United States
Department of
Agriculture

**Soil
Conservation
Service**

National
Engineering
Handbook

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Section 15

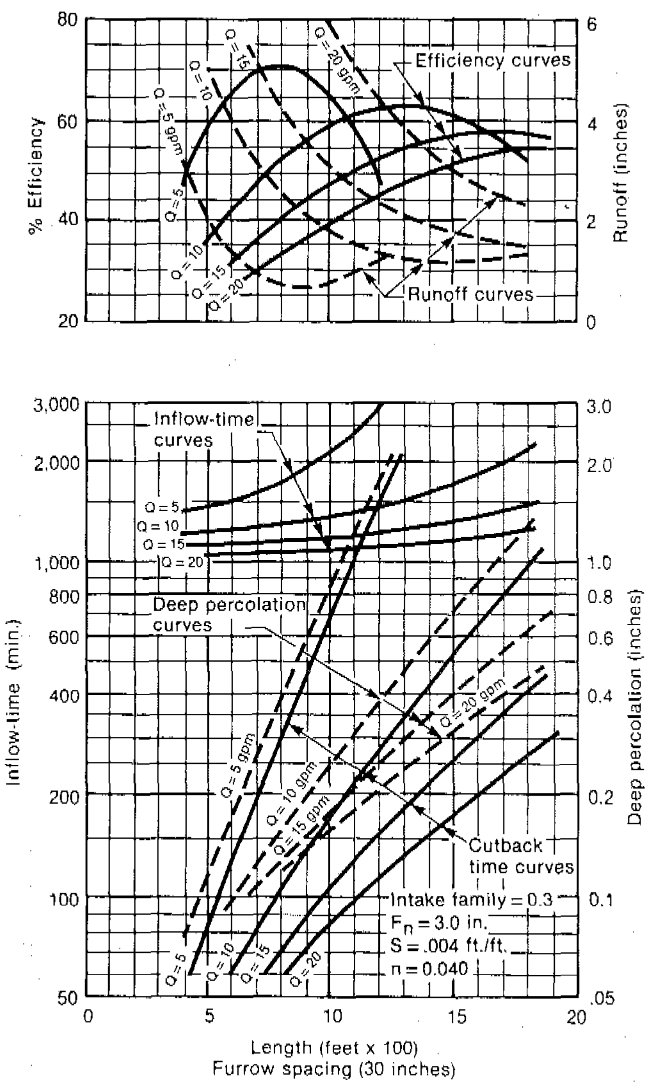
Irrigation

Chapter 5

Furrow Irrigation

Figure 5-19

Cutback-Inflow Furrow Design Chart



4. The ends of the furrows are blocked or diked to prevent outflow and the depth of flow can be contained within the furrow.

The gross application is determined by the inflow rate Q, inflow time T_i, furrow spacing W, and the length L as described by the equation:

$$F_g = \frac{1.6041\, Q\, T_i}{WL}$$

The gross application is also a function of the net application F_n and application efficiency AE as described by:

$$F_g = 100\, F_n/AE = \frac{100}{AE}\,(a\, T_n^{\,b} + 0.275)\,\frac{P}{W}$$

Substituting relationships for gross and net application yields an equation for application efficiency:

$$AE = \frac{100\, PL\, (aT_n^{\,b} + 0.275)}{(1.6041\, Q\, T_i)} \qquad (5\text{–}23)$$

The intake opportunity time at the end of the furrow, to meet assumption 2, is equal to the net intake opportunity time T_n. The average opportunity time for the furrow length is then the average opportunity time during advance time plus the net application time, or:

$$T_{o_{ave}} = T_t - \left[\frac{1}{L}\int_o^L T_t\right] + T_n$$

After integration of equation 2 for advance time (T_t) between the limits of 0 and L and dividing by L, the equation for average intake opportunity time becomes:

$$T_{o_{ave}} = T_n + T_t - \left[\frac{1}{cL\left(\frac{d}{QS^{1/2}}\right)^2}\right.$$

$$\left.\left[\left(\frac{dL}{QS^{1/2}} - 1\right) e^{(dL/QS^{1/2})} + 1\right]\right] \qquad (5\text{–}24)$$

where T_n, from equation 7, is:

$$T_n = \left[(F_n \frac{W}{P} - 0.275)\, 1/a\right]^{1/b}$$

The inflow depth for level furrows may be approximated by the empirical equation:

$$\text{Inflow depth} = 0.1116\, Q^{0.3419}$$

where Q is inflow rate in gpm.

The hydraulic gradient then becomes:

$$S = \frac{1}{L}(0.1116\, Q^{0.3419}) \qquad (5\text{–}25)$$

The first assumption is met by equating the gross application to the average intake:

$$F_g=\left[a(T_{o_{ave}})^b+0.275\right]\frac{P}{W}$$

or

$$\frac{100}{AE}(a\,T_n^{\,b}+0.275)\,\frac{P}{W}=\left[a(T_{o_{ave}})^b+0.275\right]\frac{P}{W}$$

Solving for application efficiency yields the equation:

$$AE=100\frac{(a\,T_n^{\,b}+0.275)}{(a\,(T_{o_{ave}})^b+0.275)} \qquad (5\text{–}26)$$

Combining the equations for efficiency, equations 23 and 26, yields the following equation for inflow time, T_i:

$$T_i=\frac{PL}{1.6041\,Q}\left[a(T_{o_{ave}})^b+0.275\right] \qquad (5\text{–}27)$$

Deep percolation, expressed as an average for the furrow length (L) and spacing (W) is the difference between the gross and net application, or

$$DP=F_g-F_n \qquad (5\text{–}28)$$

Application efficiency is, as previously described:

$$AE=100\,\frac{F_n}{F_g}=\frac{100\,F_n\,WL}{1.6041\,Q\,T_i} \qquad (5\text{–}13)$$

Table 5–10 illustrates design tables prepared using the level furrow relationships. Similar tables for selected net application depth (F_n), furrow length (L), and roughness coefficient (n) can be developed to facilitate design and managment of level furrows. Design charts also can be prepared.

Summary of Level Furrow Equations

Wetted perimeter plus constant

(5–1) $$P=0.2686\,(Qn/S^{0.5})^{\,0.4247}+0.7462$$

Inflow time

(5–27) $$T_i=\frac{PL}{1.6041\,Q}\left[(a(T_{o_{ave}})^b+0.275)\right]$$

Average intake opportunity time

(5–24) $$T_{o_{ave}}=T_n+T_t-\left[\frac{1}{cL\left(\frac{d}{QS^{1/2}}\right)^2}\right]\left[\left(\frac{dL}{QS^{1/2}}-1\right)e^{(dL/QS^{1/2})}+1\right]$$

Net opportunity time

(5–7) $$T_n=\left[(F_n\frac{W}{P}-0.275)\,\frac{1}{a}\right]^{1/b}$$

Advance time

(5–2) $$T_t=\frac{L}{c}\,e^{\,(dL/QS^{1/2})}$$

Hydraulic gradient

(5–25) $$S=\frac{1}{L}\,(0.1116\,Q^{0.3419})$$

Deep percolation

(5–28) $$DP=F_g-F_n$$

Gross application depth

(5–5) $$F_g=\frac{1.6041\,Q\,T_i}{WL}$$

Application efficiency

(5–13) $$AE=100\,\frac{F_n}{F_g}=\frac{100\,F_n\,WL}{1.6041\,Q\,T_i}$$

Design Example of Level Furrows

Information Available:

Type: Level impoundment

Intake family: $I_f=0.3$

Desired application depth: $F_n=3.0$ in

Length: L=900 ft

Spacing: W=2.5 ft

TABLE 5-10.—*Level furrows*

n=0.04 W=30 inches

F_n (in)	L (feet)	I_f	Q (gpm)	AE (pct)	Inflow time (min)	Deep perc. (in)	Advance time (min)	T_n (min)
3.0	600	0.1	5	80.9	693	.71	1,432	2,902
			10	97.3	288	.08	152	2,357
			15	98.5	189	.04	77	2,062
		.3	10	79.8	351	.76	368	712
			15	91.3	205	.29	131	630
			20	94.3	149	.18	81	575
			30	96.1	97	.12	51	501
			40	96.7	73	.10	41	453
			50	96.9	58	.10	36	417
		.5	10	47.9	585	3.26	897	399
			15	76.4	245	.92	224	354
			20	85.7	164	.50	117	324
			30	91.3	102	.29	63	284
			40	93.1	74	.22	47	258
			50	93.8	59	.20	40	238
			60	94.2	49	.18	36	223
		.75	15	50.8	368	2.91	440	223
			20	69.3	202	1.33	186	204
			30	82.7	113	.63	83	180
			40	87.0	81	.45	56	164
			50	89.0	63	.37	45	152
			60	90.0	52	.33	39	142
		1.00	20	50.2	279	2.97	297	147
			30	71.7	130	1.19	108	130
			40	79.6	88	.77	67	119
			50	83.2	67	.61	51	110
			60	85.1	55	.52	43	103
		1.50	30	48.7	192	3.17	188	86
			40	63.2	111	1.75	97	79
			50	70.7	79	1.24	67	72
			60	75.0	62	1.00		
		2.0	40	47.0	149	3.39	141	60
			50	57.8	97	2.19	87	56
			60	64.4	73	1.66	64	52
3.0	800	.1	10	90.2	415	.33	532	2,223
			15	96.1	260	.12	187	1,942
			20	97.5	192	.08	115	1,752
		.3	15	74.3	336	1.04	438	596
			20	85.2	220	.52	207	543
			30	91.6	136	.27	102	472
			40	93.6	100	.21	73	425
			50	94.4	78	.18	61	391

TABLE 5-10.—*Level furrows* (cont.)

				n=0.04	W=30 inches			
F_n (in)	L (feet)	I_f	Q (gpm)	AE (pct)	Inflow time (min)	Deep perc. (in)	Advance time (min)	T_n (min)
		.5	15	41.6	599	4.20	1,023	336
			20	63.4	295	1.73	375	307
			30	80.4	165	.73	145	268
			40	85.9	109	.49	93	242
			50	88.4	85	.40	72	224
			60	89.6	70	.35	61	209
		.75	20	34.9	536	5.60	790	194
			30	61.6	202	1.87	227	170
			40	73.2	128	1.10	126	154
			50	78.6	95	.82	90	143
			60	81.6	76	.68	72	133
		1.00	30	42.7	292	4.03	354	123
			40	58.7	159	2.11	170	112
			50	67.4	111	1.45	112	104
			60	72.6	86	1.15	86	97
		1.50	40	34.0	275	5.82	315	75
			50	46.1	162	3.50	176	69
3.0	1,000	.1	15	90.1	346	.33	464	1,852
			20	94.5	247	.18	233	1,668
			30	96.8	161	.10	122	1,428
		.3	15	45.5	686	3.60	1,546	571
			20	67.5	346	1.44	544	518
			30	83.5	187	.59	203	450
			40	88.5	132	.39	128	404
			50	90.6	103	.31	98	371
		.5	20	34.6	675	5.66	1,270	293
			30	62.5	249	1.80	338	256
			40	74.4	157	1.03	181	231
			50	79.9	117	.75	127	213
			60	82.9	94	.62	101	199
		.75	30	36.3	430	5.27	641	162
			40	53.7	218	2.59	282	147
			50	63.7	147	1.71	175	135
			60	69.6	112	1.31	130	127
		1.00	40	35.3	331	5.51	440	107
			50	47.5	197	3.32	245	99
			60	55.7	140	2.39	168	93
3.0	1,200	.1	15	77.3	484	.88	1,184	1,780
			20	88.6	317	.39	480	1,600
			30	94.4	198	.18	204	1,367

TABLE 5-10.—*Level furrows* (cont.)

n=0.04 W=30 inches

F_n (in)	L (feet)	I_f	Q (gpm)	AE (pct)	Inflow time (min)	Deep perc. (in)	Advance time (min)	T_n (min)
		.3	20	43.9	639	3.83	1,482	499
			30	70.7	264	1.24	406	432
			40	80.6	174	.72	220	388
			50	84.9	132	.53	155	356
			60	87.2	107	.44	124	331
		.5	30	41.4	452	4.25	805	246
			40	58.8	238	2.10	355	222
			50	68.3	164	1.39	222	204
			60	73.7	127	1.07	164	190
		.75	40	33.8	414	5.86	645	141
			50	46.5	242	3.46	347	130
			60	55.0	170	2.45	232	122
		1.00	60	38.4	243	4.81	332	89
4.0	600	.3	10	85.4	438	.68	368	1,086
			15	94.0	265	.26	131	963
			20	96.1	195	.16	81	880
		.5	10	56.7	660	3.06	897	599
			15	82.5	302	.85	224	533
			20	89.7	208	.46	117	489
			30	93.9	133	.26	63	430
			40	95.2	97	.20	47	391
		.75	15	59.4	420	2.74	440	332
			20	76.4	245	1.23	186	305
			30	87.4	143	.58	83	269
			40	90.7	103	.41	56	245
			50	92.2	81	.34	45	227
			60	92.9	66	.31	39	213
		1.00	15	35.3	705	7.32	864	237
			20	58.7	318	2.81	297	218
			30	78.3	159	1.11	108	193
			40	84.8	110	.72	67	176
			50	87.7	85	.56	51	164
			60	89.2	70	.49	43	154
		1.50	30	57.0	219	3.01	187	127
			40	70.9	132	1.65	97	116
			50	77.4	97	1.17	67	108
			60	81.0	77	.94	52	102
		2.00	30	36.7	339	6.89	329	96
			40	55.3	169	3.23	141	88
			50	65.8	114	2.08	87	82
			60	71.8	87	1.57	64	77

Roughness coefficient: $n=0.04$

Procedure:

(1) Assume inflow rate is 20 gpm

(2) Compute hydraulic gradient, using equation 25:

$$S=\frac{1}{L}(0.1116\ Q^{0.3419})$$

$$S=(0.1116\ (20)^{0.3419})/900=0.000345 \text{ ft/ft}$$

(3) Compute wetted perimeter plus constant, using equation 1:

$$P=0.2686\left[\frac{20\times 0.04}{\sqrt{0.000345}}\right]^{0.4247}+0.7462$$

$$P=2.07 \text{ ft}$$

(4) Find coefficients from table 5–9:

Intake family 0.3

$a=0.0364$ $b=0.7204$ $c=24.9706$
$d=9.1977\times 10^{-4}$

(5) Compute net opportunity time, using equation 7:

$$T_n=\left[(F_n\frac{W}{P}-0.275)\frac{1}{a}\right]^{1/b}$$

$$T_n=\left[\left(\frac{3.0\times 2.5}{2.07}-0.275\right)\frac{1}{0.0364}\right]^{1/0.7204}$$

$$T_n=532 \text{ min}$$

(6) Compute advance time, or the time water is predicted to reach the end of the furrow, using equation 2:

$$T_t=\frac{L}{c}e^{(dL/QS^{1/2})}=\frac{900}{24.9706}e^{2.228}=335 \text{ min}$$

(7) Compute average opportunity time, using equation 24:

$$T_{o_{ave}}=T_n+T_t-\left[\frac{1}{cL\left(\frac{d}{Q\sqrt{S}}\right)^2}\right]$$

$$\left[\left(\frac{dL}{Q\sqrt{S}}-1\right)e^{(dL/Q\sqrt{S})}+1\right]$$

$$T_{o_{ave}}=532+335-\left(\frac{1}{(24.9706)(900)\frac{(9.1977\times 10^{-4})^2}{20\sqrt{0.000345}}}\right)$$

$$\left[\left[\frac{(9.1977\times 10^{-4})(900)}{20\sqrt{0.000345}}-1\right]\right.$$

$$\left.e^{\left[\frac{(9.1977\times 10^{-4})(900)}{20\sqrt{0.000345}}\right]}+1\right]$$

$$T_{o_{ave}}=532+335-7.26\ (1.228\ e^{2.228}+1)$$

$$T_{o_{ave}}=532+335-7.26\ (12.395)=777 \text{ min}$$

(8) Compute inflow time, using equation 27:

$$T_i=\frac{PL}{1.6041\ Q}(a\ (T_{o_{ave}})^b+0.275)$$

$$T_i=\frac{(2.07)(900)}{(1.6041)(20)}(0.0364\ (777)^{0.7204}+0.275)$$

$$T_i=271 \text{ min inflow time}$$

(9) Compute gross application, using equation 5:

$$F_g=\frac{1.6041\ Q\ T_i}{WL}=\frac{1.6041\ (20)(271)}{(2.5)(900)}=3.9 \text{ in}$$

(10) Compute average deep percolation, using equation 28:

$$DP=F_g-F_n=3.9-3.0=0.9 \text{ in}$$

(11) Compute application efficiency, using equation 13:

$$AE = 100\frac{F_n}{F_g} = \frac{100\,(3.0)}{3.9} = 77\%$$

(12) Summary

$W = 2.5$ ft

$F_n = 3$ in

$L = 900$ ft

$I_f = 0.3$

$Q = 20$ gpm

$T_i = 271$ min

$F_g = 3.9$ in

$AE = 77\%$

$DP = 0.9$ in

$T_t = 335$ min

$T_n = 532$ min

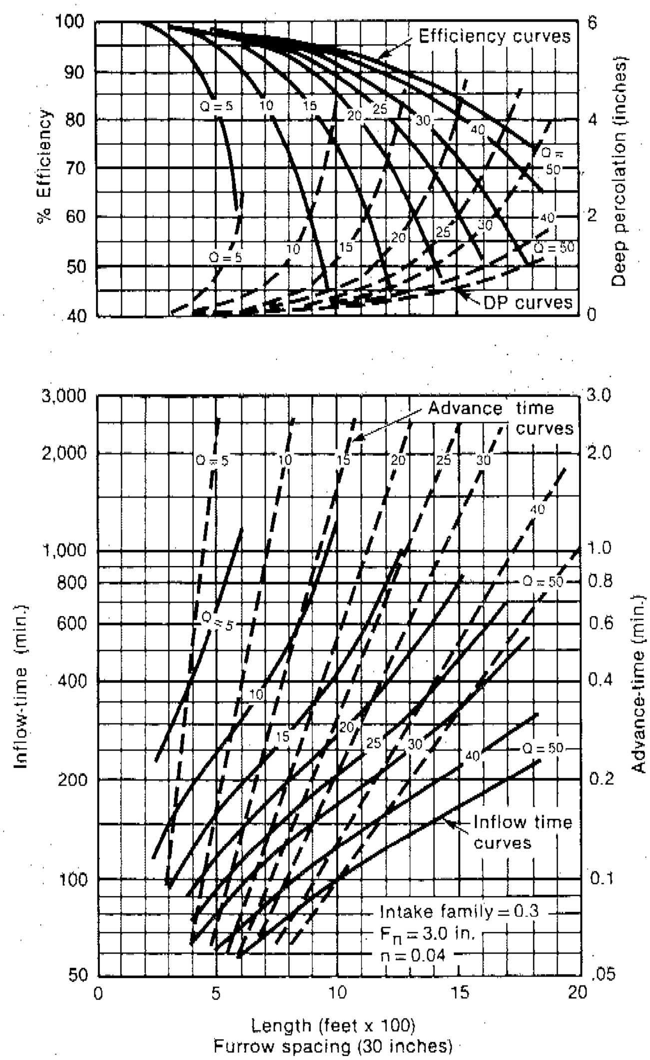
(13) Assume different flow rate and repeat steps 1–11 until an acceptable inflow time and/or efficiency is obtained.

The solution of equations may be avoided by use of design tables.

Preparation of design charts for selected values of intake family and net application depth, using hand calculators or computer facilities, is recommended to avoid the relatively laborious calculations involved. Figure 5–20 is a design chart for intake family 0.3 and a 3.0-inch net application depth.

Figure 5-20

Level Impoundment Furrow Design Chart



Distribution System

The onfarm water conveyance portion of a furrow or corrugation irrigation system consists of all the ditches, conduits, structures, and outlets necessary to deliver the water from the supply source to the individual furrows where it is to be applied. The water conveyance system should be located so that all sections are convenient for operation and maintenance. A properly designed underground pipeline requires the least maintenance and labor. The distribution system should be designed to:

1. Deliver the required quantity of water to each segment of the furrow or corrugation at an elevation that permits proper operation of the system.
2. Be accessible for operation and maintenance.
3. Be flexible in operation.
4. Convey the water as economically, efficiently, and safely as possible.
5. Not permit excess loss in transit.
6. Include facilities for water measurement.

The planned layout of the distribution system should be such that tailwater recovery can be readily incorporated when the system is installed. Other potential uses, such as distribution of livestock waste on the field, should also be considered when making the system layout.

Cost is a major factor in determining the kind of distribution system to use. It is also important in the system layout. The system should be planned so that the minimum amount of ditch and/or pipeline services the entire area and so that the cost of supporting structures is minimal. The system includes either farm ditches or pipelines in conjunction with related structures for conveyance, grade control, water distribution, measurement, and application to the field.

Farm Ditch

Irrigation ditches are open channels used to carry irrigation water to or part way to its point of use. Small, inadequate ditches without proper control structures and maintenance probably cause more trouble in operating a furrow irrigation system than any other factor. In porous soils, unlined ditches lose considerable quantities of water by seepage. This loss frequently accounts for 25 percent or more of the water delivered to the conveyance system. Vegetation along a ditch contributes to water loss through transpiration. There is potential for damage to the distribution system if open ditches are located where they are accessible to livestock or to vehicular traffic. Open, unlined ditches in permeable soils can also cause waterlogged areas.

Lining is an effective way to control seepage and prevent ditch erosion. Concrete linings have proved the most satisfactory type over a period of years. Permanent ditches may, however, obstruct the use of farm equipment. Since the quantity of water needed for most farm irrigation systems is small enough to be carried in a pipeline, surface or underground pipe generally is recommended instead of surface irrigation ditches.

Pipelines

Irrigation pipelines can be placed on the surface or underground. Portable surface pipe has an advantage over underground pipe in that it can be moved and used in more than one location. The disadvantages are that labor is required to move the pipe and it is more susceptible to damage.

Pipeline delivery systems may consist of a combination of buried line and surface pipe. A buried main line may extend from the water source to individual fields and surface pipe may be used for the field main. This permits moving the surface pipe to other fields. The buried main can also extend into the fields as a field main and have risers and valves appropriately spaced to deliver water to surface ditches or gated pipe. The pipe size should limit the velocity to about 5 feet per second.

Related Conveyance Structures

If open ditch systems are used to deliver water to a furrow or corrugation system, frequently it is necessary to provide some type of structure to carry the water across depressions or drains and under roads or other obstructions. Flumes, inverted siphons, and culverts are the structures most commonly used.

Flumes.—Flumes are artificial channels supported by substructures that carry water across areas where ditches are not practical. They must be large enough to carry the full discharge of the ditch and the substructures must be strong enough to support the channel when it is filled with water.

Inverted siphons.—Inverted siphons are closed conduits that carry water under depressions, roads, or other obstructions.

Culverts.—Culverts are closed conduits installed at ditch grade and are commonly used to carry water under farm roads. They are usually corrugated metal, but they can also be concrete pipe.

Where the ditch grade is so steep that the design flow would have an erosive velocity, some protective structure, such as a drop spillway or pipe drop, must be used. These structures control ditch velocity by abruptly lowering the water level. A pipe drop has an advantage in that it can also serve as a ditch crossing.

Distribution Structures

Distribution-control structures are required for easy and accurate distribution of irrigation water to the various fields on a farm or to various parts of a field. They may consist of division boxes to divide or direct the flow of water between two or more ditches, checks that form adjustable dams to control the elevation of the water surface upstream so that water can be diverted from the ditch, or turnout structures to divert part or all of the irrigation stream to a selected portion of the irrigated area.

Application Control Structures

Various devices are used for controlling the flow of water into each furrow or corrugation. Since it is generally desirable to deliver nearly equal flows into a number of rows at one time, control is based on the hydraulic concept that outlets of equal size operating under the same pressure head have equal flows. Rates of flow are changed during the irrigation by altering the size of the outlets, varying the number of outlets used, or changing the operating head over the outlets. The most common type of outlets used are siphon tubes or spiles for delivery from open ditches, and gates installed in sections of a pipe for delivery from surface or underground pipelines.

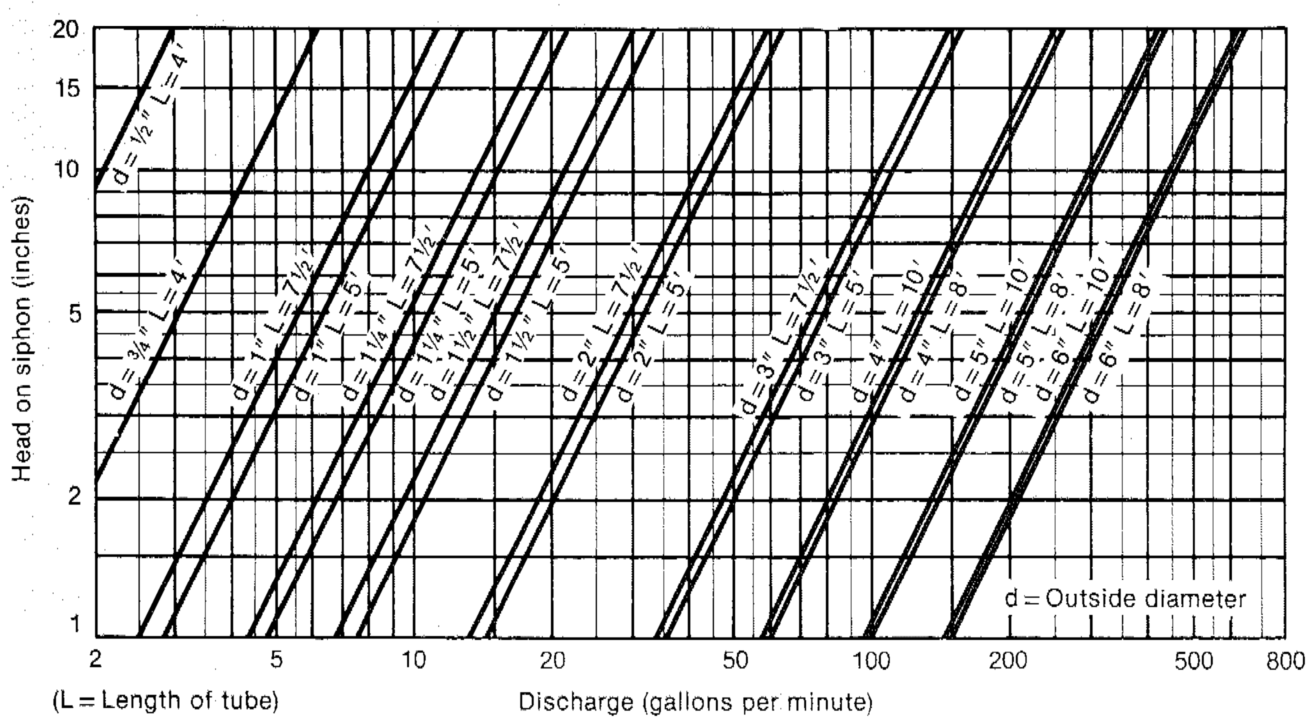
Siphon tubes.—Siphon tubes are usually aluminum or plastic pipe preformed to fit a half cross section of an irrigation ditch. Normal diameters used for furrow or corrugation irrigation range from 0.5 to 2.0 inches. Tubes are available in various lengths but normally are either 5.0 or 7.5 feet long. The discharge of a siphon tube depends on: (1) the inside diameter of the tube, (2) the length of the tube, (3) inside roughness, (4) number and degree of bends, and (5) the head under which the tube is operating. When the outlet end is submerged, the operating head is the difference in elevation between the water surfaces at the entrance and outlet ends of the tube. When water in the tube is flowing freely, the operating head is the difference in elevation between the water surface at the entrance and the center of the outlet end of the tube. Figure 5–21 can be used to estimate the flow from standard aluminum or plastic siphon tubes. When the water supply decreases or is interrupted, standard siphon tubes lose their prime. A siphon tube that automatically resumes operation after interruptions in the water supply is a labor-saving device and provides more safety in furrow water application.

Spiles.—Spiles are pipes, 1.0 to 2.5 inches in diameter, used to distribute water from a ditch into corrugations or furrows. They are set permanently in the bank of the head ditch, and they must be long enough to extend through the bank and linings, if any.

Care must be taken to install spiles at the proper elevation so that the same amount of flow enters all the rows being irrigated at the same time. Spiles are used where the head ditch is nearly level. The water elevation in each ditch section can then be controlled by a check. It should be high enough above the center of the spile opening to deliver the maximum design furrow stream. The water can then be lowered to a point at which the cutback stream flows through the spiles. Flow can also be controlled by gates at the inlet end.

Figure 5-21

Discharge of Aluminum Siphon Tubes at Various Heads



Gated pipe.—Gated pipes are portable pipes with uniformly spaced outlets for releasing irrigation water into individual furrows or corrugations. Gated pipe can be used in place of a head ditch at the top of a field, or it can be used in conjunction with the head ditch. It is well suited to use in place of an intermediate head ditch on fields too long to be irrigated in one length of run. This permits cultivation through longer rows since the pipe can be moved readily.

When connected to buried pipelines through hydrants, gated pipes allow the water to be conveyed in an enclosed system from the source to the head of the furrows or corrugations, thereby reducing seepage losses to a minimum. They also provide a convenient means of regulating flow. The gates provide positive control and are especially good if cutback streams are used. They may be slide gates covering either round or rectangular holes in the pipeline, or they may be round alfalfa-type valves or round butterfly valves in short sections of the properly sized tubing connected to the pipe. Flexible sleeves are frequently attached to the gates to aid in distribution and to minimize erosion at the inlet to the rows. Water flow can be regulated by the degree of gate opening.

High labor costs have caused many farmers to seek labor-saving devices for their irrigation enterprises. These irrigators are interested in some method of making their systems automatic or, at least, semiautomatic. The first requirement for automation of a furrow system is that it be properly designed, installed, and maintained. Systems can be completely automatic, with reset features and water sensors that detect the need for irrigation, turn on the water if from farm sources, correctly irrigate the field portion by portion, turn off the water when the irrigation is complete, and reset so that the system is prepared for the next irrigation.

Most automated farm systems are semiautomatic, with the irrigator deciding when irrigation is needed and delivering the irrigation water to the field. Delivery to a field is by surface ditches or by surface or underground pipelines. Where surface ditches are used, the head ditches are lined and have check gates that are tripped by the weight of accumulated water from a controlled rate of flow that slowly fills a container. The ditch must have a predetermined grade so that water is applied uniformly to the correct number of furrows at a proper design rate. The furrows can be irrigated by use of spiles through the ditch or by use of the fail-safe siphon tubes.

Automation is more commonly used with underground pipe in conjunction with surface gated pipe. Pneumatic valves in hydrants attached to the underground pipe control the flow to sections of gated pipe. These valves are usually controlled by a time clock that allows the irrigation to continue for a predetermined time, and diverts water to sequencing sets across the field or fields.

If farm irrigation systems are to be automated, the following requirements should be met:

1. The system should be such that failure of the automation does not result in excessive damage to the immediate farm, or to other property.
2. The system should be simple, reliable, and easily maintained.
3. It should be economically feasible.
4. It should operate at low cost.
5. It should irrigate the field efficiently and distribute water uniformly.
6. It should be capable of applying various depths of water according to seasonal plant needs.

It is essential that any automatic or semiautomatic system include provisions for tailwater recovery.

The irrigation water can also be controlled by using sensing or timing devices that change the irrigation from one set of furrows to the next by automatically controlling gates or valves in the distribution system. Moisture resistance blocks and tensiometers are used as sensing devices. Tensiometers can be used only where soil moisture tensions are less than one atmosphere. The resistance blocks can measure a greater range of soil moisture conditions and, therefore, are probably more satisfactory for most uses.

Provisions to remove water promptly and safely from the irrigated land should be an integral part of the design of a farm irrigation system. The excess water may be surface runoff from rainfall, tailwater from irrigation, or excess percolation of either irrigation or rainfall. It may also include leakage or seepage from parts of the conveyance system.

Storm runoff must be diverted around or carried through the irrigation system to protect the land, the irrigation system, and the crop. Special erosion control measures may require modifications in the design or layout of the irrigation system. Tailwater from irrigation must be recovered or disposed of without damage to lower lands. Excess percolation of either irrigation water or rainfall may lead to a high water table that restricts root growth or promotes a saline or alkaline condition. Seepage from ditches, reservoirs, and sumps may waterlog adjacent land, requiring tile or open drains to control the water table.

Outflow Control

Rainfall Runoff

Standard Soil Conservation Service procedures are available to determine the volume and rate of runoff from precipitation. Runoff can leave the land through natural water courses. Tailwater or waste ditches are needed at the lower end of irrigation runs to collect both this rainfall runoff and tailwater from irrigation. Storm runoff generally governs the capacity requirements. Where storage and tailwater recovery facilities are provided for irrigation, the storm runoff should bypass the storage reservoir to prevent rapid loss of storage capacity by silt carried in the storm runoff.

Irrigation Runoff

Provisions for storage, safe disposal, or recovery of tailwater must be included in any graded furrow or corrugation irrigation layout if efficient irrigation is to be achieved. To obtain good water distribution in a furrow or corrugation system, the advance time should be as rapid as is practical. This requires an initial furrow stream considerably larger than needed to meet the intake rate of the soil, which results in considerable outflow or tailwater. By use of an inflow-cutback procedure, the tailwater can be reduced. The irrigation tailwater must be collected and reused on the farms or disposed of safely in accordance with state requirements. Some states now require that irrigation water not be allowed to trespass on lands not under the control of the irrigator. It is then necessary to provide some means of collecting the tailwater, transporting it to a pit or reservoir, and either storing or providing recovery facilities as needed.

Subsurface Drains

Irrigation water applied plus effective precipitation usually exceeds crop evapotranspiration. Most of the excess water percolates below the root zone, and unless the underlying material is sufficiently permeable to allow penetration below drainage depth, a water table may form a few feet below the soil surface and require drainage facilities. If drainage facilities are needed, the water table must be held below the root zone to provide aeration and to control salinity. This control is accomplished by subsurface drains that intercept or accumulate the excess ground water and return it to the surface. Subsurface drains are normally designed to lower and maintain the water table at a level ranging from 4.0 to 8.0 feet below the ground surface. A subsurface-drainage system may consist of interceptor drains, relief drains, or pumped drains.

Interceptor drains.—Interceptor drains are used on the more sloping areas with a high water-table gradient. They are aligned perpendicular to the direction of ground-water flow. Subsurface drains are commonly used because the drain must be located according to ground-water conditions, which generally do not correspond to field boundaries, fences, or property lines.

Relief drains.—Relief drains are generally used on level to gently sloping areas with a low water-table gradient. They are usually aligned parallel to the direction of ground-water flow. Relief drains are usually planned as a series of lateral tile lines in a gridiron or herringbone pattern in which each line is connected to a main that leads to an open drain.

Pumped drains.—Pumped drains are used in areas in which the soils are underlain by porous sand or gravel aquifers that can be lowered by pumping. Detailed subsurface and ground-water studies are required to determine the possibility of satisfactorily lowering the water table by pumping.

Tailwater Recovery

Recovery or recirculating facilities collect irrigation runoff and return it to the same or adjacent field for irrigation use. Such systems can be classified according to the method of handling runoff or tailwater. If the water is returned to a field lying at a higher elevation, it is usually referred to as a return-flow system; if the water is applied to a lower lying field, this is termed sequence use. The components consist of tailwater ditches to collect the runoff, drainageways or waterways to convey water to a central collection area, a sump or reservoir for water storage, a pump, a power unit, and a pipeline or ditch to convey water for redistribution. Under certain conditions where gravity flow can be used, neither pump nor pipeline may be necessary.

A return-flow system provides for the temporary storage of a given amount of water and includes the pumping equipment and pipeline needed to deliver the water back into the application system. The sequence system generally has a pump and only enough pipe to convey the water to the head ditch of the next field. The farm often can be planned so that there is enough elevation difference between fields to apply the runoff water to a lower field in sequence by gravity. Recovery systems can also be classified according to whether they accumulate and store runoff water. Systems storing collected runoff water are referred to as reservoir systems. Systems that immediately return the runoff water require little storage capacity. They have automatically cycled pumping systems and are called cycling-sump systems. One or more types of systems may be applicable to a given farm. A sump is used where land value is high, water cannot be retained in a reservoir, or water ponding is undesirable. Dugouts or reservoirs are more common and are easily adapted to storage and planned recovery of irrigation tailwater.

A reservoir system collects enough water to be used as an independent supply or as a supplement to the original supply. The reservoir size depends on whether collected water is handled as an independent supply and, if not, on the rate water is pumped for reuse. A smaller reservoir is required if the system is used for cutback irrigation. Reservoirs should be at least 8.0 and preferably 10 feet deep to discourage growth of aquatic weeds. Side slopes should be 2 or 2.5 feet horizontal for each 1 foot vertical to prevent sloughing of the banks. Where dugouts may be a safety hazard, one end slope should be 5 to 1 or less to provide a way of escape in case of accidents. The reservoir should provide for an unused storage depth of at least 1.0 foot.

The cycling-sump system consists of a sump and a pump large enough to handle the expected rate of runoff that enters the sump. The sump is generally a vertical concrete or steel tube with a concrete bottom. The tube is approximately 48 inches in diameter and installed to a depth of approximately 10 feet. Pump operation is controlled automatically by a float-operated or electrode-operated switch. Some storage can be provided in the collecting ditch.

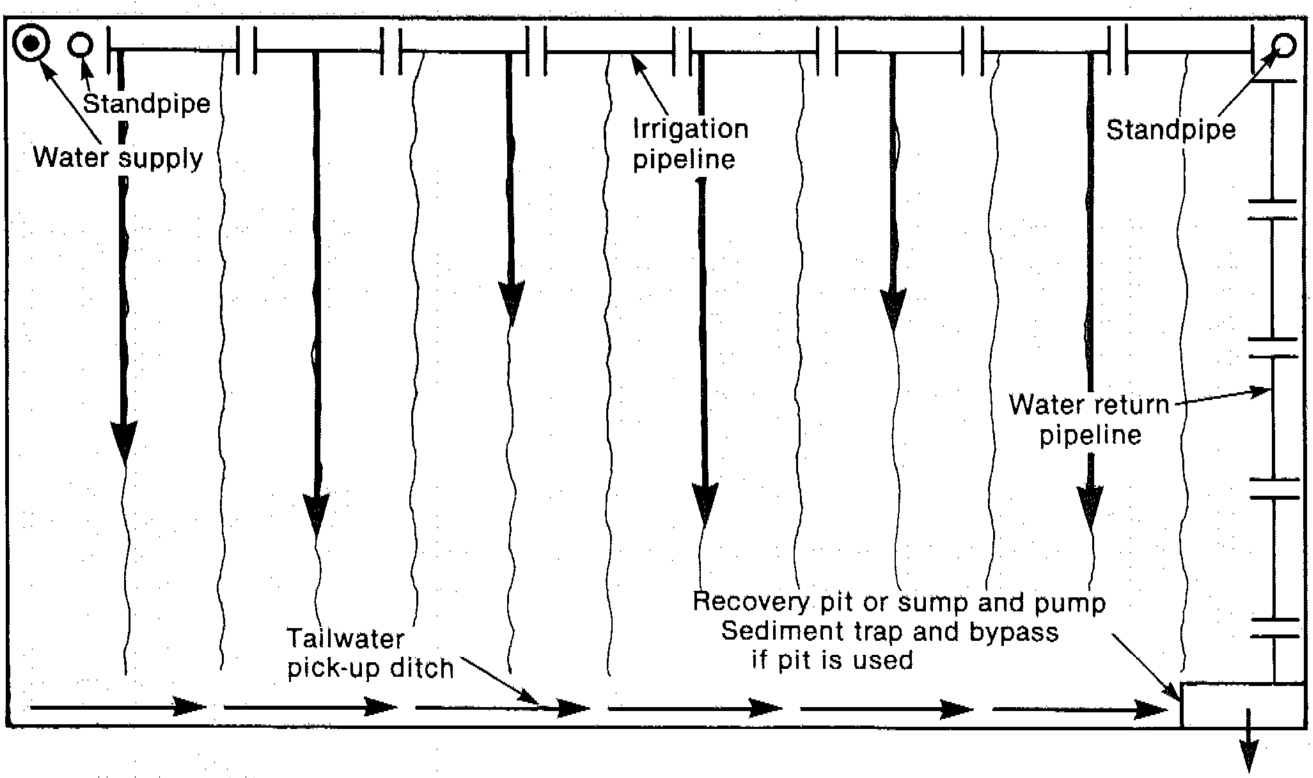
The size, capacity, location, and selection of equipment for these systems are functions of the main irrigation system, the topographic layout of the field or fields, and the farmer's irrigation practice and desires (fig. 5–22).

If a sump is used, the pump should be capable of pumping 40 percent of the initial water supply. This system has the disadvantage that water is applied intermittently, making efficient application rather difficult.

When a dugout is used, it should have the capacity to store the tailwater from a complete irrigation set. The pump capacity depends on the method or schedule of reuse planned. The pump can be designed to empty the storage in approximately one-fourth to one-third the desired application time and, in this way, provide a cutback operation, or it can be designed for continuous operation after the first set is completed with additional furrows watered after the first set.

Figure 5-22

Plan for a Return-Flow System Used in Conjunction With an Underground Pipeline Distribution



There are two purposes for making a furrow intake evaluation. The first is to aid in placing a named soil or group of soils in the intake family for design purposes. The second is to determine the intake time relationship for the specific conditions on an individual farm.

Identifying the furrow intake family associated with a soil series and placing it into an irrigation design group may require evaluations on only a few representative sites in an area. To determine a design criterion adequate for irrigation under the specific conditions on an individual farm, an evaluation must be made on a specific field under a given set of conditions. Recommendations can then be made as to management adjustments needed.

In making an evaluation, inflow and outflow measurements representing an entire irrigation set are most desirable. An alternative is to measure inflow and outflow for the first one-fourth to one-half of the irrigation set. If all irrigations during the season cannot be measured, it is best to make the furrow-intake evaluations during the middle of the irrigation season when conditions are about average; intake rates are usually high in the early part of the irrigation season and lower toward the end of the season.

Site Selection

Furrow tests to determine the intake characteristics must be made on carefully selected sites representative of the soil being evaluated. The site should have no recognizable difference in soils throughout the length that is to be evaluated. The furrows should have a uniform cross section and a uniform grade between the inflow and outflow measuring points. Individual wheel rows should not be evaluated, but they may be included when evaluating a group of furrows.

At least three adjacent furrows or furrow groups should be measured on each test site. Adjacent furrows on each side of the test area should also be irrigated simultaneously.

Soil Conditions

Onsite estimates of soil moisture are essential and should be made when evaluating a specified field. Where feasible, studies should be made if moisture conditions indicate that a normal irrigation application is needed. The condition of the furrows (freshly cultivated, cloddy, dispersed soil, smoothed by previous irrigation, etc.) should be recorded because they influence furrow intake rates. The number of times the field has been irrigated during the season should also be recorded.

Cropping History

The present crop, stage of growth, and previous crop grown should be recorded.

Flow Measurements

The flow of water in furrows can be measured in several ways. If the flow is small (up to about 20 gpm), inflow can be measured volumetrically with a calibrated container and stop-watch, or with other small measuring devices (e.g., orifice plates, V-notch weirs, or trapezoidal flumes). Outflow can be measured with any of the above small measuring devices. See NEH Section 15, Chapter 9, "Measurement of Irrigation Water," for additional information. Care should be taken in selecting and installing measuring devices so as not to block the furrow flow. The outflow measuring device should be located at a point where backwater does not affect the flow to the extent that false intake rates are measured.

Flow Control

The inflow rate should be constant throughout the test. Otherwise, the volume of water in channel storage in the furrow also changes. The inflow rate throughout the test must be described by measured flow rates and the time of measurement.

Procedures

Measure, do not estimate, the furrow length between the inflow and outflow measuring stations. Evaluate the full furrow length. The minimum evaluation length should be 200 to 300 feet for high-intake-rate soils, and 500 to 600 feet for low-intake-rate soils. Determine the average furrow slope and cross section. Take readings to determine uniformity of grade. Adequate cross section measurements usually can be obtained by measuring down from a straight edge placed level across the ridges. Measure cross sections at representative locations (usually two or three) in each test furrow or furrow group. Locate flow-measuring stations at intervals of 50 to 100 feet along the furrow. The furrow stream introduced should not cause erosion. It is, however, desirable, as part of the evaluation, to use the same flow rate that the farmer normally uses, even if it results in erosion. The minimum flow should be large enough to produce a fairly uniform rate of advance. As shown in figure 5-24, record the time water starts flowing into each furrow. Adjust streams so that flows into all furrows are approximately equal. Record the time at which the water in each furrow reaches each station. Periodically or when the inflow rate changes, measure the inflow stream and record the rate of flow and the time. Record the time at which water starts to flow through the outflow measuring device. Periodically measure and record the outflow. If ending the intake evaluation before completion of the full irrigation, record final inflow-outflow measurements and the maximum depth of flow.

Although not needed for the intake evaluation, for the field evaluation it is desirable to measure the wetted bulb after the completed irrigation. A soil moisture probe will readily define the boundary line between the wet soil and the relatively dry soil. The intake opportunity time needed to obtain this wetted pattern should be included with the sketch of the bulbs. Another method that can be used is to excavate a trench across the furrow and observe the wetted area. Examples of data collected from a field trial are given on the furrow intake-data sheets (figs. 5-23, 5-24, and 5-25).

Computation and Evaluation

Compute the inflow and outflow volumes. For each furrow or groups of furrows, determine the average inflow (Q_1), the inflow time (T_1), and the cumulated volumes of inflow (v_1) and outflow (v_0) at the end of the irrigation and at selected intermediate times. The first intermediate time selected should be after flow has reached the outflow station, flow is reasonably uniform, and surface storage in the furrow reach is stable. For each furrow, determine a minimum of three points on the cumulative intake vs. time line. Each point is described by the coordinates: (1) cumulative intake for the furrow length (F_{ave}), and (2) the average opportunity time for intake in the furrow length (T_o).

The average intake ($F_{(0-L)}$) is determined using the following equation:

$$F_{(0-L)} = \frac{1.604}{L(P)}(v_{in} - v_{out} - v_s) = \text{in}$$

where

v_{in} = volume of inflow, gal

$= Q_1 \times T_1$

Q_1 = average inflow rate, gpm

T_1 = inflow time, min

v_{out} = volume of outflow, gal

$= Q_2 \times T_2$

Q_2 = average outflow rate, gpm

T_2 = outflow time, min

v_s = surface storage in gallons in evaluation length, L

L = evaluation length, feet (distance between inflow and outflow measuring stations)

P = width over which intake occurs, equal to wetted perimeter plus a constant

The intake width (P) can be determined using the following:

$$P = 0.2686(Q_1 n/S^{0.5})^{0.4247} + 0.7462 = \text{ft}$$

where

n = Manning coefficient of roughness

S = furrow slopes, ft/ft

Surface storage (v_s), in lieu of actual measurements, can be estimated by the following:

$$v_s = L\,[0.09731(Q_1 n/S^{0.5})^{0.7527} - 0.00574] = \text{gal}$$

The average opportunity time (T_o), in minutes, may be determined as the average of the inflow time (T_1) and the outflow time (T_2).

or: $T_o = 0.5\,(T_1 + T_2)$

When the advance is curvilinear, a more exact value of average opportunity time can be obtained by averaging the opportunity time at various points

FURROW INTAKE

Owner J. Walker State Idaho County Payette

Legal Description Section 1, T7N R4W Date 7/12/78

Soil Series Moulton sandy loam Cylinder Family 1.0
(Attach Soils 232 Card)

Tilth Good Compaction Moderate

Surface Condition Firm

Crop Corn Stage of Growth 48 inches Previous Crop Corn

Tillage Practices Shovel type cultivator

Date Last Irrigation 6/13/78 Inches Applied $\frac{(1.6041)(14.09)(480)}{(900)(2.5)} = 4.82$ gross

Rainfall Since Irrigated: Date — Amount none

This is the Second (Pre: 1st, 2nd, etc.) Irr. of Crop

Additional Observations Flows were erosive at upper end

Normal Irrigating Time (inflow) 8 hours

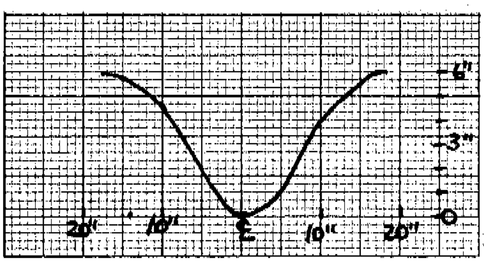
Furrow Spacing 30 Inches Furrow Length 900 Feet

Furrow Profile: Furrow No. 1

Station	0+00	1+00	2+00	3+00	4+00								
Rod Reading	8.4	9.0	9.3	9.5	9.6								

Furrow Cross Section: Sketch or Rod Readings

Station 1+00 Station



Furrow Data Summary:

Q_1 (gpm)	T_1 (min.)	Q_2 (gpm)	T_2 (min.)	L (feet)	S (ft/ft)	W (feet)
14.09	480	8.48	361	900	0.003	2.5

Trial Furrow Intake Family (I'_f) 0.50

Figure 5-23.—Furrow-intake data sheet.

along the furrow length or by integration of the advance curve.

Computation of the opportunity time is facilitated by converting the 24-hour clock time used to record the time of measurements to decimal hours. For example, the 24-hour clock time of 1120 would become 11.33 (11+20/60).

If simultaneous measurements of flow are not made, a plot of cumulative inflow and outflow in gallons vs. clock time from the start of irrigation makes it easier to determine the intake volume at any elapsed time. Subtracting the cumulative outflow from the cumulative inflow yields the intake and storage. Subtracting the surface storage yields the volume of intake, in gallons, at any time. This is illustrated in figure 5–26.

The cumulative intake ($F_{(0-L)}$) and associated opportunity time (T_o) points, when plotted on log-log paper, define the measured intake line. This line is then compared to the intake-family lines (fig. 5–15) to determine the most representative intake family. This is illustrated on figure 5–26, examples 1 and 2.

Example 1

Determination of furrow-intake family from trial measurements where the total irrigation is measured (using example set of data as contained in furrow-intake data sheet).

Soil: Moulten sandy loam

$L=900$ ft $\qquad W=2.5$ ft

$S=0.003$ ft/ft $\qquad Q_1=14.09$ gpm

$$P=(0.2686)(14.09\times 0.04/0.003^{0.5})^{0.4247}+0.7462$$

$$P=1.47 \text{ ft}$$

$$v_s=900\,[(0.09731)(14.09\times 0.04/0.003^{0.5})^{0.7527}-0.00574]$$

$$v_s=500 \text{ gal}$$

Plotting points

$$T_o=0.5\times 60 \text{ min/hr [inflow time (hr)} - \text{outflow time (hr)]}$$

$$aT_o^b+c=\frac{1.6041}{\text{Length}\times P}[\text{inflow vol (gal)}-\text{outflow volume (gal)}-\text{surface storage (gal)}]$$

Intake at 1701 hours

$$T_o=0.5\times 60\,[(16.5-8.5)+(17.0-11.0)]=420 \text{ min}$$

$$aT_o^b+c=\frac{1.6041}{900\times 1.47}(6764-3060-0)=4.49 \text{ in}$$

Intake at 1430 hours (14.5)

$$T_o=0.5\times 60\,[(14.5-8.5)+(14.5-11.0)]=285 \text{ min}$$

$$aT_o^b+c=\frac{1.6041}{900\times 1.47}(5090-1771-500)=3.42 \text{ in}$$

Intake at 1330 hours (13.5)

$$T_o=0.5\times 60\,[(13.5-8.5)+(13.5-11.0)]=225 \text{ min}$$

$$aT_o^b+c=\frac{1.6041}{900\times 1.47}(4235-1212-500)=3.06 \text{ in}$$

Intake at 1230 hours (12.5)

$$T_o=0.5\times 60\,[(12.5-8.5)+(12.5-11.0)]=165 \text{ min}$$

$$aT_o^b+c=\frac{1.6041}{900\times 1.47}(3380-666-500)=2.68 \text{ in}$$

Plot cumulative intake vs. opportunity time (aT_o^b+c vs. T_o) as in figure 5–26 and find intake family (I_f) equals 0.5. Equivalent application depth is:

$$F_{900}=4.49\times 1.47/2.5=2.65 \text{ in}$$

Furrow Flow Data

Sheet 1 of 2
Date 4/5/78
By [illegible]

Farm J. Walker SCD or SWCD Payette

Legal Description Sec. 1, T7N, R4W

Furrow No. 1 Station 0+00 Inflow X or Outflow ____

Measuring Device 1.5" Orifice free flow

(1) Clock* Time	(2) Elapsed Time (min)	(3) ΔT (min)	(4) Gage H ( )	(5) Flow Rate (gpm)	(6) Average Flow Rate (gpm)	(7) Volume (gal)	(8) Σ Volume (gal)	(9) Advance Time: Clock Time	(10) Advance Time: Elapsed Time (min)	(11) Advance Time: Station (ft)
0830	0			0				0841	11	2+00
		5			6.31	31.52	31.52			
0835	5			12.61				0857	27	4+00
		5			13.42	67.10	98.6			
0840	10			14.23				0914	44	5+00
		20			14.25	285.0	383.6			
0900	30			14.27				0932	62	6+00
		60			14.28	856.8	1240.4			
1000	90			14.29				0955	85	7+00
		60			14.27	856.2	2096.6			
1100	150			14.25				1024	114	8+00
		120			14.26	1711.2	3807.8			
1300	270			14.27				1100	150	9+00
		180			14.25	2565.0	6372.8			
1600	450			14.23						
		25			14.22	355.6	6728.4			
1625	475			14.22						
		5			7.11	35.6	6764.0			
1630	480			0						

$Q_i = \frac{6764}{480} = 14.09$ gpm

*24 hour clock time

Figure 5–24.—Furrow-intake evaluation—flow data example 1.

Example 2

Determination of furrow-intake family from trial measurements where only part of the irrigation is measured (using example set of data as contained on furrow-intake data sheets, figs. 5–27, 5–28).

Soil: Moulten sandy loam

$L=400$ ft $\quad W=2.5$ ft

$S=0.003$ ft/ft $\quad Q_1=14.12$ gpm

$P=(0.2686)(14.12\times0.04/0.003^{0.5})^{0.4247}+0.7462$

$P=1.47$ ft

$v_s=400\,[(0.09731)(14.12\times0.04/0.003^{0.5})^{0.7527}-0.00574]$

$v_s=222.9$ gal

Plotting points

$T_o=30$ [inflow time (hr)—outflow time (hr)]

$aT_o^{\,b}+c=\frac{1.6041}{\text{Length}\times P}$ [inflow vol (gal)—outflow vol (gal)—surface storage (gal)]

Furrow Flow Data

Sheet 2 of 2
Date 4/5/78
By [illegible]

Farm J. Walker SCD or SWCD Payette

Legal Description Sec. 1, T 7N R

Furrow No. 1 Station 9+00 Inflow ____ or Outflow X

Measuring Device ____

(1) Clock* Time	(2) Elapsed Time (min)	(3) ΔT (min)	(4) Gage H ( )	(5) Flow Rate (gpm)	(6) Average Flow Rate (gpm)	(7) Volume (gal)	(8) Σ Volume (gal)	(9) Advance Time: Clock Time	(10) Advance Time: Elapsed Time (min)	(11) Advance Time: Station (ft)
1100	0			0						
		10			2.14	21.4	21.4			
1110	10			4.28						
		20			6.32	126.4	147.8			
1130	30			8.36						
		60			8.63	517.8	665.6			
1230	90			8.90						
		60			9.10	546.0	1211.6			
1330	150			9.30						
		120			9.32	1118.4	2330.0			
1530	270			9.34						
		60			9.34	560.4	2890.4			
1630	330			9.34						
		10			8.64	86.4	2976.8			
1640	340			7.93						
		21			3.96	83.2	3060.0			
1701	361			0						

$$Q_2 = \frac{3060}{361} = 8.48 \text{ gpm}$$

*24 hour clock time

Intake at 1330 hours

$$T_o = 0.5 \times 60\,[(13.5-8.5)+(13.5-8.95)] = 286.5 \text{ min}$$

$$aT_o^b + c = \frac{1.6041}{400 \times 1.47}(4235.6-2721.6-222.9)$$
$$= 3.52 \text{ in}$$

Intake at 1230 hours

$$T_o = 0.5 \times 60\,[(12.5-8.5)+(12.5-8.95)] = 286.5 \text{ min}$$

$$aT_o^b + c = \frac{1.6041}{400 \times 1.47}(3380-2034-222.9)$$
$$= 2.97 \text{ in}$$

Intake at 1200 hours

$$T_o = 0.5 \times 60\,[(12.0-8.5)+(12.0-8.95)] = 196.5 \text{ min}$$

$$aT_o^b + c = \frac{1.6041}{400 \times 1.47}(2921-1691.9-222.9)$$
$$= 2.75 \text{ in}$$

Estimated Moisture Condition

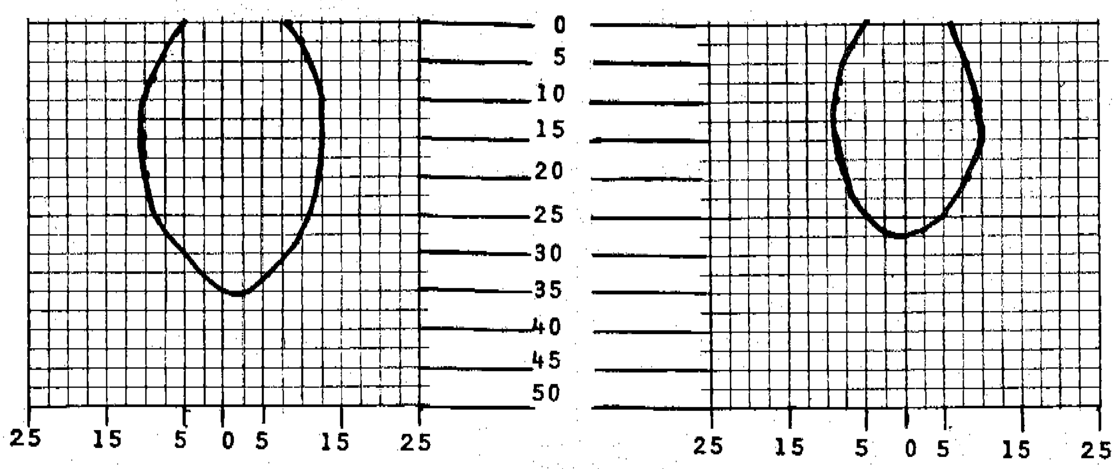
Furrow No. 1

Soil Depth Ft.	Station 0+20				Station 3+80				Station ___			
	Soil Texture	Water Holding Capacity	Percent Remaining	Amount To Be Applied	Soil Texture	Water Holding Capacity	Percent Remaining	Amount To Be Applied	Soil Texture	Water Holding Capacity	Percent Remaining	Amount To Be Applied
0-1	sl	1.4	25	1.05	sl	1.4	30	0.98				
1-2	s.l	1.8	50	.90	s.l	1.8	60	0.72				
2-3	s.l	1.8	75	.45	s.l	1.8	80	0.36				
3-4												
Totals				2.4				2.06				

Wetted Bulbs Sketch:

Station 0+50 Station 3+50

Depth-Inches



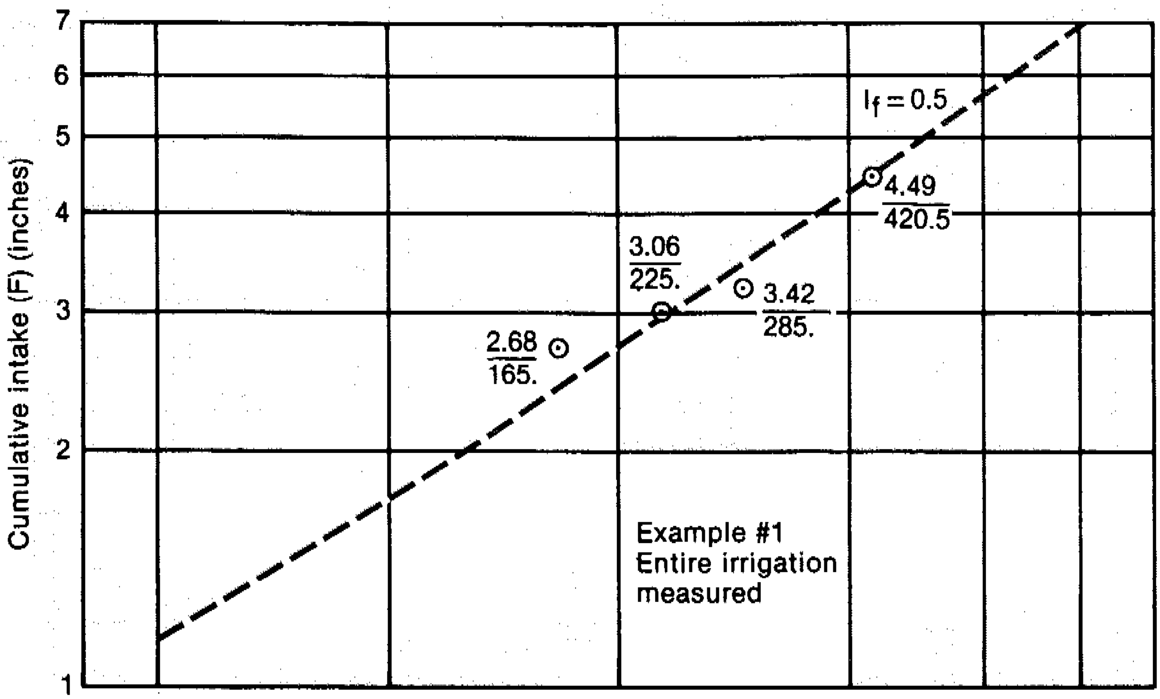
Bulb width - Inches Bulb width - Inches

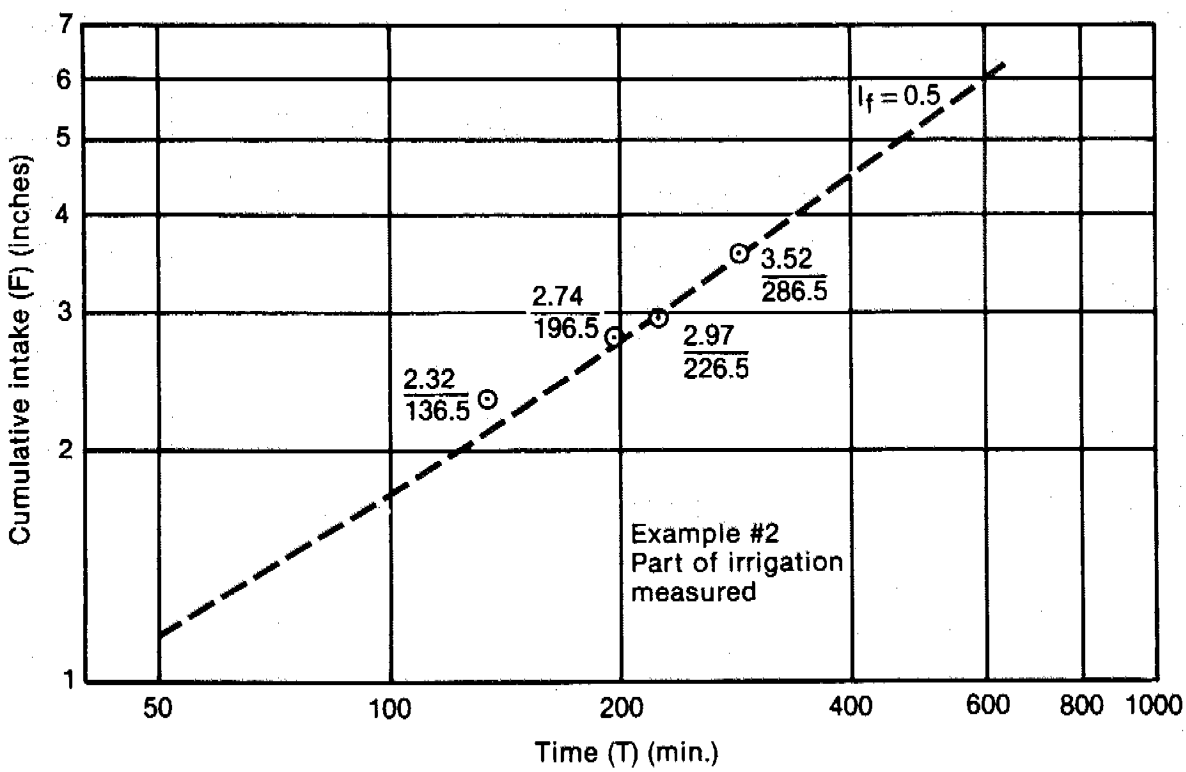
Time Bulbs Measured 24 hours after irrigation

Figure 5-25.—Furrow-intake evaluation—soil water.

Figure 5-26

Cumulative Intake vs. Time—Evaluation Examples





Furrow Flow Data

Sheet 1 of 2
Date 4/15/78
By [illegible]

Farm J. Walker SCD or SWCD Payette

Legal Description Sec 1, T 7N R4W

Furrow No. 1 Station 0+00 Inflow X or Outflow

Measuring Device 1.5" Orifice - free flow

(1) Clock* Time	(2) Elapsed Time (min)	(3) ΔT (min)	(4) Gage H ( )	(5) Flow Rate (gpm)	(6) Average Flow Rate (gpm)	(7) Volume (gal)	(8) Σ Volume (gal)	(9) Advance Time: Clock Time	(10) Advance Time: Elapsed Time (min)	(11) Advance Time: Station (ft)
0830	0			0				0841	11	2+00
		5			6.31	31.52	31.52			
0835	5			12.61				0857	27	4+00
		5			13.42	67.10	98.62			
0840	10			14.23						
		20			14.25	285.0	383.6			
0900	30			14.27						
		60			14.28	856.8	1240.4			
1000	90			14.29						
		60			14.27	856.2	2096.6			
1100	150			14.25						
		120			14.26	1711.2	3807.8			
1300	270			14.27						
		30			14.26	427.8	4235.6			
1330	300			14.25						

$Q_1 = \frac{4235.6}{300} = 14.12$ gpm

*24 hour clock time

Figure 5-27.—Furrow intake evaluation—flow data example 2.

Intake at 1100 hours

$$T_o = 0.5 \times 60\,[(11.0-8.5)+(11.0-8.95)] = 136.5 \text{ min}$$

$$aT_o^b + c = \frac{1.6041}{400 \times 1.47}(2096.6 - 1022.9 - 222.9)$$
$$= 2.32 \text{ in}$$

Plot cumulative intake (aT_o^b+c) vs. opportunity time (T_o) as in figure 5-15 and find intake family equals 0.5.

Furrow Flow Data

Date 4/5/78

By HDC

Farm J. Walker SCD or SWCD Payette

Legal Description Sec1, T7N R4W

Furrow No. 1 Station 4+00 Inflow ____ or Outflow X

Measuring Device 1.5" orifice - free flow

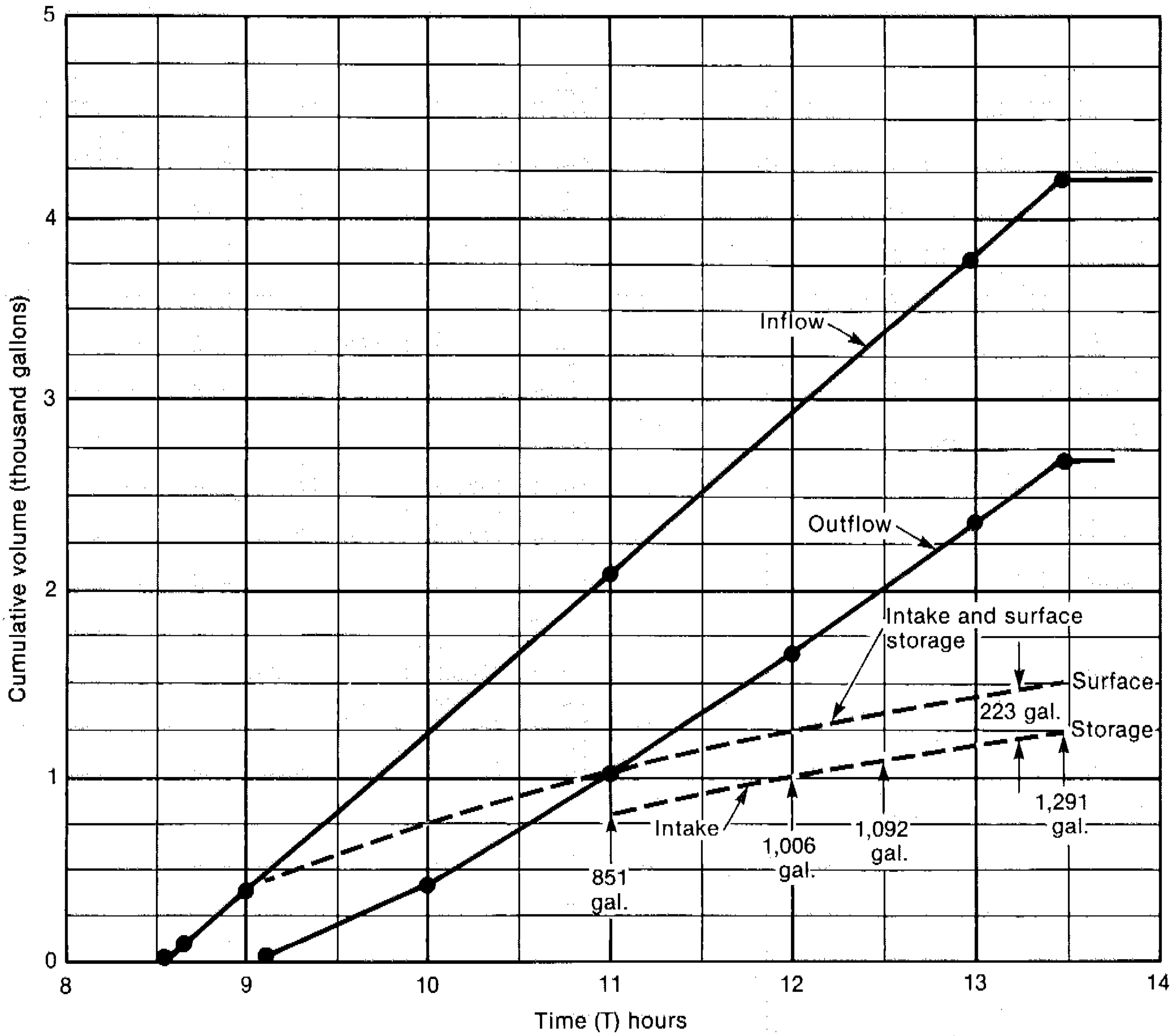
(1) Clock* Time	(2) Elapsed Time (min)	(3) ΔT (min)	(4) Gage H ( )	(5) Flow Rate (gpm)	(6) Average Flow Rate (gpm)	(7) Volume (gal)	(8) Σ Volume (gal)	(9) Advance Time: Clock Time	(10) Advance Time: Elapsed Time (min)	(11) Advance Time: Station (ft)
0857	0			0						
		10			2.57	25.7	25.7			
0907	10			5.14						
		53			7.28	386.1	411.8			
1000	63			9.43						
		60			10.18	611.1	1022.9			
1100	123			10.94						
		60			11.15	669.0	1691.9			
1200	183			11.36						
		60			11.42	684.9	2376.8			
1300	243			11.47						
		30			11.50	344.8	2721.6			
1330	273			11.52						

$$Q_2 = \frac{2721.6}{273} = 9.97 \text{ gpm}$$

*24 hour clock time

Figure 5-28

Cumulative Inflow, Outflow, and Intake—Evaluation Example 2



Many terms used in irrigation work are frequently interpreted differently by personnel working in the irrigation field. The following definitions explain these terms as they apply to furrow irrigation.

Adequacy Terms

The following terms are useful for describing the adequacy of a given irrigation or series of irrigations.

Adequate Irrigation. An irrigation that replaces the management-allowed deficiency (MAD). Where MAD is equal to soil water deficiency (SWD), an adequate irrigation is also a full irrigation.

Full Irrigation. An irrigation that brings the entire root zone to field capacity (FC). After a full irrigation, the soil water deficiency (SWD) will be equal to zero in all parts of the field.

Efficiency Terms

The following efficiency terms are useful in evaluating the potential and/or actual effectiveness of irrigation water applications by a given system. The definitions are usually expressed in equivalent depths of free water (volumes per unit area).

Application Efficiency (AE). The ratio of the average depth of the irrigation water stored in the root zone to the average depth of irrigation water applied.

$$AE = \frac{\text{Average depth of water stored in root zone}}{\text{Average depth of water applied}}$$

AE gives no indication of the adequacy of the irrigation, and with underirrigation it can equal 100 percent. AE merely shows the fraction of applied water stored within the root zone that is potentially accessible for evaporation and transpiration.

Design Efficiency (DE). The ratio of planned depth or irrigation, usually equal to management allowed deficiency (MAD), in a large part of the area, usually 70 to 100 percent, to the average depth of water applied. The design efficiency can be expressed:

$$DE = \frac{\text{Planned depth of irrigation equal to MAD in j part of the area}}{\text{Average depth applied}}$$

$DE_{(j)}$ is used for system design. For example, a $DE_{80} = 75\%$ implies that 80 percent of the area should receive at least 75 percent of the average depth of application. It is not always economical or advisable to use a design efficiency that would result in having 100 percent of the area fully irrigated. There is always a certain amount of nonuniformity of distribution in any system. To fully irrigate the very driest part of the area may require excessive irrigations elsewhere.

Distribution Uniformity (DU). The ratio of the minimum depth of irrigation water infiltrated to the average depth of the irrigation water infiltrated.

$$DU = \frac{\text{Minimum depth of water infiltrated}}{\text{Average depth of water infiltrated}}$$

The minimum depth can be determined as the average of the lowest one-fourth of measured values of water stored, where each measured value represents an equal area. DU is a useful indicator of distribution problems. A low DU indicates that deep percolation losses are excessive if adequate irrigation is supplied to all areas.

Irrigation Efficiency (IE). The ratio of the average depth of irrigation water that is used beneficially to the average depth of irrigation water applied.

$$IE = \frac{\text{Average depth of water used beneficially}}{\text{Average depth of water applied}}$$

IE is a general term, useful for describing the effectiveness of irrigation on a single field, especially if irrigation is used for other than satisfying SWD, i.e., used for salt leaching, frost protection, crop cooling, pesticide, or fertilizer applications. For multiple fields, IE can be used to take into account the beneficial reuse of runoff, deep percolation, and other return flows.

Management Allowed Deficit (MAD). The desired soil moisture deficit at the time of irrigation. It can be expressed as the percentage of available soil water capacity or as the depth of water that has been depleted from the root zone. In arid areas, the ideal irrigation is generally scheduled to just cancel MAD if no leaching is required. In humid areas, ideal supplemental irrigations are often scheduled only to partly cancel MAD, i.e., to leave some root-zone capacity for the storage of anticipated rainfall.

Soil Water Deficit (SWD). The difference between field capacity and the actual moisture in the soil root zone at any given time. It is the amount of water required to bring the soil in the root zone to field capacity.

Other Irrigation Terms

Advance Time (T_t). The time it takes water to advance from the upper end to a selected station along the furrow, frequently called travel time.

Alternate-Row Irrigation. The practice of applying water to every other furrow and then, at the next irrigation, applying a similar amount of water only to the alternate furrows.

Application Rate. The rate at which water is applied to a given area. Usually expressed in inches of depth per hour or in gallons per minute.

Application Time (T_i). The amount of time that water is applied to an irrigation set.

Cumulative Intake. The depth of water absorbed by a soil from the time of initial water application to a specified elapsed time.

Deep Percolation Loss. The water that penetrates below the root-zone depth. The depth of root zone is generally the depth from which the crop is currently capable of extracting soil water. However, it may also be expressed as the depth from which the crop can extract water when mature or the depth from which a crop to be planted in the future can extract soil water.

Effective Precipitation (PE). That part of the total precipitation that is not lost to runoff, deep percolation, or evaporation before the crop can use it.

Evapotranspiration (ET) (Consumptive use). The sum of the transpiration and evaporation from an area coverd by vegetation. It is composed of four factors: evaporation from water surfaces, soil-water evaporation, evaporation from the surface of plants, and transpiration.

Every-Other-Row Irrigation (Skip row). The practice of applying water to every other furrow and applying water to the same furrows every irrigation throughout the cropping season.

Final Intake Rate. The rate at which the soil absorbs water when the infiltration velocity has become nearly constant.

Gated Pipe. A portable pipe with small gates installed along one side for distributing water to corrugations or furrows.

Head. The height of water surface above any plane or reference expressed in units of length.

Hydraulic Radius. The cross-sectional area of a stream or conduit divided by the length of the periphery that is in contact with the water.

Initial Intake. The depth of water absorbed by a soil during the period of rapid or comparatively rapid intake following the initial application.

Initial Intake Rate. The average rate at which water is absorbed by a soil during the period of rapid or comparatively rapid intake following the initial application of water.

Intake Opportunity Time. The amount of time water is infiltrating at any given point along an irrigated corrugation or furrow.

Moisture Replacement Depth. The depth of soil to be brought to field capacity.

Permeability (as used in describing soils). The readiness with which water penetrates or passes through soil pores.

Recession Curve. The descending part of a stream flow or the time lapse after water application has stopped until the water recedes or disappears from the surface at selected stations along the furrow.

Runoff Loss. The irrigation water that leaves the field as surface flow. Irrigation runoff can be returned for beneficial use by a tailwater recovery and return flow system.

Saturate. To fill all the voids between soil particles with irrigation water.

Soil Density. The mass per unit-bulk volume of soil that has been dried to constant weight at 150°C.

Soil Sealing. The orientation and packing of dispersed soil particles in the intermediate surface layer of soil so that it becomes almost impermeable to water.

Surface Soil. The upper part of the soil ordinarily moved in tillage, about 4 to 8 inches in thickness.

Soil Water Terms

The following terms are used to describe soil-water status or the soil's water-holding characteristics. The definitions are admittedly simplified descriptions of the actual physical conditions. Such simplification is necessary for practical use of the concepts. For precise use, the method of measurement or estimation should be stated along with the numerical value of each term. The term soil moisture is assumed to be synonymous with the term soil water. Soil-water units can be expressed as percentages of dry weight of soil, percentages of volume of soil, or equivalent surface depth of water per unit depth of soil. Generally, depth of water per depth of soil in the root zone is the most convenient measurement for irrigation evaluation and management.

Available Soil Water Capacity (AWC). The water that can be held in the soil's root zone between field capacity and wilting point.

Available Soil Water (ASW). The difference at any given time between the actual water content in the soil's root zone and the wilting point.

Field Capacity (FC). Water remaining in a soil following wetting and natural drainage until free drainage has practically ceased. The time required for cessation of free drainage varies with soil texture and structure and the rate of water use by crops.

Limited Irrigation. An irrigation that replaces less than SWD in the total depth and/or area of the entire root zone. High frequency limited irrigation may permit maximum yield if the evapotranspiration requirements of the crop are met.

Wilting Point (WP). The water content in the soil's root zone at which plants can no longer extract water at a sufficient rate for survival.

Appendix—Programmable Calculator Programs for Texas Instruments Model 59

Graded Furrow Design

The program computes inflow time (T_i), efficiency (E), runoff (RO), and deep percolation (DP) for selected values of intake family (I_f), furrow spacing (W), design application depth (F_x = da), slope (S), inflow rate (Q), and furrow length (L).

User's Instructions:

Step	*Procedure*	*Enter*	*Press*		*Display*
1	Enter card, or place in LRN mode and key in program	1 2			1 2
2	Enter data Intake family	I_f	2nd	A′	
	Furrow spacing, ft	W	2nd	B′	
	Design applic., in.	F_x=da		A	
	Furrow slope, ft/ft	S		B	
	Inflow rate, gpm	Q		C	
	Furrow length, ft	L		D	
3	Initiate program			E	
	Inflow time, min.				T_i
	Efficiency, %			R/S	E
	Runoff, in.			R/S	RO
	Deep perc. in.			R/S	DP

Program Limits:

1. Maximum efficiency less than 100%.
2. Average intake (F_{ave}) must be less than total inflow depth (F_i).

Program Listing

000	91	R/S
001	76	LBL
002	16	A′
003	42	STO
004	01	01
005	91	R/S
006	76	LBL
007	11	A
008	42	STO
009	02	02
010	91	R/S
011	76	LBL
012	12	B
013	42	STO
014	03	03
015	91	R/S
016	76	LBL
017	13	C
018	42	STO
019	04	04
020	91	R/S
021	76	LBL
022	14	D
023	42	STO
024	05	05
025	91	R/S
026	76	LBL
027	17	B′
028	42	STO
029	23	23
030	91	R/S
031	76	LBL
032	15	E
033	53	(
034	53	(
035	53	(
036	93	.
037	02	2
038	06	6
039	08	8
040	06	6
041	65	X
042	53	(
043	43	RCL
044	04	04
045	65	x
046	93	.
047	00	0
048	04	4
049	55	÷
050	43	RCL
051	03	03
052	34	$\sqrt{X}$
053	54	)
054	45	Y^x
055	93	.
056	04	4
057	02	2
058	04	4
059	07	7
060	54	)
061	54	)
062	85	+
063	93	.
064	07	7
065	04	4
066	06	6
067	02	2
068	54	)
069	55	÷
070	43	RCL
071	23	23
072	54	)
073	42	STO
074	06	06
075	53	(
076	43	RCL
077	01	01
078	65	x
079	93	.
080	00	0
081	00	0
082	01	1
083	05	5
084	07	7
085	06	6
086	04	4
087	85	+
088	93	.
089	00	0
090	00	0
091	00	0
092	04	4
093	04	4
094	06	6
095	08	8
096	05	5
097	54	)
098	42	STO
099	07	07
100	53	(
101	43	RCL
102	01	01
103	65	X
104	05	5
105	93	.
106	08	8
107	06	6
108	05	5
109	03	3
110	85	+
111	02	2
112	03	3
113	93	.
114	02	2
115	01	1
116	01	1
117	54	)
118	42	STO
119	08	08
120	53	(
121	53	(
122	53	(
123	43	RCL
124	01	01
125	85	+
126	93	.
127	01	1
128	06	6
129	06	6
130	02	2
131	08	8
132	01	1
133	54	)
134	55	÷
135	04	4
136	07	7
137	93	.
138	04	4
139	06	6
140	07	7
141	09	9
142	00	0
143	04	4
144	54	)
145	45	Y^x
146	93	.
147	07	7
148	01	1
149	06	6
150	03	3

Program Listing (cont.)

151	07	7	201	01	01	251	65	x
152	08	8	202	75	—	252	43	RCL
153	54	)	203	93	.	253	05	05
154	42	STO	204	06	6	254	54	)
155	09	09	205	03	3	255	42	STO
156	01	1	206	09	9	256	12	12
157	32	XIT	207	07	7	257	22	INV
158	43	RCL	208	03	3	258	23	LNX
159	01	01	209	07	7	259	42	STO
160	77	GE	210	54	)	260	13	13
161	19	D′	211	55	÷	261	53	(
162	53	(	212	03	3	262	43	RCL
163	53	(	213	03	3	263	05	05
164	53	(	214	03	3	264	65	x
165	43	RCL	215	00	0	265	43	RCL
166	01	01	216	04	4	266	13	13
167	75	—	217	93	.	267	55	÷
168	93	.	218	06	6	268	43	RCL
169	00	0	219	07	7	269	08	08
170	02	2	220	02	2	270	54	)
171	54	)	221	09	9	271	42	STO
172	55	÷	222	02	2	272	14	14
173	03	3	223	54	)	273	53	(
174	03	3	224	45	Y^x	274	53	(
175	93	.	225	93	.	275	53	(
176	03	3	226	00	0	276	43	RCL
177	06	6	227	02	2	277	02	02
178	04	4	228	01	1	278	55	÷
179	05	5	229	01	1	279	43	RCL
180	07	7	230	07	7	280	06	06
181	03	3	231	01	1	281	54	)
182	54	)	232	54	)	282	75	—
183	45	Y^x	233	42	STO	283	93	.
184	93	.	234	10	10	284	02	2
185	00	0	235	76	LBL	285	07	7
186	06	6	236	34	$\sqrt{X}$	286	05	5
187	08	8	237	53	(	287	54	)
188	06	6	238	53	(	288	55	÷
189	02	2	239	43	RCL	289	43	RCL
190	54	)	240	07	07	290	09	09
191	42	STO	241	55	÷	291	54	)
192	10	10	242	43	RCL	292	45	Y^x
193	61	GTO	243	04	04	293	43	RCL
194	34	$\sqrt{X}$	244	55	÷	294	10	10
195	76	LBL	245	43	RCL	295	35	1/X
196	19	D′	246	03	03	296	54	)
197	53	(	247	34	$\sqrt{X}$	297	42	STO
198	53	(	248	54	)	298	15	15
199	53	(	249	42	STO	299	85	+
200	43	RCL	250	11	11	300	43	RCL

Program Listing (cont.)

301	14	14
302	54	)
303	42	STO
304	16	16
305	91	R/S
306	53	(
307	53	(
308	53	(
309	53	(
310	43	RCL
311	13	13
312	65	x
313	53	(
314	43	RCL
315	12	12
316	75	—
317	01	1
318	54	)
319	54	)
320	85	+
321	01	1
322	54	)
323	55	÷
324	43	RCL
325	08	08
326	55	÷
327	43	RCL
328	05	05
329	55	÷
330	43	RCL
331	11	11
332	33	X^2
333	54	)
334	94	+/-
335	85	+
336	43	RCL
337	16	16
338	54	)
339	42	STO
340	17	17
341	53	(
342	53	(
343	53	(
344	43	RCL
345	17	17
346	45	Y^x
347	43	RCL
348	10	10
349	54	)
350	65	x
351	43	RCL
352	09	09
353	85	+
354	93	.
355	02	2
356	07	7
357	05	5
358	54	)
359	65	X
360	43	RCL
361	06	06
362	54	)
363	42	STO
364	18	18
365	53	(
366	01	1
367	93	.
368	06	6
369	00	0
370	04	4
371	01	1
372	65	x
373	43	RCL
374	04	04
375	65	x
376	43	RCL
377	16	16
378	55	÷
379	43	RCL
380	05	05
381	55	÷
382	43	RCL
383	23	23
384	54	)
385	42	STO
386	19	19
387	35	1/X
388	65	x
389	43	RCL
390	02	02
391	65	x
392	01	1
393	00	0
394	00	0
395	54	)
396	42	STO
397	20	20
398	01	1
399	00	0
400	00	0
401	32	XIT
402	43	RCL
403	20	20
404	77	GE
405	18	C′
406	43	RCL
407	20	20
408	91	R/S
409	53	(
410	43	RCL
411	19	19
412	75	—
413	43	RCL
414	18	18
415	54	)
416	42	STO
417	21	21
418	91	R/S
419	53	(
420	43	RCL
421	18	18
422	75	—
423	43	RCL
424	02	02
425	54	)
426	42	STO
427	22	22
428	91	R/S
429	92	RTN
430	76	LBL
431	18	C′
432	81	RST
433	92	RTN
434	00	0

Labels Used

002	16	A′
007	11	A
012	12	B
017	13	C
022	14	D
027	17	B′
032	15	E
196	19	D′
236	34	$\sqrt{X}$
431	18	C′

Sample Problem:

Input

0.5	I_f'
2.5	W, ft
3.	F_x, in.
0.001	S, ft/ft
10.00	Q, gpm
1000.00	L, ft.

Output

2361.066087	T_i, min.
19.80257608	E, %
6.510412807	RO, in.
5.639131312	DP, in.

Register Contents

	No.	
0.	00	
0.5	01	I_f'
3.	02	F_x
0.001	03	S
10.	04	Q
1000.	05	L
.6141336954	06	P/w
0.00123505	07	d
26.14365	08	c
.0470691052	09	a
.7474788656	10	b
0.003905571	11	$d/QS^{1/2}$
3.905571024	12	$dL/QS^{1/2}$
49.67843941	13	$e^{dL/QS^{1/2}}$
1900.210545	14	T_T
460.8554922	15	T_n
2361.066037	16	T_i
1996.595433	17	T_o
8.639131312	18	F_{ave}
15.14954412	19	F_i
19.80257608	20	E
6.510412807	21	RO
5.639131312	22	DP
2.5	23	W

Level Furrow Design

The program computes advance (T_t), inflow time (T_i), deep percolation (DP), and application efficiency (E). This program can also be used for computing plotting points for level furrow design charts. Use of a printer is optional.

User's Instructions:

Step	*Procedure*	*Enter*	*Press*	*Display*
1	Partition Registers	3	2nd OP 17	719.29
2	Enter cards or place	1		1.
	in LRN mode and key	2		2.
	in program	3		3.
3	Enter Data			
	Furrow intake family	I_f	2nd A′	I_f*
	Furrow spacing, ft	W	2nd B′	W*
	Inflow rate, gpm	Q	A	Q*
	Length, ft	L	B	L*
	Design application, in	F_n	C	F_n*
4a	Initiate program w/o printer Inflow time, min		E	T_i
	Advance time, min		R/S	T_t
	Deep percolation, in		R/S	DP
	Application efficiency,%		R/S	E
4b	Initiate program w/printer Inflow time, min		E	T_i*
	Advance time, min			T_t*
	Deep percolation, in			DP*
	Application efficiency,%			E*
5	Repeat for different values			

*Printed by printer

Any one or all input values may be changed for another solution.

Program Limits:

Error display will occur when:

1. Inflow rate is greater than 60 gpm.
   a. Without printer blinking 60 (decrease Q).
   b. With printer—"DECREASE Q-60."
2. Furrow width, W, is exceeded.
   a. Without printer blinking excess Q (decrease Q).
   b. With printer—"DECREASE Q—excess Q value printed."
3. Inflow time is greater than 3000 min.
   a. Without printer blinking T_i value shown. This will usually be a very large number (increase Q).
   b. With printer "INCREASE Q—Large T_i number printed."
4. T_t/T_n (ratio advance time to net opportunity time) greater than or equal to 5.
   a. Without printer blinking 3737 (increase Q).
   b. With printer "INCREASE Q—TT."

Program Listing

000	98	ADV	051	42	STO	101	93	.
001	61	GTO	052	15	15	102	02	2
002	98	ADV	053	00	0	103	01	1
003	91	R/S	054	02	2	104	01	1
004	76	LBL	055	07	7	105	95	=
005	16	A′	056	00	0	106	42	STO
006	42	STO	057	00	0	107	20	20
007	10	10	058	69	OP	108	43	RCL
008	02	2	059	04	04	109	10	10
009	04	4	060	43	RCL	110	65	x
010	02	2	061	15	15	111	93	.
011	01	1	062	69	DP	112	00	0
012	69	OP	063	06	06	113	00	0
013	04	04	064	91	R/S	114	01	1
014	43	RCL	065	76	LBL	115	05	5
015	10	10	066	13	C	116	07	7
016	69	OP	067	42	STO	117	06	6
017	06	06	068	16	16	118	04	4
018	81	R/S	069	02	2	119	85	+
019	76	LBL	070	01	1	120	93	.
020	17	B′	071	03	3	121	00	0
021	42	STO	072	01	1	122	00	0
022	12	12	073	69	OP	123	00	0
023	04	4	074	04	04	124	04	4
024	03	3	075	43	RCL	125	04	4
025	00	0	076	16	16	126	06	6
026	00	0	077	69	OP	127	08	8
027	69	OP	078	06	06	128	05	5
028	04	04	079	91	R/S	129	95	=
029	43	RCL	080	76	LBL	130	42	STO
030	12	12	081	15	E	131	21	21
031	69	OP	082	02	2	132	43	RCL
032	06	06	083	00	0	133	13	13
033	91	R/S	084	69	OP	134	45	Y^x
034	76	LBL	085	07	07	135	93	.
035	11	A	086	69	OP	136	03	3
036	42	STO	087	19	19	137	04	4
037	13	13	088	25	CLR	138	01	1
038	03	3	089	43	RCL	139	09	9
039	04	4	090	10	10	140	65	x
040	00	0	091	65	x	141	93	.
041	00	0	092	05	5	142	01	1
042	69	OP	093	93	.	143	01	1
043	04	04	094	08	8	144	01	1
044	43	RCL	095	06	6	145	06	6
045	13	13	096	05	5	146	55	÷
046	69	OP	097	03	3	147	43	RCL
047	06	06	098	85	+	148	15	15
048	91	R/S	099	02	2	149	95	=
049	76	LBL	100	03	3	150	42	STO
050	12	B						

Program Listing (cont.)

151	11	11	201	08	8	251	22	INV
152	06	6	202	06	6	252	53	(
153	01	1	203	95	=	253	53	(
154	32	XIT	204	85	+	254	43	RCL
155	43	RCL	205	93	.	255	10	10
156	13	13	206	07	7	256	75	—
157	77	GE	207	04	4	257	93	.
158	34	$\sqrt{X}$	208	06	6	258	00	0
159	43	RCL	209	02	2	259	02	2
160	12	12	210	95	=	260	54	)
161	75	—	211	42	STO	261	55	÷
162	93	.	212	22	22	262	03	3
163	03	3	213	43	RCL	263	03	3
164	04	4	214	10	10	264	93	.
165	05	5	215	85	+	265	03	3
166	95	=	216	93	.	266	06	6
167	55	÷	217	01	1	267	04	4
168	93	.	218	06	6	268	05	5
169	00	0	219	02	2	269	07	7
170	02	2	220	02	2	270	03	3
171	02	2	221	08	8	271	54	)
172	95	=	222	01	1	272	45	Y^x
173	42	STO	223	95	=	273	93	.
174	24	24	224	55	÷	274	00	0
175	32	XIT	225	04	4	275	06	6
176	43	RCL	226	07	7	276	08	8
177	13	13	227	93	.	277	06	6
178	77	GE	228	04	4	278	02	2
179	23	LNX	229	06	6	279	95	=
180	43	RCL	230	07	7	280	42	STO
181	13	13	231	09	9	281	19	19
182	65	x	232	00	0	282	61	GTO
183	93	.	233	04	4	283	43	RCL
184	00	0	234	95	=	284	76	LBL
185	04	4	235	45	Y^x	285	22	INV
186	55	÷	236	93	.	286	53	(
187	43	RCL	237	07	7	287	53	(
188	11	11	238	01	1	288	43	RCL
189	34	$\sqrt{X}$	239	06	6	289	10	10
190	95	=	240	03	3	290	75	—
191	45	Y^x	241	07	7	291	93	.
192	93	.	242	08	8	292	06	6
193	04	4	243	95	=	293	03	3
194	02	2	244	42	STO	294	09	9
195	04	4	245	18	18	295	07	7
196	07	7	246	01	1	296	03	3
197	65	x	247	32	XIT	297	07	7
198	93	.	248	43	RCL	298	54	)
199	02	2	249	10	10	299	55	÷
200	06	6	250	77	GE	300	03	3

Program Listing (cont.)

301	03	3	351	07	07	401	95	=
302	03	3	352	43	RCL	402	55	÷
303	00	0	353	15	15	403	43	RCL
304	04	4	354	55	÷	404	18	18
305	93	.	355	43	RCL	405	95	=
306	06	6	356	20	20	406	45	Y^x
307	07	7	357	55	÷	407	43	RCL
308	02	2	358	43	RCL	408	19	19
309	09	9	359	14	14	409	35	1/X
310	02	2	360	33	x^2	410	95	=
311	54	)	361	95	=	411	42	STO
312	45	Y^x	362	65	x	412	09	09
313	93	.	363	53	(	413	85	+
314	00	0	364	53	(	414	43	RCL
315	02	2	365	43	RCL	415	08	08
316	01	1	366	14	14	416	95	=
317	01	1	367	75	—	417	45	Y^x
318	07	7	368	01	1	418	43	RCL
319	01	1	369	54	)	419	19	19
320	95	=	370	65	x	420	65	x
321	42	STO	371	53	(	421	43	RCL
322	19	19	372	43	RCL	422	18	18
323	76	LBL	373	14	14	423	95	=
324	43	RCL	374	54	)	424	85	+
325	43	RCL	375	22	INV	425	93	.
326	21	21	376	23	LNX	426	02	2
327	55	÷	377	85	+	427	07	7
328	43	RCL	378	01	1	428	05	5
329	13	13	379	54	)	429	95	=
330	55	—	380	95	=	430	65	x
331	43	RCL	381	94	+/–	431	43	RCL
332	11	11	382	85	+	432	22	22
333	34	$\sqrt{X}$	383	43	RCL	433	65	x
334	95	=	384	07	07	434	43	RCL
335	65	x	385	95	=	435	15	15
336	43	RCL	386	42	STO	436	55	÷
337	15	15	387	08	08	437	01	1
338	95	=	388	43	RCL	438	93	.
339	42	STO	389	16	16	439	06	6
340	14	14	390	65	x	440	00	0
341	22	INV	391	43	RCL	441	04	4
342	23	LNX	392	12	12	442	01	1
343	65	x	393	55	÷	443	55	÷
344	43	RCL	394	43	RCL	444	43	RCL
345	15	15	395	22	22	445	13	13
346	55	÷	396	75	—	446	95	=
347	43	RCL	397	93	.	447	42	STO
348	20	20	398	02	2	448	17	17
349	95	=	399	07	7	449	03	3
350	42	STO	400	05	5	450	00	0

Program Listing (cont.)

451	00	0
452	01	1
453	32	XIT
454	43	RCL
455	17	17
456	77	GE
457	35	1/X
458	05	5
459	32	XIT
460	43	RCL
461	07	07
462	55	÷
463	43	RCL
464	09	09
465	95	=
466	77	GE
467	50	IxI
468	43	RCL
469	17	17
470	65	x
471	43	RCL
472	13	13
473	65	x
474	01	1
475	93	.
476	06	6
477	00	0
478	04	4
479	01	1
480	95	=
481	35	1/X
482	65	x
483	43	RCL
484	15	15
485	65	x
486	43	RCL
487	12	12
488	65	x
489	43	RCL
490	16	16
491	65	x
492	01	1
493	00	0
494	00	0
495	95	=
496	42	STO
497	06	06
498	35	1/X
499	65	x
500	43	RCL
501	16	16
502	65	X
503	01	1
504	00	0
505	00	0
506	95	=
507	75	—
508	43	RCL
509	16	16
510	95	=
511	42	STO
512	05	05
513	87	IFF
514	07	07
515	24	CE
516	58	FIX
517	00	00
518	43	RCL
519	17	17
520	91	R/S
521	43	RCL
522	07	07
523	91	R/S
524	58	FIX
525	02	02
526	43	RCL
527	05	05
528	91	R/S
529	43	RCL
530	06	06
531	58	FIX
532	01	01
533	56	DEL
534	22	INV
535	52	EE
536	22	INV
537	58	FIX
538	91	R/S
539	76	LBL
540	24	CE
541	98	ADV
542	58	FIX
543	00	00
544	03	3
545	07	7
546	02	2
547	04	4
548	69	DP
549	04	04
550	43	RCL
551	17	17
552	69	OP
553	06	06
554	03	3
555	07	7
556	03	3
557	07	7
558	69	OP
559	04	04
560	43	RCL
561	07	07
562	69	OP
563	06	06
564	01	1
565	06	6
566	03	3
567	03	3
568	69	OP
569	04	04
570	58	FIX
571	02	02
572	43	RCL
573	05	05
574	69	OP
575	06	06
576	01	1
577	07	7
578	02	2
579	01	1
580	02	2
581	01	1
582	69	OP
583	04	04
584	43	RCL
585	06	06
586	58	FIX
587	01	01
588	52	EE
589	22	INV
590	52	EE
591	22	INV
592	58	FIX
593	69	OP
594	06	06
595	98	ADV
596	91	R/S
597	76	LBL
598	34	$\sqrt{X}$
599	86	STF
600	01	01

Program Listing (cont.)

601	61	GTO
602	45	Y^x
603	76	LBL
604	23	LNX
605	86	STF
606	02	02
607	76	LBL
608	45	Y^x
609	69	OP
610	00	00
611	03	3
612	05	5
613	01	1
614	07	7
615	01	1
616	06	6
617	04	4
618	01	1
619	01	1
620	05	5
621	69	OP
622	02	02
623	01	1
624	07	7
625	00	0
626	00	0
627	03	3
628	04	4
629	00	0
630	00	0
631	00	0
632	00	0
633	69	OP
634	03	03
635	69	OP
636	05	05
637	87	IFF
638	01	01
639	39	COS
640	87	IFF
641	02	02
642	30	TAN
643	76	LBL
644	39	COS
645	06	6
646	00	0
647	99	PRT
648	81	RST
649	76	LBL
650	30	TAN
651	43	RCL
652	24	24
653	99	PRT
654	81	RST
655	76	LBL
656	35	1/X
657	86	STF
658	00	00
659	76	LBL
660	50	IxI
661	69	OP
662	00	00
663	02	2
664	04	4
665	03	3
666	01	1
667	01	1
668	05	5
669	03	3
670	05	5
671	01	1
672	07	7
673	69	OP
674	02	02
675	01	1
676	03	3
677	03	3
678	06	6
679	01	1
680	07	7
681	00	0
682	00	0
683	03	3
684	04	4
685	69	OP
686	03	03
687	69	OP
688	05	05
689	87	IFF
690	00	00
691	44	SUM
692	69	OP
693	00	00
694	03	3
695	07	7
696	03	3
697	07	7
698	69	OP
699	02	02
700	69	OP
701	05	05
702	81	RST
703	76	LBL
704	44	SUM
705	03	3
706	07	7
707	02	2
708	04	4
709	69	OP
710	04	04
711	43	RCL
712	17	17
713	69	OP
714	06	06
715	81	RST
716	00	0
717	00	0
718	00	0
719	00	0

Labels Used

005	16	A′
020	17	B′
035	11	A
050	12	B
066	13	C
081	15	E
285	22	INV
324	43	RCL
540	24	CE
598	34	$\sqrt{X}$
604	23	LNX
608	45	Y^x
644	39	COS
650	30	TAN
656	35	1/X
660	50	IxI
704	44	SUM

Sample Problem:

Sample Problem (with printer)

2.	IF	Input Data
2.5	W	
5.	Q	
600.	L	
3.	FN	
INCREASE Q		Error Condition, $T_i > 3000$
3.199639 10	TI	
10.	Q	
INCREASE Q		Error Condition, $T_i > 3000$
358954.039	TI	
20.	Q	
INCREASE Q		Error Condition, $T_t/T_n \geq 5$
TT		
30.	Q	
INCREASE Q		Error Condition, $T_t/T_n \geq 5$
TT		
40.	Q	
149.	TI	Output data
141.	TT	
3.39	DP	
47.	EFF	

Try a Q of 70 gpm as a sample.

70.	Q
REDUCE Q	Error Condition, $Q > 60$
60.	

Sample Problem (w/o printer)

2.	I_f	Input Data
2.5	W	
5.	Q	
600.	L	
3.	F_n	
2450791353.		Error Condition, (blinking value) shows that T_i>3000 minutes
10.	Q	Try 10 gpm
52683.33062		Error Condition, (blinking value) shows that T_i>3000 minutes
20.	Q	Try 20 gpm
3737.		Error Condition, (blinking value) the number 3737 indicates that T_t is too great
30.	Q	Try 30 gpm
3737.		Error Condition, (blinking value) the number 3737 indicates that T_t is too great
40.	Q	Try 40 gpm
102.	T_i	Output Data
141.	T_t	
1.37	DP	
68.6	E	

Try a Q of 70 gpm as a sample

70.	Q	Try 70 gpm
60.		Error Condition, (blinking 60) $Q > 60$

Sample Problem:

Register Content

		Register
0.		00
0.		01
0.		02
0.		03
0.		04
3.38630671	DP	05
46.8755077	E	06
141.2504802	T_t	07
102.1624894	T_{adv}	08
59.94169168	T_n	09
2.	I_f	10
.0007949722	s	11
2.5	W	12
60.	Q	13
2.107283211	$d/QS^{1/2}$	14
600.	L	15
3.	F_n	16
149.2964913	T_i	17
.1095374361	a	18
.8073892693	b	19
34.9416	c	20
0.00359965	d	21
2.300916425	p	22
0.		23
97.95454545	$Qmas^2$	24
0.		25
0.		26
0.		27
0.		28
0.		29

Cutback Furrow Design

The program computes total inflow time (T_i), time at which the inflow rate is reduced to one-half (T_t), surface runoff (RO), deep percolation (DP), and application efficiency (E). The program can also be used for computing plotting points for cutback furrow design charts. Use of a printer is optional.

User's Instructions:

Step	*Procedure*	*Enter*	*Press*	*Display*
1	Partition Registers	3	2nd OP 17	719.29
2	Enter cards or place in	1		1.
	LRN mode and key program	2		2.
		3		3.
3	Enter data			
	Furrow intake family	I_f	2nd A′	I_f*
	Furrow slope, ft/ft	S	2nd B′	S*
	Furrow spacing, ft	W	2nd C′	W*
	Inflow rate, gpm	Q	A	Q*
	Length, ft	L	B	L*
	Design application, in	F_n	C	F_n*
4a	Initiate program w/o printer Inflow			
	time, min		E	T_i
	Advance (cutoff) time, min		R/S	T_t
	Runoff, in		R/S	RO
	Deep percolation, in		R/S	DP
	Application efficiency,%		R/S	E
4b	Initiate program w/printer			
	Inflow time, min		E	T_i*
	Advance (cutoff) time, min			T_t*
	Runoff, in			RO*
	Deep percolation, in			DP*
	Application efficiency,%			E*
5	Repeat for different input values Any one or all input values may be changed for another solution.			

*Printed by printer

Program Limits:

Inflow rate is limited to 50 gpm. Error display will occur when inflow time is greater than 3000 min:

1. Without printer blinking T_i value shown. Increase Q or reduce length.
2. With printer increase Q and large T_i number printed. Increase Q, or reduce length.

Program Listing

000	98	ADV
001	61	GTO
002	98	ADV
003	91	R/S
004	76	LBL
005	16	A′
006	42	STO
007	10	10
008	02	2
009	04	4
010	02	2
011	01	1
012	69	OP
013	04	04
014	43	RCL
015	10	10
016	69	OP
017	06	06
018	91	R/S
019	76	LBL
020	17	B′
021	42	STO
022	11	11
023	03	3
024	06	6
025	00	0
026	00	0
027	69	OP
028	04	04
029	43	RCL
030	11	11
031	69	OP
032	06	06
033	91	R/S
034	76	LBL
035	18	C′
036	42	STO
037	12	12
038	04	4
039	03	3
040	00	0
041	00	0
042	69	OP
043	04	04
044	43	RCL
045	12	12
046	69	DP
047	06	06
048	91	R/S
049	76	LBL
050	11	A
051	42	STO
052	13	13
053	03	3
054	04	4
055	00	0
056	00	0
057	69	OP
058	04	04
059	43	RCL
060	13	13
061	69	OP
062	06	06
063	91	R/S
064	76	LBL
065	12	B
066	42	STO
067	15	15
068	00	0
069	02	2
070	07	7
071	00	0
072	00	0
073	69	OP
074	04	04
075	43	RCL
076	15	15
077	69	DP
078	06	06
079	91	R/S
080	76	LBL
081	13	C
082	42	STO
083	16	16
084	02	2
085	01	1
086	03	3
087	01	1
088	69	OP
089	04	04
090	43	RCL
091	16	16
092	69	OP
093	06	06
094	91	R/S
095	76	LBL
096	15	E
097	02	2
098	00	0
099	69	OP
100	07	07
101	69	OP
102	19	19
103	25	CLR
104	43	RCL
105	10	10
106	65	x
107	05	5
108	93	.
109	08	8
110	06	6
111	05	5
112	03	3
113	85	+
114	02	2
115	03	3
116	93	.
117	02	2
118	01	1
119	01	1
120	95	=
121	42	STO
122	20	20
123	43	RCL
124	10	10
125	65	x
126	93	.
127	00	0
128	00	0
129	01	1
130	05	5
131	07	7
132	06	6
133	04	4
134	85	+
135	93	.
136	00	0
137	00	0
138	00	0
139	04	4
140	04	4
141	06	6
142	08	8
143	05	5
144	95	=
145	42	STO
146	21	21
147	53	(
148	43	RCL
149	13	13
150	65	x

Program Listing (cont.)

151	93	.
152	00	0
153	04	4
154	55	÷
155	43	RCL
156	11	11
157	34	√X
158	54	)
159	45	Y^x
160	93	.
161	04	4
162	02	2
163	04	4
164	07	7
165	65	x
166	93	.
167	02	2
168	06	6
169	08	8
170	06	6
171	95	=
172	85	+
173	93	.
174	07	7
175	04	4
176	06	6
177	02	2
178	95	=
179	55	÷
180	43	RCL
181	12	12
182	95	=
183	42	STO
184	22	22
185	53	(
186	43	RCL
187	13	13
188	65	x
189	93	.
190	05	5
191	65	x
192	93	.
193	00	0
194	04	4
195	55	÷
196	43	RCL
197	11	11
198	34	√X
199	54	)
200	45	Y^x
201	93	.
202	04	4
203	02	2
204	04	4
205	07	7
206	65	x
207	93	.
208	02	2
209	06	6
210	08	8
211	06	6
212	95	=
213	85	+
214	93	.
215	07	7
216	04	4
217	06	6
218	02	2
219	95	=
220	55	÷
221	43	RCL
222	12	12
223	95	=
224	42	STO
225	28	28
226	43	RCL
227	10	10
228	85	+
229	93	.
230	01	1
231	06	6
232	06	6
233	02	2
234	08	8
235	01	1
236	95	=
237	55	÷
238	04	4
239	07	7
240	93	.
241	04	4
242	06	6
243	09	9
244	00	0
245	04	4
246	95	=
247	45	Y^x
248	93	.
249	07	7
250	01	1
251	06	6
252	03	3
253	07	7
254	08	8
255	95	=
256	42	STO
257	18	18
258	01	1
259	32	XIT
260	43	RCL
261	10	10
262	77	GE
263	22	INV
264	53	(
265	53	(
266	43	RCL
267	10	10
268	75	—
269	93	.
270	00	0
271	02	2
272	54	)
273	55	÷
274	03	3
275	03	3
276	93	.
277	03	3
278	06	6
279	04	4
280	05	5
281	07	7
282	03	3
283	54	)
284	45	Y^x
285	93	.
286	00	0
287	06	6
288	08	8
289	06	6
290	02	2
291	95	=
292	42	STO
293	19	19
294	61	GTO
295	43	RCL
296	76	LBL
297	22	INV
298	53	(
299	53	(
300	43	RCL

Program Listing (cont.)

301	10	10	351	29	29	401	00	0
302	75	—	352	65	x	402	01	1
303	93	.	353	43	RCL	403	32	XIT
304	06	6	354	15	15	404	43	RCL
305	03	3	355	54	)	405	14	14
306	09	9	356	22	INV	406	77	GE
307	07	7	357	23	LNX	407	35	1/X
308	03	3	358	65	x	408	53	(
309	07	7	359	43	RCL	409	43	RCL
310	54	)	360	15	15	410	20	20
311	55	—	361	55	÷	411	65	x
312	03	3	362	43	RCL	412	43	RCL
313	03	3	363	20	20	413	15	15
314	03	3	364	95	=	414	65	x
315	00	0	365	42	STO	415	43	RCL
316	04	4	366	07	07	416	29	29
317	93	.	367	53	(	417	33	X^2
318	06	6	368	53	(	418	54	)
319	07	7	369	53	(	419	35	1/X
320	02	2	370	43	RCL	420	65	x
321	09	9	371	16	16	421	53	(
322	02	2	372	65	x	422	53	(
323	54	)	373	43	RCL	423	43	RCL
324	45	Y^x	374	28	28	424	29	29
325	93	.	375	35	1/X	425	65	x
326	00	0	376	75	—	426	43	RCL
327	02	2	377	93	.	427	15	15
328	01	1	378	02	2	428	75	—
329	01	1	379	07	7	429	01	1
330	07	7	380	05	5	430	54	)
331	01	1	381	54	)	431	65	x
332	95	=	382	55	÷	432	53	(
333	42	STO	383	43	RCL	433	43	RCL
334	19	19	384	18	18	434	29	29
335	76	LBL	385	54	)	435	65	x
336	43	RCL	386	45	Y^x	436	43	RCL
337	53	(	387	43	RCL	437	15	15
338	43	RCL	388	19	19	438	54	)
339	21	21	389	35	1/X	439	22	INV
340	55	÷	390	54	)	440	23	LNX
341	53	(	391	42	STO	441	85	+
342	43	RCL	392	09	09	442	01	1
343	13	13	393	85	+	443	54	)
344	65	x	394	43	RCL	444	54	)
345	43	RCL	395	07	07	445	42	STO
346	11	11	396	95	=	446	08	08
347	34	$\sqrt{X}$	397	42	STO	447	01	1
348	54	)	398	14	14	448	93	.
349	54	)	399	03	3	449	06	6
350	42	STO	400	00	0	450	00	0

Program Listing (cont.)

451	04	4
452	01	1
453	65	x
454	53	(
455	53	(
456	43	RCL
457	13	13
458	65	x
459	43	RCL
460	07	07
461	54	)
462	85	+
463	53	(
464	43	RCL
465	13	13
466	65	x
467	93	.
468	05	5
469	65	x
470	43	RCL
471	09	09
472	54	)
473	54	)
474	55	÷
475	43	RCL
476	12	12
477	55	÷
478	43	RCL
479	15	15
480	95	=
481	42	STO
482	24	24
483	53	(
484	43	RCL
485	14	14
486	75	—
487	43	RCL
488	08	08
489	54	)
490	45	Y^x
491	43	RCL
492	19	19
493	65	x
494	43	RCL
495	18	18
496	95	=
497	85	+
498	93	.
499	02	2
500	07	7
501	05	5
502	95	=
503	65	x
504	43	RCL
505	28	28
506	95	=
507	42	STO
508	06	06
509	43	RCL
510	08	08
511	45	Y^x
512	43	RCL
513	19	19
514	65	x
515	43	RCL
516	18	18
517	95	=
518	85	+
519	93	.
520	02	2
521	07	7
522	05	5
523	95	=
524	65	x
525	53	(
526	43	RCL
527	22	22
528	75	—
529	43	RCL
530	28	28
531	54	)
532	95	=
533	85	+
534	43	RCL
535	06	06
536	95	=
537	42	STO
538	06	06
539	94	+/-
540	85	+
541	43	RCL
542	24	24
543	95	=
544	42	STO
545	17	17
546	53	(
547	43	RCL
548	06	06
549	75	—
550	43	RCL
551	16	16
552	54	)
553	42	STO
554	23	23
555	53	(
556	43	RCL
557	16	16
558	55	÷
559	43	RCL
560	24	24
561	65	x
562	01	1
563	00	0
564	00	0
565	54	)
566	42	STO
567	25	25
568	87	IFF
569	07	07
570	24	CE
571	58	FIX
572	00	00
573	43	RCL
574	14	14
575	91	R/S
576	43	RCL
577	07	07
578	91	R/S
579	58	FIX
580	02	02
581	43	RCL
582	17	17
583	91	R/S
584	43	RCL
585	23	23
586	91	R/S
587	43	RCL
588	25	25
589	58	FIX
590	01	01
591	52	EE
592	22	INV
593	52	EE
594	22	INV
595	58	FIX
596	91	R/S
597	76	LBL
598	24	CE
599	98	ADV
600	58	FIX

Program Listing (cont.)

601	00	00
602	03	3
603	07	7
604	02	2
605	04	4
606	69	OP
607	04	4
608	43	RCL
609	14	14
610	69	OP
611	06	06
612	03	3
613	07	7
614	03	3
615	07	7
616	69	OP
617	04	04
618	43	RCL
619	07	07
620	69	OP
621	06	06
622	03	3
623	05	5
624	03	3
625	02	2
626	69	OP
627	04	04
628	58	FIX
629	02	02
630	43	RCL
631	17	17
632	69	OP
633	06	06
634	01	1
635	06	6
636	03	3
637	03	3
638	69	OP
639	04	04
640	43	RCL
641	23	23
642	69	OP
643	06	06
644	01	1
645	07	7
646	02	2
647	01	1
648	02	2
649	01	1
650	69	OP
651	04	04
652	43	RCL
653	25	25
654	58	FIX
655	01	01
656	52	EE
657	22	INV
658	52	EE
659	22	INV
660	58	FIX
661	69	OP
662	06	06
663	98	ADV
664	91	R/S
665	81	RST
666	76	LBL
667	35	1/X
668	86	STF
669	00	00
670	76	LBL
671	50	IxI
672	69	OP
673	00	00
674	02	2
675	04	4
676	03	3
677	01	1
678	01	1
679	05	5
680	03	3
681	05	5
682	01	1
683	07	7
684	69	OP
685	02	02
686	01	1
687	03	3
688	03	3
689	06	6
690	01	1
691	07	7
692	00	0
693	00	0
694	03	3
695	04	4
696	69	OP
697	03	03
698	69	OP
699	05	05
700	03	3
701	07	7
702	02	2
703	04	4
704	69	OP
705	04	04
706	43	RCL
707	14	14
708	69	OP
709	06	06
710	81	RST
711	00	0
712	00	0

Labels Used

005	16	A′
020	17	B′
035	18	C′
050	11	A
065	12	B
081	13	C
096	15	E
297	22	INV
336	43	RCL
598	24	CE
667	35	1/X
678	50	IxI

Sample Problem

Sample Problem (with printer)

Input	0.3	IF
	0.004	S
	2.5	W
	10.	Q
	900.	L
	3.	FN
Output	1344.	TI
	133.	TT
	2.07	RO
	0.20	DP
	57.	EFF

Register Content

0.		00
0.		01
0.		02
0.		03
0.		04
0.		05
3.221026651	F_{ave}	06
133.426623	T_t	07
88.3318671	To	08
1210.134647	Tnc	09
0.3	I_f	10
0.004	S	11
2.5	W	12
10.	Q	13
1343.56127	T_i	14
900.	L	15
3.	Fn	16
2.043942858	RO	17
.0364487762	a	18
.7203376724	b	19
24.97059	c	20
0.00091977	d	21
5336399931	P/W	22
.2210266506	DP	23
5.264969508	Fg	24
56.98038698	E	25
45.09475593		26
0.		27
.4736726975	P_1/W	28
.0014542841	$d/QS^{½}$	29

1.	IF	Input
0.002	S	
2.5	W	
10.	Q	
1200.	L	
3.	FN	
INCREASE Q		Error
9676.736769	TI	$T_i > 3000$
15.	Q	Try Q=15 gpm
1785.	TI	Output
1540.	TT	
0.99	RO	
9.35	DP	
22.5	EFF	
30.	Q	Try Q=30 gpm
455.	TI	Output
252.	TT	
0.61	RO	
2.06	DP	
52.9	EFF	

Chapter 5
Furrow Irrigation

Contents

Figures

Tables

Nomenclature

A = Area in square feet

a = Intercept of cumulative intake at unit time

AE = Application efficiency in percent

AE_c = Cutback application efficiency in percent

ASW = Available soil water

AWC = Available soil water capacity

B = Bottom width of furrow or corrugation in feet

b = Exponent of time in intake equation

c = Advance coefficient depending on furrow-intake family

D = Depth of flow in feet

d = Advance coefficient depending on furrow-intake family

Da = Average depth of flow in feet

DE = Design efficiency

DP = Deep percolation loss in inches

DP_c = Cutback deep percolation in inches

DU = Distribution uniformity

ET = Evapotranspiration

F = Cumulative intake in inches

F_g = Gross depth of irrigation in inches

F_{gc} = Cutback gross application in inches

F_n = Design application depth in inches

F_{nc} = Cutback design application in inches

$F_{(0-L)}$ = Average intake over a reach L feet long

$F_{(0-L)c}$ = Cutback average intake over a reach L feet long

$F_{(0-x)}$ = Average intake over a reach x feet long

F_x = Intake depth for any point x

IE = Irrigation efficiency

I_f = Furrow-intake family number

L = Furrow length in feet

ln = Logarithm (natural)

MAD = Management allowed deficiency

n = Roughness coefficient in Manning equation

P′ = Wetted perimeter in furrow in feet

P = Wetted perimeter plus constant in feet

P_1 = Wetted perimeter plus constant for $\frac{Q}{2}$ in feet

P_e = Effective precipitation in inches

Q = Irrigation stream or inflow rate for a furrow or corrugation in gallons per minute

RO = Surface runoff depth from the furrow or corrugation in inches

RO_c = Cutback runoff in inches

r = Hydraulic radius

S = Slope of furrow or corrugation in feet per foot

SWD = Soil water deficiency

T_i = Time of application or inflow time in minutes

T_{ic} = Cutback time of application or inflow time in minutes

T_n = Opportunity time in minutes required for cumulative intake of F_n inches

T_{nc} = Cutback opportunity time required for cumulative intake of F_n inches

T_o = Intake opportunity time in minutes

$T_{(0-L)}$ = Average opportunity time for the furrow length L in minutes

$T_{(0-x)}$ = Average intake time for length 0 to x in minutes

T_{ox} = Intake opportunity time at point x along furrow length in minutes

$T_{o_{adv}}$ = Average opportunity time during the advance period in minutes

$T_{o_{ave}}$ = Average intake opportunity time in minutes

T_r = Recession time in minutes

T_t = Time of advance or travel in minutes

T_{tc} = Cutback time of advance or travel in minutes

$T_{t_{ave}}$ = Average time of advance

V = Velocity of flow in feet per second

v = Volume of water in cubic feet

v_{RO} = Volume of surface runoff in acre-feet

v_s = Volume of surface storage in gallons

W = Furrow or corrugation spacing in feet

x = Furrow length to point x

z = Side horizontal distance divided by vertical distance

Chapter 5

Furrow Irrigation

Description

Furrow irrigation is a method of applying water at a specific rate of flow into shallow, evenly spaced channels. These small channels convey the water down or across the slope of the field to the vicinity of plants growing in the furrows or on the beds between the furrows. This method differs from border irrigation in that only part of the ground surface is covered with water. The water infiltrates the soil both vertically and horizontally. The furrow stream is applied until the desired application depth and lateral penetration are obtained. How long water must be applied in the furrows depends on the volume of water required to fill the soil to the desired depth, the intake rate of the soil, and the spacing of the furrows. Land grading to provide uniform slopes is essential to permit uniform water application and efficient irrigation.

Furrow irrigation consists of four kinds of systems that are used according to the crops and furrows needed to distribute the irrigation water. Level, graded straight, and graded contour furrows are used primarily to irrigate clean-tilled crops planted in rows with one furrow between crop rows. For bedded crops where two rows are planted on each bed, the furrows are along each pair of rows. The size and shape of the furrows vary with the crop grown, the equipment used, and the spacing between crop rows. Furrow irrigation also includes applying water to small grain or similar crops drilled on flat-top furrow beds where the water is applied either on the bare ground or on ground with low vegetative retardance conditions. Corrugation furrows are small, closely spaced irrigation channels used primarily to irrigate noncultivated, close-growing crops on moderately steep land. Corrugations are also commonly used to guide irrigation streams on bordered land where the design is based on the border method instead of the corrugation method. Corrugations are frequently formed after the crop has been seeded. For perennial crops they are reshaped as needed to maintain the desired channel cross section.

Water application principles are the same for all types of furrow irrigation; furrow spacing, size and shape, and retardance characteristics are the primary differences. Corrugation streams are smaller than furrow streams. Because of the smaller channel generally used and the resistance to flow caused by the growing crop, the length of run is relatively short.

Adaptability

The adaptability of furrow irrigation to a specific site depends on climate, soils, topography, crops to be grown, and water supply.

Climate

Aside from the fact that climatic factors generally are of prime importance in determining the need for irrigation, precipitation and wind may also affect suitability as well as the design criteria. If precipitation occurs at an intensity and volume that result in either surface runoff and excessive soil erosion where runoff is concentrated in the channels or in crop damage from flooding, these conditions must be considered in determining which furrow method is suitable for a given climatic area. The requirements for erosion control or protection against flooding may impose severe restrictions on the use of furrow irrigation. Corrugations are seldom used on slopes of less than 1 percent. In areas of high rainfall the hazard of water erosion is high if corrugations are used on steeper slopes. Therefore, they are not recommended in the humid climatic areas except to irrigate perennial crops. The climatic areas to which specific restrictions apply are shown on the following generalized climatic area map (fig. 5–1).

Soils

Furrow irrigation is suitable for most irrigable soils if the soil depth and the surface topography permit the needed land leveling at an economically feasible cost and without permanent reduction of soil productivity. This method is best suited to medium to moderately fine-textured soils of relatively high available-water-holding capacity and intake characteristics that provide both lateral and vertical water penetration. These soil characteristics permit uniform irrigation with a minimum of water loss to deep percolation or surface runoff from the end of the rows.

In coarse-textured sands and loamy sands, irrigation water moves mainly downward and very little laterally. Efficient furrow irrigation on these soils requires a short run, a short application time, relatively narrow row spacing, and a small depth of water application. These severe limitations result in high labor and operating costs; therefore, furrow irrigation is not generally recommended on these soils.

Fine-textured, very slowly permeable soils present a different problem. Water must be impounded or a very small stream applied for long periods to obtain the desired intake. Unless a small stream is used, excessive surface runoff will require extensive tailwater recovery or safe disposal facilities. Many of these soils crack before they reach the moisture level at which irrigation is needed. These cracks frequently make it difficult to confine the irrigation water within the furrow. The restrictive features of these soils should be carefully considered before recommending any type of furrow irrigation. Corrugation irrigation is generally unsuitable on these types of soils.

Furrow irrigation generally is not recommended on soils containing high concentrations of salts. In most irrigated soils, salts are supplied from the waters being used and/or from the parent materials in which the soils formed. The irrigation water absorbs the salts from the soil; through capillary movement and subsequent evaporation of the water, the salts are concentrated in the surface soil of the furrow ridge where crop roots are most likely to be.

Topography

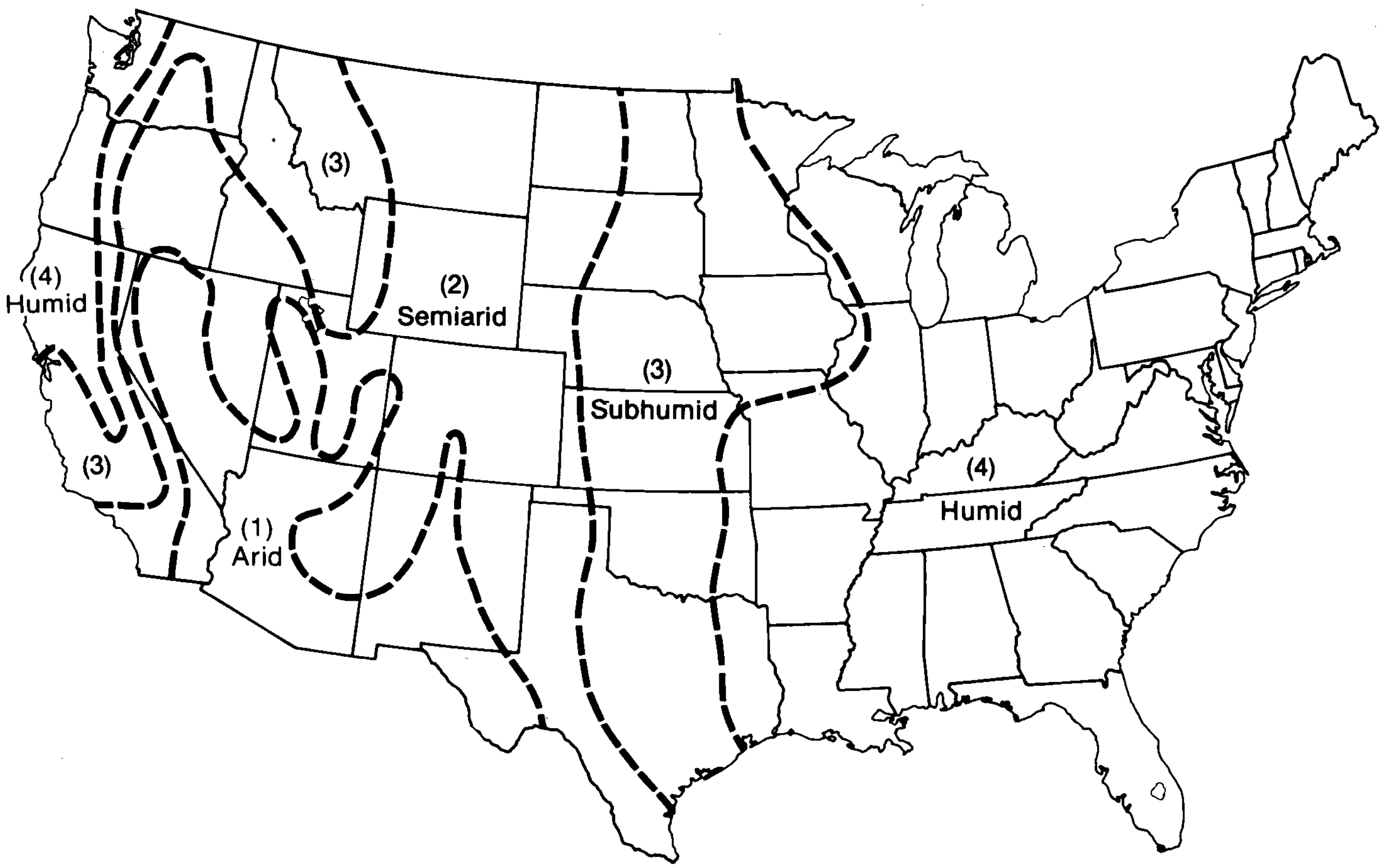
The topography of an individual field is an important consideration in determining the suitability of furrow irrigation. The topography must be such that within the grade limitations for the climatic area the rows can be laid out on a continuous grade. If land leveling is required to provide the design grade, the topography must be such that leveling does not expose unproductive soil or that the cost of leveling is not excessive. The topography must not be so steep that it exceeds the allowable corrugation grade or prohibits installation of graded contour furrows that meet the design grade and cross-slope criteria.

Crops

Furrow irrigation can be adapted for nearly all irrigated crops except those grown in ponded water, such as rice. Tillage, harvest, or other cultural

Figure 5-1

Climatic Areas



practices associated with the site may be so restrictive, however, that some other method of irrigation should be selected. Furrows are particularly suitable for irrigating crops subject to injury if water covers the crown or stems of the plants.

Water Supply

The quantity and quality of the water supply determine its suitability for use in furrow irrigation.

Water Quantity

Furrow irrigation can be used with any amount of water (either rate-of-flow or volume) if the acreage to be irrigated does not exceed the acreage for which the supply available can meet the needs of the crop to be grown.

If the systems are properly designed and water management is good, furrow irrigation can be as efficient as any other method of water application except a properly designed and managed trickle system. For maximum use of a limited water supply, alternate-row irrigation or other procedures can be used. Furrows are well suited to nearly any irrigation delivery rate because the number of rows irrigated in a set can be varied as needed.

Water Quality

Irrigation water may be of good quality or it may contain considerable amounts of colloidal material or various salts and minerals. Furrow irrigation can be used if the water quality is good and, on some soils, if the water contains moderate amounts of colloidal materials. These colloidal materials will be deposited in the furrows and may materially decrease the intake rate of the soil. This can be to the irrigator's advantage when irrigating high-intake-rate soils such as sands. The colloidal materials may increase soil fertility and may make these soils easier to irrigate by allowing a longer furrow and increased application time. On other soils these materials may accumulate on the surface, making tillage more difficult and required more frequently.

Most irrigation water contains appreciable amounts of various salts or minerals that can be beneficial or harmful, depending on the kinds being carried. Plant use of soil moisture contributes to the accumulation of salts. Because most plants can select nitrate, potassium, and phosphate ions from the soil solution, these ions are seldom found in appreciable amounts in saline accumulations. Sodium, sulfate, and chloride ions, however, are taken up by the plants in very limited amounts. Evaporation from the soil surface and selective use by the plants cause these salts to accumulate in the furrow ridge. Most of the crop roots develop in the ridge where salts accumulate; therefore, furrow irrigation is not suitable if the water supply contains considerable amounts of detrimental salts such as sodium.

Advantages of Furrow Irrigation

Furrow irrigation has many advantages on suitable sites. Some of these are:

1. Irrigation streams can be large or small because the number of rows irrigated at one time can be adjusted as needed according to the available flow.
2. Efficient application can be obtained if water management practices are followed and the land has been properly prepared.
3. The initial capital investment is relatively low on lands not requiring extensive land leveling, since the furrows and corrugations are constructed by commonly used farm implements.
4. The water distribution systems do not normally require high water pressure to operate; therefore, pumping costs are relatively low.
5. Soils that form surface crusts when irrigated by flood methods can be readily irrigated by furrows because water moves across the row under the surface.
6. Water is not applied directly on the plants, thus eliminating scalding of the foliage and loss of insecticides.
7. Excellent field surface drainage is obtained where adequate outlet facilites are provided.
8. Alternate-row furrow irrigation allows the use of a greater part of the rainfall.

Limitations of Furrow Irrigation

Furrow irrigation also has certain limitations. Some of these are:

1. Salts from either the soil or water supply may concentrate in the ridges and depress crop yields.
2. The lateral spread of water in some soils is not adequate to provide full irrigation.
3. The difference in intake opportunity time along the furrow due to the time required for the stream to advance makes it difficult to obtain uniform application depths.
4. Corrugations create a rough field surface difficult to cross with harvesting and other farm equipment.
5. The soil-erosion hazard limits use to land having very little slope.
6. Labor requirements may be high because irrigation streams must be carefully regulated to achieve uniform water distribution.
7. Leaching of salts is difficult or impossible.
8. Land leveling is normally required to provide uniform furrow grades.

Kinds of Furrow Irrigation

There are four kinds of furrow systems: level furrows, graded straight furrows, graded contour furrows, and corrugations. Each system requires specific designs and layouts. The suitability of each depends on the topography, kind of soil, kind of crop, cultural practices, and climatic factors.

Level Furrows

Level furrows are small irrigation channels, with blocked or diked ends laid out with little or no grade (fig. 5–2). They generally require extensive land preparation and careful water management for successful operation. Irrigation water must be applied rapidly, using a stream as large as the furrow can contain, until the designed volume is applied. The ponded water stands at a uniform depth in the furrow until it is absorbed by the soil. Lateral or capillary movement of water throughout the soil distributes the water to areas between the furrows.

Adaptability

The level furrow is best suited to soils with a moderate to slow intake rate and moderate to high available-water-holding capacity. The topography must be relatively flat with smooth, uniform slopes. The crops most easily irrigated by level furrows are those grown in rows on beds between the furrows, because relatively large channels must be maintained to provide the necessary capacity. Level furrows are suited to all climatic areas except the humid area where a minimum grade is required to achieve the surface drainage needed to prevent crop damage or waterlogging of soils.

Advantages

The amount of water applied can be adjusted to the needed seasonal variations by changing the duration of application or the size of furrow stream, or both. No change in layout is needed. Efficient application can be obtained if the system is properly operated. No irrigation water need be lost through runoff. Maximum use can be made of rainfall even when the intensity of storms exceeds the soil intake rate. Provisions for disposal or reuse of tailwater are not needed. Water can be introduced at both ends of the furrows so that the furrow length can be twice the design length, which allows more efficient use of farm equipment. This method is well suited to automation.

Limitations

In areas where wind velocity exceeds 15 to 20 miles per hour, it is difficult to apply irrigation water if the wind blows in the opposite direction of water flow in the furrow. Some crops such as potatoes can be damaged by water ponded over the root system. Drainage of excess rainfall may require extensive water-disposal facilities. Furrow capacity must be large enough to carry rainfall excess without overtopping. Furrows should have adequate capacity for approximately one-half the volume of the net irrigation application. The irrigation application time must be short; therefore, frequent change of sets is required. The surface topography, furrow shape, and cross section must be carefully maintained. The farm operator must know about these specific needs and requirements for successful operation of the system.

Graded Straight Furrows

Graded straight furrows are small irrigation channels on relatively flat land laid out either in the direction of or across the slope of the land. They are constructed in a straight line, preferably parallel to a field boundary, and have a continuous, nearly uniform slope in the direction of irrigation. The length of time that water must flow in the furrows depends on the amount of water required to refill the root zone, the intake rate of the soil, and the rate of lateral spread of water in the soil. For most soils, the initial irrigating stream must greatly exceed the intake rate to provide an adequate advance rate that will result in a reasonably uniform intake-opportunity time along the furrow. When water reaches the lower end of the furrow, the flow rate must be reduced to prevent excessive runoff or provisions must be made to dispose of the tailwater safely or to recover and reapply it. Even where the streams are cut back, an appreciable amount of tailwater will collect. Therefore, a tailwater recovery system and provisions for safe disposal according to state regulations are normally integral parts of a graded furrow system.

Adaptability

Graded straight furrows can be used to irrigate all cultivated crops planted in rows. Graded furrows can be used on all soils except sands that have a very high intake rate and provide poor lateral spread of

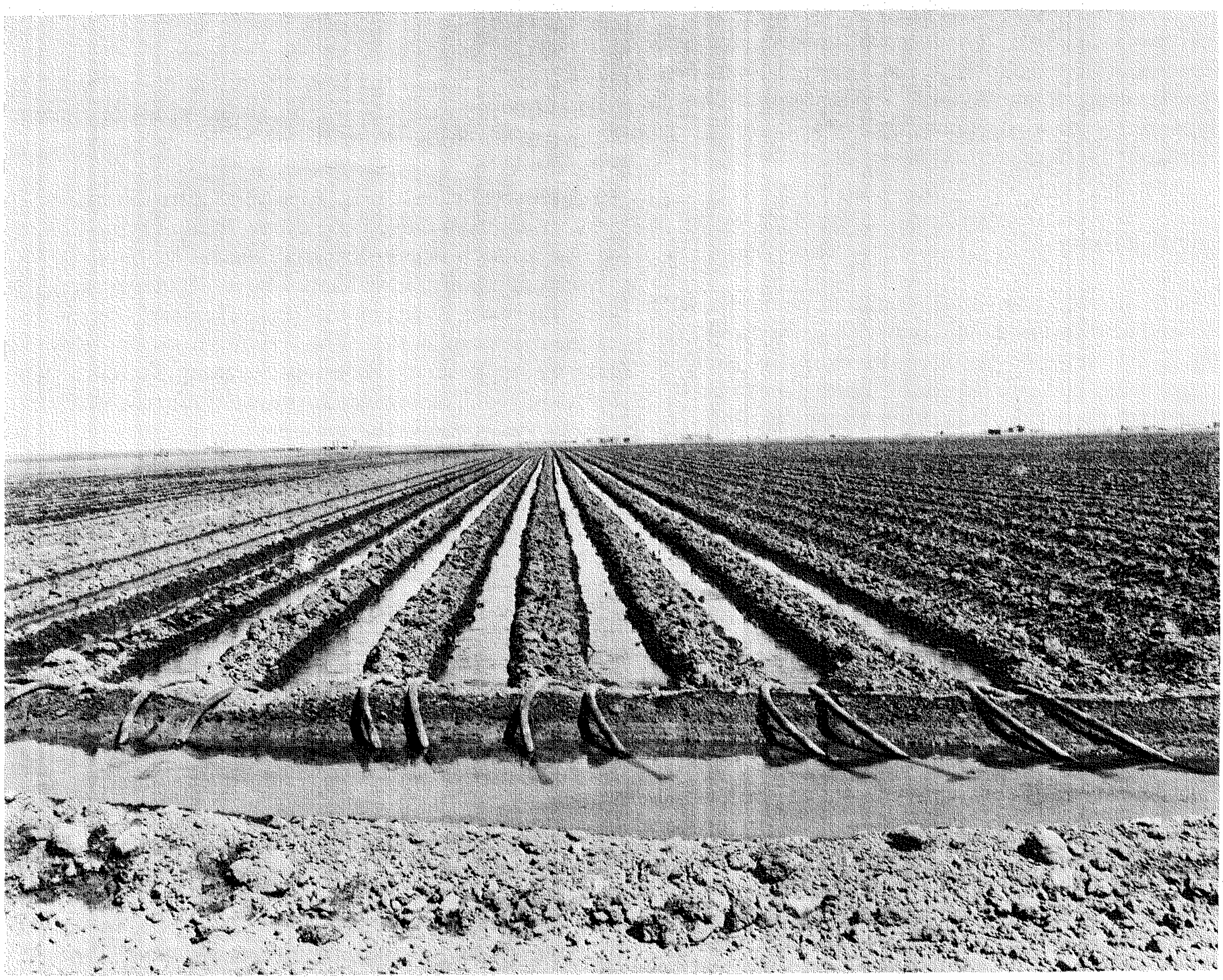


Figure 5–2.—Level furrow irrigation.

water between furrows (fig. 5–3). This method is best suited to sites where land slopes are at least 0.1 percent but no more than 3 percent in arid areas and no more than 2 percent in semiarid areas, 1 percent in subhumid areas, and 0.5 percent in humid areas. On smooth, uniformly sloping fields with slopes of 3 percent or less, crops can be planted across the slope to reduce the furrow grade (fig. 5–4). Where the cross slope is such that there is danger of the furrows breaking, graded furrows can be used on graded benches built across the slopes. If these benches are used, they should be spaced to meet the round-trip width requirements of the row-crop equipment to be used. For example, spacing should be in multiples of eight rows if four-row equipment is used. If the slope is not uniform in one direction, the benches may have one or more turns. To permit turning large equipment, the turn angles should not exceed 30 degrees. The turns in adjoining benches should be along the same radii path to eliminate the need for irrigating point rows (fig. 5–5). The cross slope within the benches should normally be as flat as practicable and should not exceed the 3 percent limitation.

Advantages

Graded straight furrows can be used with both large and small irrigation streams by adjusting the number of furrows irrigated at any one time to fit the available flow. Therefore, any method of water delivery from continuous flow to full demand can be

Figure 5-3.—Graded straight furrows.

accommodated. Where surface drainage is needed, the furrows act as channels to carry the excess surface water to safe disposal areas. Application efficiency can be high if proper recovery systems or cutback principles are used.

Limitations

Labor requirements are high unless the system is automated. Flow into each furrow must be carefully regulated to achieve uniform water distribution and minimum waste. Fields must be carefully leveled and facilities for collecting and disposing of surface runoff must be provided. Small irrigations especially needed for seed germination or for shallow-rooted crops are difficult to apply efficiently. Uniform application is difficult on soils with high intake rates. Land slopes must be relatively flat and uniform to permit installation within design limitations.

Graded Contour Furrows

Graded contour furrows are small graded irrigation channels on fields with uneven or warped surfaces where it generally is not practical to use straight furrows within permissible grade limitations (fig. 5-6). The furrows are curved to fit the general contour of the land and have enough grade to carry the irrigation stream to the end of the furrow. The grade must be somewhat variable to prevent creating

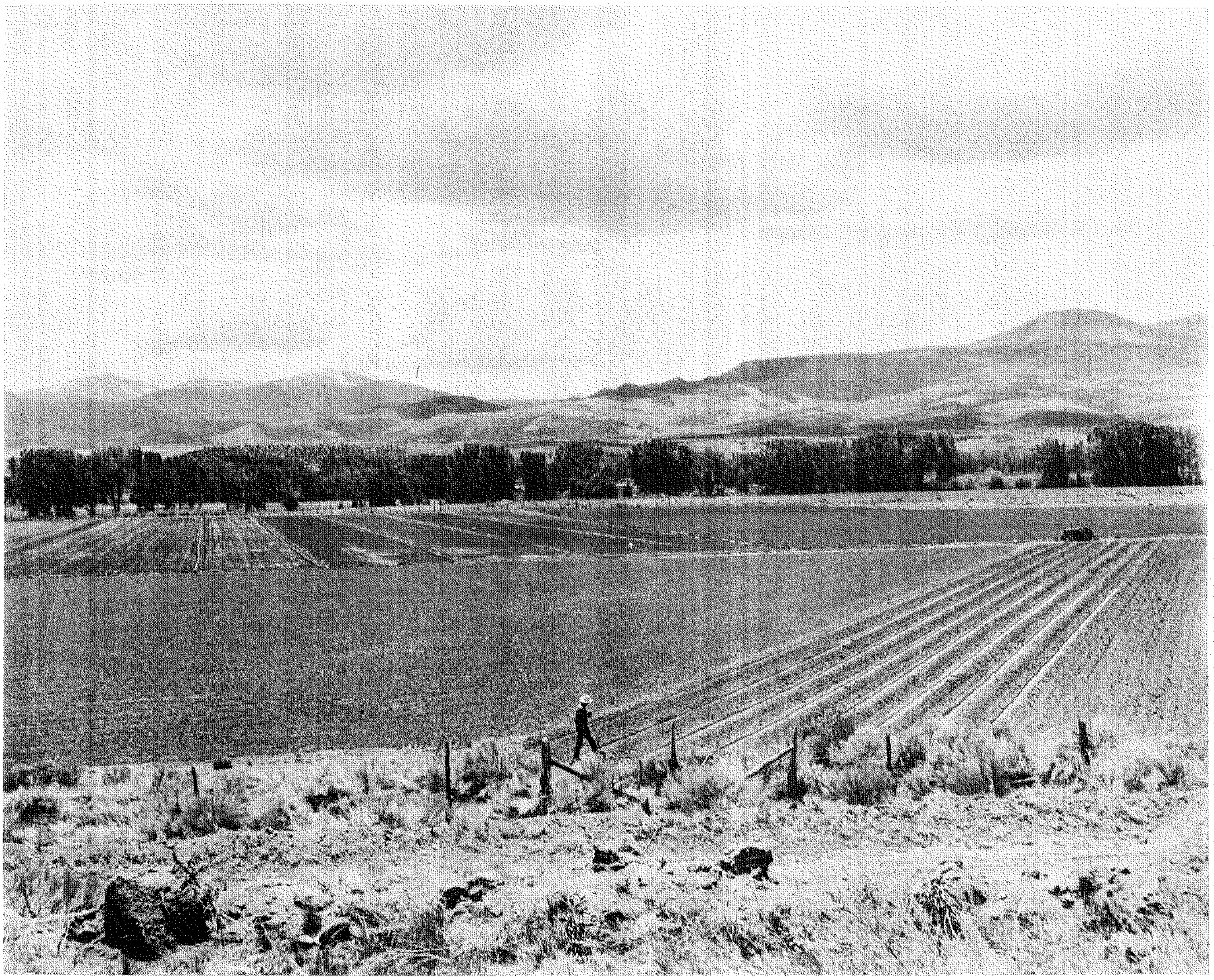


Figure 5-4.—Graded straight furrows across the slope.

numerous point furrows. Water application principles, including requirements for reuse or safe disposal of runoff, are the same as for graded straight furrows. Frequently, disposal systems require structural protection as a safeguard against water erosion.

Adaptability

The graded contour furrow method can be used on most moderately sloping fields and on most soils except sandy soils and soils that crack badly when dry. The ridges between furrows in sandy soils tend to break down or wash out, destroying the furrow and creating channels directly down the slope. Soils that crack provide channels for water, causing similar downslope furrow breaks. The graded contour method is particularly suited to fields of uniform slope in two directions because most of the furrows can be aligned across the slope. This method can be used for nearly all cultivated crops planted in rows. In arid or semiarid sections, deep-furrowed row crops on medium- or fine-textured soils can be irrigated if the land slope does not exceed 5 percent. On the coarser textured soils, the land slope must not exceed 4 percent because of the danger of furrow breaks. Maximum land slopes in semihumid areas should be approximately 1 percent less than those discussed above. Graded contour furrows are generally not recommended for humid areas. Land with slopes of up to 6 percent can be irrigated by this

Figure 5-5.—Benches to support furrows on sloping fields.

method if the furrows are supported by a system of parallel terraces. A parallel terrace system requires enough land leveling to ensure a continuous furrow grade. The terraces should be spaced to provide complete round trips with the farm equipment to be used.

Advantages

The graded contour furrow method can be used to safely irrigate land too steep for downhill furrows. Other advantages are the same as for straight graded furrows.

Limitations

Water delivery ditches frequently must be built on erosive grades that require structural protection or use of pipelines. Distribution to individual furrows from the head ditch is difficult. Tailwater-pickup systems normally have an erosive grade and require structural protection to provide stability. Considerable time is necessary to lay out a field; planting and tillage require considerable care. The irrigator must carefully guard against furrow overflow and washout. Grassed waterways and structures are usually needed to carry tailwater down the slope. Deep, large-capacity furrows must be built and maintained throughout the irrigation season. Rodent control is needed to prevent cross breakage and the flow of water from higher into lower furrows.

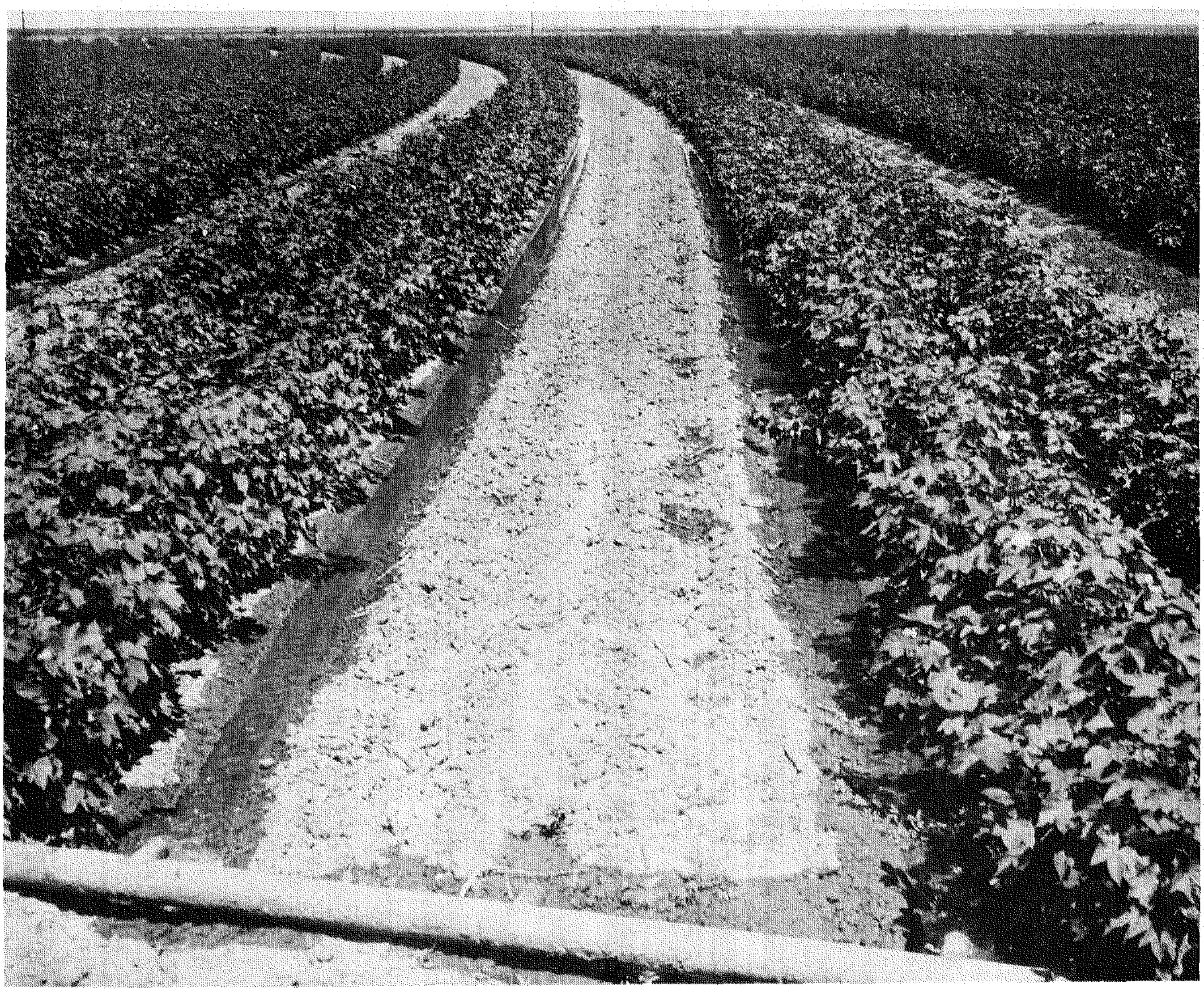


Figure 5–6.—Graded contour furrows.

Corrugations

Corrugations are small, closely spaced irrigation channels used to irrigate close-growing crops on moderately steep land (fig. 5–7). Irrigation water does not cover the entire field but is applied in small channels or corrugations evenly spaced across the field. Corrugations generally must conform to the slope of the land because of the small capacity of the water channels. For this reason level or graded contour corrugations are not recommended as a method for applying irrigation water. Corrugation irrigation is commonly considered a temporary method of water application to be used for the first irrigation on fields that later will be irrigated by the border method or as a method of spreading water in graded borders. However, corrugation irrigation as described in this chapter is a permanent system designed to apply water uniformly and efficiently. For efficient irrigation by the corrugation method, land slopes must be uniform and the water applied according to an irrigation water management plan. The length of time that water must flow in the corrugations varies with the amount of water required to refill the root zone and the intake rate of the soil. The rules governing the flow of irrigation water in graded furrows apply also to corrugations. Flow at the beginning of the irrigation should be as large as can safely be carried in the corrugations without causing erosion. Because of the small flows

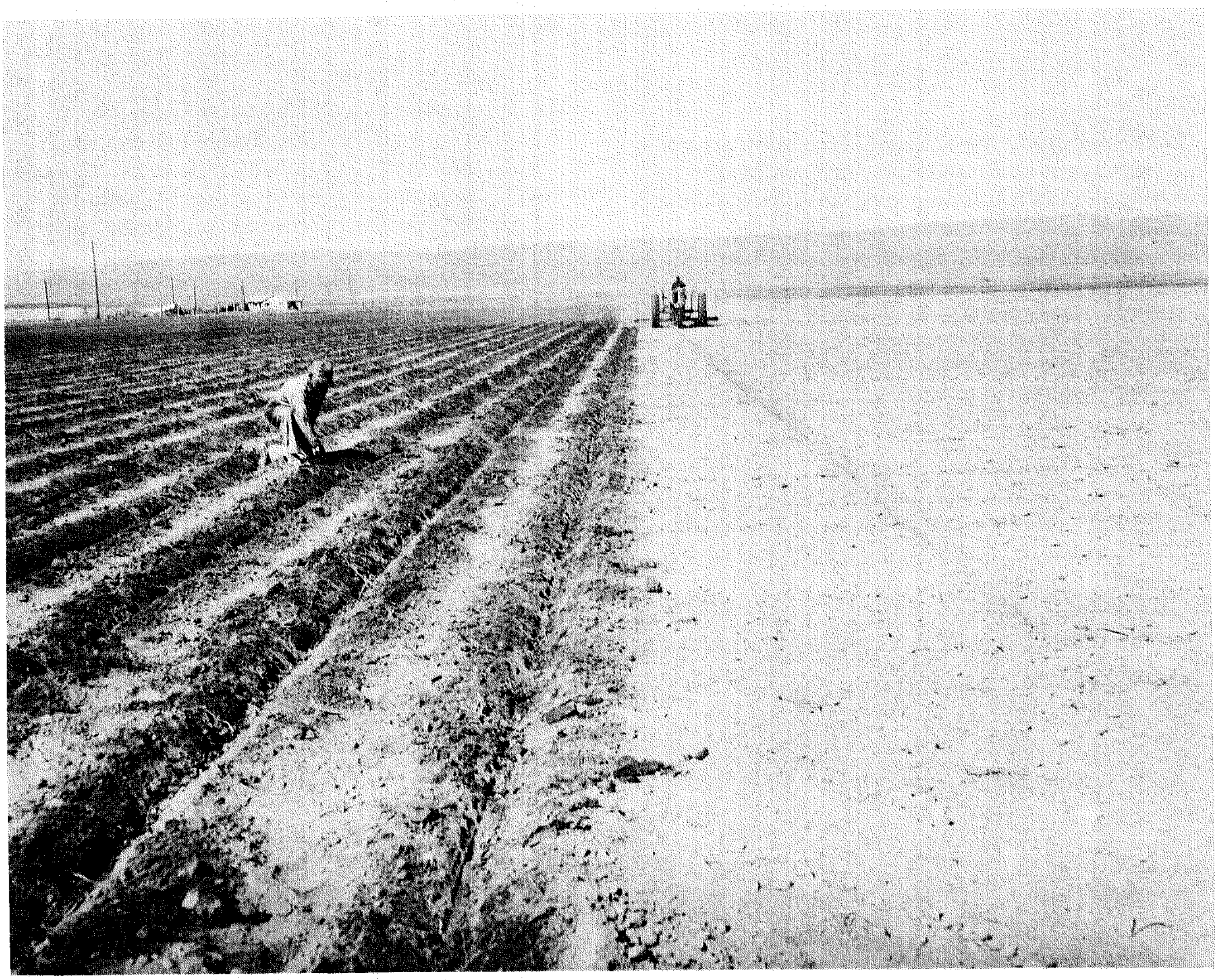


Figure 5–7.—Corrugation irrigation.

used, cutting back the flow after water advances to the end of the furrow is usually not feasible. Therefore, facilities for recovery or safe disposal of tailwater are essential.

Adaptability

Corrugation irrigation is best suited to areas of moderately low rainfall and smooth fields with land slopes of between 1 and 4 percent. The use of corrugation furrows in humid areas usually creates a serious erosion hazard and, therefore, is not recommended. Except for those grown in ponded water, all close-growing, noncultivated crops such as legumes, grasses, and small grains can be irrigated by this method. Corrugation furrows are best suited to soils of fine to moderately coarse texture. They are not suitable for coarse-textured, high-intake-rate, or saline soils. The method is especially good for irrigating soils that tend to bake or crust, since only a small part of the surface is wetted.

Advantages

Close-growing crops can be irrigated efficiently if proper water management practices are followed. Corrugations can be constructed and maintained with commonly available tillage implements. Land preparation costs are relatively low, and irrigation streams can be large or small according to the available water supply.

Limitations

Labor requirements are high. Irrigation streams must be carefully regulated for uniform water distribution and minimum water loss. Fields must be corrugated at least once every year and, in many cases, more often. Equipment operating costs are also high, because the rough field surface is difficult to cross. The method is not well suited to slopes of less than 1 percent or to high rainfall areas because of the erosion hazard.

The application of water by furrows or corrugations appears to be a simple method. If efficient uniform water application is to be obtained, however, the systems must be properly designed, installed, and operated according to certain established criteria.

Before the specific design units can be selected, many determinations must be made in regard to soils, crops, topography, size, and shape of irrigable areas; farm equipment; and the farmer's personal preferences and operational practices. The designer must know the intake characteristics of each major soil type for placement in the proper design group. The crops to be grown and the available-water-holding capacity of the soils determine the normal design depth of application and whether furrows or corrugations are to be used.

The topography of the field determines the direction of irrigation and, in many cases, the grade of the corrugations or furrows and the appropriate lengths that will fit individual field boundaries. The farm equipment to be used determines the spacing and the maximum capacity that can be expected. The farmer's operational practices affect whether a cutback, tailwater recovery, or reuse or tailwater disposal system should be planned and what irrigation operating schedules will meet his needs.

The size of furrow stream and the time of application are both influenced by the operational method of water application to be used. If cutback-inflow operations are to be used, the design must be based on two different sizes of furrow streams, and these require a specific procedure and time of application. If the impoundment method is used, the application time will be relatively short and the application rate correspondingly high.

A continuous stream with reuse facilities will have a different design than either of the other operations methods. Above all, the selected design and layout must meet the owner's approval if the system is to operate satisfactorily. The selected design will be for a normal irrigation application, but adjustments for application depth, time of application, and furrow flow rate for specific irrigations may be needed during the season.

Land Preparation

Efficient irrigation is most easily accomplished on land with uniform topography. If the area to be irrigated can be divided into uniform operational segments, a single set of furrow or corrugation design criteria and operational procedures can be used. Since neither soil nor topography is normally uniform over large areas, it is generally advisable to divide fields into design areas according to soil uniformity and do the land leveling needed to develop uniform land slopes within the limitations imposed by the design criteria. For uniform operation of a furrow or corrugation system, each furrow or corrugation within a design segment should have the same length and grade. To obtain uniform furrow length, the segment must have parallel sides of uniform length, and to obtain uniform grade, the surface must conform to a plane. (See SCS National Engineering Handbook, Section 15, Irrigation; Chapter 12, Land Leveling.)

Layout and Construction

The design of an irrigation system sets the limits for the system on an individual farm or field. The design criteria specify the inflow rate for the design length of furrows on a predetermined grade on a soil characterized by a given intake family. A number of points must be considered when selecting the design or designs to be used on an individual farm. An irrigation system layout should be based on the following items as they relate to a specific field or fields.

Fields of workable size and shape are important to successful irrigation farming. Unless a system is carefully laid out, some areas may not receive irrigation water, or may be virtually inaccessible and useless to the farm enterprise. Sharp turns or acute angles must be avoided. Fields should be as nearly rectangular as possible. Furrows or corrugations in any field should be as nearly equal in length as is practicable to obtain. Irrigation in adjoining fields generally should be in the same direction or at right angles. Water application is normally difficult if irrigations in adjacent fields are in opposite directions. Permanent surface features such as power lines, buildings, structures, and other obstructions influence the field shape that can be used or the division to be made between fields. The cropping pattern to be followed is also a determining factor in field layout.

A good soil map is essential in the layout of any irrigation system. Where soils have appreciable differences in intake rate and water-holding capacity, the fields should be divided as nearly along soil boundaries as is practicable and provide uniform row lengths. The outlet end of the rows can cross the boundary between a slow intake rate soil and a somewhat higher intake rate soil and still permit efficient application. Crossing the boundary between a high intake rate soil and a lower intake rate soil for any appreciable distance should be avoided.

The need for a field road system is frequently overlooked in laying out an irrigation system. As a result, that part of the farm is inaccessible to farm machinery, the system is damaged by travel of equipment, or the roads are impassable after an irrigation or a rain. For the operation of the system, roads should be provided above the field head ditches or mains and below field drains. The following points should be considered in the layout of a farm road system:

1. Ease of operating the water-distribution system.
2. Ready access to all areas of the farm for farm equipment.
3. Transportation of farm produce from the fields.
4. Dryness and usability of roads.
5. Requirements for farm-crossing structures.

Erosion Control

The furrow system must be designed to avoid conditions that would contribute to soil erosion. Serious erosion can occur without any soil being removed from the field. In surface methods of irrigation, the irrigating streams are largest and most erosive where they first enter the field. As the streams progress toward the lower end of the field, they are reduced by the amount of water infiltrated into the soil. The accumulated sediment load also reduces their erosivity. Often the streams erode the soil at the upper end of the field but have insufficient carrying capacity at the lower end to transport material from the field. About the only characteristic that erosion under furrow irrigation and erosion under rainfall have in common is that each is caused by flowing water. In most other respects they are diametrically opposite. Under irrigation, the amount of erosion depends on the condition in the furrow and not on the overall condition of the field. It matters very little whether the area between the furrows is vegetated or bare, compacted or loose. The specified limitations for land slope, furrow length and grade, and stream size should ensure that erosion from the water application system is within allowable limits.

Soil Water Intake Characteristics

The water intake rate of a soil is the most important item to be considered in the design of a furrow or corrugation system. The higher the intake rate, the larger the inflow rate and the shorter the application time should be. Furrows and corrugations, in contrast to borders or sprinkler systems, depend on both vertical and lateral transmission of the applied water to obtain the needed intake. A number of factors influence intake and make it especially difficult to set specific design limits for furrow systems. Among them are: (1) physical features of the soil, (2) cultural practices used, (3) cropping practices, (4) soil water level at time of irrigation, (5) water quality, and (6) previous irrigations during the irrigation season.

Physical Features of Soil

The major soil physical characteristics that affect the water intake rate are the texture, structure, and tilth. Because the texture of a soil changes very little, the intake rate of a specific soil can be determined if farming practices are used that do not materially change soil tilth. Generalized intake equations as related to intake-family groups for various kinds of soils are given in a later section of this chapter. Tests to determine the placement of an individual soil into one of these family groups are described in the Evaluation section.

Cultural Practices

Tillage practices can greatly increase or decrease the water-intake rate of soils, depending on the equipment used and the moisture condition of the soil at the time the tillage is performed. Subsoiling or deep chiseling of a soil breaks up plowpans and fractures other very slowly permeable horizons, thereby increasing the capacity of the soil to take in water as long as the artificially increased porosity remains. The effect of this tillage disappears by the second or third irrigation. Listing or other tillage that leaves the soil loosened also produces a temporary increase in soil intake rates. In contrast, tillage of wet soils causes the soil to compact and form plowpans that may permanently reduce intake. Intake rates are also reduced in furrows compacted by tractor wheels. Furrow intake rates are often purposely reduced on sandy soils to allow longer runs and longer time of sets by pulling a drag or other smoothing and compacting implement down the furrows in which water is to be applied.

Cropping Practices

Intake rates can be increased by incorporating crop residues evenly into the first few inches of the soil surface layer. This practice also helps prevent surface puddling of the soil, which can reduce soil intake to almost zero. A higher content of relatively large aggregates of soil particles and greater water-intake capacity generally result from good crop rotation practices.

Soil Water Level

The intake rate of a wet soil is slower than that of a dry soil. Intake results from a combination of soil tension or suction, and gravitational pull. The tensional force is the difference in tension between the wetted front and the adjoining dry area. Therefore, this force decreases as soil water content increases. Tests show that a soil with 80 percent available water has an intake rate of approximately 70 to 80 percent of that for a soil with 60 percent available water. In contrast, the wetting front advances more rapidly when the soil is wet because less water is needed to saturate the soil. Thus, the effect of initial wetness can be significant during early stages of infiltration but decreases with time and eventually tends to vanish.

For maximum crop production, adequate water should be available at very low tension so that the root system can easily withdraw as much soil water as the plants can use. The response of a crop to different soil-water levels varies according to the crop's growth characteristics and its inherent ability to obtain water under changing tensions. High soil water levels are especially important for such crops as potatoes, particularly at critical growth periods such as the fruiting stage. Salts in the soil solution are also a factor in determining the optimum water level. The higher the concentration of salts in the soil solution, the higher the available water level that must be maintained. Generally, the level of readily available water in the major root zone of a soil should be maintained above 50 percent. Where practical to do so, the level of readily available water of a silty clay soil should be maintained at 60 to 75 percent, whereas on a fine sandy loam, the water can be safely depleted to 35 to 40 percent before irrigation water is applied. The soil water level that is to be maintained is a factor in determining the design application depth and frequency of application.

Water Quality

Irrigation water contains dissolved materials that accumulate in soils. These materials may cause profound changes in water-intake characteristics. The material may be a kind of salt or a colloidal substance. Some of the dissolved salts, such as calcium and magnesium, may increase the intake rate of a soil, but an excess of sodium is very detrimental. Excessive sodium replaces the other cations attached to the soil particles, changing a calcareous soil to a sodic soil. A calcareous soil is aggregated, very granular, and permeable to water. Sodic soil is gelatinous, deflocculated, and nearly impervious to water. Colloidal materials generally are clay particles that may also decrease soil intake rates.

Seasonal Variation

The intake rate of a soil in a furrow or corrugation irrigation system normally becomes progressively less for each irrigation during the season, with possibly the exception of the last irrigation. Then crop residues or growing plants tend to accumulate in the water channels, restricting water flow and increasing intake.

In colder climates, heaving of soils during the winter produces more voids. But as farming operations are conducted, the soils settle back and become more compact. Spring plowing loosens the soil surface, allowing increased intake during the initial irrigation. As the season progresses, however, this loosening effect disappears unless the soil is cultivated during the season. An example of the seasonal change in intake rates measured at Grand Junction, Colo., is shown by the following data:

Date:	*Average intake rate* [1]
June 5	0.083
July 2	.138
Aug. 5	.126
Aug. 26	.100
Sept. 9	.126

[1] Inches per hour

The design must be such that inflow rate and application time can be adjusted readily during the season without changing the furrow layout.

Distribution of Intake

Knowledge of the wetting pattern—the shape of the wetted bulb in the soil beneath the surface—is needed for designing the system. The uniformity of the soil greatly affects both the intake rate of a soil and the shape of the wetted bulb.

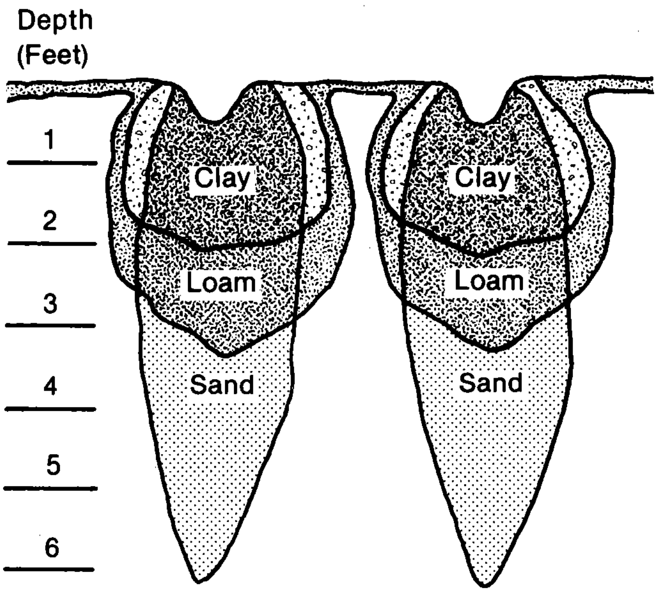
Wetted bulbs.—The designs in this chapter are based on the assumption that the wetted bulbs from adjacent furrows will overlap or nearly overlap by the time the desired application has been obtained. This assumption is valid if furrows are properly spaced according to soil intake and depth of water application. Where bulbs do not overlap furrow spacings should be adjusted so that they do overlap. It may be desirable to irrigate only alternate furrows. This practice provides storage for rainfall or for maximum use of the available irrigation water and intentionally irrigates only a percentage of the area between the watered furrows. In such cases, the design should be based on the width of area irrigated instead of the spacing between furrows.

Homogeneous soils.—Water intake in a homogeneous soil initially occurs in a radial pattern. The movement is almost as great outward as it is downward. The force responsible for this type of water movement is mainly soil tension. As the soil becomes saturated, tension force decreases and gravity force predominates. In homogeneous soils, the wetted bulb forms the shape of a parabola, with the horizontal and vertical intake relationship changing with increasing time of application. The lateral movement depends primarily on soil texture. Wetting patterns are broader in fine-textured soils than in coarse-textured soils (fig. 5-8).

Nonhomogeneous soils.—Soils with nonuniform profiles have greater lateral movement of water than soils with uniform profiles (fig. 5-9). Any deviation in the physical characteristics of a soil changes the wetted bulb pattern under furrow or corrugation irrigation. For example, a horizontal layer of coarse

Figure 5-8

Typical Patterns of Moisture Penetration by the Same Amount of Water from Furrows in Different Homogeneous Soils



material or a layer of finer material causes the parabolic wetted bulb to flatten and actually assists in obtaining a more uniform water application than is possible in a homogeneous soil. A large percentage of irrigated soils is layered in one of these fashions.

Spacing

Spacing affects the irrigation system in two ways. First, the spacing dictates the maximum capacity, which determines the maximum inflow rate. That, in turn, dictates the maximum furrow or corrugation length. Second, if spacing is such that the wetted bulbs do not overlap, the area between the rows receives only a partial irrigation.

Furrow Spacing

Furrow spacing must be compatible with the crop to be grown, the farm machinery to be used, and the lateral transmission of soil water in relation to vertical intake. For most field crops such as corn, cotton, or potatoes, the furrow spacing is the distance between crop rows and is selected to facilitate the use of planting, cultivating, and harvesting implements. Bedded crops such as lettuce, carrots, or onions may require furrows only between pairs of rows.

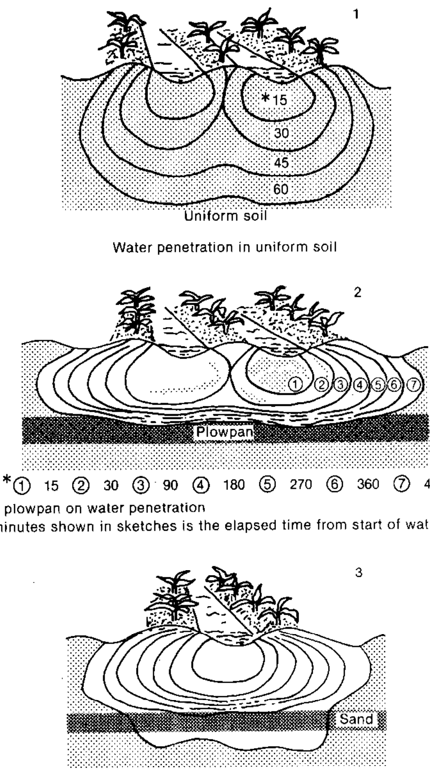
Normally an irrigator uses a standard width between furrows for a number of different crops to make use of the same planting and cultivating equipment and frequently to facilitate the use of gated pipe for applying irrigation water. Regardless of the crop being irrigated, the furrow spacing must permit water moving laterally to meet between adjacent furrows within the time allotted for the gross application and before an appreciable amount of water penetrates below the root zone.

For most soils, spacing does not ordinarily present a problem unless water is applied to shallow depths, crops are planted on high beds, or alternate-row irrigation is used. The problem of obtaining adequate lateral spread is especially severe where these conditions are compounded by irrigation grades steep enough to limit the depth of flow in the furrows.

Flat irrigation grades permit the use of furrow streams with deeper flow, a greater wetted perimeter, and corresponding wider spacing of furrows. If the soil is relatively dry before the

Figure 5-9

Examples of Water Penetration from an Irrigation Furrow



Effect of a plowpan on water penetration

*Time in minutes shown in sketches is the elapsed time from start of water application.

Effect of a sand lens on water penetration irrigation is applied, wetting patterns can be determined by using a soil-water probe. Examination of a number of furrows in which water has been applied for different periods of time is usually the best way to determine the maximum furrow spacing for any particular soil.

Corrugation Spacing

The spacing of corrugations also depends on how rapidly water moves laterally through the soil. Because they are generally independent of crop spacing, corrugations can be spaced readily according to the soil intake characteristics, the depth of irrigation desired, and the corrugation grade to be used. They generally can be farther apart on fine-textured soils than on coarse-textured soils and closer on steep slopes than on flat slopes. Table 5-1 can be used in selecting corrugation spacings.

TABLE 5-1.—*Maximum corrugation spacing (inches)*[1]

Depth of irrigation application	Soil intake family		
	0.1 to 0.4	0.5 to 0.9	1.0 to 2.0
Inches:			
2	18	15	12
3	20	18	15
4	22	20	18
5	24	22	20

[1] If the corrugation grade is 2 percent or less, spacing can be increased to the next wider spacing, such as from 15 to 18 or from 22 to 24 inches.

Equivalent Intake

Intake from furrows where only part of the soil surface is in contact with water is measured in volume, e.g., cubic feet per foot of furrow length. This volume measurement is irrespective of furrow spacing. The depth of irrigation application needed on a specific area is usually expressed in inches. If application depth is expressed in inches, spacing is of utmost importance. Cubic feet per foot of length can be converted to equivalent inches of water depth for the area irrigated by use of the equation:

$$\text{Equivalent inch depth} = \frac{144 \times \text{ft}^3 \text{ per ft}}{\text{furrow spacing in inches}}$$

It can readily be seen that, for a given volume of intake, a furrow spacing of 48 inches would have an average application depth of one-half as many inches as would a furrow spacing of 24 inches (table 5-2).

Table 5-2.—*Conversion—cubic feet per foot of furrow to inches of equivalent depth*

(Ft³/Ft)	Furrow or corrugation spacing (inches)							
	18	20	22	24	30	36	40	48
0.05	0.40	0.36	0.33	0.30	0.24	0.20	0.18	0.15
.10	.80	.72	.66	.60	.48	.40	.36	.30
.15	1.20	1.08	.98	.90	.72	.60	.54	.45
.20	1.60	1.44	1.31	1.20	.96	.80	.72	.60
.25	2.00	1.80	1.64	1.50	1.20	1.00	.90	.75
.30	2.40	2.16	1.96	1.80	1.44	1.20	1.08	.90
.35	2.80	2.52	2.29	2.10	1.69	1.40	1.26	1.05
.40	3.20	2.88	2.62	2.40	1.92	1.60	1.44	1.20
.45	3.60	3.24	2.95	2.70	2.15	1.80	1.62	1.35
.50	4.00	3.60	3.27	3.00	2.40	2.00	1.80	1.50
.55	4.40	3.96	3.60	3.30	2.64	2.20	1.98	1.65
.60	4.80	4.32	3.93	3.60	2.88	2.40	2.16	1.80
.65	5.20	4.68	4.25	3.90	3.12	2.60	2.34	1.95
.70	5.60	5.04	4.58	4.20	3.36	2.80	2.52	2.10
.75	6.00	5.40	4.91	4.50	3.60	3.00	2.70	2.25
.80	6.40	5.76	5.24	4.80	3.84	3.20	2.88	2.40
.85	6.80	6.12	5.56	5.10	4.08	3.40	3.06	2.55
.90	7.20	6.48	5.89	5.40	4.32	3.60	3.24	2.70
.95	7.60	6.84	6.22	5.70	4.56	3.80	3.42	2.85
1.00	8.00	7.20	6.55	6.00	4.80	4.00	3.60	3.00
1.10	....	7.92	7.20	6.60	5.28	4.40	3.96	3.30
1.20	....	....	7.85	7.20	5.76	4.80	4.32	3.60
1.30	....	....	....	7.80	6.24	5.20	4.68	3.90
1.40	....	....	....	....	6.72	5.60	5.04	4.20
1.50	....	....	....	....	7.20	6.00	5.40	4.50
1.60	....	....	....	....	7.70	6.40	5.76	4.80
1.70	....	....	....	....	8.16	6.80	6.12	5.10
1.80	....	....	....	....	....	7.20	6.48	5.40
1.90	....	....	....	....	....	7.60	6.84	5.70
2.00	....	....	....	....	....	8.00	7.20	6.00

Shape

Furrows and corrugations are constructed in a number of different shapes, depending on the crop to be grown and type of equipment used. The shape or cross section is one of the features that determine flow capacity as well as the area of soil that is in contact with the flowing water. The shape is determined by the equipment used in constructing the channels and is modified by subsequent tillage, growing vegetation, and flowing water.

Furrow Shape

The furrow cross section must be large enough to contain the largest irrigation stream to be introduced without overtopping and to contain the runoff resulting from expected rainstorms. Soil from the ridges tends to partially fill the furrows and, as the growing season progresses, the depth and area of the channels usually decrease. Allowances should be made for such decreases when the furrow capacity is determined.

Furrow shape is modified by the water as it moves down the slope. On steep slopes the water tends to form a narrow channel, whereas on flatter slopes it forms a broad channel. These tendencies are greater on sandy soils than on clay soils.

Many different furrow system designs would be necessary if one were made for each of the many furrow shapes used. Most furrows constructed between rows of cultivated crops are either parabolic or trapezoidal (shallow, flat bottoms). Field observations indicate few differences between these two furrow shapes for design purposes. Therefore, designs in this chapter are based on a trapezoidal furrow. Although the actual furrow cross section may be considerably different, the effect on flow and intake characteristics is not significant enough that other cross sections need to be considered in developing furrow designs. As previously discussed, the furrow cross section must be adequate to contain the planned furrow stream. Table 5-3 can be used in estimating the required furrow cross section for various furrow streams.

TABLE 5-3.—*Required furrow cross-sectional area in square feet*

Furrow grade (ft/ft)	Furrow stream (gpm)						
	50	40	30	25	20	15	10
Level [1]	0.70	0.59	0.48	0.42	0.35	0.25	0.21
0.0005	.38	.32	.26	.23	.19	.14	.11
0.0010	.29	.25	.20	.17	.15	.11	.09
0.0020	.23	.19	.15	.13	.11	.08	.07
0.0040	.17	.15	.12	.10	.07	.06	.05
0.0075					.06	.05	.04
0.0100						.04	.04

[1] Level furrow cross sections were calculated by using S=0.0001.

The furrow cross section plus the furrow grade also determine the volume of water in channel storage during an irrigation. Table 5-4 gives an estimate of this storage.

TABLE 5-4.—*Furrow storage in gallons per foot length*[1]

Furrow grade (ft/ft)	Furrow stream (gpm)						
	50	40	30	25	20	15	10
Level	5.24	4.43	3.57	3.11	2.63	1.90	1.56
0.0005	2.85	2.41	1.94	1.69	1.43	1.03	.85
0.0010	2.20	1.86	1.50	1.30	1.10	.79	.65
0.0020	1.69	1.43	1.15	1.00	.85	.61	.50
0.0040	1.30	1.10	.89	.77	.65	.47	.38
0.0075					.51	.39	.30
0.0100						.33	.27

[1] The average storage for a furrow reach is approximately 80 percent of these values.

Corrugation Shape

Corrugations are seldom more than 0.10 square foot in cross-sectional area unless they are formed by lister-type equipment. They vary widely in shape because of the numerous tools used to construct the channels. Among the implements used are lister bottoms with the wings cut off to provide a water channel without high beds, lister bottoms followed by a drag to flatten the beds, corrugating shovels, wooden-sled-type corrugators with sharpened runners, and round metal pipes mounted as runners similar to the wooden-sled type. Most of these implements construct small channels that have cross-sectional shapes of about 0.2-foot bottom width and 1:1 side slopes.

A Manning's roughness coefficient value of 0.10 for drilled crops is commonly used for design purposes. This higher retardance value means that the capacity of corrugations is about 40 percent of that for furrows of equal cross-sectional area.

Grade

The grade of a furrow or corrugation irrigation system should be slight enough that soil loss from either rainfall runoff or irrigation streams is kept within allowable limits. Conversely, grade should be adequate to provide surface drainage where needed to prevent waterlogging the soil.

Furrow Grade

Furrow grade should generally be 1 percent or less. In arid areas where erosion from rainfall is not a problem, the grade can be as much as 3 percent. In humid areas, furrow grade usually should not exceed

0.3 percent, but up to 0.5 percent may be safe if runs are short enough to prevent accumulation of runoff water that would cause soil erosion. The maximum length of a run can be determined by the procedure given under furrow length. In arid and semiarid areas, the minimum grade can be a zero if the planned crop allows impoundment of water around the root system. In humid and subhumid areas, a minimum grade of 0.05 foot per 100 feet should be provided to ensure surface drainage. The cross slope, the slope perpendicular to the direction of irrigation, must be limited to that which will not result in either irrigation water or storm runoff overtopping the ridges. Cross slope for furrows with grades of 0.5 percent or more should be limited to 1 percent or to the furrow grade, whichever is the lesser, unless the furrows are supported by benches or by terraces.

Wherever practical, the furrow grade should be uniform. Under certain conditions, however, it may be desirable to use variable furrow grades, if the steepest grade is not more than twice the flattest slope. To obtain reasonably uniform application of water, the furrows should have grades that vary in one direction only. They may increase or they may decrease, but they should not do both. Reverse grades are not permissible. The maximum recommended furrow grade for erodible soils can be calculated by the formula: $S_{(max.)}=(P_{30})^{-1.3}$, where P_{30} is the 30-minute rainfall on a 2-year frequency and S is the furrow grade in percent (fig. 5–10). A solution to the above formula follows:

30-min rainfall (inches)	Maximum furrow grade (percent)
0.4	3.3
.6	1.9
.8	1.3
1.0	1.0
1.2	.8
1.4	.65
1.6	.55
1.8	.50

Less erodible soils may exceed these limits by approximately 25 percent.

Corrugation Grade

Corrugations are aligned in the direction of the steepest slope and are recommended only on slopes of 1 to 4 percent.

Length

The length of a furrow or corrugation system is in direct proportion to the size of furrow or corrugation stream applied. The maximum length is generally based on the maximum nonerosive furrow stream or the capacity of the furrow, whichever is less.

Furrow Length

The optimum furrow length is the longest length that permits efficient water use, accumulates no greater quantities of storm runoff than can be accommodated without erosion or overtopping, and provides adequate drainage. Long furrows are more efficient because they require fewer turns for farm equipment. Several factors place limitations on length of run. The more important of these are: (1) intake rate of the soil; (2) grade of the furrows; (3) rainfall intensity; (4) depth of application; (5) field dimensions; and (6) location of soil boundaries. Other factors being equal, furrows must be much shorter on coarse-textured soils with high intake rates than on fine-textured soils with low intake rates. The length of run also depends on the water inflow rate to the furrow. Since the grade of the furrow, for the most part, determines the maximum nonerosive furrow stream that can be applied, it necessarily places a limit on the length of run. Steep grades require shorter lengths of run than do flatter grades.

In removing storm runoff, each furrow acts as a channel with a drainage area equal to the furrow spacing multiplied by its length. Runoff is collected throughout the length of the furrow, and the flow becomes progressively greater down the furrow. If no limitation is placed on the length of the furrow, the rainfall-runoff stream will become large enough to erode or overtop the furrow. The volume of runoff in the furrow is determined by the intensity of rainfall and the area of drainage. Because the furrow length is the only factor that can be controlled, it must be limited to prevent erosion and overtopping. The furrow stream from rainfall runoff can be determined by calculating the runoff expected from a 6-hour, 2-year frequency storm (fig. 5–11). The hydrograph from this storm can be considered as a rectangular hydrograph and the average furrow flow calculated. Tables 5–5, 5–6, and 5–7, and figures 5–11 and 5–12 can be used in determining the maximum furrow length as governed by rainfall intensity.

Figure 5-10

2-Year, 30-Minute Rainfall (Inches)

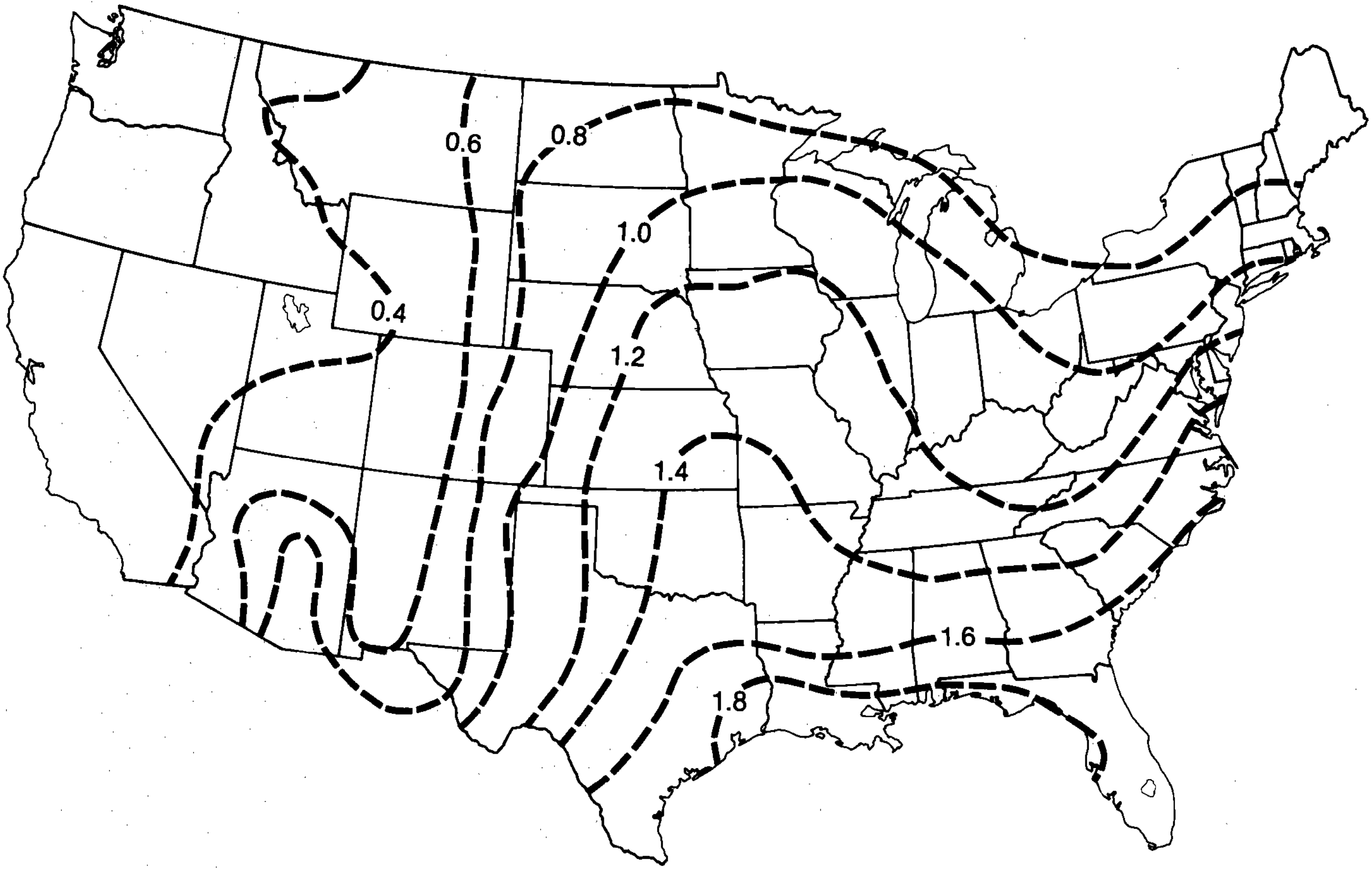


TABLE 5-5.—*Runoff for inches of rainfall*

	Curve No. 75 (inches)									
Tenths:	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
1	0.03	0.05	0.07	0.10	0.13	0.16	0.20	0.24	0.28	0.33
2	0.38	0.43	0.48	0.53	0.59	0.65	0.71	0.77	0.83	0.89
3	0.95	1.02	1.09	1.16	1.23	1.30	1.37	1.44	1.52	1.59
4	1.67	1.74	1.82	1.89	1.97	2.04	2.12	2.20	2.82	2.36

TABLE 5-6.—*Runoff for inches of rainfall*

	Curve No. 80 (inches)									
Tenths:	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.05
1	0.08	0.11	0.15	0.19	0.24	0.29	0.34	0.39	0.44	0.50
2	0.56	0.62	0.68	0.75	0.82	0.89	0.96	1.03	1.10	1.17
3	1.25	1.33	1.40	1.48	1.56	1.64	1.72	1.80	1.88	1.96
4	2.04	2.12	2.20	2.29	2.38	2.46	2.55	2.63	2.72	2.81

Figure 5-11

2-Year, 6-Hour Rainfall (Inches)

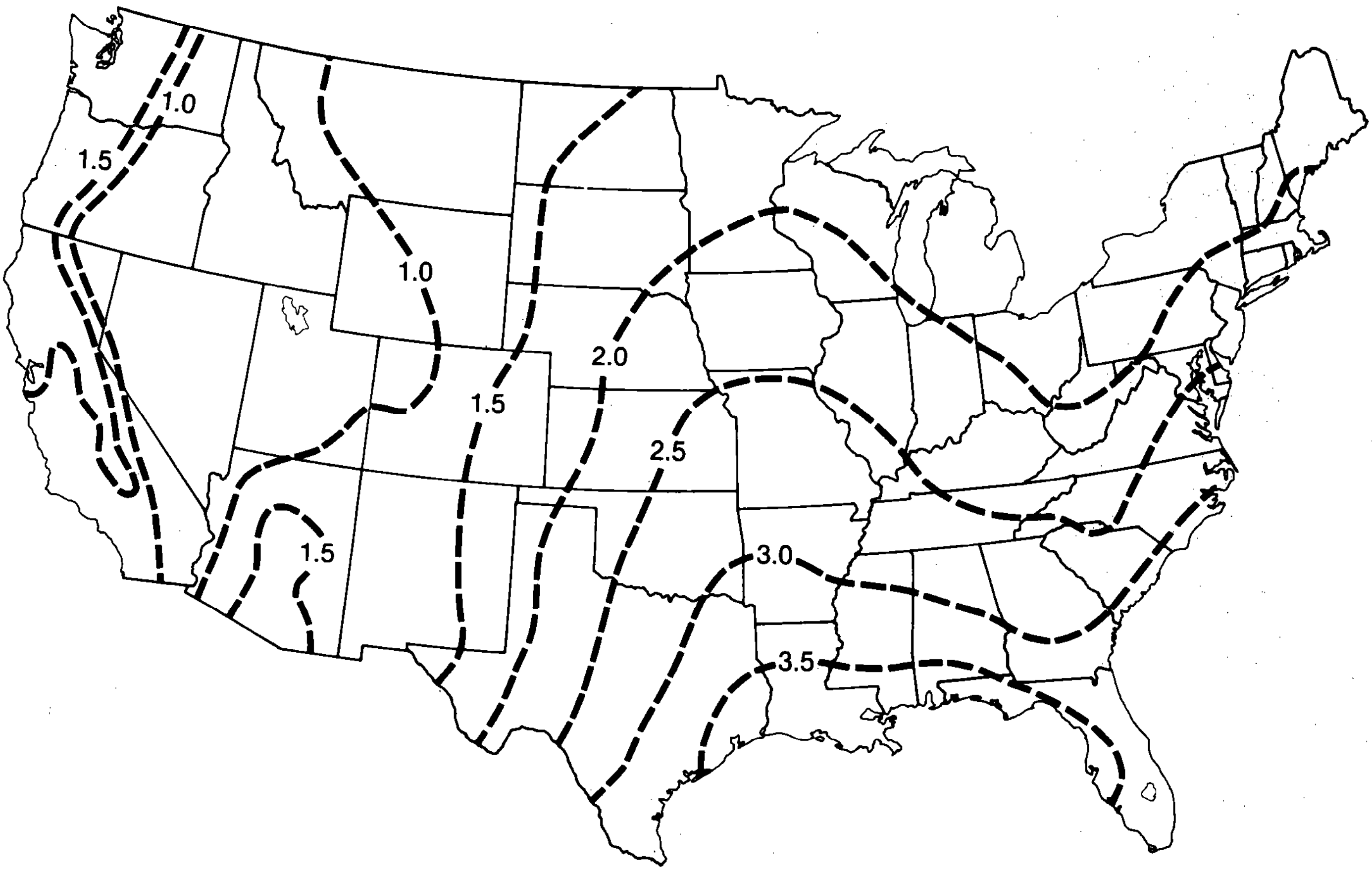


TABLE 5-7.—*Runoff for inches of rainfall*

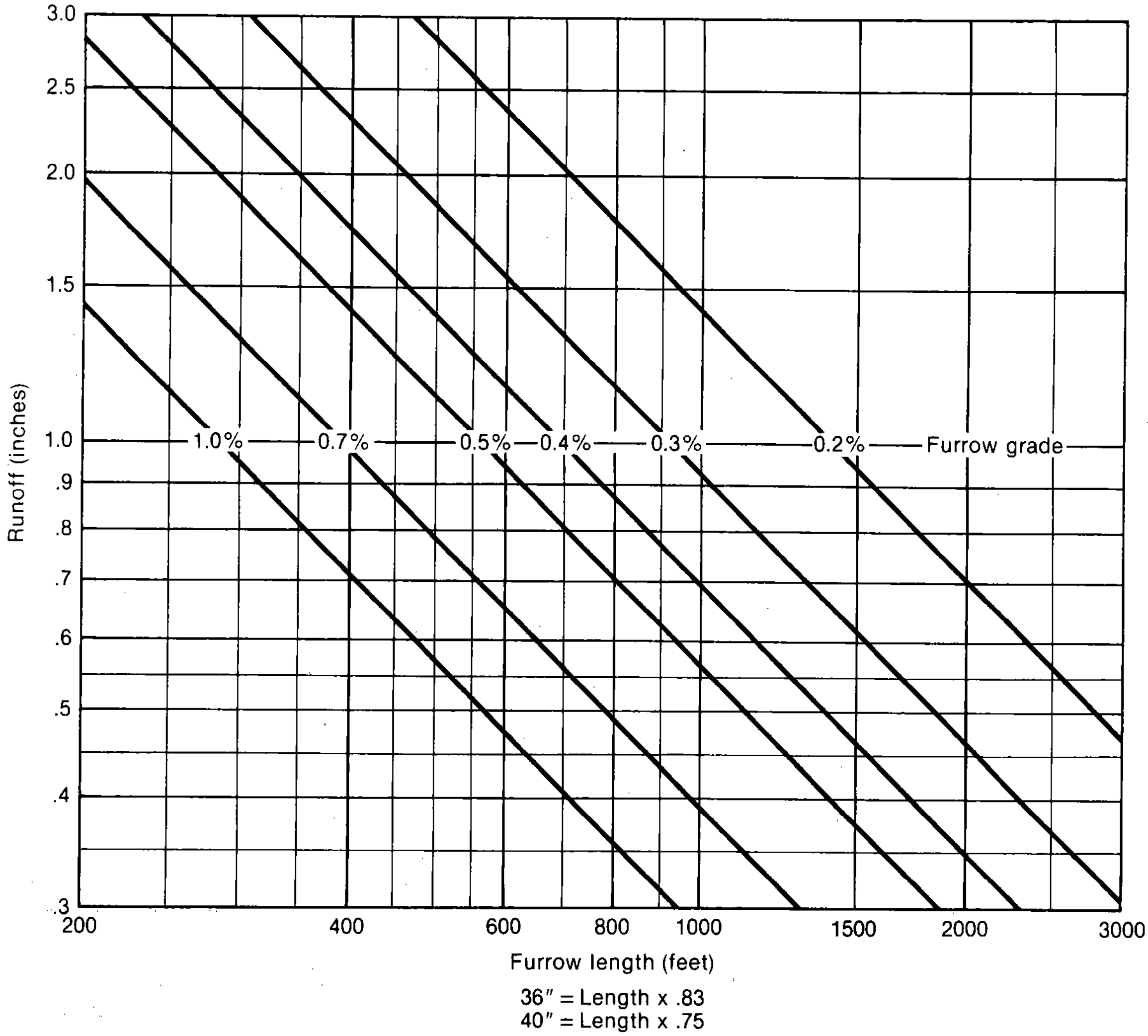
	Curve No. 85 (inches)									
Tenths:	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.09	0.13
1	0.18	0.22	0.28	0.33	0.39	0.45	0.52	0.59	0.65	0.73
2	0.80	0.87	0.95	1.02	1.10	1.18	1.26	1.34	1.42	1.51
3	1.59	1.68	1.76	1.85	1.93	2.02	2.11	2.10	2.28	2.37
4	2.46	2.55	2.64	2.73	2.82	2.91	3.00	3.09	3.19	3.28

Example: Determine furrow length on a 0.3 foot per 100 feet grade at Sikeston, Mo., for a soil in hydrologic group 75. Furrow spacing is 36 inches. Solution: From figure 5–11, the 2-year, 6-hour rainfall is 2.7 inches. From table 5–5, runoff is 0.77 inch. From figure 5–12, maximum length for 30-inch furrows is 1,250 feet. For 36-inch furrows, the length is $1{,}250 \times 0.83 = 1{,}040$ feet.

The length of furrow may also be limited by the size and shape of the field. If the field length exceeds the maximum design furrow length, the field must be divided into two or more lengths. In selecting lengths, consider boundaries between adjoining soils that have appreciably different intake rates or water-holding capacity. For example, low intake rate soils located in the upper reaches of the furrow length can sometimes be included with soils having a higher intake rate. Design criteria describe the maximum furrow length that should be considered for efficient water application with various intake rates, furrow grades, and application depths.

Figure 5-12

Runoff From 2-Year, 6-Hour Frequency Storm
Maximum Length of Furrows on 30″ Spacing



Corrugation Length

Corrugation length is generally restricted by the combination of soil intake rate and the flow capacity of the corrugations. Water should reach the end of the corrugations in the time necessary to provide a uniform application. Design criteria in this section provide guidance in selecting the proper corrugation length.

Stream Size

The proper furrow or corrugation inflow rate depends on the furrow or corrugation length. Therefore, if a maximum length is to be considered, it is necessary to determine the maximum nonerosive stream size that can be used for each design segment of the irrigation system.

Furrow Stream

Furrow designs in this chapter relate the inflow rate to soil intake rate; furrow length, slope, and spacing; and the desired application depth. One of the major limiting factors in furrow design is the maximum stream size that can be used safely. The maximum allowable nonerosive stream depends on a number of factors, including the slope of the furrow, the furrow shape or capacity, and the erodibility of the soil. A common method of determining this maximum stream size is by use of the empirical formula, $Q=\frac{10}{S}$ where, Q=maximum allowable stream in gallons per minute and S = slope of furrow in percent. This formula is independent of the furrow shape or the erodibility of the soil. A better criterion is to limit the velocity of the furrow stream according to the erodibility of the soil.

Soils may erode if the furrow stream velocity exceeds about 0.5 foot per second, whereas the less erodible soils may safely withstand velocity of 0.6 foot per second. Figure 5–13 shows velocity and depth of flow for various stream sizes and furrow grades in a standard shaped furrow. Where furrows are constructed with wide bottoms, the velocity would be less than indicated, and larger furrow streams can be used safely. If empirical formulas are used to determine the maximum furrow grade, $Q = \frac{10}{S}$ should be used for erodible soils, $Q = \frac{15}{S}$ for erosion-resistant soils, and $Q = \frac{12.5}{S}$ for average soils.

A practical upper limit for inflow rate is 50 gpm, regardless of furrow slope. Streams larger than 50 gpm usually require a larger cross-sectional area of furrow than the usual planting and tillage equipment provides.

Corrugation Stream

The capacity and grade of the corrugations determine the maximum stream size that can be used. Most corrugations do not accommodate an inflow rate much in excess of 10 gpm. If corrugations are to be constructed or opened before each irrigation, the same criteria should be used for maximum stream size as are used for furrows. If corrugations are such that the growing crop or crop residues retard water flow, the maximum nonerosive stream can be estimated by the formula $Q\ max = \frac{40}{S}$; however, the corrugation capacity may be the limiting factor.

Methods of Water Control

The depth of irrigation water absorbed at a station along the furrow or corrugation length is proportional to the time that water is in contact with the station, the opportunity time. For uniform intake, opportunity time should be as nearly uniform as is practicable for each segment of furrow length. To meet this objective, three methods of water control are applicable: (1) reducing the inflow rate after water has advanced to the end of the furrow, (2) recirculating or recovering surface runoff, or (3) impounding the water in the furrow and eliminating surface runoff.

Cutback Inflow

The cutback method requires that the water be introduced rapidly so that the entire furrow length is wetted in a minimum time, and then the size of the furrow stream reduced so that it is approximately equal to the intake rate of the soil. This method should be carefully considered for use in furrow irrigation because it requires a minimum use of power. If the cutback furrow stream is to be used, the method must be made practical to follow by developing an irrigation schedule that will fit normal farm operation or by automating the system. The following guidelines provide a practical procedure for using the cutback-inflow method:

1. The initial furrow stream should be applied until the water has advanced to the end of the furrow.
2. The inflow rate should then be reduced to one-half the initial rate.
3. The reduced inflow rate should be applied until the design application depth is reached.
4. Provisions should be made for storage, disposition, or recovery of the runoff water.

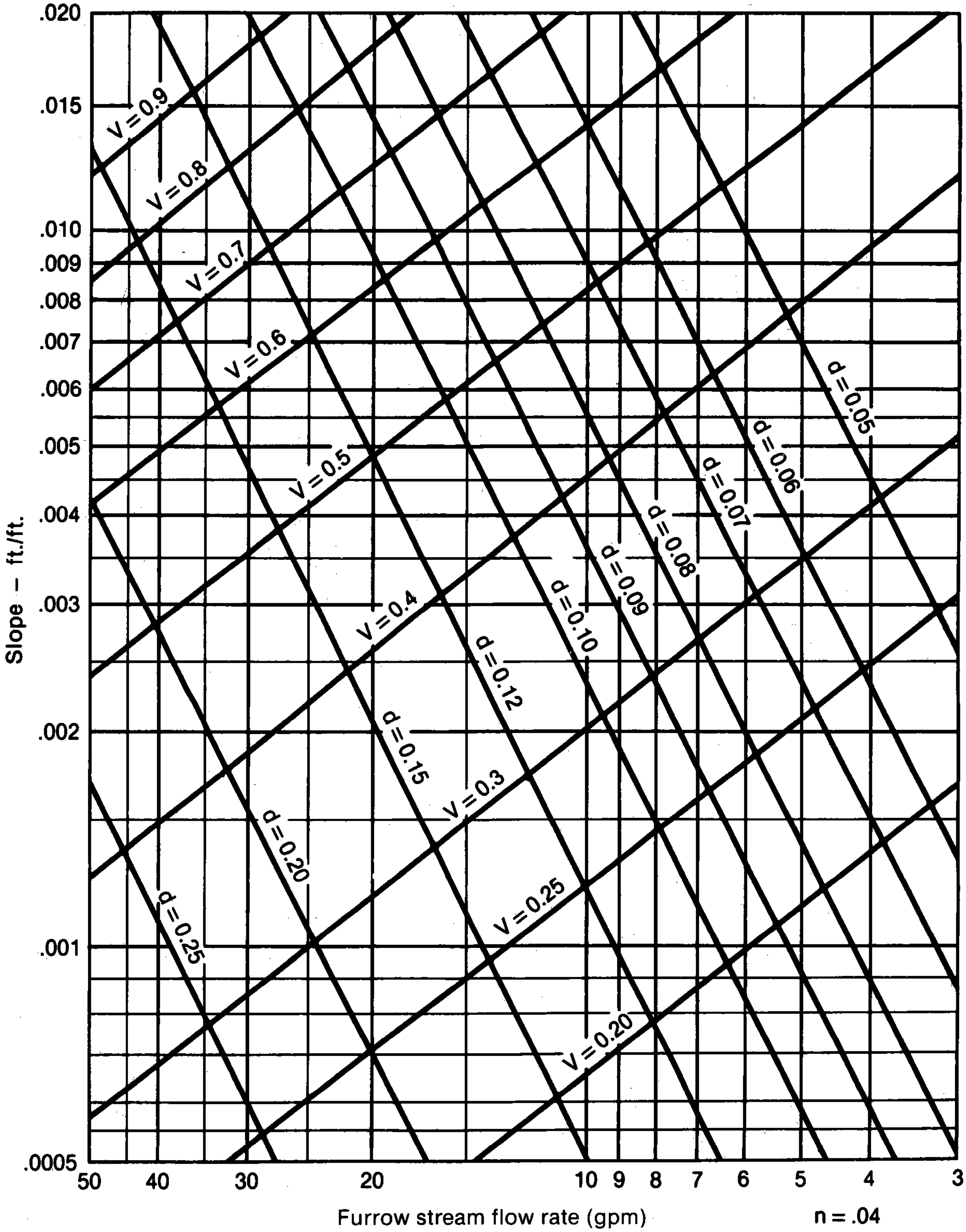
Gated pipe, siphon tubes, and spiles or ports in lined ditches are well suited for applying water by the cutback method. It may not be necessary to cut back the initial stream to get high irrigation efficiency on some soils. If at least three-fourths of the net intake is absorbed during the first one-fourth of the needed intake time, the use of cutback streams is questionable. An example is a fine-textured soil that cracks on drying.

Impoundment

The impoundment method requires that water be introduced rapidly so that the entire furrow length is wetted in a minimum time and the water impounded or held in place until the required application has entered the soil. This method does not require recovery or disposal of tailwater. It can be used for level furrows or where the fall in the total length of the furrow does not exceed the design depth of application. Impoundment can also be used on only the lower part of a graded furrow by impounding water that would otherwise be surface runoff.

Figure 5-13

Furrow Stream Velocity and Flow Depth



Continuous Inflow and Recovery

Many irrigators desire a water-application procedure by which they can obtain uniform, efficient irrigation by using a continuous inflow rate and avoid the added labor required in the cutback procedure. Irrigators often sacrifice both efficiency and uniformity of application merely for operating convenience or to minimize labor requirements. They do this by applying too small a furrow stream for longer than needed to obtain the desired intake rate. For the irrigator's convenience, this application time is usually in multiples of 12 hours. With the critical needs to use available water supplies with maximum efficiency and to conserve energy, this method of operation may become unacceptable. For efficient irrigation with a continuous inflow rate, it is usually necessary to provide for recovery of the irrigation tailwater and to apply furrow streams large enough to meet adequately the soil's intake requirements. The tailwater should be collected and reapplied to the furrows or corrugations or used on other irrigated fields. The design of tailwater-recovery pits is discussed in a later section.

Application Depth

The general irrigation practice has been to determine the root-zone depth of a mature crop, estimate the available water capacity of the soil to this depth, and design the system to apply 40 to 50 percent of this amount of water at each application. This practice does not always provide the best environment for plant growth. It is generally assumed that a crop will extract approximately 70 percent of its water requirement from the upper one-half of the zone in which the roots have developed. Most annual crops rated as deep-rooting crops have a root depth of 18 to 24 inches during most of the irrigation season. For maximum yields, water should be applied frequently enough to maintain a good water supply in the upper 12 to 18 inches of soil. This depth, of course, depends on the crop to be grown. To meet this requirement, a design net irrigation application of 2 to 4 inches is required for a corn or grain sorghum crop, depending on the water-holding capacity of the soil. If the soil is full of water at the start of the irrigation season, these frequent, relatively light water applications will provide readily available water for the crop throughout the growing season. In some areas of high rainfall, precipitation normally has filled the root zone of the soil to field capacity at the start of the growing season. In areas of low rainfall, it may be desirable to preirrigate and fill the soil to the mature root-zone depth of the crop to be grown. In either case, the growing crop starts out under field capacity water conditions.

The normal depth of application is defined as a full irrigation or the depth needed to bring the soil, within the water extraction depth of a mature crop, to field capacity after depletion to the management-allowed deficiency (MAD) level. MAD usually should not be greater than 50 percent of the total available-water-holding capacity of the soil. The total amount of soil water held available to plants in any soil is the sum of the available-water-holding capacity of all horizons occupied by plant roots.

Several other factors need to be considered when establishing the design application depth. It may be advantageous to increase or decrease the application depth to fit a practical application time schedule. A somewhat smaller application would result in only slightly fewer days between irrigations, and a larger application would result in a somewhat larger loss through deep percolation and a corresponding lower efficiency. Adjustments in design may also be needed if: (1) alternate furrows are to be irrigated, (2) smaller applications are desirable to leave storage capacity in the soil for rainfall, or (3) water supplies are limited to the extent that smaller-than-normal applications are made to ensure against crop failure rather than to produce maximum crop yields. The design depth must also be evaluated under conditions where smaller applications may be applied, such as early season irrigations.

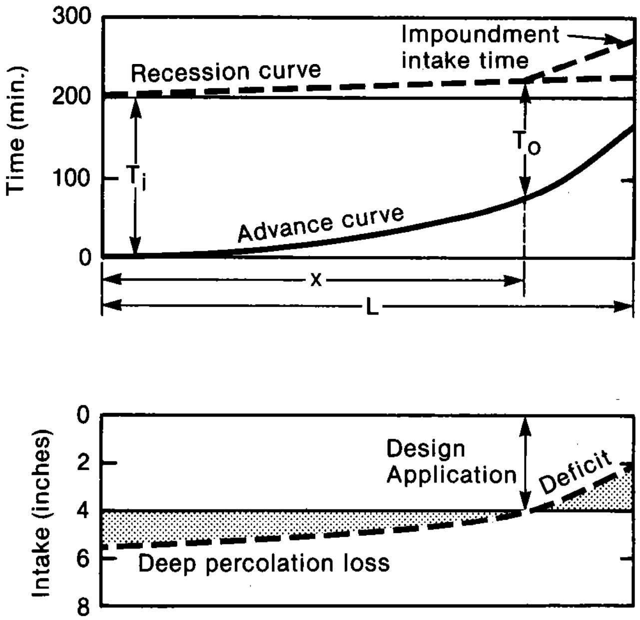
In areas where irrigation water is in short supply and rainfall can normally be expected to supplement the irrigation water, it is permissible to allow the water level to drop below the recommended levels, except during the critical crop production stages, such as tasseling to denting stage for corn. Under these conditions, alternate furrow irrigation is frequently practiced, whereby only a percentage of the area between the furrows receives a complete irrigation. These factors must be considered in selecting the proper furrow design.

Assumptions

Some assumptions or approximations must be made in developing design equations and tables for furrow and corrugation systems. These assumptions are valid enough that designs based on them result in irrigation systems that operate efficiently and uniformly, with only seasonal adjustments in stream size and application time. Design assumptions are made for the intake-time relationship, rate of advance, time for recession, opportunity time, retardance coefficient, and intake as related to furrow-wetted perimeter. (See fig. 5–14.)

Figure 5-14

Application Time, Advance and Recession Time vs. Intake Relationship



Intake-Time Relationship

Theoretically, intake uniformity along the entire length of a furrow would require that the intake time be equal at all points along the furrow. This is not possible with furrow or corrugation irrigation where water is applied at the upper end and progresses down the furrows with time. The length of time that water is in contact with segments of the system is, therefore, different at different points along the furrows or corrugations. For acceptable uniformity and adequacy of application, the minimum time that water is in contact with any point along the furrow length should not be less than that required for intake of the desired net application. Also, the maximum application time should be such that deep percolation losses are not excessive.

The time that water is in contact with a given segment of the furrow is defined as the opportunity time (T_o), or the amount of time that elapses after the furrow stream reaches the furrow stations until that water disappears from the surface at these points. This is the time increment between the advance and recession curves. These two curves are of prime importance in the design of a furrow or corrugation irrigation system because they describe the intake opportunity time for the various segments along the furrow length.

Advance Time

The rate of advance is influenced by the water inflow rate, the soil intake rate, and the furrow shape, grade, length, and surface roughness. The flow rate is largest at the upper end of the furrow and becomes successively smaller at each point downstream as water infiltrates. The result is a reduction in the rate of advance at successive points downstream. If the furrow length is such that the entire stream is absorbed by the soil, the advance stops. For efficient irrigation, advance must be rapid throughout the length.

Recession Time

The time for outflow of water to stop after inflow at the head of the furrow has ended is defined as recession time (T_r). This time is mostly affected by flow rate and furrow length, shape, and slope. The furrow surface generally becomes relatively smooth during the irrigation period so that retardance has progressively less influence on recession. Accumulation of crop residues in the furrows greatly affects the rate of advance, and, to a lesser degree, the rate of recession. In graded furrow or corrugation irrigation, the recession curve is relatively flat. If grades exceed approximately 0.25 percent, the recession time is so short that it has little effect on the soil intake. If the grade is 0.05 percent or less, impoundment of the stream can be used to increase the recession time and, in this manner, balance the advance-recession curve.

Because the recession time is relatively short compared with the needed intake time, it has little influence in graded furrow design. Recession time is considered when determining the opportunity time for a selected station. It is shown as zero in design equations for graded furrows, however, because a period of time is required for the furrow stream to build to the design flow volume after the advance stream reaches the design station, and this required buildup time and the recession time, for practical purposes, cancel each other.

Opportunity Time

The design of a furrow system is based partly on opportunity time (T_o), the time that water is in contact with a given station in the furrow. For a constant inflow rate, the infiltration of water into the soil is less at successive points along a furrow length because of a reduction in both flow rate and opportunity time. A design based on the opportunity time needed at the upper end would result in inadequate intake for all successive stations down the furrow.

A furrow-system design based on the opportunity time needed for intake at the distal end of the furrow results in excessive intake at all stations upstream. Because the rate of advance decreases rapidly with increased length, systems can be designed to provide the opportunity time needed to apply the desired application at a point less than the entire length, for example, approximately 80 percent of the total length from the upper end. The best balance must be determined between excess application at the upper end and insufficient application in the section below the design point. For specific crops, this point must be selected after determining the effect of the application deficiency downstream of the design point.

Retardance Coefficient

The roughness or retardance in the furrow determines the velocity and depth of flow that result when a specified flow rate is applied in a furrow of a certain cross section and grade. This retardance is represented by the Manning "n" in the equation

$$Q=\left(\frac{666.96}{n}\right)\left(\frac{A^{5/3}\,S^{1/2}}{P^{2/3}}\right)$$

where

Q = flow in gpm

n = roughness coefficient

P = wetted perimeter of furrow in feet

S = furrow slope in feet per foot

A = cross-sectional area of water in the furrow in square feet

The Manning "n" varies with the furrow roughness and shape and the flow rate. Furrow roughness is readily altered by farm tillage equipment. Furrow and corrugation shapes also vary and, therefore, designs are based on the most common shapes. With the retardance condition and shape of the furrows standardized, the flow rate becomes the determining factor. The flow rate for most furrow streams is about 10 to 30 gpm and for most corrugation streams, 4 to 10 gpm. A study of furrow flows within this range indicates that designs based on retardance "n" value of 0.04 for furrows and 0.10 for corrugations result in design values most appropriate for these methods of water application.

Wetted Perimeter

The wetted perimeter of a furrow or corrugation at any point is the cross-sectional area that is in contact with the flowing stream. The rate of infiltration in a furrow or corrugation is a function of this area. This contact area decreases as the distance from the inflow end increases. Therefore, the design formulas must take into account this decrease in wetted area to determine the intake at a given point along a furrow.

Intake-Family Curves

A series of intake-family curves have been developed that relate cumulative depth of intake to opportunity time. Each type of soil has unique intake characteristics. Many soils, differ so little, however, that for practical purposes they can be grouped in one of a number of intake families. For design purposes, most soils, except those that crack by the time irrigation is needed, can be associated with one of these families. If the soil has a higher or lower intake rate at the time of a specific irrigation, the application rate and time can be adjusted accordingly by use of a higher or lower adjacent intake-rate curve. The intake curves developed for furrow or corrugation irrigation have the same general shape as curves developed for the border- and contour-ditch methods. The furrow curves on a specific site are not necessarily the same as the border curves but should generally be parallel. There is no simple guideline, such as soil texture, to govern the placement of a soil in a specific group. If field experience is inadequate to group the soils properly, field evaluations should be made. Such evaluations provide reliable data for furrow and corrugation designs on specific soils of an area.

The general formula describing the intake-family curves is:

$$F = aT_o^b + 0.275$$

where

F = cumulative intake in inches for time, t

a = intercept of cumulative intake at unit time

T_o = opportunity time in minutes

b = exponent of time in intake equation

The values for a and b are listed on figure 5–15 and in table 5–9.

Limitations

Furrow- and corrugation-design tables and charts allow a wide selection in length of run and grade and furrow streams. However, for efficient uniform water application, specific guidelines or limitations should be observed in selecting the design to be recommended. Limitations include permissible deep percolation losses, allowable amount of irrigation water runoff, and minimum application efficiency.

Deep Percolation

Water that percolates below the root zone of the crop not only is lost to the plants but frequently contributes to a buildup of the ground-water level, which may damage or destroy lower lying land where water returns to the surface and waterlogs the soil. In addition to the loss of water, deep percolation results in the loss of plant nutrients. An acre-inch of water that percolates below the root zone frequently carries with it as much as 4 to 5 pounds of nitrogen. It may also unnecessarily leach soluble minerals from the underlying strata.

Runoff

Water-use regulations in many states now prohibit an irrigator from allowing irrigation water to leave his land. Runoff water frequently contains colloidal material, minerals, and pesticides that are detrimental to adjoining landowners or to surface water. Runoff water can also be detrimental if ponded on neighboring farms or public or private property. It is extremely difficult to have efficient furrow or corrugation irrigation without tailwater. Provisions must be made for recovery or safe disposal of all runoff resulting from irrigation, regardless of the operating procedures used. Runoff from rainfall is not so easily regulated. However, the system design must include needed facilities for its safe disposal.

Design Efficiency

Design efficiency is defined as the ratio of the desired depth of irrigation to the gross depth of irrigation water applied. If the design depth of application is planned for a section other than the total length, such as 80 percent of the furrow or corrugation length, the design efficiency is expressed as DE_{80}. Optimum efficiency may not always be practical to obtain. Designs selected to fit the individual field requirements generally should have efficiency of no more than 10 percent below the optimum.

Equations

Design equations have been developed that describe the relationship between furrow length, inflow time, inflow rate, deep percolation, surface runoff, and field application efficiency for selected design values of application depth, soil intake family, and furrow slope and spacing.

Separate design equations and procedures are shown for each of the three types of furrow or corrugation irrigation:

1. Graded furrows or corrugations with open ends.
2. Cutback-inflow furrows with open ends.
3. Level-impoundment furrows.

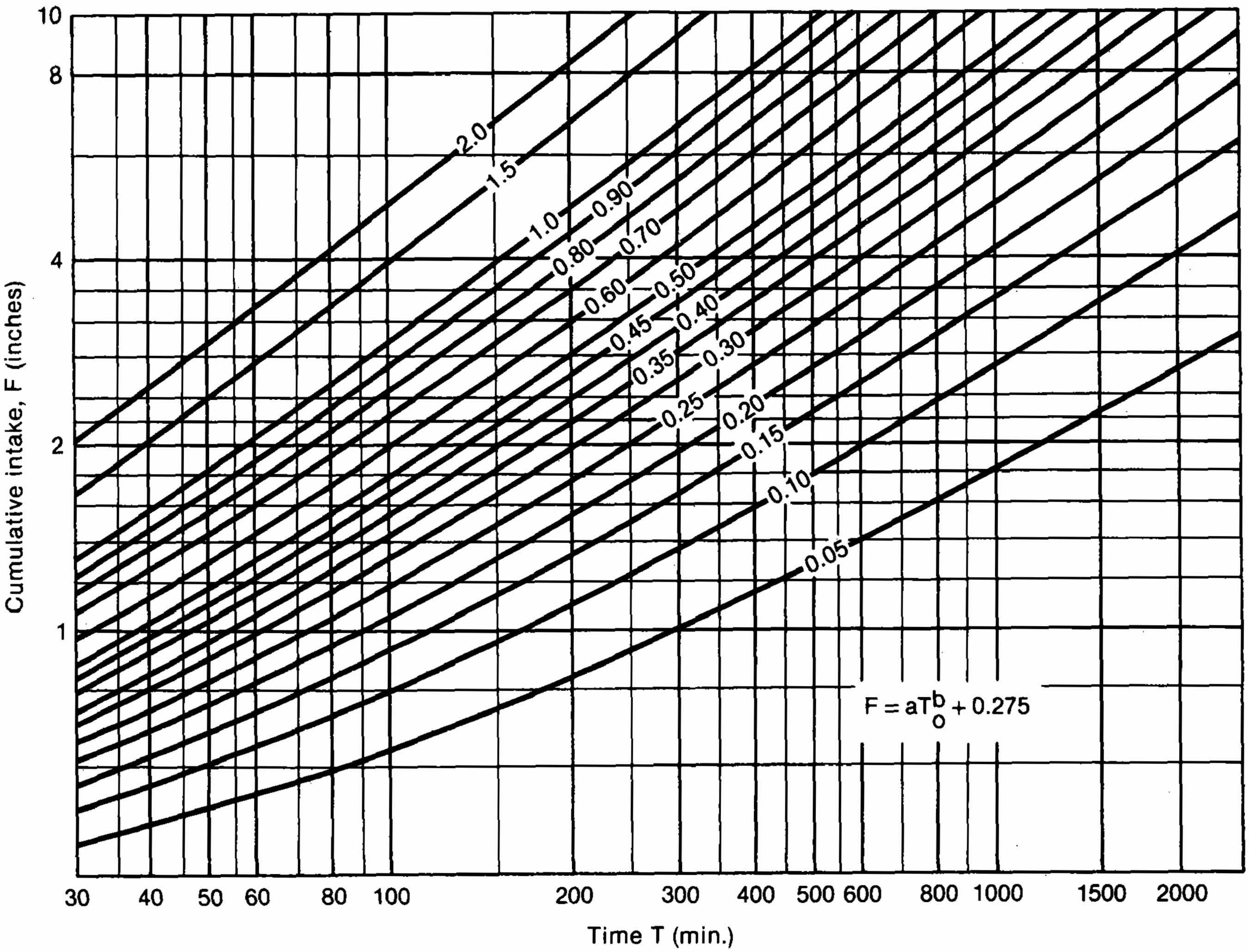
Graded Furrows

Equations for system design have been developed for the following items that must be determined in preparing a furrow or corrugation design: (1) wetted perimeter, (2) advance time or travel time, (3) opportunity time, (4) gross application depth, (5) intake depth at selected length, (6) average intake over the entire length of furrow, (7) surface runoff, (8) deep percolation, and (9) field application efficiency. All depths are expressed as equivalent depths over the furrow spacing.

Wetted perimeter.—The opportunity for water intake from a furrow is directly related to the cross section that is in contact with the water. The contact

Figure 5-15

Intake-family Curves



area per unit of length is the wetted perimeter and can be defined from the Manning formula as follows:

$$A = Bd + zd^2$$

$$P' = B + 2\sqrt{d^2 + (zd)^2}$$

$$Q = AV = A\,\frac{1.486}{n}\left(\frac{A}{P}\right)^{2/3} S^{1/2}$$

$$\frac{Qn}{S^{1/2}} = \frac{1.486\,A^{5/3}}{P^{2/3}}$$

A relationship between wetted perimeter and Qn $S^{-1/2}$ is derived using a minimum bottom width of 0.2 foot with 1:1 side slopes and a maximum bottom width of 0.5 foot with 2:1 slopes, and a number of cross-sectional shapes between these two extremes.

The resulting equation for wetted perimeter after units conversion is:

$$P' = 0.2686\,(Qn/S^{0.5})^{0.4247} + 0.0462$$

where

P′ = wetted perimeter, ft

Q = furrow inflow, gpm

n = Manning roughness coefficient

S = furrow slope, ft/ft

Intake from a furrow occurs only over the part of the soil surface that is in contact with the furrow stream or the wetted perimeter of the furrow. However, intake is vertical and horizontal in contrast to flooding or sprinkler methods where intake is only vertical. To account for both vertical intake, which is influenced by gravitational forces, and horizontal intake, which is influenced by suction forces, the wetted perimeter is increased by an empirical constant of 0.700. This factor is an average value derived from studies that indicate that horizontal intake is a function of the 0.4 power of intake opportunity time.

The relationship for wetted perimeter, after adding the constant for horizontal intake, becomes:

$$P = 0.2686\,(Qn/S^{0.5})^{0.4247} + 0.7462 \qquad (5\text{-}1)$$

The value of P determined from equation 1 cannot exceed the furrow spacing W. Values of wetted perimeter plus constant are given in table 5-8 for selected inflow rates and furrow slopes.

Advance time.—The reduction of the stream as it travels down the furrow results in decreasing velocity and thus a continually decreasing rate of advance along the length of the furrow.

A regression analysis of velocity advance was made from several hundred furrow trials to relate effect of inflow rate, slope, length, and furrow-intake family. These studies resulted in a semilogarithmic equation for advance time in the form:

$$T_t = \frac{x}{c}\, e^{(dx/QS^{1/2})} \qquad (5\text{-}2)$$

where

T_t = advance time, minutes

x = furrow length to point x, feet

Q = inflow rate, gpm

S = furrow slope, ft/ft

c = advance coefficient varying with furrow-intake family

$c = (23.211 + 5.8653\, I_f)$

d = advance coefficient varying with furrow-intake family

$d = (4.4685 \times 10^{-4} + 1.5764 \times 10^{-3}\, I_f)$

I_f = furrow-intake family number

TABLE 5-8.—*Wetted perimeter plus constant (feet)* [1]

Furrows
n = 0.04

Q (gpm)	S (ft/ft) 0.0005	0.001	0.002	0.004	0.006	0.008	0.010	0.020	0.030
2			1.09	1.04	1.02	1.00	0.99	0.96	0.94
4			1.21	1.14	1.11	1.09	1.07	1.03	1.01
6			1.29	1.22	1.18	1.15	1.14	1.08	1.05
8			1.37	1.28	1.24	1.21	1.19	1.13	1.09
10	1.66	1.54	1.43	1.33	1.29	1.25	1.23	1.16	1.13
15	1.83	1.68	1.56	1.44	1.39	1.35	1.32		
20	1.97	1.81	1.66	1.54	1.47	1.42			
25	2.10	1.91	1.75	1.61	1.54				
30	2.20	2.00	1.83	1.68					
35	2.30	2.09	1.91	1.75					
40	2.39	2.17	1.97	1.81					
45	2.48	2.24	2.04						
50	2.56	2.31	2.10						

Corrugations
n = 0.10

Q (gpm)	S (ft/ft) 0.004	0.006	0.008	0.01	0.02	0.03	0.04
2	1.25	1.15	1.15	1.11	1.06	1.03	1.01
4	1.43	1.29	1.29	1.23	1.16	1.13	1.11
6	1.56	1.39	1.39	1.32	1.24	1.20	1.17
8	1.60	1.47	1.47	1.40	1.31	1.26	1.23
10	1.75	1.54	1.54	1.46	1.36	1.31	1.28

[1] Values of P cannot exceed furrow spacing W.

The maximum length of advance is reached at the point at which the volume of intake along the furrow length equals the volume of inflow. The advance time equation is not applicable to furrow slopes of less than 0.05 percent.

Intake family and advance coefficients are listed for various intake-family numbers in table 5-9. Figures 5-16(a) through 5-16(f) describe advance time in relation to furrow length for intake families ranging from $I_f = 0.05$ to $I_f = 2.0$. The curves are developed for an inflow rate of 1 gpm and a specific furrow slope. Curves are shown for slopes of 0.0005, 0.001, 0.005, 0.01, 0.02, and 0.03 ft/ft.

TABLE 5-9.—*Furrow-intake family and advance coefficients*

I_f	a	b	c	d
0.05	0.0210	0.6180	23.5040	5.2567×10^{-4}
.10	.0244	.6610	23.7975	6.0449×10^{-4}
.15	.0276	.6834	24.0908	6.8331×10^{-4}
.20	.0306	.6988	24.3841	7.6213×10^{-4}
.25	.0336	.7107	24.6773	8.4045×10^{-4}
.30	.0364	.7204	24.9706	9.1977×10^{-4}
.35	.0392	.7285	25.2639	9.9859×10^{-4}
.40	.0419	.7356	25.5511	1.0774×10^{-3}
.45	.0445	.7419	25.8504	1.1562×10^{-3}
.50	.0471	.7475	26.1436	1.2350×10^{-3}
.60	.0520	.7572	26.7302	1.3427×10^{-3}
.70	.0568	.7656	27.3167	1.5503×10^{-3}
.80	.0614	.7728	27.9032	1.7080×10^{-3}
.90	.0659	.7792	28.4898	1.8656×10^{-3}
1.00	.0703	.785	29.0763	2.0232×10^{-3}
1.50	.0899	.799	32.0090	2.8114×10^{-3}
2.00	.1084	.808	34.9416	3.5996×10^{-3}

The following example illustrates use of the figures for a slope of 0.005 ft/ft, furrow length of 900 feet, inflow rate of 10 gpm, and a furrow-intake family of 0.3.

$$\frac{\text{Furrow length}}{\text{Inflow rate}} = \frac{900}{10} = 90$$

At the intersection of $\frac{L}{Q}=90$ and $I_f=0.3$, read the ratio $\frac{T_t}{Q}$ as 11.6. Advance time is then 11.6×10 gpm $=116$ minutes.

Recession time.—The amount of time it takes for water to disappear from the furrow after inflow stops is termed recession time. After inflow stops, water in the furrow is removed by the flow continuing down the furrow and/or by infiltration into the soil. The time of recession increases at successive points downstream.

Recession time for graded furrows with open ends is comparatively short and has little effect on the quantity of intake. The time required for the furrow stream to increase to a quantity used in the design after it reaches a specified station and the time of recession from that point tend to balance each other so that recession time can be omitted from the design criteria for graded furrows with open ends. Time of recession is significant for low graded or level furrows with blocked ends. Runoff is eliminated in these types of furrow systems and a different design procedure is required, which will be described separately.

Intake opportunity time.—Another factor influencing design is the intake opportunity time, the time water is available for infiltration at any point along the furrow. The opportunity time (T_o) also decreases at successive points downstream and depends on the inflow time, the advance time, and the recession time as shown by the following equation:

$$T_o = T_i - T_t + T_r$$

Inflow time (T_i) is a constant for a specific irrigation. Advance time (T_t) increases at successive points downstream. Recession time (T_r) is assumed to be zero for graded open-end furrows. This assumption results in an equation for opportunity time at any given point (x) along the furrow as follows:

$$T_o = T_i - T_t$$

Substituting equation 2 for T_t yields:

$$T_o = T_i - \frac{x}{c} e^{(dx/QS^{1/2})} \qquad (5\text{-}3)$$

where

T_o = intake opportunity time in minutes at any point, a distance of x from the inlet. The subscript n is used rather than o to describe the net opportunity time required for a cumulative intake F_n.

T_i = inflow time in minutes.

It is also necessary to determine the average intake opportunity time for the entire furrow length to determine the total amount of applied water that has infiltrated. The average opportunity time, assuming recession time is 0, is equal to the inflow time (T_i) less the average advance time. The average advance time is determined by integration of advance equation 2 between the limits of 0 and L and dividing by the length L.

$$T_{(0-L)} = \left[T_i - \frac{1}{cL} \int_0^L L \; e^{(dL/QS^{1/2})} \right]$$

Integration by parts yields the following equation for average opportunity time:

Figure 5-16(a)

Advance Time vs. Length (S = 0.0005 ft./ft.)

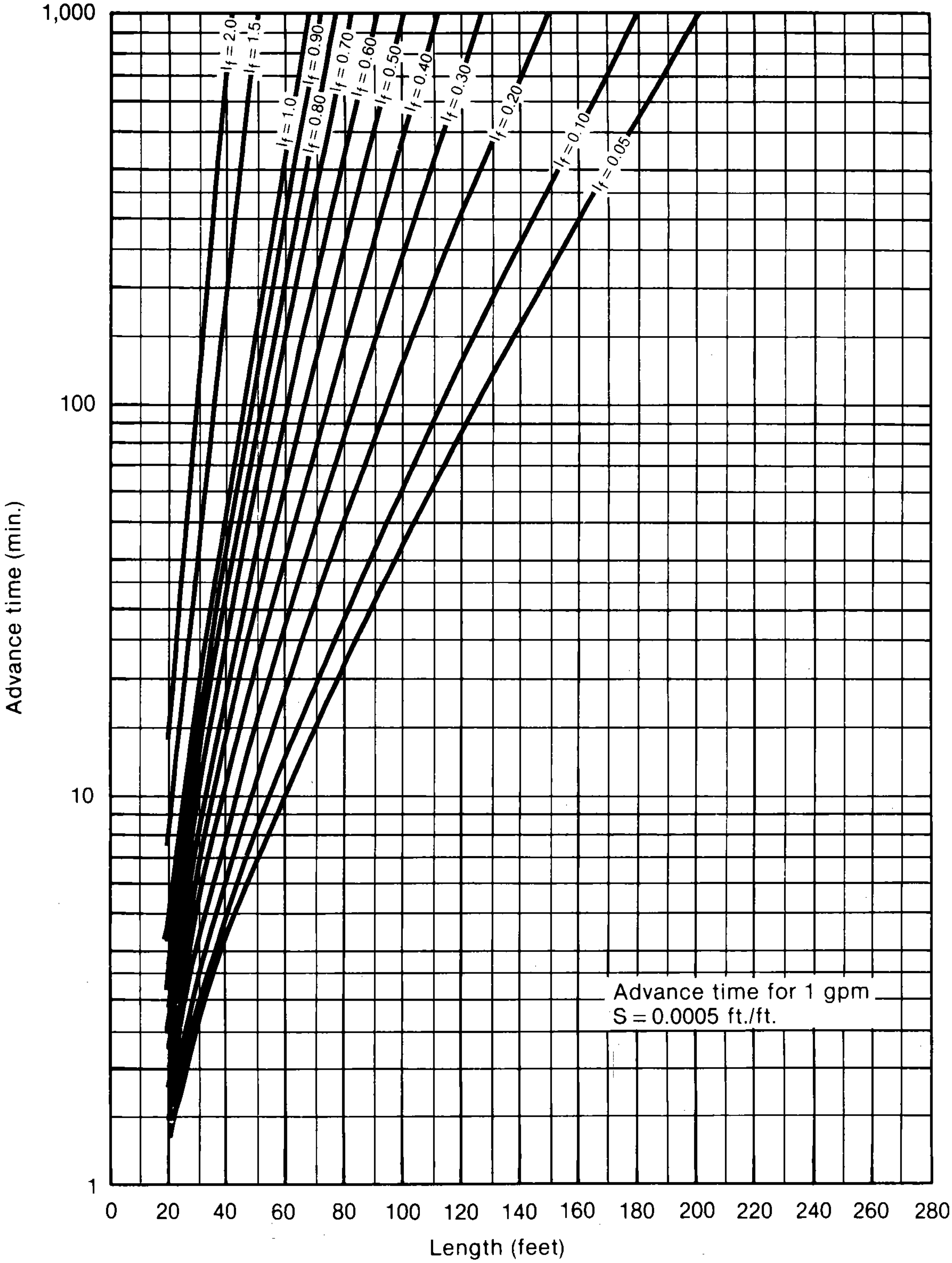


Figure 5-16(b)

Advance Time vs. Length (S = 0.001 ft./ft.)

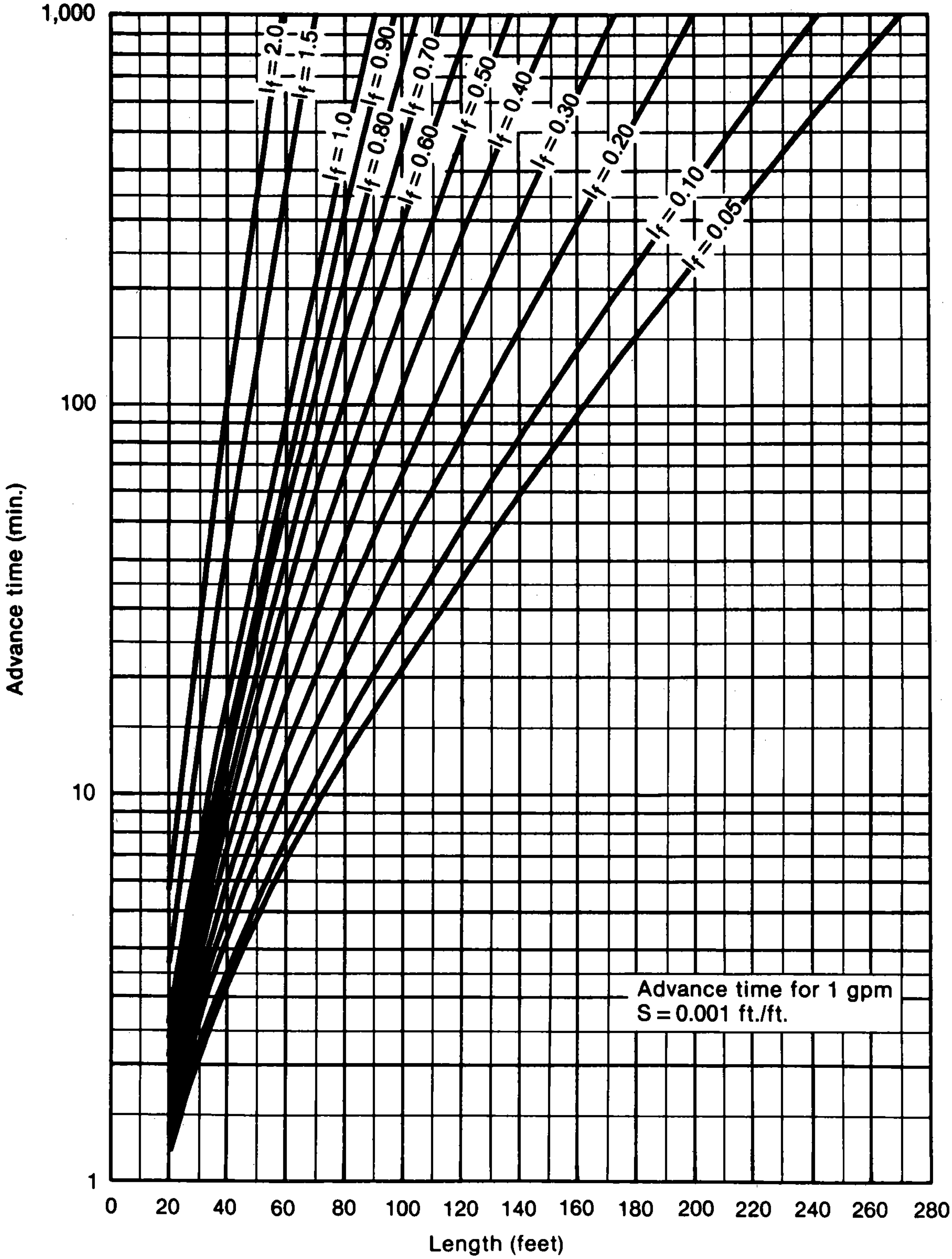


Figure 5-16(c)

Advance Time vs. Length (S = 0.005 ft./ft.)

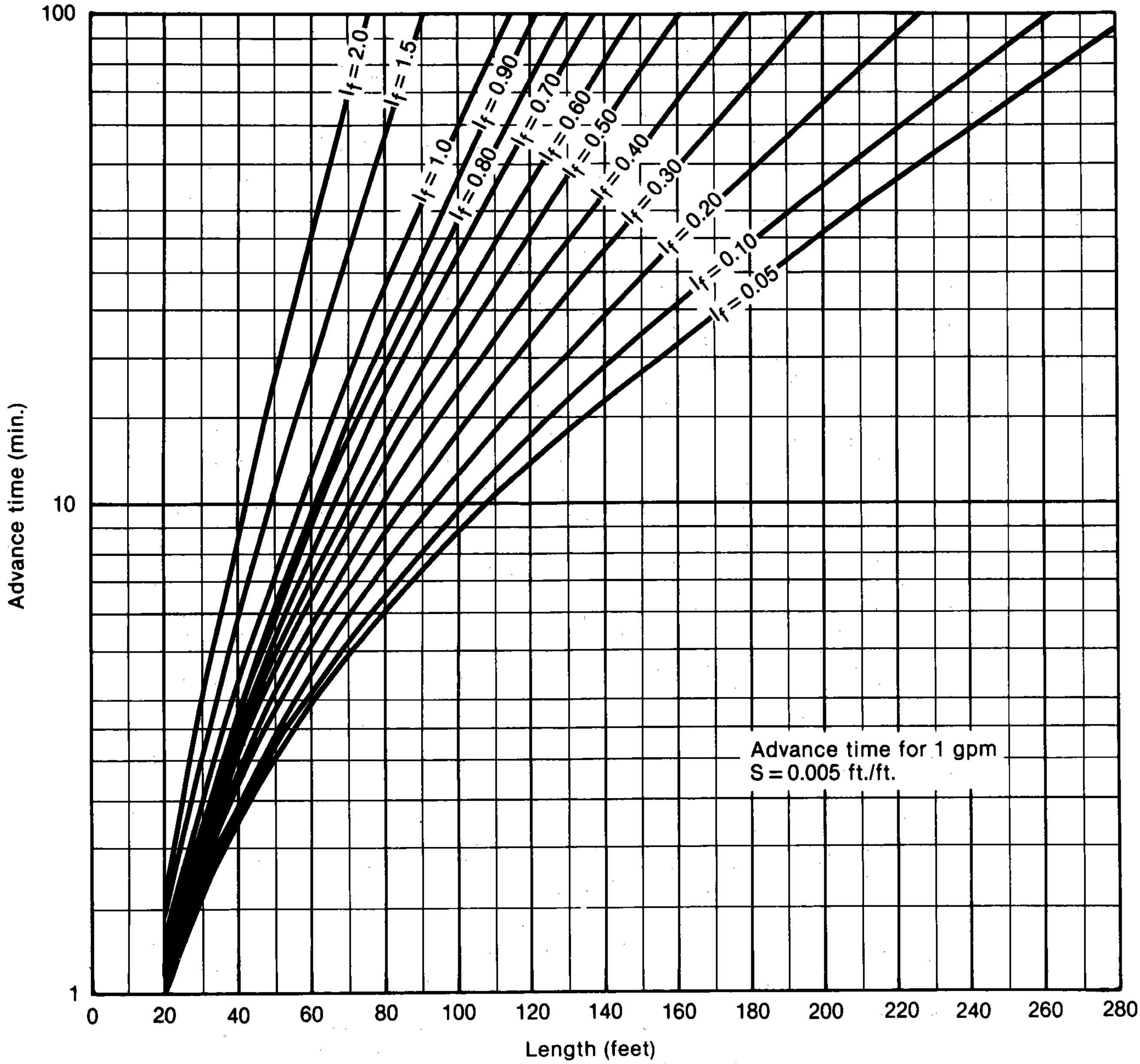


Figure 5-16(d)

Advance Time vs. Length (S = 0.01 ft./ft.)

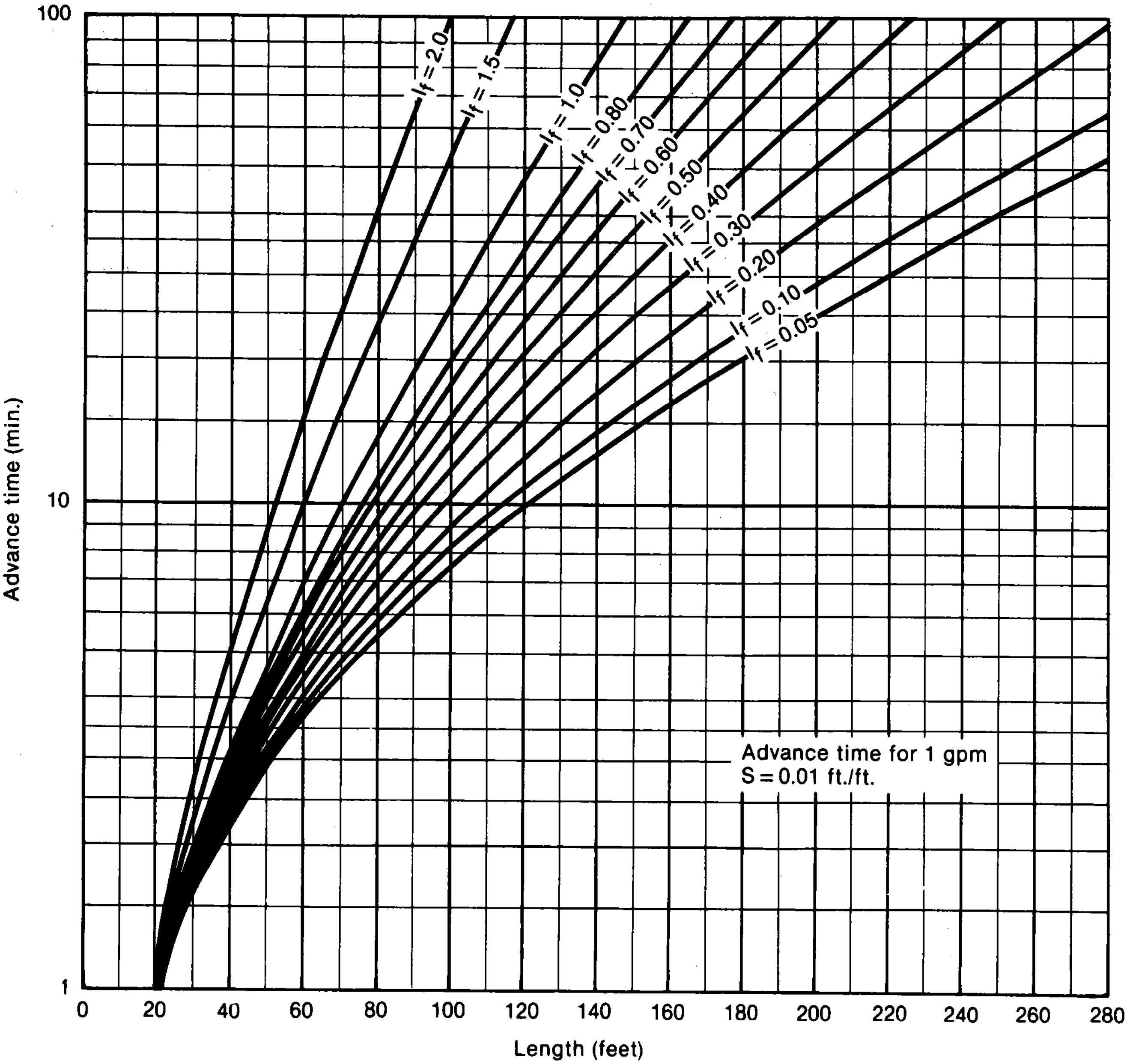


Figure 5-16(e)

Advance Time vs. Length (S = 0.02 ft./ft.)

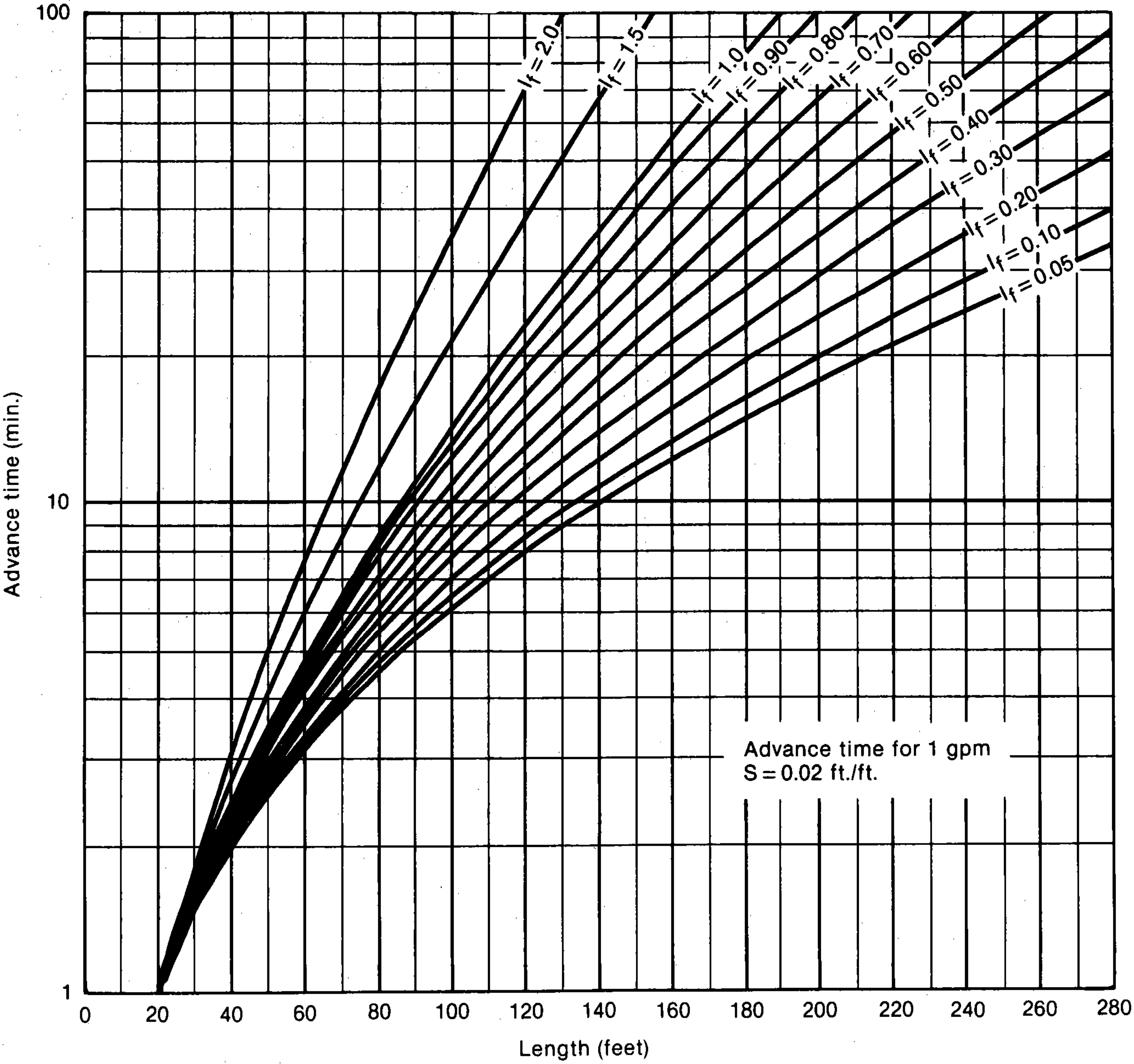
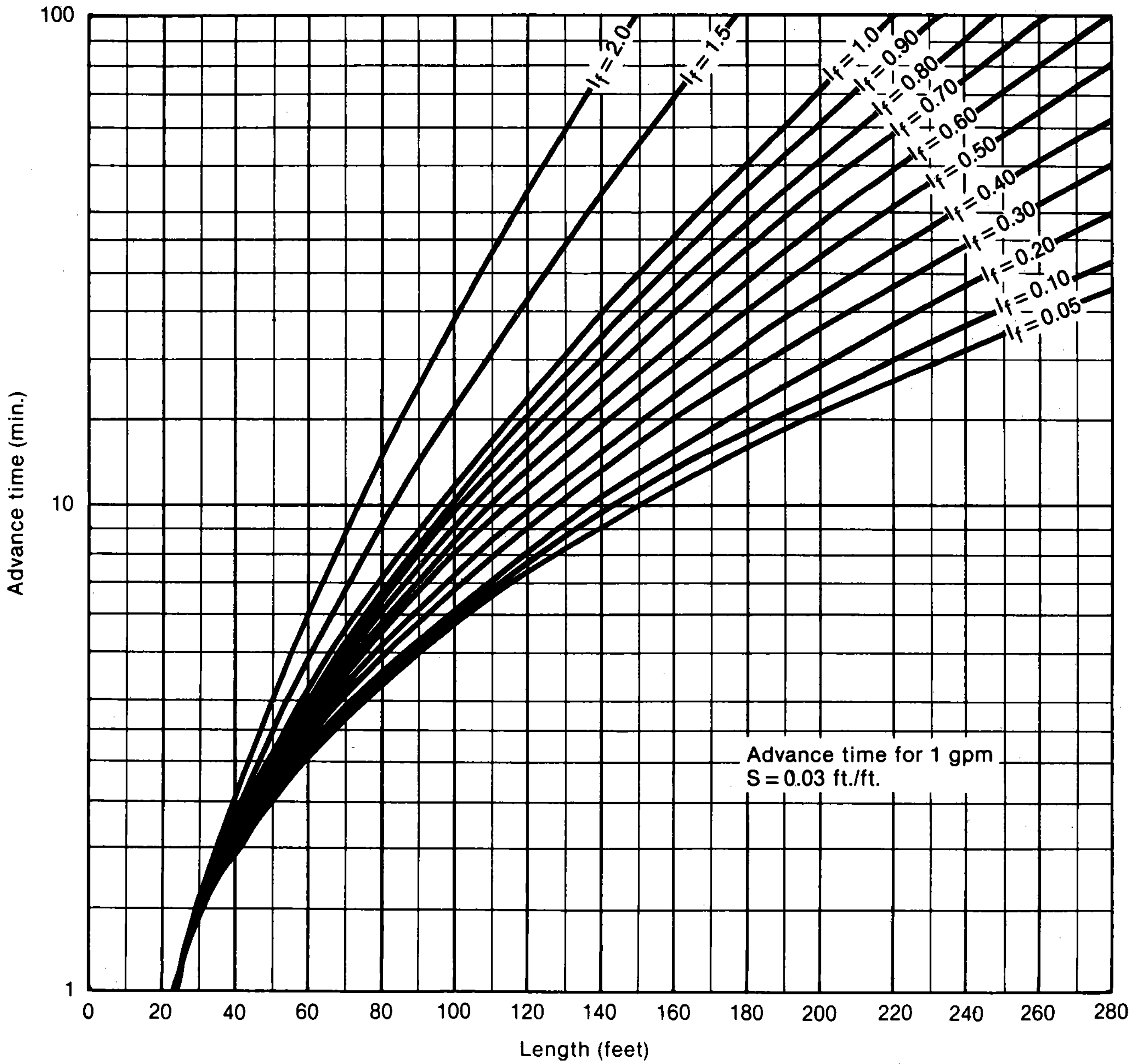


Figure 5-16(f)

Advance Time vs. Length (S = 0.03 ft./ft.)



$$T_{(0-L)} = T_i - \left[\frac{1}{cL\left(\frac{d}{QS^{1/2}}\right)^2} \left(\frac{dL}{QS^{1/2}} - 1 \right) e^{(dL/QS^{1/2})} + 1 \right] \quad (5\text{-}4)$$

where $T_{(0-L)}$ is the average opportunity time for the furrow length (L) in minutes.

The same equation can be used to determine the average opportunity time to point x, ($T_{(0-x)}$) along the furrow length by substituting the distance to point x for L in equation 4.

Gross application depth.—The gross application depth must be known to determine the amount of surface runoff and the application efficiency that can be expected with the selected design. The gross application depth can be calculated by use of the equation:

$$F_g = \frac{1.6041\, Q\, T_i}{WL} \quad (5\text{-}5)$$

where

F_g = gross depth applied, in

Q = inflow rate, gpm

T_i = application time, min

W = furrow spacing, ft

L = furrow length, ft

Intake depth.—The point intake at which the entire surface is covered by the irrigation stream is expressed by the intake equation in the formula:

$$F = (a\, T^b + 0.275)$$

where F is the point cumulative intake in inches; a and b are coefficients for each intake family as listed in table 5-9. T is the intake opportunity time at the intake point. Intake from a furrow occurs only over the portion of the soil surface that is in contact with the furrow stream or the wetted perimeter of the furrow. The wetted perimeter is adjusted by the addition of a constant (0.7) to account for both vertical and horizontal intake, as previously discussed.

The point intake equation for furrows is:

$$F = (a\, T^b + 0.275)\, (P)$$

Intake depth is normally expressed as the depth over the entire furrow width or area. The equivalent intake depth for furrows then becomes x at any point along the furrow length:

$$F_x = (a\, T_{ox}{}^b + 0.275) \frac{P}{W} \quad (5\text{-}6)$$

where

F_x = cumulative intake at any point x along the furrow in inches

T_{ox} = opportunity time at point x along the furrow in minutes

a & b = intake-family coefficients as given in table 5-9

P = wetted perimeter, in feet, determined from equation 1. The maximum value cannot exceed furrow spacing W.

W = furrow spacing in feet

Equation 6 can be used to determine the cumulative intake at any point x along the furrow. The designer may, for example, select a point x equal to 80 percent of the furrow length at which to apply the design application depth. Normally, furrow designs provide for application of the design depth at the end of the furrow and the subscripts of cumulative intake F and opportunity time T are changed to F_n and T_n, respectively.

Equation 6 then becomes:

$$F_n = (a(T_n)^b + 0.275)\, P/W \quad (5\text{-}7)$$

where F_n is the design depth in inches and T_n is the required opportunity time for the design depth.

The average cumulative intake for the entire furrow length can be determined using equation 7 by substituting the average opportunity time $T_{(0-L)}$ computed by using equation 4 for the opportunity time (T_n) at length L.

$$F_{(0-L)} = \left[a(T_{(0-L)})^b + 0.275 \right] P/W \quad (5\text{-}8)$$

The average cumulative intake ($F_{(0-x)}$) for a length less than L can also be determined by substituting the average opportunity time ($T_{(0-x)}$) in equation 8 for $T_{(0-L)}$.

Surface runoff.—Outflow from the end of a graded furrow is necessary to provide opportunity time for intake at the lower end of a furrow, unless the ends are blocked and the water is ponded in the furrow. Properly designed furrow systems must provide for recovery and reuse or safe disposal of the surface runoff. The expected average depth of runoff can be estimated by use of the equation:

$$RO = F_g - F_{(0-L)} \qquad (5\text{-}9)$$

where RO = average surface runoff depth in inches.

The surface runoff can be expressed in volume units by the equation:

$$v_{RO} = \frac{RO\,(W)\,(L)}{12\,(43{,}560)} \qquad (5\text{-}10)$$

where

v_{RO} = volume of runoff, acre-ft

RO = surface runoff, in.

W = furrow spacing, ft

L = furrow length, ft

Deep percolation.—Deep percolation is the average depth of irrigation water that infiltrates the soil in excess of the design application depth. Deep percolation is determined from the equation:

$$DP = F_g - RO - F_n \qquad (5\text{-}11)$$

where DP = average deep percolation over the furrow length in inches. The equation can also be expressed as:

$$DP = F_{(0-L)} - F_n$$

When the design application, at the option of the designer, is to be applied at a point x that is less than the furrow length L, the equation for deep percolation expressed as equivalent depth over the entire length becomes:

$$DP = (F_{(0-x)} - F_n)\frac{x}{L} \qquad (5\text{-}12)$$

Application efficiency.—The application efficiency is defined as the percentage of the applied irrigation water that is stored in the soil at design application depth. Efficiency as a decimal is expressed as the inflow volume less the runoff and deep percolation volumes, divided by the inflow volume.

The equation for efficiency if the design application is applied at furrow length L is:

$$AE = 100\frac{F_n}{F_g} \qquad (5\text{-}13)$$

where AE is application efficiency in percent.

The equation for efficiency where the design application is applied at a point x that is less than the furrow length L becomes:

$$AE = 100\frac{(F_{(0-x)} - DP)}{F_g} \qquad (5\text{-}14)$$

where

AE = application efficiency, percent

DP = deep percolation, inches, as computed in equation 12

Summary of Graded Furrow Equations

Wetted perimeter plus constant

(5-1) $P = 0.2686\,(Qn/S^{0.5})^{0.4247} + 0.7462$

Advance time

(5-2) $T_t = \frac{x}{c}\,e^{(dx/QS^{1/2})}$

Opportunity time

(5-3) $T_o = T_i - \frac{x}{c}\,e^{(dx/QS^{1/2})}$

Average opportunity time

(5-4) $T_{(0-L)} = T_i - \left[\frac{1}{cL\left(\frac{d}{QS^{1/2}}\right)^2}\left(\frac{dL}{QS^{1/2}} - 1\right)e^{(dL/QS^{1/2})} + 1\right]$

Gross application depth

(5-5) $F_g = \frac{1.6041\,Q\,T_i}{WL}$

Cumulative intake at a point x

(5-6) $F_x = (a\,T_{ox}^{\,b} + 0.275)\,\frac{P}{W}$

Cumulative intake at a design point

(5-7) $F_n = (aT_n^{\,b} + 0.275)\,P/W$

Average cumulative intake for furrow length L

(5-8) $F_{(0\text{-}L)} = \left[a\,(T_{(0\text{-}L)})^b + 0.275\right] P/W$

Runoff depth

(5-9) $RO = F_g - F_{(0-L)}$

Runoff volume

(5-10) $v_{RO} = \frac{RO\,(W)\,(L)}{12\,(43{,}560)}$

Deep percolation and application efficiency at length L

(5-11) $DP = F_g - RO - F_n$

(5-13) $AE = 100\,\frac{F_n}{F_g}$

Deep percolation and application efficiency at length less than L

(5-12) $DP = (F_{(0\text{-}x)} - F_n)\,\frac{x}{L}$

(5-14) $AE = 100\,\frac{(F_{(0\text{-}x)} - DP)}{F_g}$

Design Examples of Graded Furrows

Information available:

Type: Graded

Intake family: $I_f = 0.3$

Design application depth: $F_n = 3.0$ in

Length: $L = 900$ ft

Slope: $S = 0.004$ ft/ft

Spacing: $W = 2.5$ ft

Roughness coefficient: $n = 0.04$

Design assumptions:

(1) The water will spread laterally across the 2.5-ft furrow spacing.

(2) The design application is to be applied at the end of the 900-ft furrow.

Procedure:

(1) Assume the inflow rate Q is 10 gpm.

(2) Find intake and advance coefficients for the 0.3 intake family from table 5-9:

$a = 0.0364 \quad b = 0.7204 \quad c = 24.9706 \quad d = 9.1977 \times 10^{-4}$

(3) Compute the advance time for the 900-ft furrow, using equation 2.

$$T_t = \frac{900}{24.9706}\, e^{\left(\frac{(9.1977 \times 10^{-4})(900)}{10\sqrt{0.004}}\right)}$$

$T_t = 133$ min

(4) Calculate the wetted perimeter plus constant using equation 1.

$$P = 0.2686\left(\frac{Qn}{S^{0.5}}\right)^{0.4247} + 0.7462$$

$$P = 0.2686\left(\frac{(10 \times 0.04)}{\sqrt{0.004}}\right)^{0.4247} + 0.7462 = 1.33 \text{ ft}$$

or from table 5-8, find for $Q = 10$ gpm
$P = 1.33$ ft

(5) Calculate net opportunity time (T_n) required for design application (F_n) of 3.0 inches using equation 7.

$$F_n = (0.0364\,T_n^{\,0.7204} + 0.275)\,\frac{P}{W}$$

Solving for T_n:

$$T_n = \left[\frac{\left((F_n \times \frac{W}{P}) - 0.275\right)}{0.0364}\right]^{1/0.7204} = 1023 \text{ min}$$

(6) Calculate the application time T_i:

$T_i = T_t + T_n = 133 + 1023 = 1{,}156$ min

(7) Calculate the gross application:

$$F_g = \frac{1.6041\ Q\ T_i}{WL} = \frac{1.6041\ (10)\ (1{,}156)}{2.5 \times 900} = 8.2 \text{ in}$$

(8) Calculate the average opportunity time for the 900-ft furrow, $T_{(0-L)}$:

$$T_{(0-L)} = T_i -$$

$$\left[\frac{1}{cL\,(d/QS^{1/2})^2}\left[\left(\frac{dL}{QS^{1/2}} - 1\right) e^{(dL/QS^{1/2})} + 1\right]\right]$$

$$T_{(0-L)} = 1{,}156.7 - 45.1 = 1{,}111.6 \text{ min}$$

(9) Calculate average intake for the entire furrow length.

$$F_{(0-L)} = (aT_{(0-L)}{}^b + 0.275)\ P/W$$

$$F_{(0-L)} = (0.0364\ (1111.6)^{0.7204} + 0.275)\frac{1.33}{2.50} = 3.2 \text{ in}$$

(10) Calculate the deep percolation.

$$DP = F_{(0-L)} - F_n = 3.2 - 3.0 = 0.2 \text{ in}$$

(11) Calculate the surface runoff.

$$RO = F_g - F_{(0-L)} = 8.2 - 3.2 = 5 \text{ in}$$

(12) Calculate the application efficiency.

$$AE = 100\frac{F_n}{F_g} = \frac{100\ (3.0)}{8.2} = 37\%$$

(13) Summary of the results:

$I_f = 0.3$

$W = 2.5$ ft

$S = 0.004$ ft/ft

$F_n = 3.0$ in

$Q = 10$ gpm

$L = 900$ ft

$T_i = 1{,}156$ min

$RO = 5$ in

$DP = 0.2$ in

$AE = 37\%$

(14) Assume different inflow rates and repeat steps 1–12 until either an acceptable inflow time or application efficiency, or both, is obtained.

Procedure for Using Design Charts

A series of design charts similar to figures 5–17 and 5-18 can be prepared to simplify the design procedure for graded furrows and eliminate the use of solutions by equations. Each chart is for a specific intake family, furrow slope, design depth of application, furrow spacing, and Manning roughness coefficient. Each chart has four sets of inflow-rate curves describing the relationship of furrow length to: (1) inflow time, (2) deep percolation, (3) runoff, and (4) application efficiency. Solutions can be obtained from charts for a known or assumed value of either inflow rate, deep percolation, runoff, or efficiency paired with a known or assumed value of either inflow rate or furrow length. For example, for an assumed efficiency and inflow rate, the furrow length, runoff, deep percolation, and inflow time can be determined to provide the most practical farm operating schedule.

Charts can be converted to furrow spacings other than 30 inches by the following procedure:

1. Divide net application F_n by the ratio of 2.5 ft divided by the desired spacing in feet, which gives an adjusted net application.
2. Using the adjusted net application, select a chart that has an F_n value nearest the adjusted value.
3. From the selected chart read inflow time T_i, runoff RO, and efficiency AE.
4. Determine the gross depth of application F_g by multiplying the net application F_n from the selected chart by 100 and dividing by efficiency AE.
5. Multiply gross application F_g, design application F_n, and runoff RO by the ratio found in step 1 above to get adjusted gross application ($F_{g\ adj}$), adjusted design application ($F_{n\ adj}$) and adjusted runoff (RO_{adj}) for the desired furrow spacing.
6. Obtain adjusted deep percolation (DP_{adj}) by subtracting the sum of the adjusted design application ($F_{n\ adj}$) and the adjusted runoff (RO_{adj}) from the adjusted gross application ($F_{g\ adj}$).
7. No adjustment is required for the inflow time T_i, inflow rate Q, and efficiency AE. If a cutback method is to be used, further calculations are necessary.

Example

The following example illustrates the use of the design charts for a specific graded furrow irrigation

Figure 5-17

Graded Furrow Design Chart

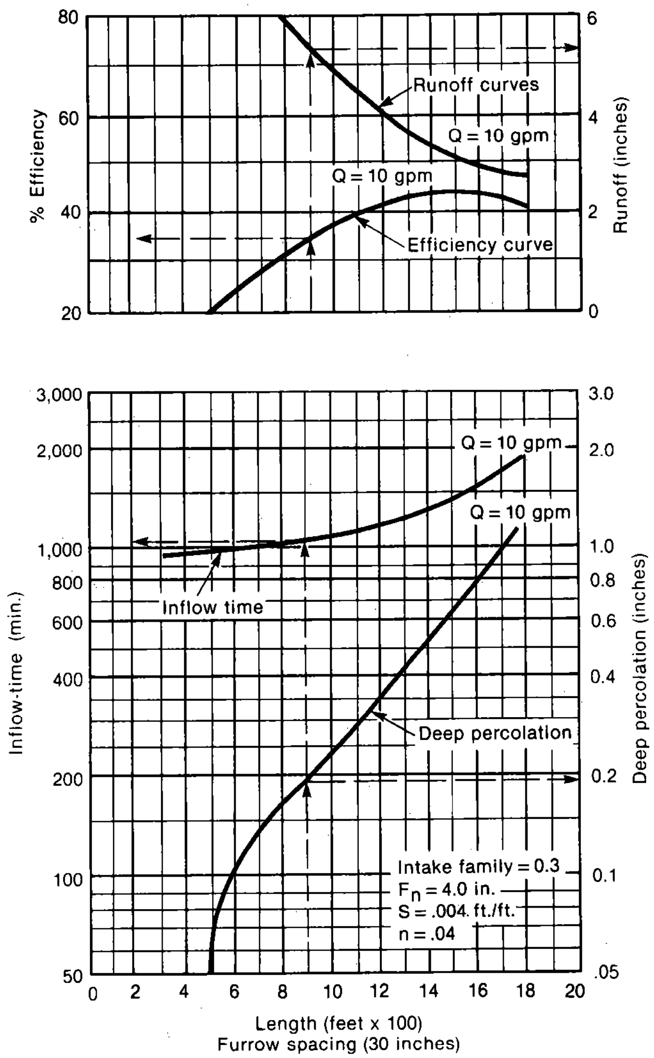
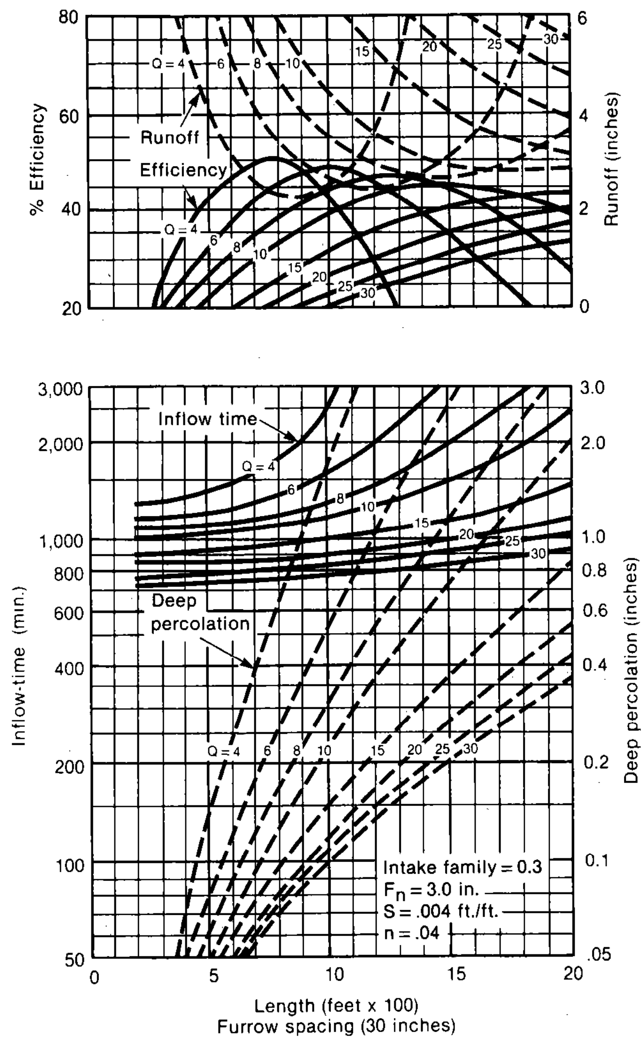


Figure 5-18

Graded Furrow Design Chart



system. The same information and assumptions are used as in the example illustrating solution by equations:

Intake family (I_f) = 0.3

Design application depth (F_n) = 3.0 in

Length (L) = 900 ft

Slope (S) = 0.004 ft/ft

Spacing (W) = 2.5 ft

Roughness coefficient (n) = 0.04

By using the chart in figure 5–18 and a furrow length of 900 feet, the following solutions are possible:

(1) Assume inflow time T_i is 18 hours or 1,080 minutes:

At the intersection of 1,080 minutes inflow time and 900 ft length on the various curves, the inflow rate is approximately 12 gpm, deep percolation is approximately 0.15 inch, efficiency is 33 percent, and runoff is 6 inches.

Using the same procedure, find solutions for the following:

(2) Assume efficiency is 49 percent.

$AE = 49\%$

$L = 900$ ft

Find:

$Q = 5.0$ gpm

$RO = 2.5$ in

$T_i = 1{,}700$ min $= 28.3$ hr

$DP = 0.60$ in

(3) Assume inflow rate is 10 gpm

$Q = 10$ gpm

$L = 900$ ft

Find:

$T_i = 1{,}150$ min $= 19.2$ hr

$DP = 0.2$ in

$RO = 5.0$ in

$AE = 37\%$

(4) Assume the furrow spacing in example 3 is 3.33 ft rather than 2.5 ft for which the chart was prepared. The following computations are necessary:

(a) Ratio $= 2.5$ ft $\div$ W $= 2.5$ ft $\div$ 3.33 ft $= 0.750$

Adjusted net application $= 3$ in $\div 0.75 = 4.0$ in

(b) Select chart, figure 5–17

(c) $T_i = 1{,}050$ min $= 17.5$ hr

$RO = 5.4$ in

$AE = 35\%$

(d) $F_g = (4.0 \text{ in} \times 100) \div 35\% = 11.4$ in

(e) $F_{g\ adj} = 11.4 \text{ in} \times 0.75 = 8.6$ in

$F_{n\ adj} = 4.0 \text{ in} \times 0.75 = 3$ in

$RO_{adj} = 5.4 \text{ in} \times 0.75 = 4$ in

(f) $DP_{adj} = 8.6 \text{ in} - (3 \text{ in} + 4 \text{ in}) = 1.6$ in

Cutback-Inflow Method

The volume of surface runoff resulting from irrigations using a constant inflow rate can be reduced, and the application efficiency thereby significantly improved, by reducing the inflow rate for part of the application time. Such a cutback procedure increases the labor requirements because an adjustment to reduce the flow to the furrows must be made during the irrigation. Also, unless the supply flow is reduced at the source, the remaining supply flow must be either applied to other field areas or stored. If surface runoff from constant inflow graded furrows can be reused, the cutback method may not be desirable or feasible from a labor standpoint.

The assumption is made that in using the cutback-inflow method the initial flow rate will be reduced to one-half when it has advanced to the end of the open-end furrow. The time of cutback is then equal to the advance time as described by equation 2, after substituting length L for distance x:

$$T_t = \frac{L}{c} e^{(dL/QS^{1/2})}$$

The time required for intake of the design application F_{nc} at the end of the furrow is from equation 7:

$$T_{nc} = \left[\left(\frac{F_{nc}W}{P_1} - 0.275\right)\frac{1}{a}\right]^{1/b} \qquad (5\text{–}15)$$

where P_1 is the wetted perimeter for the cutback-inflow rate Q/2 or:

$$P_1 = 0.2686\left(\frac{Qn}{2S^{0.5}}\right)^{0.4247} + 0.7462$$

The total inflow time for the cutback method is then the sum of the opportunity time required at the end of the furrow T_{nc} and the advance time T_t or

$$T_{ic} = T_{nc} + T_t \qquad (5\text{–}16)$$

The average advance time, T_{tave} is:

$$T_{tave} = \left[\frac{1}{cL\left(\frac{d}{QS^{1/2}}\right)^2}\left[\left(\frac{dL}{QS^{1/2}} - 1\right)e^{(dL/QS^{1/2})} + 1\right]\right] \qquad (5\text{–}17)$$

The average opportunity time for intake during the time for the initial inflow rate to advance to the end of the furrow is described by the second term in equation 4, subtracted from travel time to furrow length, L or:

$$T_{oadv} = T_t - T_{tave} \qquad (5\text{–}17a)$$

The average intake during the advance period then becomes, from equation 8:

$$F_{adv} = [a\,(T_{o_{adv}})^b + 0.275]\,\frac{P}{W}$$

The average intake under cutback conditions is the sum of intake during the advance period and the intake during the remainder of the inflow time during which the inflow rate is reduced to one-half the initial inflow, or:

$$F_{(0\text{-}L)c} = [a\,(T_{ic} - T_{tave})^b + 0.275]\,\frac{P_1}{W} +$$

$$\left[(a\,T_{o_{adv}}{}^b + 0.275)\,\frac{P}{W} - (a\,T_{o_{adv}}{}^b + 0.275)\,\frac{P_1}{W}\right]$$

which becomes:

$$F_{(0\text{-}L)c} = [a\,(T_{ic} - T_{tave})^b + 0.275]\,\frac{P_1}{W} +$$

$$\left[\frac{(a\,(T_{o_{adv}})^b + 0.275)\,(P - P_1)}{W}\right] \quad (5\text{–}18)$$

The gross application under cutback conditions becomes:

$$F_{gc} = \frac{1.6041}{WL}\,(Q\,T_t + \frac{Q}{2}\,T_{nc}) \quad (5\text{–}19)$$

Runoff, deep percolation, and efficiency under cutback conditions are:

$$RO_c = F_{gc} - F_{(0\text{-}L)c} \quad (5\text{–}20)$$

$$DP_c = F_{(0\text{-}L)c} - F_{nc} \quad (5\text{–}21)$$

$$AE_c = 100\,\frac{F_{nc}}{F_{gc}} \quad (5\text{–}22)$$

Design tables or charts for the cutback-inflow method can be prepared for specific intake families and net application depths for a range of slopes, lengths, and flow rates to facilitate use of the design procedure.

Summary of Cutback-Inflow Equations

(5–2) $$T_t = \frac{L}{c}\,e^{(dL/QS^{1/2})}$$

(5–1) $$P = 0.2686\left(\frac{Qn}{S^{1/2}}\right)^{0.4247} + 0.7462$$

$$P_1 = 0.2686\left(\frac{Qn}{2S^{1/2}}\right)^{0.4247} + 0.7462$$

(5–15) $$T_{nc} = \left[\left(\frac{F_{nc}W}{P_1} - 0.275\right)\frac{1}{a}\right]^{1/b}$$

(5–16) $$T_{ic} = T_{nc} + T_{tc}$$

(5–17) $$T_{tave} = \left[\frac{1}{cL\left(\frac{d}{QS^{1/2}}\right)^2}\left[\left(\frac{dL}{QS^{1/2}} - 1\right)e^{(dL/QS^{1/2})} + 1\right]\right]$$

(5–17a) $$T_{o_{adv}} = T_t - T_{tave}$$

(5–18) $$F_{(0\text{-}L)c} = [a\,(T_{ic} - T_{o_{adv}})^b + 0.275]\,\frac{P_1}{W} + \left[\frac{(a(T_{o_{adv}})^b + 0.275)\,(P - P_1)}{W}\right]$$

(5–19) $$F_{gc} = \frac{1.6041}{WL}\,(Q\,T_t + \frac{Q}{2}T_{nc})$$

(5–20) $$RO_c = F_{gc} - F_{(0\text{-}L)c}$$

(5–21) $$DP_c = F_{(0\text{-}L)c} - F_{nc}$$

(5–22) $$AE_c = 100\,\frac{F_{nc}}{F_{gc}}$$

Design Example of Cutback-Inflow Equations

Information available:

Type: Graded furrow

Intake family: $I_f = 0.3$

Desired applied depth: $F_{nc} = 3.0$ in

Length: L= 900 ft

Slope: S=0.004 ft/ft

Spacing: W=2.5 ft

Roughness coefficient: n=0.04

Procedure

(1) Assume inflow rate Q is 10 gpm.

(2) Find intake and advance coefficients for the 0.3 intake family from table 9:

$$a=0.0364 \quad b=0.7204 \quad c=24.9706 \quad d=9.1977\times10^{-4}$$

(3) Calculate advance time to the furrow length of 900 feet, using equation 2:

$$T_t = \frac{L}{c} e^{(dL/QS^{1/2})} = \frac{900}{24.9706} e^{\left[\frac{(9.1977\times10^{-4})(900)}{(10)\sqrt{0.004}}\right]}$$

$$T_t = 133.4 \text{ min}$$

(4) Calculate wetted perimeter plus constant P using equation 1 with a 10-gpm inflow rate:

$$P = 0.2686\left(\frac{Qn}{S^{1/2}}\right)^{0.4247} + 0.7462$$

$$P = 0.2686\left(\frac{10\times0.04}{\sqrt{0.004}}\right)^{0.4247} + 0.7462 = 1.33 \text{ ft}$$

P could be obtained from table 5–8 rather than by calculation.

(5) Calculate wetted perimeter plus constant P_1 using equation 1 with an inflow rate of Q/2 or 5 gpm:

$$P_1 = 0.2686\left(\frac{5\times0.04}{\sqrt{0.004}}\right)^{0.4247} + 0.7462 = 1.18 \text{ ft}$$

(6) Calculate the net application time T_{nc} required for intake of the desired application (F_n) using equation 15:

$$T_{nc} = \left[\left(\frac{F_{nc}W}{P_1} - 0.275\right)\frac{1}{a}\right]^{1/b}$$

$$T_{nc} = \left[\left(\frac{3.0\times2.5}{1.18} - 0.275\right)\frac{1}{0.0364}\right]^{1/0.7204}$$

$$T_{nc} = 1{,}218 \text{ min}$$

(7) Calculate the inflow time (T_i) required using equation 16:

$$T_{ic} = T_{nc} + T_{tc} = 1{,}218 + 133 = 1{,}351 \text{ min}$$

(8) Calculate the average opportunity time T_{tave} during the advance period using equation 17 and the initial inflow rate Q:

$$T_{tave} = \left[\frac{1}{cL\left(\frac{d}{QS^{1/2}}\right)^2}\left[\left(\frac{dL}{QS^{1/2}} - 1\right)e^{(dL/QS^{1/2})} + 1\right]\right]$$

$$T_{tave} = \frac{1}{(24.9706)(900)\left[\frac{(9.1977\times10^{-4})^2}{10\sqrt{0.004}}\right]}$$

$$\left[\left(\frac{(9.1977\times10^{-4})(900)}{10\sqrt{0.004}} - 1\right)\right.$$

$$\left. e^{\left(\frac{(9.1977\times10^{-4})(900)}{10\sqrt{0.004}}\right)} + 1\right]$$

$$= 21.039[(1.3088-1)e^{1.3088} + 1]$$

$$= 21.039\,(2.143) = 45 \text{ min}$$

$$T_{oadv} = T_t - T_{tave}$$

$$= 133.4 - 45$$

$$= 88.4 \text{ min}$$

(9) Calculate the average intake ($F_{0\text{-}t}$) under cutback-inflow conditions using equation 18:

$$F_{(0\text{-}L)c} = [a\,(T_{ic} - T_{t_{ave}})^b + 0.275]\,\frac{P_1}{W} + \left[\frac{(a\,T_{o_{adv}})^b + 0.275)}{W}\right](P - P_1)$$

$$F_{(0\text{-}L)c} = [0.0364\,(1351 - 45)^{0.7204} + 0.275]\frac{1.18}{2.5} + \left[\frac{0.0364\,(88)^{0.7204} + 0.275}{2.5}\right](1.33 - 1.18)$$

$$F_{(0\text{-}L)c} = (3.15) + (0.476)\,(0.15) = 3.2 \text{ in}$$

(10) Calculate the gross application (F_g) using equation 19:

$$F_{gc} = \frac{1.6041}{WL}(Q\,T_{tc} + \frac{Q}{2}T_{nc})$$

$$F_{gc} = \frac{1.6041}{2.5(900)}\left[(10 \times 133.4) + (\frac{10}{2} \times 1218)\right]$$

$$F_{gc} = 5.3 \text{ in}$$

(11) Calculate runoff (RO) using equation 20:

$$RO_c = F_{gc} - F_{(0\text{-}L)c} = 5.3 - 3.2 = 2.1 \text{ in}$$

(12) Calculate deep percolation (DP) using equation 21:

$$DP_c = F_{(0\text{-}L)c} - F_{nc} = (3.2 - 3.0) = 0.2 \text{ in}$$

(13) Calculate application efficiency (AE) using equation 22:

$$AE_c = 100\frac{F_{nc}}{F_{gc}} = \frac{100\,(3.0)}{5.3} = 57\%$$

(14) Summary of results:

I_f = 0.3
Q = 10 gpm
S = 0.004 ft/ft
W = 2.5 ft
F_n = 3.0 in
L = 900 ft
T_{ic} = 1,351 min = 22.5 hr
T_{tc} = time to cutback = 133 min = 2.2 hr
RO_c = 2.1 in
DP_c = 0.2 in
AE_c = 57%
F_{gc} = 5.3 in

(15) Assume different inflow rates and repeat steps 1–14 until either an acceptable inflow time or an application efficiency is obtained, or both.
Figure 5–19 illustrates design charts that simplify the design of cutback-inflow-furrow systems. The chart is for an intake family of 0.3, design application depth of 3.0 inches, and a slope of 0.004 ft per ft.

Level Impoundment Furrows

Surface runoff is eliminated in level furrow systems with diked ends. Water is applied at one end of the furrow at a rate that quickly provides coverage of the entire length, and is then ponded until it infiltrates the soil.

Design equation assumptions.—The design equations for level impoundment are based on the following assumptions:

1. The volume of water delivered to the furrow is equal to the average intake over the entire furrow length.
2. The intake opportunity time at the last point covered is equal to the time required for the net irrigation to enter the soil.
3. The longest intake opportunity time at any point along the furrow is such that deep percolation is not excessive.