiltrated depth, mm,
k, b, and c = constants,
a = exponent, dimensionless.

The bt term in Eq. 20.1 is not in the NRCS intake family equation, but is often added to the surface irrigation infiltration equation in order to better represent steady infiltration due to the downward force of gravity. The first term, kt^a or at^b, represents the decreasing rate of infiltration due to decreased capillary suction and larger distance between the soil surface and the infiltration wetting front (Fig. 3.12). The third term, c, represents initial rapid infiltration into cracks.

In cracking clay soils, the c term can constitute the majority of infiltration. Some furrow irrigation models use the $kt^a + c$ term during the initial infiltration and $bt + c$ during the final stages of infiltration Clemmens et al. (2006).

Many furrow irrigation models only use the first term, kt^a, which is called the Kostiakov equation. Merriam and Clemmens

Table 20.1 Comparison of NRCS (Eq. 20.1a $d = at^b$) and Merriam and Clemmens (1985) infiltration equation ($d = kt^a$) with time in units of hours in infiltration depth in units of mm

NRCS ($at^b + c$)				Infiltration (100 mm) time (hr)	Merriam and Clemmens (kt^a)	
Intake family	a	b	c		k	a
0.05	6.69	0.618	7.0	70.70	30.09	0.28
0.1	9.28	0.661	7.0	32.66	29.18	0.35
0.15	11.5	0.683	7.0	21.29	30.08	0.39
0.2	13.5	0.699	7.0	15.87	31.33	0.42
0.25	15.7	0.711	7.0	12.27	32.88	0.44
0.3	17.7	0.720	7.0	10.03	34.45	0.46
0.35	19.7	0.729	7.0	8.44	36.06	0.48
0.4	21.6	0.736	7.0	7.27	37.69	0.49
0.45	23.6	0.742	7.0	6.36	39.33	0.5
0.5	25.5	0.748	7.0	5.64	41	0.52
0.6	29.3	0.757	7.0	4.59	44.29	0.53
0.7	33.2	0.766	7.0	3.85	47.62	0.55
0.8	36.9	0.773	7.0	3.31	50.91	0.56
0.9	40.7	0.779	7.0	2.89	54.19	0.58
1	44.4	0.785	7.0	2.56	57.49	0.59
1.5	60.2	0.799	7.0	1.73	71.12	0.62
2	75.3	0.808	7.0	1.30	84.31	0.65
3	103	0.816	7.0	0.88	109.05	0.69
4	129	0.823	7.0	0.67	132.88	0.71

(1985) assessed numerous infiltration curves measured throughout the Western United States and developed a relationship between a and k, based on the time to infiltrate 100 mm – a typical depth of application per irrigation event. Equation 20.2 calculates a, and subsequently, k can be calculated.

$$a = 0.675 - 0.2125\ \mathrm{LOG}_{10}(T_{100}) \qquad (20.2)$$

where

T_{100} = time to infiltrate 100 mm, hr.

Example 20.1 Find a and k if the time to infiltrate 100 mm is 15.9 hours.

First, determine a with Eq. 20.2.

$$\begin{aligned} a &= 0.675 - 0.2125\ \mathrm{LOG}_{10}(T_{100}) \\ &= 0.675 - 0.2125\ \mathrm{LOG}_{10}(15.9) = 0.42 \end{aligned}$$

Find k by rearranging Eq. 20.1.

$$k(\mathrm{mm/hr}) = d/t^a = 100/15.9^{0.42} = 31.3 \quad d = 31.3t^{0.42}$$

A comparison between NRCS intake family infiltration constants and Merriam-Clemmens calculated a and k values for equivalent times to infiltrate 100 mm are shown in Table 20.1. The two equations have dramatically different exponents with NRCS intake family exponents approximately 0.25 lower than Merriam-Clemmens intake family exponents.

Example 20.2 Compare the infiltration curve calculated with the Clemmens a and k values to the NRCS infiltration curve for a soil requiring 10 hour to infiltrate 100 mm.

The soil with a 10 hour infiltration time in Table 20.1 is the 0.3 intake family.

$$d = at^b + c = 17.7\ t^{0.72} + 7 = 17.7(600)^{0.72} + 7$$

Calculate the equivalent Clemmens infiltration exponents, a and k, for the case where 10 hours are required to infiltrate 100 mm.

$$\begin{aligned} a &= 0.675 - 0.2125\ \mathrm{LOG}_{10}(T_{100}) \\ &= 0.675 - 0.2125\ \mathrm{LOG}_{10}(10) = 0.462 \\ k(\mathrm{mm/hr}) &= d/t^a = 100/10^{0.462} = 34.4 \\ d &= 34.4\ t^{0.462} \quad (\mathrm{thours}) \end{aligned}$$

A comparison of infiltration curves is shown in Fig. 20.4.

With lower exponents, the Merriam-Clemmens intake families predict higher infiltration at the beginning of the irrigation event, which results in a slower calculated advance time. The NRSC intake family curve predicts greater infiltration at the end of the irrigation event, which results in a greater calculated depth of infiltration if the irrigation event

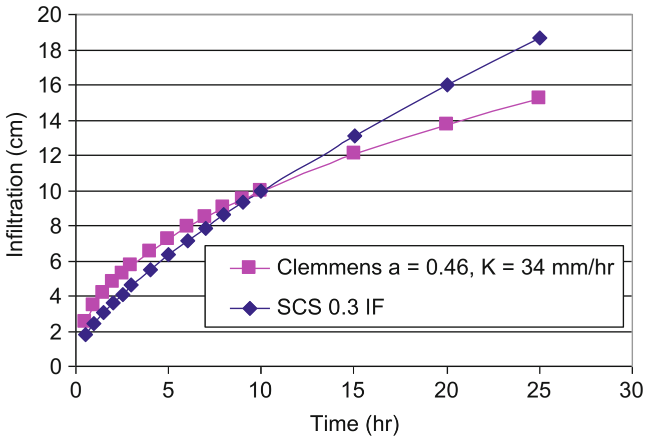

Fig. 20.4 Comparison of infiltration curves for Clemmens a and k and NRCS intake family 0.3 – soil requires 10 hours to infiltrate 100 mm

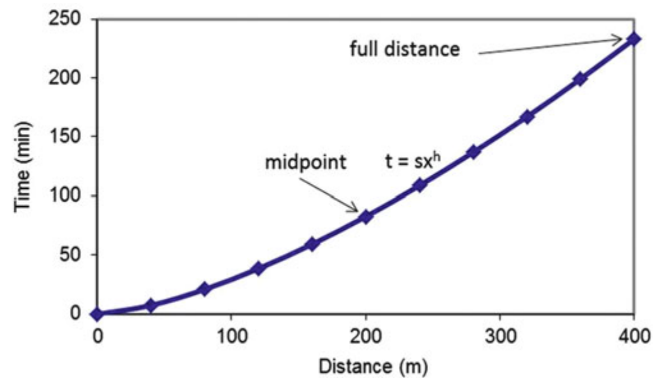

Fig. 20.5 Advance curve parameters for two-point volume balance method

is longer than 10 hours. Thus, the Merriam-Clemmens intake families provide a more conservative estimate of long-term infiltration (predict less) and advance time (takes longer).

The six methods for calculating infiltration are described in the following pages. Each of them has strengths and weaknesses and are appropriate for different applications.

1. Observe the position of the wetting front over time and plot the advance curve (Fig. 20.5). Regression can then be used to fit an exponential equation to the advance curve. The infiltration equation parameters, *k* and *a*, are adjusted by iteration until the observed advance curve matches the calculated advance curve. The inputs to the two point volume balance method are the inflow rate and the advance times to half of the length of the field and the entire length of the field. If bt is included in the infiltration Eq. (20.1), then a three point volume balance method could be used to find *k, a*, and *b*. As stated previously, the drawback with this method is that it only measures infiltration during advance. Thus, it is a poor estimator of long-term infiltration during the storage phase. This method should only be used if the rate of soil infiltration is high and the storage phase is very short in comparison to the advance time. Use of the exponential advance curve to calculate infiltration is only valid if the slope of the field is not flat, such that water does not back up (becomes deeper at the beginning of the field), and if the inflow remains on during the entire advance phase.
2. Observe a surface irrigation event and perform a mass balance by measuring the inflow, outflow, rate of advance, and time of recession. This method can be used to determine an average rate of infiltration vs. the average time of ponding for the area irrigated. The volume infiltrated is found by subtracting the total outflow volume from the total inflow volume. The average depth, $d_{average}$, infiltrated is the volume infiltrated divided by the area irrigated. The average time of infiltration is found be subtracting the advance curve from the recession curve (Fig. 20.6) at several positions and finding the intake opportunity time (IOT_i in Fig. 20.6). Then, the average intake opportunity time, $t_{average}$, is found be taking the weighted average of the intake opportunity time at the different field positions. Then $t_{average}$ and $d_{average}$ are used to find the intake family.

$$d_{average} = kt_{average}^{a} + bt_{average} + c \tag{20.3}$$

This method is likely to result in the correct calculation of the average infiltration in a field; however, because of the uncertainty of the intake family exponents, it is likely that the advance rate will be under or overestimated. For example, with the infiltration equation as written in Eq. 20.3, there are four unknowns (*k, a, b*, and *c*). Thus, an infinite assortment of a, k, b, and c values would solve the equation. However, if it is assumed that b and c are zero, and that there is a direct relationship between intake opportunity time and exponent *a* (as in Eq. 20.2), then there is only one solution. Unfortunately, as is shown in Table 20.1, there is considerable uncertainty with respect to the value of exponent *a*, for a given infiltration depth vs. time (the intake families have dramatically different exponents).
3. If a single infiltrometer test at a point in the field is combined with the irrigation event evaluation described in method 2, then the exponent *a* can be derived from the infiltrometer test, and the *k* value can be calculated based on the average infiltration rate in the field. The assumption is that the shape of the infiltration curve (represented by *a*) is relatively constant in the field, but the magnitude of infiltration varies. This method solves the problem of the uncertainty over the *a* value, and the rest of the steps in method 2 are the same. This is the method used by the NRCS for irrigation evaluations.

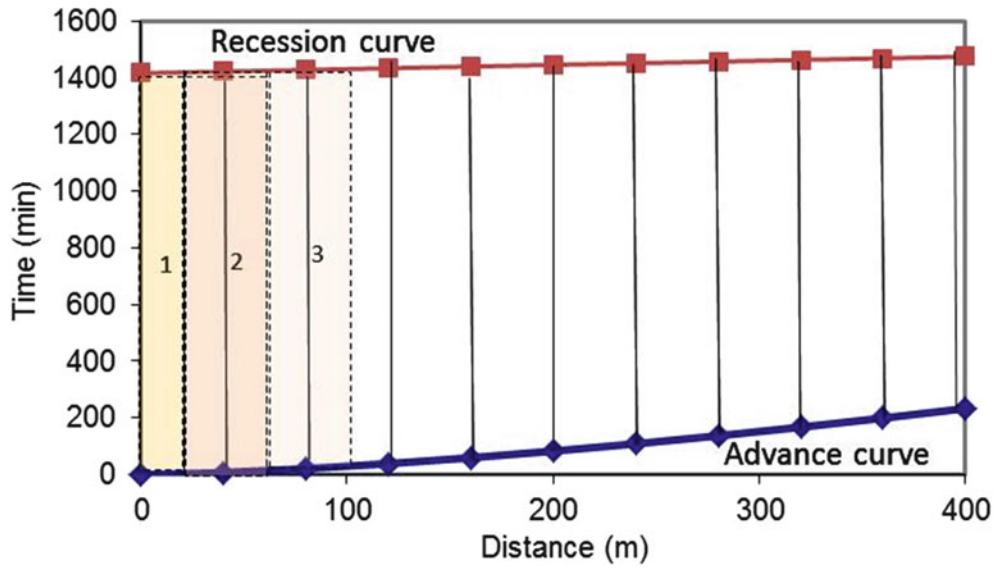

Fig. 20.6 Calculation of average intake opportunity time (IOT) by averaging depth infiltrated at each field section

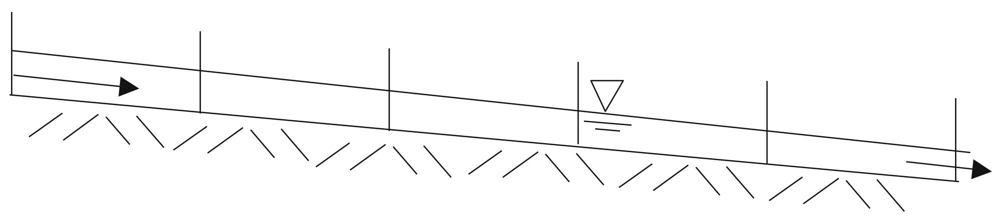

Fig. 20.7 Stakes for measuring depth of flow in furrows

4. Same as two with the addition of measuring flow depth at intervals in the field. If measuring stakes are placed in the field, and flow depth is measured in the field over time (Fig. 20.7), then the volume of infiltration can be calculated during the entire irrigation event (inflow – outflow – depth of surface storage). The stakes must be surveyed with respect to absolute elevation (not just the elevation of the stake with respect to the soil). This method is more time intensive than the other methods, and is more apropriate in a research project.

In-class Exercise 20.1 Draw a graph of the shape of the infiltrated depth vs. time curve in method 4 as it would appear on a log-log graph in Excel. How would you find a?

5. Same as two, except with the assumption of Phillips' infiltration equation. Philips derived the infiltration equation from theory. He found that the exponent, *a,* should theoretically be 0.5 and that the saturated hydraulic conductivity, K_s, should be used to model constant infiltration.

$$d = kt^{0.5} + K_s \tag{20.4}$$

The Philips infiltration equation yields reasonably accurate infiltration curves, which result in irrigation model data having a reasonably accurate agreement with field data. It is probably the best choice when limited data is available. The only unknown is k.

6. Use multiple infiltrometers (Fig. 20.8) to measure spatially varying infiltration. This method is extremely time consuming and has only been conducted in a few research studies. Recent studies show that the coefficient of variation of infiltration due to varying soil properties is in the range of 25 %.

Graded Furrow Infiltration

Graded furrows have a slope and an open ended discharge at the lower end. They are one of the most common irrigated methods and are used for row crops such as cotton, tomatoes, and cantaloupes. Water is introduced to the furrows in small streams from gated pipe, siphon tubes (Fig. 20.9), plastic risers, and other methods.

Because only a fraction of the soil surface is ponded with furrow irrigation, the average infiltration rate over the field

Fig. 20.8 Double ring infiltrometer

Fig. 20.9 Graded furrow irrigation supplied by siphon tubes from head ditch (Credit NRCS. Rick Schlegel)

area is less than infiltration in a level field. However, the infiltration rate per wetted soil area is greater than level field infiltration because water infiltrates in two directions in the furrow (Fig. 20.10).

Small flumes can be used at the upstream and downstream ends of furrows to measure flow rate (Fig. 20.11).

A furrow infiltrometer is constructed by blocking two points in a short section of the furrow. A flowing furrow

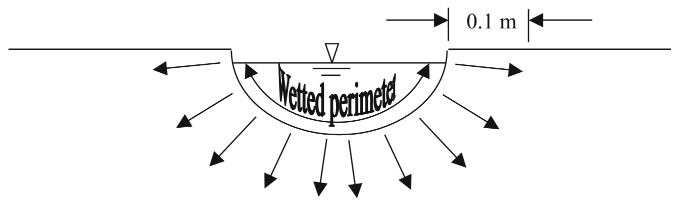

Fig. 20.10 Furrow infiltration geometry

Fig. 20.11 Furrow flume (Credit USDA-ARS David Bjorneberg)

infiltrometer (Fig. 20.12) measures inflow and outflow with flumes, orifices, or other flow measurement devices. A nonflowing infiltrometer uses a float valve that triggers a pump which replaces infiltrated water from a tank, and the water level in the tank is monitored over time. The advantage of a furrow infiltrometer is that infiltration rate is measured directly. The disadvantage is that infiltration over a short section of the furrow may not be representative of the field average, due to spatial variation of soil properties. However, even calculating infiltration based on an irrigation event over an entire furrow may not be representative of the field. Typically, the advance rate from one furrow to the next in a field varies dramatically.

If it is not possible to conduct an infiltrometer test or to monitor advance and recession during an irrigation event, then the NRCS intake families for level surfaces can be adjusted to furrows infiltration rate as follows.

- Add 0.213 m (0.1 m on each side of the furrow) to the wetted perimeter (Fig. 20.5) of the furrow to account for lateral infiltration to the center of the beds.
- Multiply the infiltration rate for a level field by the following ratio (wetted perimeter + 0.213 m)/(width between furrows).

Fig. 20.12 Blocked furrow infiltrometer (Credit NRCS)

The Two-Point Volume Balance Method

The two-point volume balance model calculates the position of the wetting front during advance based on a comparison of the applied volume to the surface and subsurface storage. The surface storage is the volume stored in the furrow and is

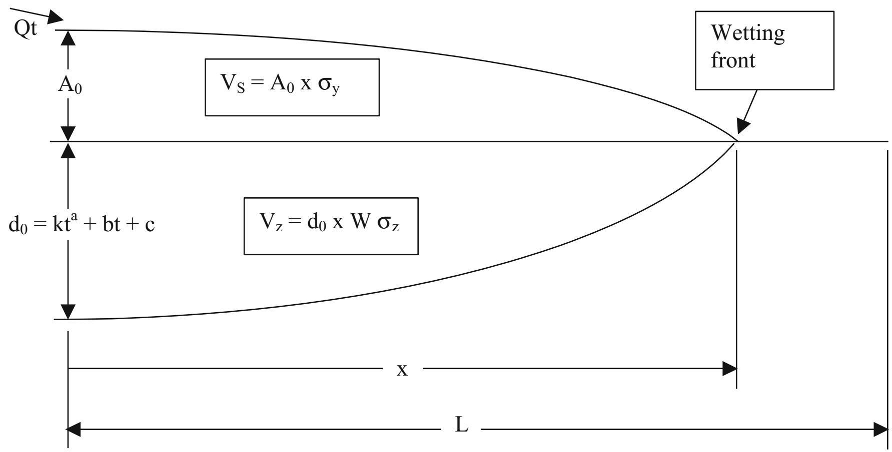

Fig. 20.13 Surface and subsurface storage for volume balance method

the product of cross-sectional area of flow at the upper end of the furrow, furrow spacing, distance to the wetting front, and a shape factor. The subsurface storage is the volume stored in the furrow and is the product of the depth infiltrated at the upper end of the furrow, distance to the wetting front, and a shape factor (Fig. 20.13).

The total storage is the sum of surface and subsurface storage.

$$V_T = V_z + V_s. \tag{20.5}$$

where

V_z = volume of subsurface storage (infiltrated volume), m^3,
V_s = volume of surface storage (water in furrow), m^3.
V_T = volume of total storage

The inflow volume is the product of inflow rate and time.

$$V_{in} = 3.6Qt \tag{20.6}$$

where

Q = inflow rate, L/sec,
t = time since irrigation water was turned on, hr,
V_{in} = volume applied to furrow since water was turned on, m^3,

The cross-sectional flow area at the upper end of the furrow can be calculated with Manning's equation. Furrow shape is typically described by a power function or a trapezoid. In this text, the furrow shape is modeled as a trapezoid. As with canals, the side slope, z, in furrows is specified as the run over the rise. The cross sectional area, A, and the wetted perimeter, P, of a trapezoidal furrow are given in Table 10.3. Typical Manning's n values for agricultural surfaces are given in Table 11.2. In smooth furrows, Manning's n is 0.04.

Example 20.3 For a 1.0 L/s flow rate, calculate the depth of flow in a trapezoidal furrow with z = 2 and a bottom width, b, of 0.1 m. The furrow has a slope of 0.002 m/m, and the Manning's n is 0.05. Finally, calculate the Clemmens *k* and *a* values for the upper end of the furrow if the time to infiltrate 100 mm is 10 hours (as in Example 20.2). Calculations made in *Furrow* worksheet.

Calculate the section factor (Chap. 10)

$$\frac{Qn}{S_f^{1/2}} = \frac{(0.001\ m^3/\sec)\ (0.05)}{0.002^{1/2}} = \mathit{Section\ factor} = 0.001118$$

$AR^{2/3}$ is calculated with the following equation.

$$AR^{2/3} = A(A/P)^{2/3}$$
$$= (b + zy)y\left(((b + zy)y)/\left(b + 2y\left(1+z^2\right)^{\wedge 0.5}\right)\right)^{2/3}$$

Make an initial guess, y = 0.04 m.

$$0.001118 = AR^{2/3} = \left(0.1 + (2)(0.04)(0.04)\left(\left(0.1 + (2)(0.04)\right)(0.04)/\left(0.1 + (2)(0.04)\left(1+2^2\right)^{\wedge 0.5}\right)\right)^{2/3}$$
$$0.001118 = 0.00063$$

Iterate by inputting the required section factor (0.01118) and the first guess for a section factor into the following equation. This equation is designed for rapid convergence for this iteration.

$$y = \text{initial } y\left(SF/AR^{2/3}\right)^{0.5} = 0.04(0.001118/0.00063)^{0.5}$$
$$= 0.0533 \text{ m.}$$

$$0.001118 = \left(0.1 + (2)(0.0533)(0.04)\left(\left(0.1 + (2)(0.0533)\right)(0.0533)/\left(0.1 + (2)(0.0533)\left(1 + 2^2\right)^{\wedge 0.5}\right)\right)^{2/3}$$
$$0.001118 = 0.001124 \rightarrow y = 0.0533.$$

Calculate wetted perimeter

$$P = b + 2y\left(1 + z^2\right)^{0.5} = 0.1 + (2)(0.0533)\left(1 + 2^2\right)^{0.5}$$
$$= 0.338 \text{ m}$$

Adjust the infiltration rate for the equivalent furrow infiltration width.

$$\frac{0.338 \text{ m} + 0.213 \text{ m}}{1.0 \ m} = 0.551$$

Clemmens k and a, from Example 20.2, are 34.45 and 0.462, respectively. Adjust k by multiplying by 0.551. No change is required for a.

$$\text{Adjusted}k = (0.551)(34.4 \text{ mm/hr}) = 19.0(\text{mm/hr})$$
$$d = 19.0 \ t^{0.462}$$

The surface shape factor is based on the shape of the water profile down the furrow. If the entire furrow was filled to the same depth, then the shape factor would be 1.0. However, the depth of water in the furrow decreases with distance down the furrow. The surface shape factor is the fraction of water in a furrow in comparison to a furrow with constant depth. It is usually assumed that the surface shape factor, σ_y, is 0.75 during the advance phase. Thus, the volume of water stored in the furrow is calculated as follows:

$$V_s = \sigma_y A_0 x \tag{20.7}$$

where

σ_y = surface shape factor, 0.75,
A_0 = cross sectional area at the upper end of the furrow at time t_x, m^2,
x = advance distance down the furrow at time t, m,
V_s = volume of surface storage at advance distance x, m^3.

The subsurface storage for furrow irrigation is a function of infiltration and field parameters. If b and c in Eq. 20.1 are zero, then the total volume of subsurface storage (infiltration) is

$$V_z = d_0\sigma_z Wx = k \ t^a \ \sigma_z Wx \tag{20.8}$$

where

W = distance between furrows, m,
d_0 = infiltration at upper end of furrow (as in Example 20.2), m,
σ_z = subsurface shape factor (Eq. 20.9),
t = time since the beginning of the irrigation event, hr,
a = exponent in infiltration equation.

If b and c are not zero, then the total volume of infiltration down the furrow is

$$V_z = d_0\sigma xW = \left(c + \sigma_z k \ t^a + \frac{h}{1+h}bt\right)xW\sigma_z \tag{20.9}$$

where

h = exponent in advance equation.

The position of the wetting front during advance is modeled with the advance equation.

$$t = sx^h \tag{20.10}$$

where

s = advance equation coefficient.

The subsurface shape factor is a function of a and h.

$$\sigma_z = \frac{h + a(h-1) + 1}{(1+a)(1+h)} \tag{20.11}$$

The relationship between the advance exponent h, and the advance times to two points in the field can be found by taking the logarithm of Eq. 20.11.

$$\log t = \log s + h \log x \tag{20.12}$$

Rearrange the equation and solve for log s

$$\log s = -h \log x + \log t \tag{20.13}$$

Equation 20.13 follows the form, y = mx + b. For two log x and log t points, the slope of the line between them is h. If the two distances (points x_1 and x_2) are the full length of the furrow, x_L, and half the length of the furrow, $x_{L/2}$, then x_2 is twice the length of x_1 and the following equation is used to calculate h.

$$h = \frac{\log\ t_2 - \log\ t_1}{\log\ x_2 - \log\ x_1} = \frac{\log\left(\frac{t_2}{t_1}\right)}{\log\left(\frac{x_2}{x_1}\right)} = \frac{\log\left(\frac{t_L}{t_{L/2}}\right)}{\log\left(\frac{2}{1}\right)} \quad (20.14)$$

The first step in the two-point volume balance method is to find the normal depth of flow at the given inflow rate. Next, an initial guess is made for t_L and $t_{L/2}$, and these values are used in Eq. 20.14 to make an initial calculation for h. Then, the subsurface shape factor is calculated (Eq. 20.11), and the surface and subsurface storage are calculated. Finally, $t_{L/2}$ is adjusted based on the inflow volume and storage at time $t_{L/2}$, and t_L is adjusted based on the inflow volume and storage at time t_L with Eq. 20.5. Next, the iteration procedure is repeated with the new estimates of t_L and $t_{L/2}$. During the iteration procedure, the time required for water to advance to a certain point in the furrow is adjusted by the ratio of inflow volume, V_{in}, to total storage volume, V_T.

$$t_{m+1} = t_m \left(\frac{V_T}{Q\ t_m}\right)^{1.4} \quad (20.15)$$

where

m = iteration number

Example 20.4 Calculate s and h and plot the advance curve for a 400 m long furrow with 1 m spacing between furrows. Inflow rate is 1.0 L/s. Ten hours are required to infiltrate 100 mm in level soil. Manning's roughness n is 0.05, slope is 0.002 m/m, bottom width is 0.1 m, z is 2, and the upstream flow depth is 0.0533 m (as calculated in Example 20.3). Use a convergence criterion of less than 1 min difference between iterations.

Calculate cross-sectional area at the furrow inlet, A_0.

$$A_0 = (b + z\ y)y = (0.1\,m + (2)(0.0533\ m))(0.0533\ m) = 0.011 m^2$$

From Table 20.1, if 10 hours are required to infiltrate 100 mm in level soil, then a = 0.46 and k = 34.4. Adjusted k for furrows (as calculated in Example 20.3) is 19.0.

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.

$$\sigma_z = \frac{h + a(h-1) + 1}{(1+a)(1+h)} = \frac{1.32 + 0.46(1.32 - 1) + 1}{(1 + 0.46)(1 + 1.32)} = 0.73$$

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.

$$d_{L/2} = kt^a = 19.0(100/60)^{0.46} = 24.0\ \text{mm infiltrated.}$$
$$d_L = kt^a = 19.0(250/60)^{0.46} = 36.6\ \text{mm infiltrated.}$$

Calculate subsurface storage at $t_{L/2}$ (time to reach L/2) and t_L

$$Vz_{L/2} = d_0 s_z W\ x = (24.0/1{,}000\ mm)(0.73)(1.0\ m)(200\ m) = 3.50\ m^3$$
$$Vz_L = d_0 s_z W\ x = (36.6/1{,}000\ mm)(0.73)(1.0\ m)(400\ m) = 10.68\ m^3$$

Calculate surface storage at $t_{L/2}$ and t_L.

$$V_{s\ L/2} = s_y A_0 x = (0.75)(0.011\ m^2)(200\ m) = 1.65\ m^3.$$
$$V_{s\ L} = s_y A_0 x = (0.75)(0.011\ m^2)(400\ m) = 3.29\ m^3.$$

Calculate total storage at $t_{L/2}$ and t_L.

$$V_{T\ L/2} = 1.65 + 3.50 = 5.15\ m^3$$
$$V_{T\ L} = 3.29 + 10.68 = 13.97\ m^3$$

The advance times are adjusted with Eq. 20.16

$$t_{m+1} = t_m\left(\frac{V_T}{Q\ t_m}\right)^{1.4} = 100\left(\frac{5.15}{6}\right)^{1.4} = 81\ \ \text{min}$$
$$t_{m+1} = t_m\left(\frac{V_T}{Q\ t_m}\right)^{1.4} = 250\left(\frac{13.97}{15}\right)^{1.4} = 226\ \ \text{min}$$

The procedure is then repeated for the next iteration with $t_{L/2}$ = 81 min, and t_L = 226 min. Subsequent iterations are shown in Table 20.2.

The solution has met the convergence criteria since there is less than one-minute change in advance times from the previous iteration. Solve for s (hours and meters) and write the advance equation; the advance time is 231/60 = 3.85 h.

$$t = sx^h \quad s = t/x^h \quad s = 231/400^{1.49} = 0.0305$$
$$t = 0.0305\ x^{1.49}$$

The advance curve is shown in Fig. 20.14.

Table 20.2 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	0.729	6	15	5.15	14.0
Iteration 1	80.7	226	1.49	0.747	4.84	13.6	4.90	13.7
Iteration 2	82.0	230	1.49	0.747	4.92	13.8	4.92	13.8
Iteration 3	82.1	231	1.49	0.747	4.92	13.8	4.93	13.8

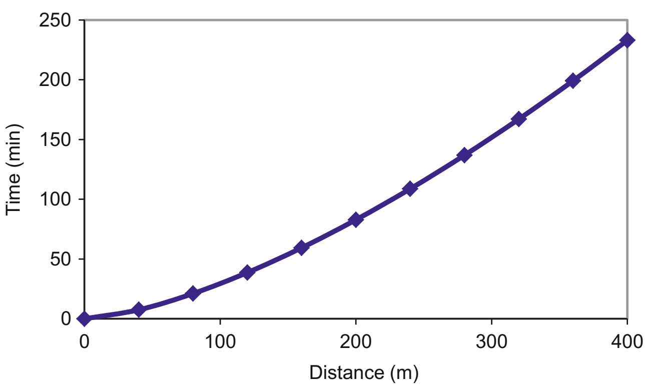

Fig. 20.14 Advance curve for Example 20.5

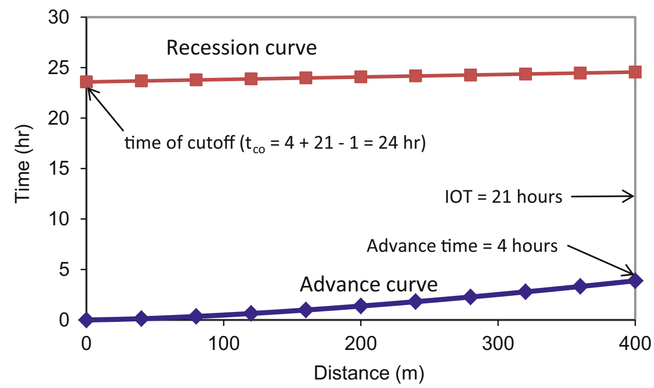

Fig. 20.15 Advance and recession curves for Example 20.6

After cutoff (the time when the water is turned off), recession time in a furrow is found by dividing volume stored in the furrow at the time of cutoff by the inflow rate (Clemmens et al. 2006). Volume stored in the furrow at the time of cutoff is calculated with a new σ_y:

$$V = A_0 L \sigma_y \tag{20.16}$$

$$t_{rec} = V/Q \tag{20.17}$$

where

t_{rec} = time of recession, min,
Q = flow rate, m^3/min,
σ_y = surface shape factor at time of cutoff, 0.8.

Example 20.5 Calculate the time of recession for Example 20.4 where Q = 1.0 L/s, A_0 = 0.011 m^2, and L = 400 m.

$$Q = \left(\frac{1.0\ L}{\sec}\right)\left(\frac{m^3}{1,000\ L}\right)\left(\frac{60\ \sec}{\min}\right) = 0.06\ m^3/\min$$

$t_{rec} = V/Q = (0.011\ m^2)(400\ m)(0.8)/0.06 = 58$ minutes (see Fig. 20.15)

Recession is assumed to be linear so linear interpolation can be used to plot the recession curve between the time of cutoff and the time of recession.

Furrow Irrigation Scheduling and Evaluation

Furrow irrigation systems generally require manual labor to cut off water to furrows and to initiate inflow to other furrows. In general, farmers prefer to have irrigation sets of 12 or 24 hours because the irrigation can be changed at the same time each day. However, if farmers have employees running irrigation systems for 24 hours per day, then dividing the irrigation schedule into days or half days is not as important since irrigation sets can be changed at any time.

If the minimum ponding time is at the end of the furrow, then the time that irrigation is cut off can be found by subtracting the recession time from the advance time + required ponding time at the end of the furrow.

$$t_{co} = t_{adv} + IOT_{req} - t_{rec} \tag{20.18}$$

where

t_{co} = time of cutoff, min,
t_{adv} = advance time, min,
IOT_{req} = required intake opportunity time, min

The length of time between irrigation events is the depth of ponding divided by the evapotranspiration rate.

Example 20.6 Adjust flow parameters and depth of infiltration so that the farmer has a 12 or 24-hour irrigation cycle. Make an initial guess that the required depth of infiltration is 100 mm. Use soil and furrow flow parameters as calculated in

Examples 20.3, 20.4 and 20.5. Determine the time of cutoff and the length of time between irrigation events if the maximum ET_c + efficiency losses in summer is 11 mm/day.

The time required to infiltrate 100 mm is calculated with the kt^a equation.

$$t = \left(\frac{d}{k}\right)^{1/a} = \left(\frac{100}{19}\right)^{1/0.46} = 37\ h$$

The required infiltration time exceeds 24 hour, which may not be acceptable to the grower. If recession time is one hour, and advance time is 4 hours, then the time available for the storage phase on a 24 hour irrigation cycle is 21 hours. Calculate the depth that infiltrates after 21 hours.

$$d = kt^a = (19)(21\ \mathrm{hr})^{0.46} = 77\ \mathrm{mm}.$$

The required ponding time at the end of the furrow is 21 hours, the advance time is 231 min (4 h), and the recession time is 58 min (1 h). Confirm that the time of cutoff is 24 hours.

$$t_{co} = t_{adv} + IOT_{req} - t_{rec} = 4 + 211 = 24\ \mathrm{hr}$$

The advance and recession curves are shown in Fig. 20.15.

One concern with furrow systems is the wetting pattern. Furrows might need to be closer together in sandy soils if complete wetting is needed.

WinSRFR

WinSRFR (Fig. 20.16) *Event Analysis World* (Fig. 20.17) calculates infiltration k & a with the two-point method.

Select *Furrow* and *Elliot-Walker Two-point* method (Fig. 20.17) in *Event Analysis World*, Enter information on the System Geometry (Fig. 20.18) page: furrow is 400 m long, furrows are 1 m apart, one furrow per set, and 0.002 m/m slope. Select a trapezoidal furrow with bottom width 100 mm.

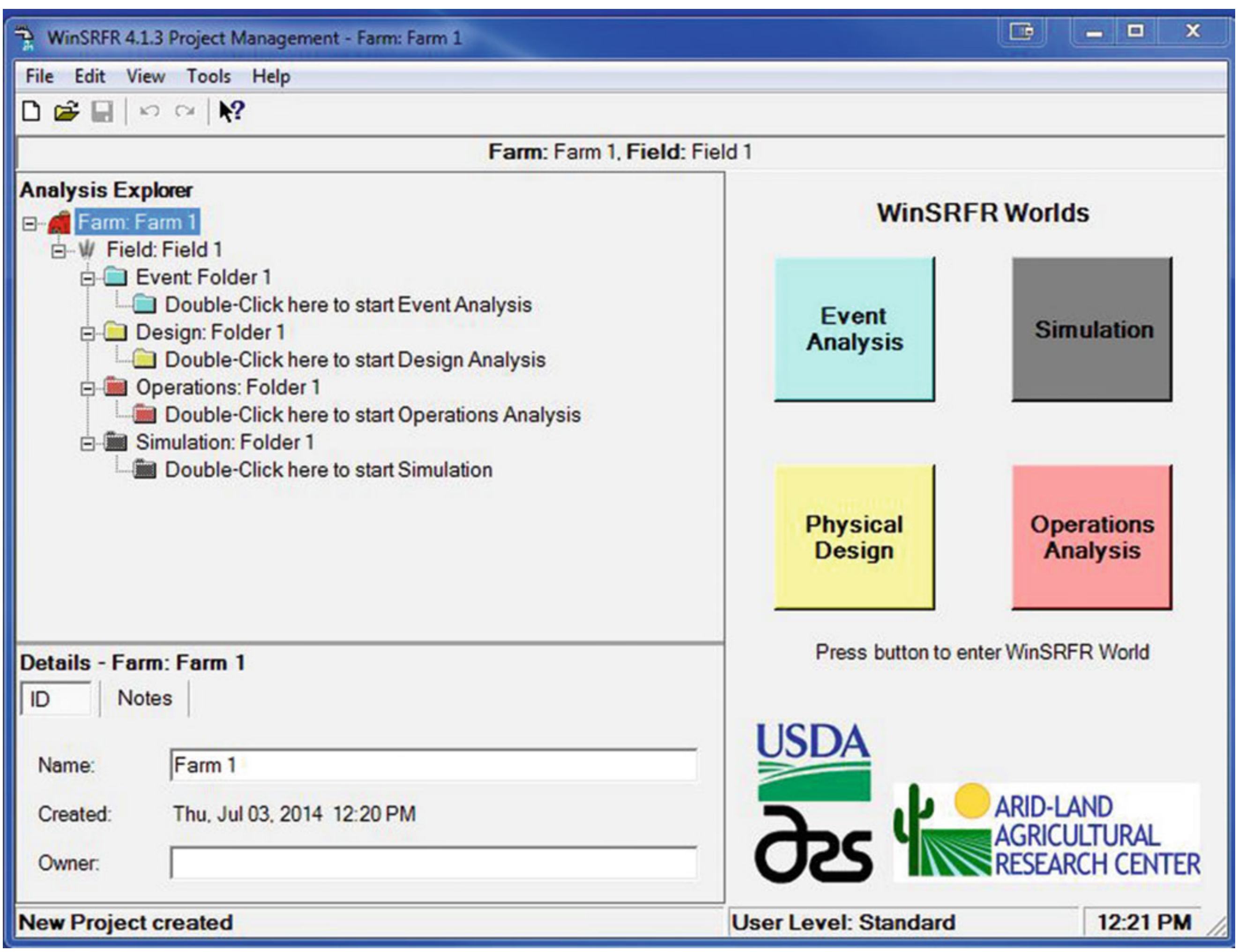

Fig. 20.16 WinSRFR front page

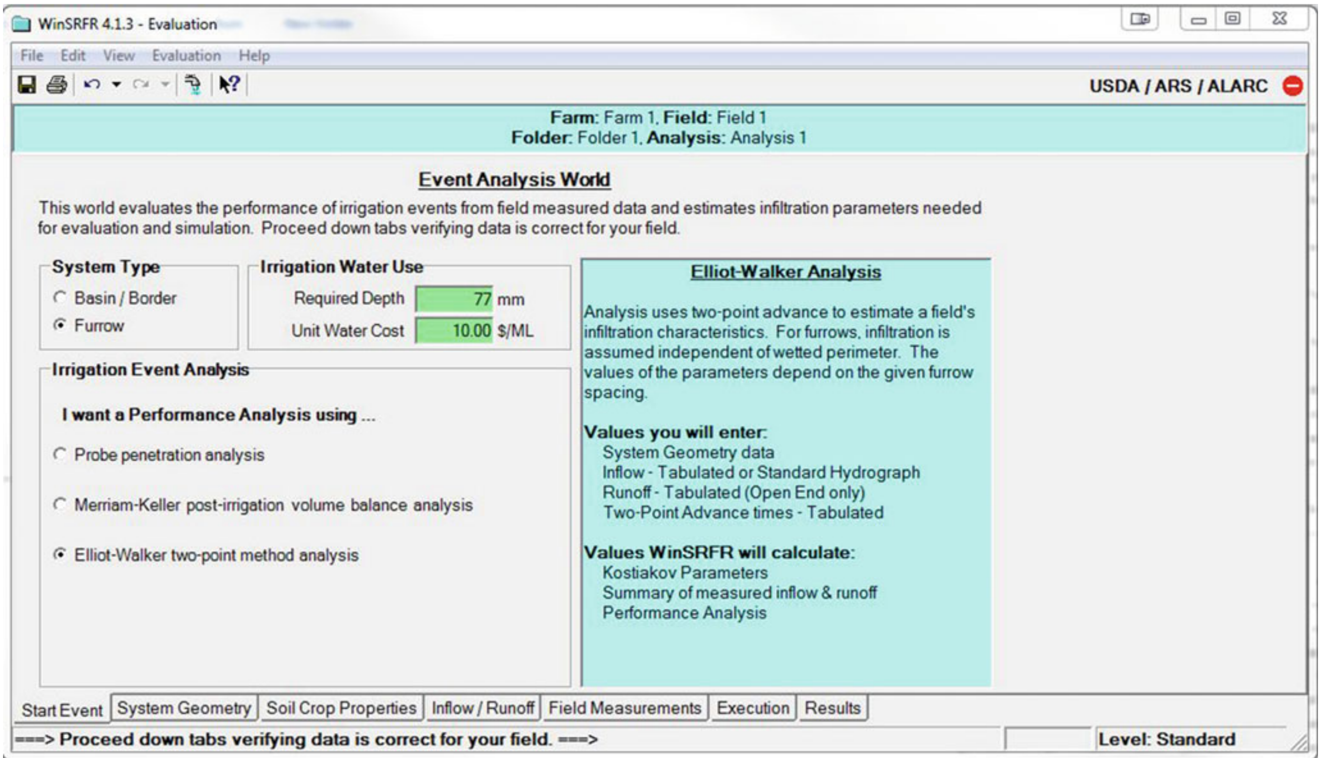

Fig. 20.17 WinSRFR event analysis world

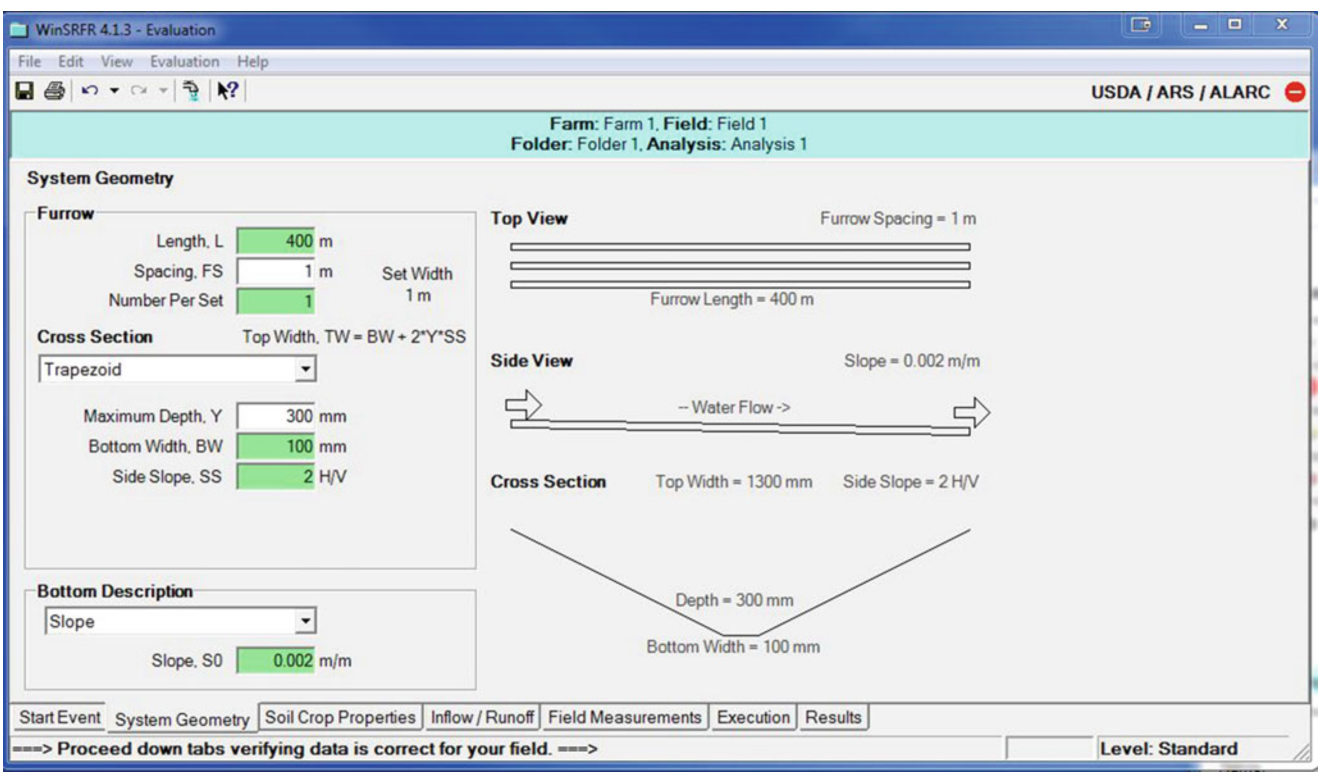

Fig. 20.18 *System geometry* page in WinSRFR event analysis world

In the *Soil/Crop Properties* page, select *User entered value* and type 0.05 (Fig. 20.19). However, you could use one of the defined n values in the other mode. The Manning n is the roughness of the soil. A higher n means that the soil is rougher and impedes the flow down the furrow.

The system operation parameters are input in the *Inflow/Runoff* page (Fig. 20.20). The only required parameter for the two-point method analysis is the inflow rate of 1.0 L/s.

On the *Field Measurements* page, enter the time that it takes for the wetting front to reach halfway down the field and all the way down the field. In this case, enter 1.35 hr for the half distance and 3.85 hr for the full distance (Fig. 20.21). These are field observed values.

The next step is to calculate the infiltration equation parameters on the Execution page (Fig. 20.22). Do not worry about the b – term. Click *estimate a and k* and the a and k coefficients are the same as those in the worksheet.

The two point volume balance method just calculates k and a in the infiltration equation; thus, b and c are zero and the infiltration equation for this example appears as follows.

Fig. 20.19 WinSRFR *soil/crop properties* page

$$d = kt^a + bt + c = 18.79\ t^{0.47}$$

The next step is to click *Verify and Summarize Analysis* on the Execution page in order to see the results. The infiltration function is shown on the *Infiltration Function* page on the *Results* page (Fig. 20.23). The cursor can be run over the page in order to find the ponding time required to infiltrate a given depth. From the *Inflow/Runoff* page, we entered 77 mm as the required depth. Thus, it shows the length of time required to infiltrate that depth.

In the *Inflow/Runoff* page, it was specified that the cutoff time was 20 hours (irrigation is left on for 20 hours) and the required depth of infiltration was 77 mm. The program can use the infiltration function and the other parameters to calculate the depth infiltrated at any point in the field. This is shown in the *Infiltrated Depths* page under *Results* (Fig. 20.24). The distance down the furrow is shown on the horizontal axis and the depth infiltrated is shown on the vertical axis.

As stated previously, the drawback with the two-point method is that it only measures infiltration during advance. Thus, it is a very poor estimator of long-term infiltration during the storage phase. This method should only be used if the rate of soil infiltration is very high and the storage phase is very short in comparison to the advance time. In addition, the exponential advance curve is only valid if the slope of the field is not flat, such that water does not back up (becomes deeper at the beginning of the field), and if the inflow

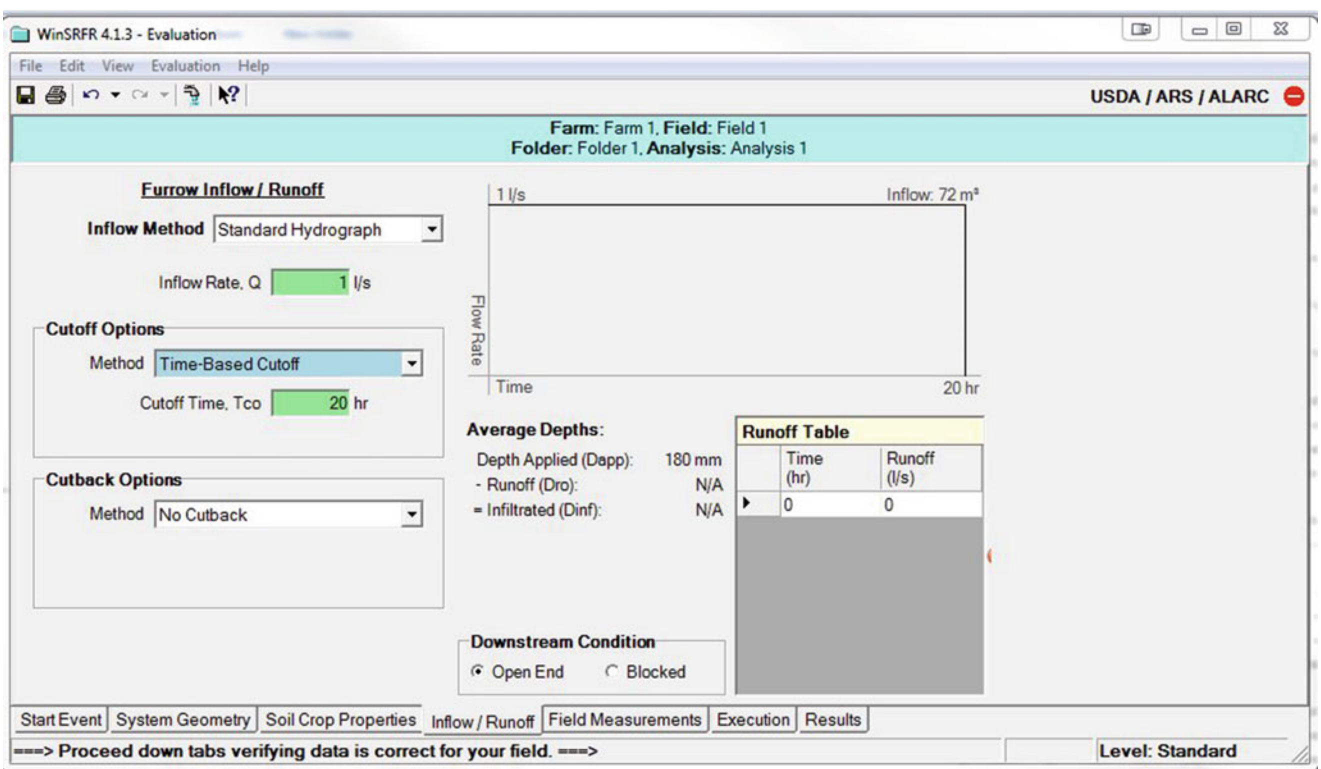

Fig. 20.20 WinSRFR inflow/runoff page

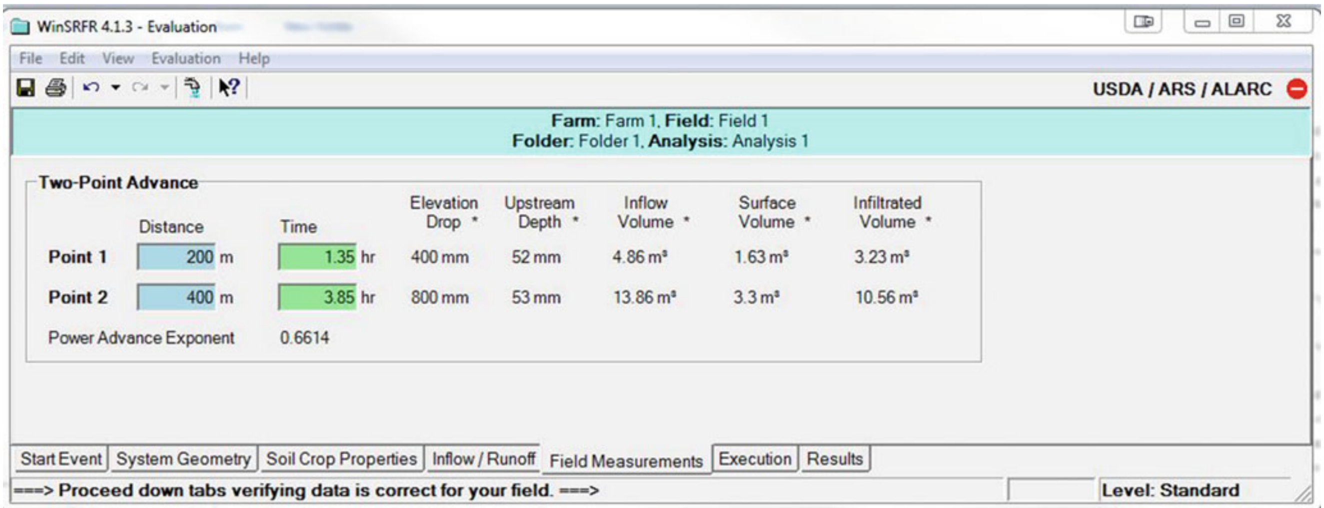

Fig. 20.21 WinSRFR two-point advance page

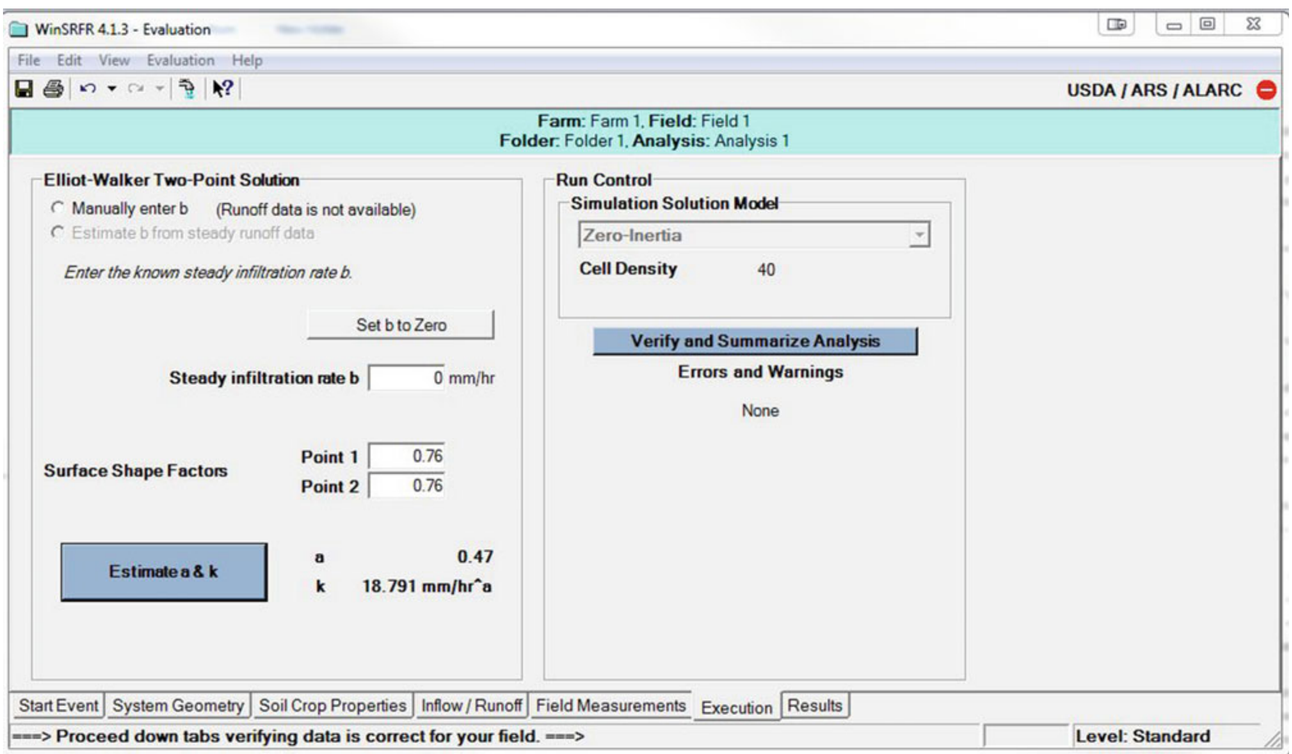

Fig. 20.22 Execution page in WinSRFR event analysis world

remains on during the entire advance phase. For other situations, the *Merriam-Keller post-irrigation volume balance analysis* is more accurate.

Distribution uniformity, DU, and efficiency are the most common parameters used for evaluation of surface irrigation systems. DU is the average of the low quarter infiltrated depths divided by the average infiltration depth over the field. Efficiency can be calculated as follows.

$$Eff = \frac{V_{in} - V_{RO} - V_{DP}}{V_{in}} \tag{20.19}$$

where

V_{RO} = volume of water that runs off the end of the field, m^3,
V_{DP} = volume of water infiltrated that is not used for leaching or ET, m^3.

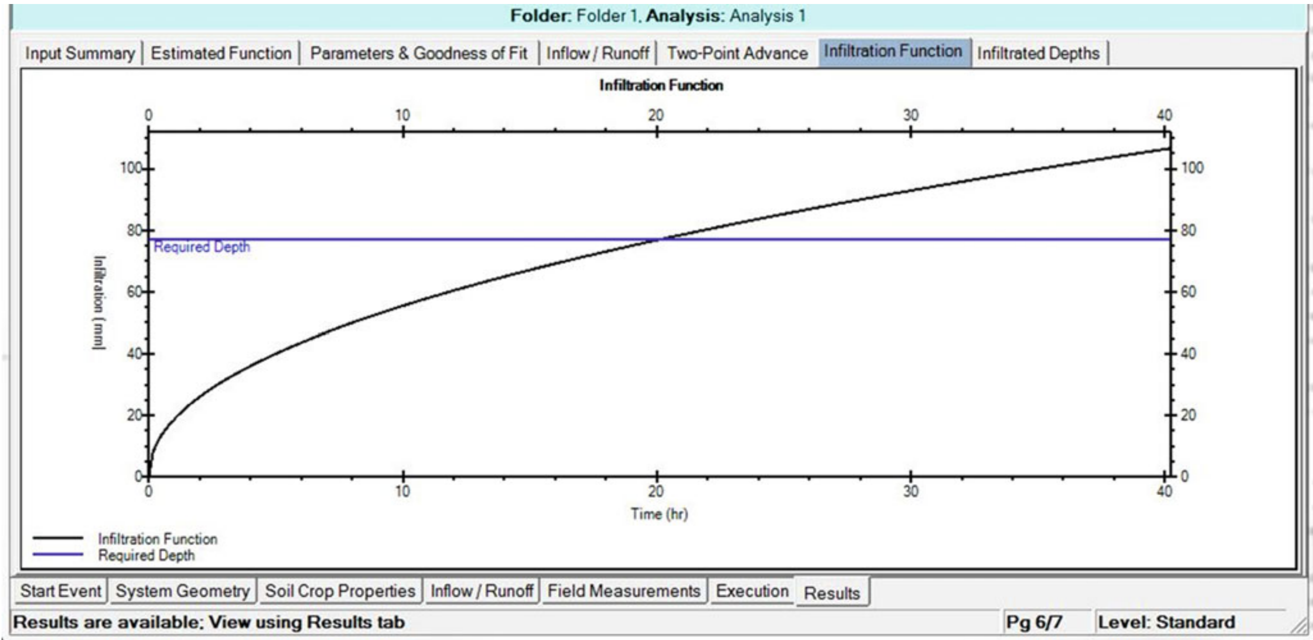

Fig. 20.23 WinSRFR *infiltration function* in *results* page

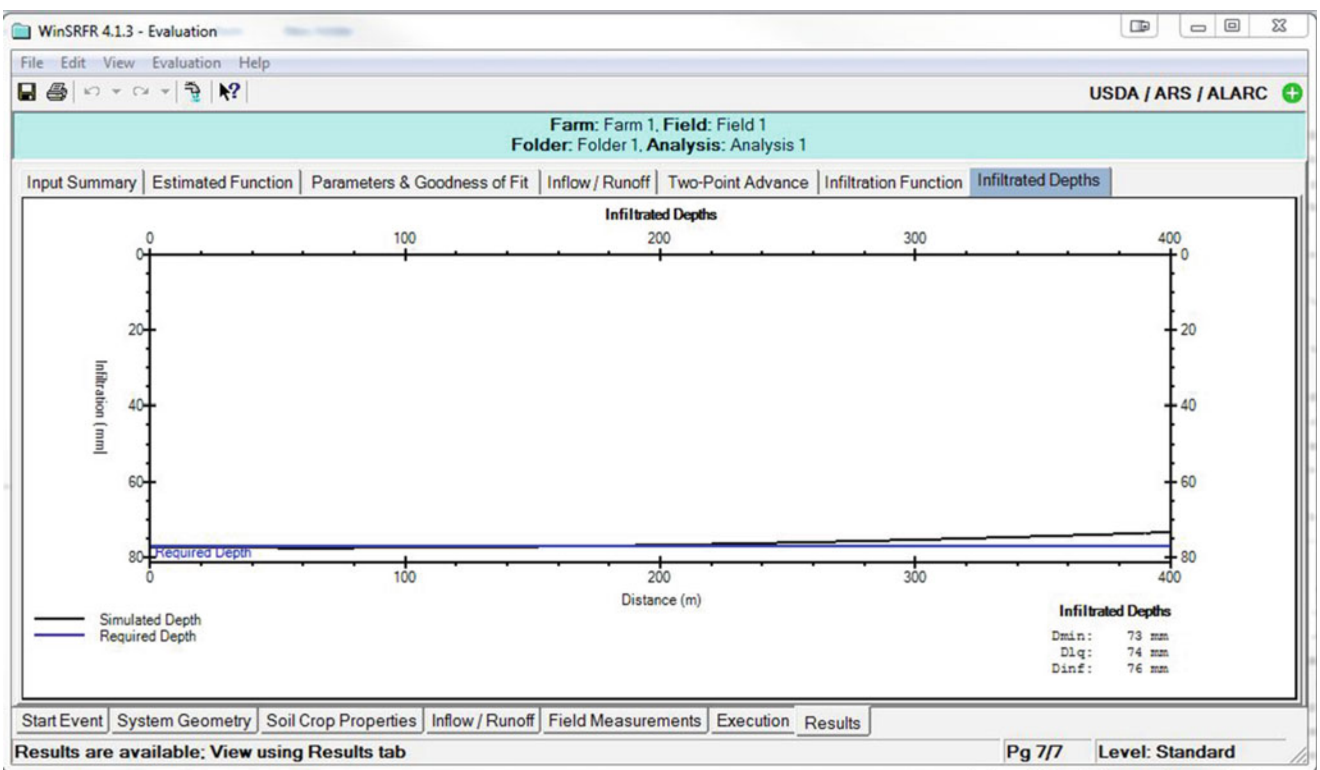

Fig. 20.24 WinSRFR *infiltrated depths* in the *results* page

Typically, the design depth of infiltration is applied to the end of the furrow, and upper sections are overirrigated. Calculation of DU and efficiency require calculation of the volume of

$$V_j = W\,\Delta x_j\, d_j \tag{20.20}$$

where

Δx_j = length of furrow represented by point j, m,

d_j = depth of infiltration at point j, m,
V_j = volume of infiltration in furrow section j, m^3.

The intake opportunity time (IOT_j as shown in Fig. 20.6) in any section of the furrow is calculated by subtracting the advance time from the recession time

$$IOT_j = t_{co} + x_j/L\, t_{rec} s x_j^h \quad (20.21)$$

where

x_j = distance to position j from inlet, m.

The depth infiltrated at position j is

$$\begin{aligned} d_j &= kt^a + bt + c \\ &= k\left(t_{co} + x_j/L\, t_{rec} s x_j^h\right)^a \\ &\quad + b\left(t_{co} + x_j/L\, t_{rec} s x_j^h\right) + c \end{aligned} \quad (20.22)$$

The volume of infiltration over the entire furrow is the summation of infiltrated volumes in furrow segments

$$V_{furrow} = \sum_{j=1}^{n} V_j \quad (20.23)$$

where

V_{furrow} = volume infiltrated into the entire furrow, m^3.

The required volume of water infiltration per furrow, V_{req}, is the product of required depth, length, and width of the furrow

$$V_{req} = W\, L\, d_{req} \quad (20.24)$$

where

d_{req} = design irrigation depth, usually depth applied at end of furrow, m,
V_{req} = volume of water required for infiltration at design irrigation depth, m^3.

If the required depth is infiltrated at the end of the furrow (no underirrigation), then the volume of deep percolation for the entire furrow, V_{DP}, is

$$V_{DP} = \sum_{j=1}^{n} V_j - V_{req} \quad (20.25)$$

The runoff volume is the volume applied – volume of infiltration

$$V_{RO} = V_{in} - V_{furrow} \quad (20.26)$$

where

V_{RO} = volume of runoff, m^3.

In this case, short furrow sections will be evaluated for yield and leaching. The volume of water required in each furrow section is

$$V_{j-req} = W\, \Delta x_j\, d_{req} \quad (20.27)$$

The volume of deep percolation in each furrow section, V_{j-dp}, is

$$\begin{aligned} &V_j > V_{j-req} \quad V_{j-DP} = V_j - V_{j-req} \\ &V_j < V_{j-req} \quad V_{j-DP} = 0 \end{aligned} \quad (20.28)$$

Example 20.7 Calculate the distribution uniformity and irrigation efficiency for the furrow described in Example 20.6. A more accurate estimate of the advance time is 3.85 h and the recession time is 0.97 h. The required depth of infiltration is 77 mm.

Equation 20.22 can be used to find the infiltrated depths at each of the 11 positions along the furrow (Fig. 20.25). For example, the infiltrated depth and volume (Eq. 20.20) at position 2 (80 m from the inlet representing the segment from 60 m to 100 m) are calculated as follows.

$$\begin{aligned} d_{80} &= k\left(t_{co} + x_j/L\, t_{rec} s x_j^h\right)^a \\ &= 19\left(24\text{ h} + (80/400)(0.97\text{ h}) - \left(0.0305{*}80^{1.49}\right)/60\right)^{0.46} \\ &= 81.4\text{ mm} \\ V_{80} &= W\Delta x_{80}\, d_{80} = 1\text{m}{*}40\text{m}{*}81.4/(1{,}000\text{ mm/m}) = 3.26\text{ m}^3 \end{aligned}$$

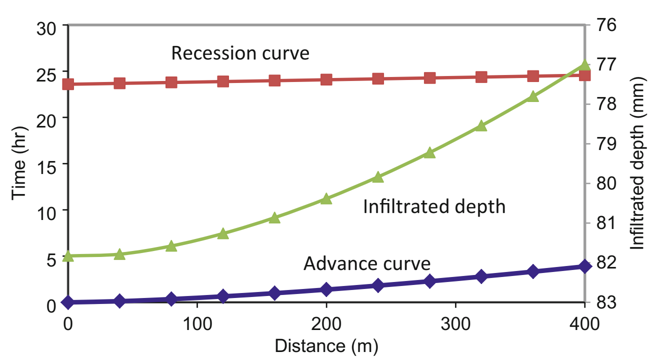

Fig. 20.25 Infiltrated depth versus distance

Table 20.3 Intake opportunity time and infiltrated depth along the furrow

Location (j)	Distance (m)	Advance time (hr)	Recession time (hr)	Opportunity time (hr)	Infiltrated depth (mm)	Inf. volume (m^3)
0	0	0	23.8	23.8	81.7	1.63
1	40	0.12	23.9	23.8	81.6	3.27
2	80	0.35	24.0	23.7	81.4	3.26
3	120	0.64	24.1	23.5	81.1	3.25
4	160	0.98	24.2	23.2	80.7	3.23
5	200	1.37	24.3	22.9	80.3	3.21
6	240	1.80	24.4	22.6	79.7	3.19
7	280	2.26	24.5	22.2	79.2	3.17
8	320	2.76	24.6	21.8	78.5	3.14
9	360	3.29	24.7	21.4	77.8	3.11
10	400	3.84	24.8	20.9	77.0	1.54

Fig. 20.26 Irrigated furrows with multiple siphon tubes (Credit Bert Clemmens, USDA-ARS)

Intake opportunity times, infiltrated depths, and infiltrated volumes in furrow segments are shown in Table 20.3. Infiltrated depths along the furrow are shown in Fig. 20.26.

The low quarter is the average of the infiltrated depths over the last quarter of the field. The following equation can be used where the field is divided into 10 sections:

$$\begin{aligned} d_{LQ} &= (d_8 + d_9 + 0.5\ d_{10})/2.5 \\ &= (78.5\ \text{mm} + 77.8\ \text{mm} + (77.0\ \text{mm})(0.5))/2.5 \\ &= 77.9\ \text{mm} \end{aligned}$$

The last term d_{10} is multiplied by 0.5 because it only represents half of a section.

The average depth infiltrated for the entire furrow, d_{ave}, is

$$d_{ave} = (0.5\ d_0 + d_1 + d_2 + d_3 + d_4 + d_5 + d_6 + d_7 + d_8 + d_9 + 0.5 d_{10})/10 = 80.0\ \text{mm}$$

Distribution uniformity is the low quarter divided by the furrow average

$$DU = d_{LQ}/d_{ave}(100\%) = 77.9\ \text{mm}/80.0\ \text{mm} = 97\%.$$

Total volume of infiltration is the total depth infiltrated over the length of the furrow. The sum of volumes, V_j, in the last column in Table 20.3 is 32.0 m^3.

Calculate deep percolation

$$\begin{aligned} V_{req} &= W\ L\ d_{req} = (1\ \text{m})(400\ \text{m})(77\ \text{mm}/1{,}000\ \text{mm/m}) \\ &= 30.8\ \text{m}^3 \end{aligned}$$

$$V_{DP} = \sum\nolimits_{j=1}^{n} V_j - V_{req} = 32.0\ \text{m}^3 30.8\ \text{m}^3 = 1.2\ \text{m}^3$$

Calculate applied volume

$$V_{in} = Q\ t_{co} = \left(0.001\ \text{m}^3/\sec\right)(24\ \text{hr})(3{,}600\ \sec/\text{hr}) = 86.4\ \text{m}^3$$

Calculate runoff volume

$$V_{RO} = V_{in} - V_{furrow} = 86.4 - 32.0 = 54.4\ \ m^3$$

Calculate the deep percolation percentage

$$DP\% = V_{DP}/V_{in} * 100\% = 1.2/86.4 * 100\% = 1.4\%$$

Calculate the runoff percentage

$$RO\% = V_{RO}/V_{in} * 100\% = 54.4/86.4 = 63\%$$

The high runoff percentage will lead to wasted water unless one of two solutions is implemented: cutback irrigation or tailwater reuse.

Flow rate can be reduced (cut back) once the wetting front reaches the end of the furrow in order to reduce runoff at the end of the furrow. For example, furrows irrigated with two siphon tubes can be cut back to one siphon tube after flow has reached the end of the furrow This technique is called cutback irrigation.

One constraint on cutback irrigation is that the cutback flow rate must be great enough to satisfy all of the infiltration needs of the furrow. If infiltration over the furrow is greater than cutback flow rate, then water recedes from the end of the furrow. The volume infiltration rate at the time that the water reaches the end of the furrow can be calculated as in the following equation (Clemmens et al. 2006); however, in the example in this text, a spreadsheet is used to calculate the infiltration at each position in the field.

$$Q_L = WL\left[b + h^{(a-1)}kt_L{}^{(a-1)}\right]/3,600 \qquad (20.29)$$

where

Q_L = volume infiltration rate, L/s.
t_L = time of advance to end of furrow, hr,
W = furrow spacing, m,
L = furrow length, m.

Equation 20.29 can also be used to find the volume infiltration rate at any time during the advance phase by substituting x for L and t_x for t_L where x is the distance from the furrow inlet to the wetting front.

As with calculation of uniformity and efficiency, numerical integration can be used to find the average infiltration rate over the field during the storage phase: volume infiltration rates are calculated for field segments and summed. The infiltration rate at any point, j, at time t is

$$i_j = ak\left(tsx_j^h\right)^{a-1} + b \qquad (20.30)$$

Once the flow is cut off, the depth of water in the furrow is reduced so the wetted perimeter and thus the infiltration rate decreases. Thus, the required intake opportunity time at the end of the furrow or depth of infiltration must be adjusted.

Example 20.8 Determine the cutback time and flow rate for Example 20.7 with 1.0 LPS initial flow rate if the cutback flow rate is half of the initial flow rate. Determine depth of infiltration.

Half of the initial flow rate (1.0 L/s) is 0.5 L/s. However, the volume infiltration rate is 0.82 L/s so cutback cannot take place at the time that water reaches the end of the furrow. Volume infiltration rate can be calculated during the storage phase using numerical integration in a spreadsheet (Table 20.4). For example, the average infiltration rate at the 80 m position 33 minutes after advance has reached the end of the field is

$$i_{80} = ak(t - sx_{80}{}^{h})^{a-1} + b = 0.46 * 19((231+33-0.0305 * 80^{1.49})/60)^{0.46-1} + 0 = 4.11 \text{ mm/h}$$

Table 20.4 Volume infiltration rate vs. time after advance reaches end of furrow.

				Infiltration rate (mm/h)				
Distance (m)	Advance time (min)	IOT at time t_L (min)	t_L	10 min after t_L	33 min after t_L	62 min after t_L	80 min after t_L	86 min after t_L
0	0	231	Calculate Q_L at time t_L (this column) with equation 20-29. Columns to the right (times after t_L) calculated with numerical integration in spreadsheet	4.13	3.93	3.71	3.60	3.56
40	7	223		4.20	3.99	3.76	3.64	3.61
80	21	210		4.34	4.11	3.86	3.73	3.69
120	38	192		4.53	4.28	4.00	3.86	3.82
160	59	172		4.80	4.51	4.19	4.03	3.98
200	82	149		5.17	4.81	4.43	4.24	4.19
240	108	123		5.69	5.22	4.75	4.52	4.46
280	136	95		6.46	5.81	5.19	4.90	4.81
320	165	65		7.73	6.70	5.82	5.42	5.30
360	197	34		10.39	8.28	6.79	6.19	6.02
400	231	0		23.00	12.11	8.56	7.47	7.20
Ave infiltration in furrow (mm/hr)				6.69	5.57	4.89	4.61	4.52
Total infiltration in furrow (L/s)			0.82	0.74	0.62	0.54	0.51	0.50

Thus, the flow can be cut back 86 minutes after water reaches the end of the furrow (231 + 86 minutes = 5.28 hr. The new cross-sectional area of flow and the wetted perimeter are calculated with Manning's equation. The new flow depth is 3.77 cm, and the new wetted perimeter is

$$\mathrm{P} = \mathrm{b} + 2\ \mathrm{y}\left(1 + \mathrm{z}^2\right)^{0.5}$$
$$= 0.1\ \mathrm{m} + (2)(0.0377\ \mathrm{m})\left(1 + 2^2\right)^{0.5} = 0.269\ \mathrm{m}.$$

Adjust the infiltration rate. $\dfrac{0.269\ \mathrm{m} + 0.213\ \mathrm{m}}{1.0\ \ m} = 0.482$

Clemmens *k* and *a*, from Example 20.2, are 34.45 and 0.462, respectively. Adjust *k* by multiplying by 0.482. No change is required for a.

$$\text{Adjusted } k = 0.482(34.4) = 16.6(\mathrm{mm/hr}).$$

Thus, if water is not backed up at the end of the furrow in order to maintain wetted perimeter, then there is a potential miscalculation associated with cutback irrigation. The ratio of the reduced infiltration rate to the infiltration rate at the original flow (1.0 L/s) is 16.6 / 19 (100 %) = 87 %. Thus, the depth of infiltration at the end of the furrow is only 87 % of the original calculated depth.

$$77\ \mathrm{mm}\ (0.87) = 67\ \mathrm{mm}.$$

Thus, water should be slightly ponded at the end of the furrow in order to avoid this problem with reduced infiltration. Assuming that infiltration is sufficient at the end of the furrow, then the volume of flow/furrow for cutback operation, would be (5.3 hr + 18.7/2) /24 hr * 100 % = 61 % of the no cutback volume. Power costs would also be 61 % of the no cutback power. If infiltration is reduced, then the *cutback* worksheet has an option to calculate the cutback time based on the reduced wetted perimeter in cells M1:S5. These cells are based on equations that are not included in this document.

Reuse Systems

An effective method for improving irrigation efficiency is to use a runoff reuse system. Runoff water is pumped from a tail water recovery point (Fig. 20.27) back up to the head ditch (Fig. 20.28) and reused. In this way, water that was lost to runoff is reused.

The number of furrows that can be irrigated with a reuse irrigation system is

$$F = N\left(\frac{Q_s\left({}^{Eff_{ds}}/_{100}\right)}{Q_f} + Q_r\left(\frac{{}^{Eff_{dr}}/_{100}}{Q_f}\right)\right) = N(n_s + n_r) \quad (20.31)$$

where

N = number of sets,
F = number of furrows,
Q_s = supply flow rate, L/s,
Q_f = individual furrow flow rate, L/s,
Q_r = pumped flow rate in reuse pipeline, L/s,
n_s = number of furrow irrigated with supply water,
n_r = number of furrows irrigated with reuse water.
Eff_{ds} = supply delivery system efficiency, %,
Eff_{dr} = reuse delivery system efficiency, %,

The calculation of reuse flow rate based on supply flow rate is

$$Q_r = Q_s(Eff_{ds}/100\%)(Eff_{rcs}/100\%)(RO\%/100\%) \quad (20.32)$$

where

Eff_{rcs} = efficiency of reuse collection system and reservoir, %.

Substitute Eq. 20.32 into Eq. 20.31.

$$F = N\frac{Q_s\left({}^{Eff_{ds}}/_{100}\right)}{Q_f}\left(1 + \left(\frac{RO\%}{100}\right)\left({}^{Eff_{dr}}/_{100}\right)\left({}^{Eff_{rcs}}/_{100}\right)\right) \quad (20.33)$$

It is more convenient to operate a runoff reuse system with a large reservoir size that holds a one to two set (zone or daily irrigation volume) supply of water. Then, the reuse pump can operate continually. For design purposes, the reservoir should be considered full at the beginning and end of the irrigation event. This is an appropriate assumption during the peak irrigation season, when the irrigation cycle must begin again as soon as the last cycle is completed. For periods of the year when less frequent irrigation is required, then the reservoir may be empty at the beginning and end of the irrigation cycle. In this case, an extra day is required for the irrigation cycle because the first day of the cycle is only irrigated with the supply source water, Q_s, as the reservoir is filled. The last day is only irrigated with the reuse water, Q_r, as the reservoir is drained.

Side slopes of on-farm reservoirs should be 2:1–2.5 to 1 with a very shallow slope (5:1) at one end for cleaning and

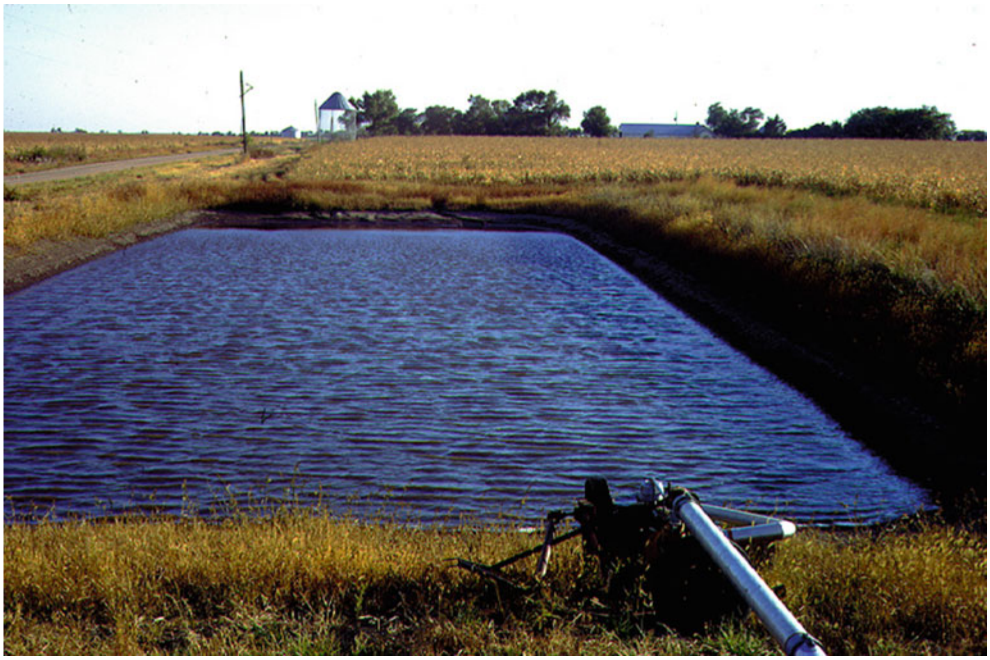

Fig. 20.27 Tailwater recovery reservoir with pumping unit (Credit USDA-ARS)

as an emergency exit. The reservoir should be designed with 30 cm extra depth because sediment builds up in the bottom of the reservoir between cleanings.

Example 20.9 Part 1: Design a runoff recovery system, and determine the required supply flow rate, Q_s, to the head ditch for the furrows described in Example 20.6 and 20.7 (s = 0.0305, h = 1.49). Assume that there is no cutback during the irrigation event. The field width is 800 m wide. The ET_c is 11 mm/day. 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. The field requires 1 m depth of irrigation per year.

Part 2: Determine whether a reuse system should be installed if the required rate of return is 8 %, and the project length is 20 years. Compare to the cost of cutback (Example 20.8) and no reuse system.

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 1,200 m, and the difference in elevation between the head ditch inlet and the reuse reservoir water surface is 3 m. Reuse pump efficiency is 70 %

There is an environmental cost of $1/ha-cm for runoff water discharged to surface streams. Assume that cutback runoff percentage (RO%) is 35 % and the runoff with no cutback is 63 %.

Cost of energy is $0.10/kW-hr.

Assume that the cost of the reuse pump and valves is $5,000. However, the cost of the well pump decreases by $2,000 because a lower flow rate is required for the reuse system. The cost of reservoir excavation is $1.00/m^3. The cost of trenching for the reuse pipe is $1.00/m.

Part 1 Solution : Design of reuse system.

The furrow is designed to apply 77 mm, d_{req} at end of furrow, per irrigation. Thus, 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

$$N = (77\ \text{mm})/(11\ \text{mm/day}) = 7\ \text{sets}$$

The field is 800 m wide, and furrows are 1 m wide so there are 800 furrows, F.

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.

$$Q_s = \frac{FQ_f}{N\left({}^{Eff_{ds}}/_{100}\right)\left(1 + \left(\frac{RO\%}{100}\right)\left({}^{Eff_{dr}}/_{100}\right)\left({}^{Eff_{rcs}}/_{100}\right)\right)}$$

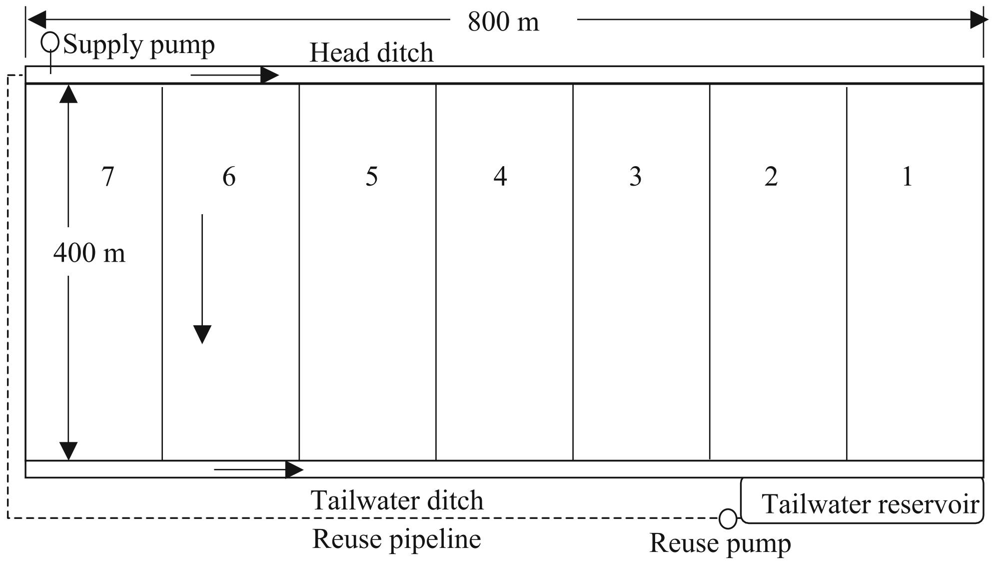

Fig. 20.28 Tailwater recovery system schematic

$$Q_s = \frac{800*1.0\ L/s}{7(0.9)(1+(0.63)(0.9)(0.87))} = 85\ L/s$$

$$Q_r = Q_s(Eff_{ds}/\ 100\%)(Eff_{rcs}/100\%)\ (RO\%/100\%) = 85(0.9)(0.87)(0.63) = 42\ L/s$$

Check results with Eq. 20.31

$$F = 7\left(\frac{85(0.9)}{1} + \frac{42(0.9)}{1}\right) = 800\ furrows$$

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 = 127 L/s.

Let the reservoir hold a 1-day water supply (48 = 42/0.87).

$$48\ L/s\ (24\ hr)(3,600\ sec/hr)/1,000\ L/m^3 = 4,000\ m^3$$

If the reservoir is 2 m deep, then the average reservoir storage area is 2,000 m^2. Average dimensions of 100 m x 20 m would be adequate. If the side slopes are 2:1, and the bottom width is 16 m, then the top (water surface) width would be 24 m, for an average width of 20 m. Likewise, the bottom length should be 93 m and the top length (water surface) should be 107 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 free-board. Thus, the width of the reservoir with a 2:1 side slope would increase by 1.2 m to 25.2 m. The length would increase by 0.3 m (2) + 0.3 m (5) = 2.1 m. Thus, the length of the reservoir is 109.1 m.

Part 2: Cost

Present value analysis (based on present value of energy costs and capital cost of pipe) was used to select a 206 mm (8 in. pipe. A low pressure rating (Cl 100) can be used because the maximum pressure in the pipe is below 15 m, because the velocity is below 1.5 m/s, and because water hammer will not occur if there is not a valve at the discharge end. The cost of 206 mm pipe is $8.00 per m so the cost of the 1,200 m reuse pipeline is $9,600. The pressure loss at 42 LPS flow rate is 8.57 m.

The irrigation time per year is found by dividing the annual required depth by the depth delivered at the end of the furrow by each irrigation

$$1,000\ mm/(77\ mm/irrigation) = 13\ irrigation\ cycles$$
$$(13\ irrigation\ cycles)(7\ irrigations/cycle)(24\ hours/irrigation) = 2,184\ hr$$

Pumping costs:

There is a lift of 3 m between the reservoir surface and the head ditch. The present value of reuse system pumping (Q_r = 42 L/s) is

$$P_r = Q_r \rho g h/Eff$$
$$P_r = 0.042(1,000 kg/m^3)(9.8 m/sec^2)(3+8.57 m)(0.001 kW/W/0.7) = 6.8 kW$$
$$E_r = 6.8 kW(2,184 hr) = 14,480 kW-hr \rightarrow \$1,448/yr \rightarrow PV = \$14,200$$

The present value of the supply system pumping during reuse (85 L/s) is

$$P_s = Q_s \rho g h / Eff$$
$$P_s = 0.085(1{,}000 kg/m^3)(9.8 m/\sec^2)(50 m)(0.001 kW/W/0.8) = 52 kW$$
$$E_s = 52 kW(2{,}184 hr) = 113{,}700 kW - hr \rightarrow \$11{,}370/yr \rightarrow PV = \$111{,}600$$

The present value of pumping without reuse or cutback (Q_s = 127 L/s) is

$$P_s = Q_s \rho g h / Eff$$
$$P_s = 0.127 m^3/s(1{,}000 kg/m^3)(9.8 m/\sec^2)(50 m)(0.001 kW/W/0.8) = 79 kW$$
$$E_s = 79 kW(2{,}184 hr) = 170{,}000 kW - hr \rightarrow \$17{,}000/yr \rightarrow \$166{,}900$$

The present value of pumping with cutback flow is 61 % of the total without cutback.

$$Cutback cost = \$166{,}900 * 0.61 = \$102{,}000$$

Environmental costs:
Cost of runoff water from the no reuse, no cutback system is

$$V_s = 0.127 m^3/s(3{,}600 s/hr)(24 hr/irrigation)(13 irrigations)(0.01 m^3/ha - cm) = 1{,}426 ha - cm$$
$$V_{RO} = Q_s(Eff_{ds})(RO\%) = 1{,}426 ha - cm(0.9)(0.63) = 809 ha - cm/yr \rightarrow \$809/yr \rightarrow PV = \$7{,}900$$

The cost of runoff with the cutback system (1/2 of no cutback) is PV = $7,900/2 = $3,950.

Capital cost:
The capital cost of the reuse system cost includes the cost of the reuse pump (minus the $2,000 saved on the supply pump), pipeline, trenching, and excavation of the reservoir. The volume of the reservoir is 2.3 m/2 m * 4,000 m^3 = 4,600 m^3. The cost of excavation is

$$\$1.00/m^3 * 4{,}600 m^3 = \$4{,}600.$$

The length of the pipeline is 1,200 m. At $1/m, the cost of trenching the pipeline is $1,200. Total capital cost of the reuse pipe system, pump, and reservoir is

$$\$4{,}600 + \$1{,}200 + \$9{,}600 + \$3{,}000 = \$18{,}400.$$

Labor costs:
Labor costs will increase with the cutback system because water will be cutback after 5 hours. When water is cutback from two furrows, then another furrow is started. Thus, irrigation sets will be staggered. It will also be more critical to monitor the end of the furrows in order to determine whether the runoff rate is adequate. Assume that an irrigator will be required for 2 hours per day with the reuse and no cutback/no reuse systems (2 hr * 13 irrigations * 7 zones * $10/hr = $1,820/yr → PV = $17,900). Assume that an irrigator is required for 4 hr/day for the cutback system (4 hr * 13 irrigations * 7 zones * $10/hr = $3,640/yr →PV = $35,700

Present values of costs are compared in Table 20.5

The cutback system has the lowest cost; however, the reuse system may be preferable since there is uncertainty regarding the infiltration rate at the end of the furrow with cutback flow.

Erosive Flow Velocity

In the case of Example 20.7, the distribution uniformity was high because the advance ratio (ratio of advance to storage phase) was low. However, in fields with high infiltration rates and long furrows, the advance ratio, the distribution uniformity will be low. One alternative is to increase the furrow flow rate so that the advance time is reduced. However, increasing furrow velocity can cause erosion. Higher velocity flow has more shear stress at the soil surface and more intense turbulent eddies. Shear stress pick up particles, and eddies keep particles suspended in the stream. The relative magnitude of eddy drag forces and gravitational forces on particles determines whether particles will remain entrained in the stream or settle to the furrow bottom. The maximum nonerosive flow velocity for erosive and non-erosive soils is 8 and 13 m/min, respectively. Sandier soils that do not form soil aggregates are more easily eroded by the furrow irrigation stream. Thus, soils that have a significant percentage of sand (sandy soils) tend to be classified as erosive. Other soils, such as unconsolidated silty soils, are known for severe erosion problems. With these soils, addition of polyacrilymide (PAM) to the irrigation water has been shown to onsolidate soil particles at the soil surface and prevent erosion.

Surge Irrigation

In high infiltration rate soils, one technique that has been used successfully to decrease the depth of water applied during the advance phase is surge irrigation. A surge valve is used to divide the water between two halves of the field. The surge valve cycles water between one side of the field and the other. With surge irrigation, water advances down a furrow and then infiltrates after the water is turned off. In medium to coarse textured soils, the surface tends to consolidate and seal up once the water is turned off. When water is

Table 20.5 Present value of costs for different irrigation systems

System	No cutback, no reuse	Cutback	Reuse
Energy	$166,900	$102,000	$111,600 + $14,200
Labor	$17,900	$35,700	$17,900
Environment	$7,900	$3,950	0
Capital	0	0	$18,400
Total	$192,700	$141,650	$162,100

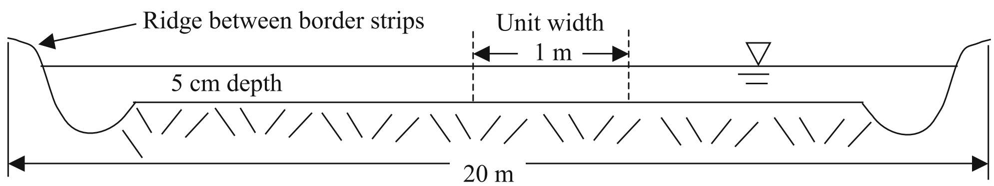

Fig. 20.29 Typical dimensions for border strip in direction perpendicular to flow

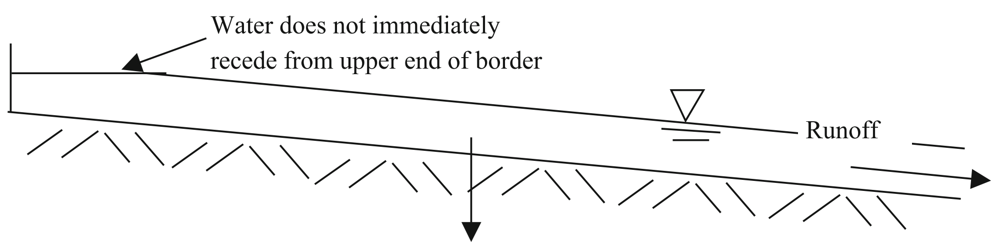

Fig. 20.30 Ponding on border strip after cutoff

reintroduced in the furrow, infiltration is low, and the advance phase is fast. With surge irrigation, the advance time can be nearly as fast as continuous flow, but use half as much water.

Border Strip Irrigation

Graded border strips are strips of flat planted crops, which are level in the direction perpendicular to flow and sloped in the direction of flow. They are confined by small ridges on either side (Fig. 20.29). Water runs down the border as a sheet. WINSRFR has a border strip option.

The advance curve for border strip irrigation is calculated in the same way as for furrow irrigation with $\sigma_y = 0.7$. However, calculation of the recession curve is more complex because, unlike furrows, recession does not occur immediately in a border strip (Fig. 20.30).

The upper end remains ponded because there is a large volume of water on top of the soil that does not immediately infiltration. As with furrows, recession is caused by the combined effects of infiltration and runoff. After cutoff, the water volume of water continues to move down the border strip such that the wetting front continues to move toward the end of the border. Thus, the time of cutoff can take place before the wetting front reaches the end of the border. Because water continues to move down the border after cutoff, the infiltration distribution is often better than that observed with furrow irrigation. In fact, the border strip can be designed so that the recession curve is parallel to the advance curve such that infiltration over the border strip is nearly uniform. Nearly level borders are known for high efficiency.

Nonuniformity in soil surface slope and sideslopes in the border strip can dramatically reduce uniformity. Just a few centimeters variation in slope can lead to dramatic variation in infiltrated depth because low areas receive ponded water for a longer period. A sideslope can cause water to primarily run down one side of the border such that one side of the border receives very little water.

Level Basin and Level Border Irrigation

Level basins are large flat areas. As such, the goal is to move the water across the border as fast as possible and then to let the water pond for the required length of time. A typical design flowrate for a square 15 acre (7 ha) level basin is 5 cfs

(8.5 m^3/min). The water is then allowed to infiltrate over time. Well-designed level basins can have irrigation efficiencies of 90 %.

Level borders are 1.0 mile (1.6 km) long at the J.G. Boswell Ranch in California. Huge axial pumps (12,000 LPM) mounted on caterpillar tractors pump canal water over levees. The water sits in the border and excess can be returned to the canal. The reason that that these long border strips have uniform irrigation is that the soil is swelling clay. Once the cracks close after approximately 5 minutes, infiltration essentially stops.

One type of level border system that is becoming more popular due to high efficiency and low labor requirement is the drain back system. In these systems, level borders are fed by a common canal/ditch at one end, when one border is finished water is allowed to drain back into the ditch, and this water is used to irrigate the next borders down the ditch.

Questions

1. Describe the three phases of surface irrigation.
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.
   (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.
   (c) The Kostiakov equation includes steady state infiltration.
   (d) The two-point volume balance method can be expanded to find the coefficient b in the steady state term by using another point.
   (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.
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.
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 question 6, adjust the k value for the wetted perimeter and a furrow spacing of 1 m. Make calculations by hand and in furrow worksheet.
5. Using the information from question 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.
6. Find the time of cutoff for the parameters in question 5. The depth required is 76 mm. You should calculate a total irrigation time of approximately 12 hr.
7. Use the Furrow times worksheet to find the depth of infiltration every 50 m down the furrow for the parameters in questions 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 question, do not use cutback irrigation. Adequately irrigate the entire field (minimum required depth is applied to end of furrow).
8. For the parameters in questions 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
9. Calculate an irrigation schedule for the parameters in previous questions for peak ETc 10 mm/day. Leaching fraction is 10 %.
10. Design a runoff-recovery system for the parameters in questions 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.
11. The required intake opportunity time is 17 hours, advance is 2 hours, and recession time is one hour. What is the t_{co}?
12. Volume of deep percolation is 20 m^3, volume of runoff is 25 m^3, and volume used in the soil profile is 60 m^3. What is the irrigation efficiency, inflow volume, deep percolation percentage, and runoff percentage?

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 LQ?
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?
15. Why does surge irrigation improve irrigation efficiency in some soils?
16. This question and the following questions use WinSRFR. 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.
18. Modify the previous question 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.
19. Modify the previous questions by changing the furrow bottom width to 200 mm and the slope to 0.003. Copy the data from the Estimated Function page.
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.

References

Clemmens AJ, Walker WR, Fangmeier DD, Hardy LA (2006) Design of surface systems, chapter 14. In: Glenn H (ed) ASABE irrigation monograph. American Society of Agricultural and Biological Engineering, St. Joseph

Merriam JL, Clemmens AJ (1985) Time rated infiltrated depth families. In: Development and management aspects of irrigation and drainage systems. ASCE, pp 67–74