
Chapter 11 Sprinkler Irrigation



Issued August 2016

The U.S. Department of Agriculture (USDA) prohibits discrimination against its customers. If you believe you experienced discrimination when obtaining services from USDA, participating in a USDA program, or participating in a program that receives financial assistance from USDA, you may file a complaint with USDA. Information about how to file a discrimination complaint is available from the Office of the Assistant Secretary for Civil Rights. USDA prohibits discrimination in all its programs and activities on the basis of race, color, national origin, age, disability, and where applicable, sex (including gender identity and expression), marital status, familial status, parental status, religion, sexual orientation, political beliefs, genetic information, reprisal, or because all or part of an individual's income is derived from any public assistance program. (Not all prohibited bases apply to all programs.)

To file a complaint of discrimination, complete, sign, and mail a program discrimination complaint form, available at any USDA office location or online at www.ascr.usda.gov, or write to:

USDA
Office of the Assistant Secretary for Civil Rights
1400 Independence Avenue, SW.
Washington, DC 20250-9410

Or call toll free at (866) 632-9992 (voice) to obtain additional information, the appropriate office or to request documents. Individuals who are deaf, hard of hearing, or have speech disabilities may contact USDA through the Federal Relay service at (800) 877-8339 or (800) 845-6136 (in Spanish). USDA is an equal opportunity provider, employer, and lender.

Persons with disabilities who require alternative means for communication of program information (e.g., Braille, large print, audiotape, etc.) should contact USDA's TARGET Center at (202) 720-2600 (voice and TDD).

Acknowledgments

Chapter 11, Sprinkle Irrigation, was originally prepared and printed in 1983 under the direction of Conservation Engineering Division (CED), Washington, DC, Soil Conservation Service (SCS), now the Natural Resources Conservation Service (NRCS).

In 2004, under the direction of **Ron Marlow** (retired), **Dr. Richard Allen**, University of Idaho, and **Dr. Gary Merkley**, Utah State University, reviewed and updated chapter 11, Sprinkle Irrigation.

Final revisions and editing to the chapter were provided by **Clarence Prestwich**, irrigation engineer, West National Technology Center (WNTSC), Portland, OR; **Jerry Walker**, water management engineer, Central National Technical Center (CNTC), Fort Worth, TX; **Peter Robinson**, water management engineer, West National Technical Center (WNTC), Portland, OR; **John Busch** (retired). It was finalized under the guidance of **Rob Sampson**, national water management engineer, Conservation Engineering Division (CED), Washington, DC.

The editing, illustrations, and formatting were provided by **Suzi Self**, editor; and **Wendy Pierce**, illustrator, National Geospatial Center of Excellence (NGCE), Fort Worth, TX.

Chapter 11

Sprinkler Irrigation

Contents

623.1100	Description	11-1
	(a) Adaptability.....	11-1
	(b) Special uses.....	11-1
	(c) Advantages.....	11-8
	(d) Disadvantages.....	11-9
	(e) Installation and operation of sprinkler systems.....	11-11
623.1101	Types of sprinkler systems	11-12
	(a) Periodic move sprinkler systems.....	11-12
	(b) Continuous-move sprinkler systems.....	11-16
	(c) Other sprinkler systems.....	11-20
623.1102	Planning concepts	11-21
	(a) Sprinkle irrigation system design.....	11-22
	(b) Application depth requirements.....	11-23
	(c) Root depth.....	11-28
	(d) Management-allowed deficit (MAD).....	11-29
	(e) Irrigation interval.....	11-31
	(f) Leaching requirement and gross depth.....	11-31
	(g) Irrigations per season.....	11-32
	(h) System capacity requirements.....	11-32
	(i) Fixed systems.....	11-36
	(j) Continuous-move systems.....	11-37
	(k) Intake and optimum application rates.....	11-38
623.1103	System layout	11-43
	(a) Number of sprinklers operating.....	11-43
	(b) Number of laterals required.....	11-43
	(c) Lateral layout.....	11-43
	(d) Mainline layout.....	11-47
	(e) Location of water source and pump.....	11-47
	(f) Adjustments to meet layout conditions.....	11-47
623.1104	Sprinkler irrigation efficiency	11-49
	(a) Uniformity.....	11-50
	(b) Water loss.....	11-52
	(c) Application efficiency.....	11-54

623.1105	Design procedure	11-56
	(a) Periodic-move and fixed systems.....	11-57
	(b) Wetted diameter and recommended spacings.....	11-62
	(c) Effects of system pressure on uniformity.....	11-63
	(d) Systemwide application uniformity.....	11-64
	(e) Application efficiency.....	11-68
	(f) Design application rate and set time.....	11-69
	(g) Sprinkler discharge rate.....	11-70
	(h) Discharge requirement.....	11-75
	(i) Nozzle size and pressure.....	11-84
	(j) Friction losses.....	11-85
623.1106	Lateral design	11-93
	(a) Laterals on level ground.....	11-93
	(b) Laterals laid uphill.....	11-94
	(c) Laterals laid downhill.....	11-94
	(d) Laterals with two pipe sizes.....	11-95
	(e) Laterals with flow-control devices.....	11-97
	(f) Hose-fed design.....	11-98
	(g) Perforated-pipe laterals.....	11-99
623.1107	Mainline design	11-101
	(a) General design procedure.....	11-104
	(b) Design for a single lateral.....	11-104
	(c) Design for a split-line layout.....	11-104
	(d) Design with multiple laterals in rotation.....	11-107
	(e) Main and submain layout.....	11-107
	(f) Water hammer analysis.....	11-108
623.1108	Pipe sizing using life-cycle costs	11-112
	(a) Economic pipe selection chart.....	11-113
	(b) Economical mainline design.....	11-116
	(c) Pipe diameter selection.....	11-117
	(d) Portable versus buried mainlines.....	11-121
	(e) Design for continuous operation.....	11-121
623.119	Pressure Requirements	11-122
	(a) Gravity pressure considerations.....	11-123
	(b) Selection of pump and power unit.....	11-124
	(c) Traveling sprinkler system.....	11-138

623.1110	Center pivot design	11-145
	(a) System capacity	11-146
	(b) Application intensity	11-146
	(c) Sprinkler-nozzle configuration.....	11-151
	(d) End gun and corner system operation.....	11-158
	(e) Lateral friction loss	11-161
	(f) Economic pipe sizes	11-166
	(g) Application uniformity and depth.....	11-167
	(h) Pressure regulators	11-167
	(i) Operating pressures.....	11-171
	(j) Elevation-discharge relationship.....	11-172
	(k) Machine selection.....	11-174
<hr/>		
623.1111	Linear-move design	11-175
	(a) Sprinkler-nozzle configuration.....	11-175
	(b) Maximizing linear-move field length	11-175
<hr/>		
623.1112	Field evaluation	11-181
	(a) Field test data	11-181
	(b) Field evaluation procedure	11-182
	(c) Application of the field data.....	11-186
	(d) Example calculation of application uniformity.....	11-189
	(e) Center pivot field evaluations.....	11-191
<hr/>		
623.1113	References	11-200

Figures

Figure 11-1	A method for adding soluble fertilizers to a centrifugal pump system	11-2
Figure 11-2	A method for adding fertilizers to a turbine pump system using a small gear or paddle pump	11-2
Figure 11-3	Hand-move sprinklers operating on rocky ground with shallow soils and difficult topography	11-9
Figure 11-4	Schematic of the move sequence between lateral positions for end-tow sprinklers with a buried mainline, and a pumping unit in the center of the field	11-13
Figure 11-5	Side-roll sprinkler lateral (with drag lines, or trail tubes) in operation	11-14
Figure 11-6	Hand-move sprinkler laterals in a solid-set portable configuration on rolling topography	11-15
Figure 11-7	Part-circle gun sprinkler with rocker-arm drive	11-16
Figure 11-8	Outer end of a center-pivot lateral in operation	11-17
Figure 11-9	Corner system in operation on a center pivot	11-17
Figure 11-10	Computer screens at a control center for managing several hundred center pivots	11-18
Figure 11-11	Hose-fed traveling gun type sprinkler	11-18
Figure 11-12	Fixed-arm boom assembly with low-pressure spray nozzles for a traveler system	11-19
Figure 11-13	Typical layout for a traveling sprinkler with a buried mainline in the center of a rectangular field	11-19
Figure 11-14	Linear-move system with a flexible hose water supply	11-20
Figure 11-15	A perforated-pipe lateral in operation	11-21
Figure 11-16	Orchard sprinklers operating from a lateral line	11-21
Figure 11-17	Layout of a periodic-move sprinkler system with	11-22
Figure 11-18	Sprinkle irrigation system design data sheet several laterals for irrigating pastures. Some of the laterals will have changing lengths for different positions to accommodate the irregular field areas.	11-24
Figure 11-19	Center-pivot design data sheet.	11-26

Figure 11-20	Subdivision of design areas having different soil zones	11-33
Figure 11-21	Infiltration rate reduction due to sprinkling on three different soil types at an application rate of approximately 0.5 in/h (13 mm/h)	11-39
Figure 11-22	Drop sizes at various distances from a standard 5/32-in (4 mm) nozzle operating at 20 and 60 lb/in ² (140 and 415 kPa)	11-39
Figure 11-23	Sprinkler and lateral spacing for a rectangular sprinkler layout (plan view)	11-40
Figure 11-24	Plan view of a circular sprinkler-irrigated area and instantaneous wetted area.	11-41
Figure 11-25	Sample layouts of periodic-move sprinkler systems that account for topography	11-44
Figure 11-26	General types of periodic-move sprinkler systems	11-45
Figure 11-27	Preset pressure regulators for sprinklers	11-53
Figure 11-28	Effective portion of water applied, R_e , by sprinkling with fine and coarse sprays in different wind conditions and with different potential evapotranspiration rates on crops with full canopies	11-54
Figure 11-29	Basic sprinkler system components	11-57
Figure 11-30	Distribution pattern and precipitation profiles from a typical double-nozzle sprinkler operating under low-wind conditions	11-60
Figure 11-31	Effect of different pressures on precipitation profiles for a typical double-nozzle sprinkler (the sprinkler is located at position zero, in the center)	11-61
Figure 11-32	Effect of wind on distribution pattern and precipitation profiles from a typical intermediate double-nozzle sprinkler	11-61
Figure 11-33	Example of the water distribution pattern between adjacent sprinklers along a lateral	11-61
Figure 11-34	Example of the water distribution pattern between overlapping sprinkler patterns between adjacent laterals	11-62
Figure 11-35	Christiansen's geometrical sprinkler profiles and optimum spacings as a percentage of the effective wetted diameter	11-62
Figure 11-36	Comparison of pressure versus discharge	11-64

	relationship for a standard fixed nozzle and a special flexible orifice nozzle.	
Figure 11-37	Relationships between surface field area and depth of water applied	11-67
Figure 11-38	Sprinkler irrigation system data design sheet	11-76
Figure 11-39	A lateral running uphill	11-94
Figure 11-40	A lateral running downhill	11-94
Figure 11-41	Schematic of a dual-pipe-size sprinkler lateral	11-95
Figure 11-42	A lateral running uphill with flow-control valves	11-97
Figure 11-43	Design of mainline running uphill with twin laterals (shown at position B), split-line operation	11-105
Figure 11-44	Design of mainline running downhill with twin laterals (shown at position B), split-line operation	11-105
Figure 11-45	Design of an uphill mainline with five 71-gpm laterals, split-line operation assuming the allowable friction head loss is 20.1 ft, and an elevation difference of 23 ft	11-107
Figure 11-46	Maximum operating conditions with submains	11-107
Figure 11-47	Water hammer example ($t = 0$)	11-109
Figure 11-48	Water hammer example ($t = L/2a$)	11-109
Figure 11-49	Water hammer example ($t = 3L/2a$)	11-110
Figure 11-50	Water hammer example ($t = 5L/2a$)	11-110
Figure 11-51	Water hammer example ($t = 7L/2a$)	11-110
Figure 11-52	Water hammer example ($t = 4L/a$)	11-110
Figure 11-53	Economic pipe selection chart for portable aluminum pipe with $C=130$, $CRF=0.214$, and $U'=\$138.601\text{WHP year}$	11-115
Figure 11-54	Flow systems with pipe sizes selected from the economic pipe size selection chart shown in figure 11-38	11-116
Figure 11-55	System layout for sample calculation 11-12	11-118
Figure 11-56	Project layout with four center-pivot sprinkler laterals	11-120
Figure 11-57	Sample sprinkler system mainline layout	11-122

Figure 11-58	Layout for example TDH and WHP calculations	11-125
Figure 11-59	Sample system curve	11-126
Figure 11-60	Sample system curve with all friction loss and no static lift	11-127
Figure 11-61	Sample system curve with mostly static lift, little friction loss	11-128
Figure 11-62	Sample system curve with negative static lift	11-128
Figure 11-63	Sample system curve with two different static lifts	11-129
Figure 11-64	Sample composite system curve	11-129
Figure 11-65	Two center pivots in a branching pipe layout	11-129
Figure 11-66	Example layout for the calculation of pump operating point	11-130
Figure 11-67	Example of a potentially unstable pump operating point	11-130
Figure 11-68	Sample layouts of periodic-move sprinkler systems that account for topography	11-137
Figure 11-69	Typical application patterns of a traveling and a set gun sprinkler operating with low wind	11-140
Figure 11-70	Water application rates at different points along a center pivot with uniform width of wetted strip	11-147
Figure 11-71	Intersection between a typical elliptical pattern of water application rate under a center pivot and a potential infiltration curve	11-147
Figure 11-72	Soil triangle showing proportions of sand, silt, and clay for different soil textures, and approximate infiltration rate contours in in/h	11-149
Figure 11-73	Watering characteristics of center pivots	11-150
Figure 11-74	Boom drops used along the outer spans of a center pivot to increase the wetted width	11-152
Figure 11-75	Boom backs behind center pivot towers	11-153
Figure 11-76	Relationship between width of wetted coverage (W) and application intensity for the same discharge rate	11-153

Figure 11-77	Relationship between required application intensity and time of application for the same depth of application	11-154
Figure 11-78	Peak application rate for a center pivot for $r = 1,300$ ft as a function of the system capacity expressed as gal/min per acre (as Q/A) and for a range of w	11-158
Figure 11-79	Example center pivot end gun installations where the pump, valve, and end gun are short-coupled at the end of the lateral (left side), and an end gun on a corner system (right side)	11-159
Figure 11-80	Top view of end gun sprinkler wetting pattern showing recommended angle of operation	11-160
Figure 11-81	General dimensionless friction curve for a center pivot lateral, where the Y-axis shows the fraction of total lateral friction loss that occurs from the pivot point to some point along the lateral	11-163
Figure 11-82	Sprinkler-lateral irrigation evaluation form	11-183
Figure 11-83	Measuring pressure at sprinkler nozzle with gage connected to a pitot tube	11-184
Figure 11-84	Loss of pressure due to friction along a lateral having only one pipe size	11-184
Figure 11-85	Measuring sprinkler discharge using a hose to direct the water into a container	11-184
Figure 11-86	Layout of catch containers for testing the uniformity of distribution along a sprinkler lateral line	11-185
Figure 11-87	A grid of catch containers between two adjacent sprinklers, straddling a single sprinkler lateral at a test facility	11-185
Figure 11-88	A radial leg of catch cans for the uniformity evaluation of a single sprinkler (data from the test would be mathematically overlapped using software to simulate different sprinkler spacings)	11-186
Figure 11-89	Measuring the volume of water in catch containers as part of a sprinkler evaluation.	11-187
Figure 11-90	Milliliters of water collected by catch cans placed with a 10 ft spacing on each side of a single lateral between sprinklers 4, 5, and 6	11-187
Figure 11-91	Water application rate, inch per hour, collected by catch cans placed at 10 ft. spacing on each side of a single lateral between sprinklers 4, 5, and 6	11-187

Figure 11-92	Sample sprinkler-lateral irrigation evaluation	11-188
Figure 11-93	Combined catch pattern in in/h between sprinklers 5 and 6 for a 50-ft lateral spacing and 30-ft sprinkler spacing along the laterals	11-189
Figure 11-94	Center-pivot sprinkle irrigation evaluation	11-192
Figure 11-95	Center-pivot field evaluation with catch-cans spaced 10-ft apart in a radial leg	11-194
Figure 11-96	Center-pivot sprinkle irrigation evaluation	11-196
Figure 11-97	Sample profile of container catch from a center pivot sprinkler evaluation test	11-198
Figure 11-98	Runoff in furrows at the downstream end of a center-pivot lateral	11-199
Figure 11D-1	Plot of application rate vs. the time of ponding from field measurements (Keller and Bliesner 1990)	11D-2

Figures

Table 11-1	Steps for estimating fertilizer application through sprinkler systems and sample calculations for two types of sprinkle system	11-4
Table 11-2	Available water-holding capacity (W_a) of soils of different texture	11-29
Table 11-3	Ranges of effective maximum crop root depths and typical values for management allowed depletion (MAD) for deep, uniform, well-drained soil profiles	11-30
Table 11-4	Terminal velocities and kinetic energies associated with different size raindrops	11-39
Table 11-5	Suggested maximum application rates for sprinklers for average soil, slope, and tilth	11-42
Table 11-6	Recommended design CU values for different sprinkler systems	11-51
Table 11-7	Ranges of target E_q and E_h values for different types of sprinkler systems	11-55
Table 11-8	Classification of impact and similar sprinklers and their adaptability	11-5
Table 11-9	Ratios of the target (desired) depth of water applied to the gross average application for various values of CU and percentages of land area adequately irrigated.	11-66
Table 11-10	Relative percentages of optimum productivity	11-67
Table 11-11	Distribution efficiency, DE_{pa} , used for system design	11-67
Table 11-12	A guide to recommended nozzle sizes and pressures with expected average CU values for different application rates and sprinkler spacings under low wind conditions (0-4 m/h, or 0 m/sec)	11-71
Table 11-13	A guide to recommended nozzle sizes and pressures with expected average CU values for different application rates and sprinkler spacings under high wind conditions (10-15 mph, or 5-7 m/sec)	11-72
Table 11-14	A guide to recommended nozzle sizes and pressures with expected average CU values for different application rates and sprinkler spacings under extreme wind conditions (15-20 mph, or 7-9 m/sec)	11-73
Table 11-15	Pressure ranges for standard sprinkler nozzles	11-73

Table 11-16	Recommended minimum sprinkler riser heights for set systems	11-73
Table 11-17	A guide to recommended nozzle sizes and pressures with expected average CU values for different application rates and sprinkler spacings under moderate wind conditions (4-10 mph, or 2-5 m/sec)	11-74
Table 11-18	Nozzle discharge and wetted diameters for typical 1/2- and 3/4-inch bearing impact sprinklers with trajectory angles between 22 and 28 degrees and standard nozzles without vanes	11-83
Table 11-19	Typical values for the orifice coefficient, K_o , as applied in eq. 11-106	11-83
Table 11-20	Suggested values of the roughness height for use in the Darcy-Weisbach and Swamee-Jain equations for typical sprinkle-system pipe materials	11-86
Table 11-21	Typical values of the Hazen-Williams C for different pipe sizes and materials	11-87
Table 11-22	Values of the local loss coefficient (K_r) for irrigation pipe fittings and valves	11-88
Table 11-23	Values of the local loss coefficient (K_r) for standard pipe fittings and valves	11-89
Table 11-24	Values of velocity head ($V^2/2g$) for different diameters and flow rates	11-90
Table 11-25	Reduction coefficients (F) for computing friction loss in pipes with multiple outlets having nearly the same discharge	11-91
Table 11-26	Friction loss rate in ft/100 ft (J) in portable aluminum pipe with 0.050 in wall and couplings every 30 ft	11-93
Table 11-27	Approximate friction loss gradients for plastic hoses and hose bibs	11-99
Table 11-28	Typical performance table for perforated pipelines	11-100
Table 11-29	Friction loss J values in ft/100 ft of portable aluminum mainline pipe with couplers connecting 30 ft lengths	11-101
Table 11-30	Friction-loss J values in ft/100 ft of SDR 41, IPS, PVC (Class 100 psi) thermoplastic pipe used for sprinkle irrigation mainlines, based on eq. 11-91	11-102

Table 11-31	Friction loss J values in ft/100 ft of SDR 41, PIP, PVC (Class 100) thermoplastic pipe used for sprinkle irrigation mainlines. Based on eq. 11-92	11-102
Table 11-32	Friction loss in ft/100 ft (J), in mainlines of 8- to 12-year-old welded steel pipe. Based on Hazen-Williams with C = 100	11-103
Table 11-33	Present worth and annual economic factors for assumed escalation in energy costs of 9 and 13.6% and various interest rates and life cycles	11-114
Table 11-34	Sample data and procedure for locating economic pipe size regions on selection chart, C = 130, CRF = 0.214, U' = \$138.60/WHP-year, and Q = 1,000 gpm	11-115
Table 11-35	Data for sample calculation 11-12 showing the total pipe friction head loss obtained by different pipe size selection methods	11-119
Table 11-36	Comparison of total annual costs for different pipe-size combinations for section C-D of sample calculation 11-13	11-119
Table 11-37	Friction head loss calculations in each section for sample calculation 11-14	11-120
Table 11-38	Location of critical pivot lateral inlet and trimming sequence for sample calculation 11-14	11-121
Table 11-39	Kinematic viscosity as a function of water temperature	11-125
Table 11-40	Typical discharges and wetted diameters for gun sprinklers with 24° angles of trajectory and tapered nozzles operating when there is no wind	11-139
Table 11-41	Recommended tow-path spacings for traveling sprinklers with ring (lower) and tapered (higher percentages) nozzles	11-141
Table 11-42	Recommended hoses sizes for traveler sprinklers	11-142
Table 11-43	Estimated pressure head loss gradients for lay-flat irrigation hose operating at approximately 100 lb/in ²	11-142
Table 11-44	Potential values of surface storage	11-148
Table 11-45	Ranges of normal operating pressures and associated pattern widths for different sprinkler type and spacing configurations most commonly used on center pivot laterals	11-154
Table 11-46	Recommended maximum nozzle spacings (feet) for spray devices at 6 foot height (Kincaid 1996)	11-155

Table 11-47	Typical values for the Hazen-Williams friction coefficient, C	11-162
Table 11-48	Typical values for inside diameters, D, of center pivot lateral pipe	11-162
Table 11-49	Length, area, discharge, flow ratio, and friction loss for a center pivot lateral irrigating a circular area	11-164
Table 11-50	Values for K_{dual}	11-165
Table 11-51	Calculation of the total inlet pressure requirement for center pivot systems	11-172
Table 11-52	DU and CU values of four standard sprinkler spacings for areas between sprinklers 5 and 6 and between sprinklers 4 and 5 (fig. 11-91)	11-191
Table 11C-1	Hydrostatic pressure (S) and modulus of elasticity (E) for common compounds of PVC, PE, and ABS, as well as for aluminum and steel	11C-2
Table 11C-2	Common abbreviations for pipe specifications	11C-3
Table 11C-3	Computed inner diameters for PVC pipe for various SDRs and pressure ratings, for $S = 2,000 \text{ lb/in}^2$ (13,800 kPa)	11C-4
Table 11C-4	Computed inner diameters for PVC pipe for various SDRs and pressure ratings $S = 13,800 \text{ kPa}$ ($2,000 \text{ lb/in}^2$) (mm)	11C-5

623.1100 Description

Sprinkle irrigation is the application of water in the form of a spray formed from the flow of water under pressure through small orifices or nozzles. The flexibility of present day sprinkle equipment, and its efficient control of water application, make the method's usefulness on most topographic conditions subject only to limitations imposed by land use capability and economics. The most common intent of sprinkle irrigation is to apply water uniformly to the soil surface to replace water extracted by plants. The pressure is usually obtained by pumping, although it may be obtained by gravity if the water source is high enough above the area irrigated.

Sprinkle irrigation systems can be divided into two general categories. In periodic-move and fixed systems, the sprinklers remain at a fixed position while irrigating, whereas in continuous move systems, the sprinklers are moved in either a circular or a straight path. The periodic-move systems include hand-move and wheel-line laterals, hose-fed sprinkler grid, perforated pipe, orchard, and gun sprinklers. The most common continuous-move systems are center-pivot and linear or lateral move sprinklers.

With carefully designed periodic-move and fixed systems, water can be applied uniformly at a rate based on the infiltration rate of the soil, thereby preventing runoff and consequent damage to land and crops. Continuous-move systems can have even higher uniformity of application than Periodic move and fixed systems, and the travel speed can be adjusted to apply light watering that reduces or eliminates runoff.

(a) Adaptability

Sprinkle irrigation is suitable for most crops and also adaptable to nearly all irrigable soils, since sprinklers are available in a wide range of discharge capacities. For periodic-move systems with proper spacing, water may be applied at any selected rate above 0.15 inch per hour (in/h). On extremely fine textured soils with low intake rates, particular care is required in the selection of proper nozzle size, operating pressure, and sprinkler spacing to apply water uniformly at low rates.

Periodic-move systems are well suited for irrigation in areas where the crop-soil-climate situation does not require irrigations more often than every 5 to 7 days. Light, frequent irrigations are required on soils with low water holding capacities and shallow rooted crops. For such applications, fixed or continuously moving systems are more adaptable; however, where soil permeability is low, some of the continuously moving systems, such as the center pivot and traveling gun, may cause runoff problems. In addition to being adaptable to all irrigation frequencies, fixed systems can also be designed and operated for frost and freeze protection, blossom delay, and crop cooling.

(b) Special uses

The various types of sprinkle irrigation systems are adaptable to a variety of uses in addition to ordinary irrigation to control soil moisture. Automatic permanent, solid-set, and center-pivot systems are the most versatile multipurpose systems. Multipurpose systems make it possible to save labor, material, and energy by requiring fewer trips across the field with machinery and by permitting timely chemical applications. The most important multipurpose functions in addition to ordinary irrigation are applying fertilizers and soil amendments with the irrigation water and applying herbicides and pesticides. The most important special use systems dispose of waste waters, prevent damage from frost, and provide control of the microclimate. Sprinkle equipment also provides farm fire protection, cooling and dust control for feedlots and poultry buildings, moisture for earth fill construction, and curing of log piles.

(1) Federal, State, and local regulations

The use of chemicals is being strictly controlled by rapidly changing governmental regulations. Consult a reputable chemical dealer, county agricultural agent, state agricultural extension specialist, State Department of Agriculture, or the U.S. Environmental Protection Agency (EPA) for those chemicals that are approved for application in irrigation water by sprinklers and on what crops the chemicals may be used.

(2) Applying fertilizers, soil amendments, and pesticides.

Dissolving soluble fertilizers in water and applying the solution through a sprinkler system is economical, easy, and effective. A minimum of equipment is re-

quired, and once the apparatus for adding the fertilizer to the irrigation water is set up, the crop being irrigated can be fertilized with less effort than is required for mechanical application. Penetration of the fertilizer into the soil can be regulated by the time of application in relation to the total irrigation. An approximate ratio of 1 pound of fertilizer per gallon of water (120 gal/l) can be dissolved in water in a barrel or closed container, or liquid fertilizer can be used.

There are several advantages in using sprinkle irrigation systems as a means of distributing fertilizers. Both irrigation and fertilization can be accomplished with only slightly more labor than is required for irrigation alone. This is particularly important in arid and semi-arid areas where the applications of irrigation water and fertilizers can, in most cases, be scheduled to coincide. Close control usually can be maintained over the depth of fertilizer placement, as well as over the lateral distribution. The uniformity of fertilizer distribution can be only as good as the uniformity of water distribution, but if the sprinkler system has been properly designed and is properly operated, fertilizer distribution will be acceptable.

(3) Injection techniques

The simplest way to apply fertilizer through a sprinkler system is to introduce the solution into the system at the suction side of a centrifugal pump (fig. 11-1). A pipe or hose is run from a point near the bottom of the fertilizer solution container to the suction pipe of the pump. A shutoff valve is placed in this line for flow regulation. Another pipe or hose from the discharge side of the pump to the fertilizer container provides an easy method of filling the container for dissolving the fertilizer and rinsing. If a closed pressure type container is used, such as one of the several commercial fertilizer applicators, the line from the discharge side of the pump can be left open and the entrance of the solution into the water regulated by the valve on the suction side of the line. It is important to have a backflow prevention valve, as seen in figures 11-1 and 11-2, upstream of the injection point to protect the water supply from contamination.

Fertilizer can also be added to sprinkler systems with a small high pressure pump, such as a gear or paddle pump. If a spray rig for orchards is available, the fertilizer solution can be pumped with the small pump on the spray rig. This method can also be used in applying fertilizer to individual sprinkler lines where more than

one sprinkler line is operating at a time; however, it may be more cumbersome to move than other types of injectors. To avoid corrosion after the fertilizer solution is pumped into the line, the empty fertilizer barrel or container should be filled with water and the water run through the pump. This operation should be repeated several times to rinse the pump and barrel thoroughly.

One common method of applying fertilizer through sprinkler systems is with an aspirator unit. Part of the water discharged from the pump is bypassed through the aspirator, creating suction that draws the fertilizer solution into the line. The objective is to create a pressure drop between the intake and outlet of the pressure-type container, creating a flow through

Figure 11-1 A method for adding soluble fertilizers to a centrifugal pump system

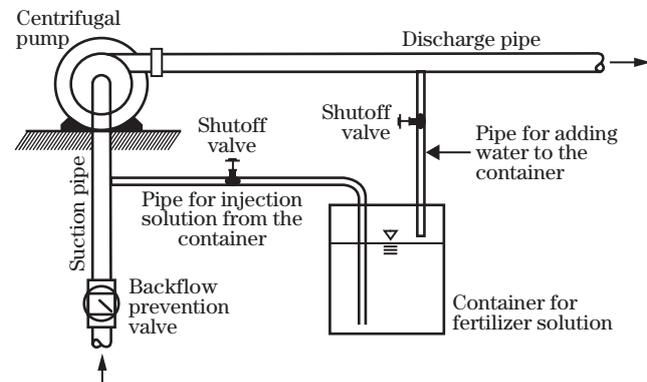
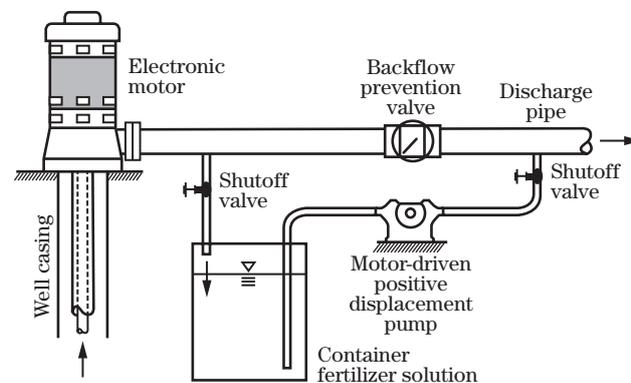


Figure 11-2 A method for adding fertilizers to a turbine pump system using a small gear or paddle pump



the container into the sprinkler mainline or lateral. Several such commercial fertilizer applicators are on the market. One of these uses the pressure gradient through a venturi section that has been inserted into the pipeline.

A second type operates on the pressure drop created by a pipe enlargement that creates sufficient pressure gradient without restricting flow. It is essential to have valves for regulating the flow through the aspirator and the main line. This type of fertilizer applicator costs about the same as a small positive displacement pump unit and it has the advantage of simplicity and freedom from moving parts.

(4) Fertilizer materials

Many liquid, dry, and liquid suspension fertilizer materials are suitable for application through sprinkler systems. The main criteria used in selecting a fertilizer material are the convenience and cost of the desired nutrients.

Clear liquid fertilizers are convenient to handle with pumps and gravity flow from bulk storage tanks. These may contain a single nutrient or combinations of nitrogen (N), phosphorus (P), and potassium (K). A wide variety of soluble dry fertilizers containing nitrogen, phosphorous, and potassium are available for dissolution into the sprinkler irrigation stream. The dry fertilizer products may be dissolved by mixing with water in a separate, open tank and then pumped into an irrigation stream, or they may be placed in a pressurized container through which a portion of the sprinkler stream is passed. In the latter instance, the flow of water continuously dissolves the solid fertilizer until it has all been applied. Sprinkler application of dry fertilizer materials and agricultural minerals is increasing, because of improved application equipment and greater use of sprinklers.

Interest in suspension-type fertilizers has increased in recent years largely because of their potential for producing higher analysis and grades high in potassium. The suspension mixtures contain 11 to 133 percent more plant nutrients than correspondingly clear liquids. Because of their higher nutrient content, suspensions usually can be manufactured, handled, and applied at significantly less cost than clear liquids. Another advantage of suspensions is that relatively large quantities of micronutrients can be held.

Only traces of many micronutrient materials can be dissolved in clear liquids. The irrigation water volume and velocity must be sufficient to maintain the fertilizers in suspension or solution to ensure proper dispersion and uniform distribution.

Materials commonly used for application through sprinkler systems are urea-ammonium nitrate solutions, ammonium nitrate, ammonium sulfate, urea (potential N loss), calcium nitrate, potassium nitrate, liquid ammonium phosphates, some dry ammonium phosphates, potassium chloride (may be hard to dissolve), and potassium sulfate (may be hard to dissolve).

Secondary and micronutrients that can be applied through sprinkler systems include magnesium sulfate, zinc sulfate and chelates; manganese sulfate and chelates; copper sulfate and chelates; iron sulfate and chelates; Solubor[®] (boron); and molybdenum.

Materials that should not be applied through sprinkler systems include:

- aqua ammonia (excessive N loss and calcium precipitation with hard water)
- anhydrous ammonium (excessive N loss and will precipitate with hard water)
- single super phosphate, concentrated or treble super-phosphate, and some dry ammonium phosphates (materials that will not dissolve)
- potassium sulfate and magnesium sulfate (hard to dissolve)
- almost all N-P-K dry fertilizers, liming materials, and elemental sulphur (materials that will not dissolve)
- ammonium polyphosphate (precipitates with hard water)
- phosphoric acid or any acid (causes corrosion and precipitation)

(5) Fertilizer applications

For periodic-move and fixed sprinkler systems, fertilizer should be applied by the batch method. With the batch method, the fertilizer required for a given area is put into a tank or metered into the system, and the solution is injected into the irrigation water. While high concentrations of solution must be avoided because of

corrosion problems, exact proportions are not important. The sprinklers in operation at one time cover a specific area, and the quantity put into the tank, or metered into the system, at one time is the quantity that should go onto that area. Obviously, the entire batch should be used in a single set.

The common procedure followed in applying fertilizer by the batch method consists of three timed intervals. During the first interval, the system operates normally, wetting the foliage and soil. During the second interval, the fertilizer is injected into the system. This application should rarely be less than 30 minutes and preferably an hour or longer. This eliminates the possibility of poor distribution due to slow or uneven rotation of sprinklers. Also, with normal fertilizer-application rates, the solution passing through the system will be better diluted. This lessens the possibility of foliage burn and corrosion damage to the system.

The last time interval should be long enough for the system to be completely rinsed with clear water and all fertilizer removed from plant foliage and moved down into the crop rootzone. Depending on the rate of application at which the system is operating, the interval should continue for 30 minutes for fast rates and 90 minutes for slower rates.

For continuously moving systems, such as center pivots, fertilizer must be applied by the proportional method. After applying fertilizer, the system should be operated with clear water long enough to completely rinse it. With the proportional method, the rate at which the fertilizer is injected is important for determining the amount of fertilizer applied.

The application precautions are based on the fact that many commercial fertilizers and soil amendments are corrosive to metals and are apt to be toxic to plant leaves. With injection on the suction side of the pump, the approximate descending order of metal susceptibility to corrosion is:

- galvanized steel
- phosphobronze
- yellow brass
- aluminum
- stainless steel

There are several grades of stainless steel, the best of which are relatively immune to corrosion. Protection is afforded by diluting the fertilizer and minimizing the period of contact with immediate, thorough rinsing after the application of chemicals. Avoid using materials containing heavy metals. The steps in table 11-1 are for estimating the fertilizer application through a

Table 11-1 Steps for estimating fertilizer application through sprinkler systems and sample calculations for two types of sprinkle system

Step		Periodic move	Continuous move
1	Decide on the amount of nitrogen to apply	40 lb/ac (45 kg/ha)	30 lb/ac (34 kg/ha)
2	Select kind of nitrogen fertilizer and percent N	32%	32%
3	Determine gallons (or pounds) per acre ^{1/}	11.4 gal/ac (107 l/ha)	8.6 gal/ac (80 l/ha)
4	Determine number of acres irrigated per set or turns ^{2/}	1.82 ac (0.74 ha)	126.7 ac (51 ha)
5	Determine the gallons (or pounds) required per set or turn	20.7 gal (78 l)	1,068 gal (4,043 l)
6	Determine the length of the application time ^{3/}	1 h	24 h
7	Calculate the required fertilizer solution injection rate ^{4/}	21 gph (79 l/h)	44.6 gal/h (169 l/h)

1 Dry fertilizers must be dissolved and put in a liquid form to be injected continuously into the system (4010.32)111 = 11.4 gal/ac.

2 For periodic-move, fixed, traveling sprinkler, and linear-move systems, use the area covered per set. For center-pivot systems, use the area covered in a complete revolution.

3 For periodic-move and fixed systems, use some convenient portion of the set time. For continuous-move systems, use the length of time required to complete a run or revolution.

4 For periodic-move systems, the injection rate only needs to be approximate. For continuous-move systems, it must be accurately controlled for precise applications of fertilizers. If the injection pump has fixed injection rates, the travel speed of continuous-move systems can be adjusted for precise applications.

sprinkler system. The examples included in the table are for applying urea-ammonium nitrate with 32 percent N and weighing 11.0 pounds per gallon (lb/gal) through a quarter-mile side-roll sprinkle system with 60 foot moves and through a quarter-mile center-pivot lateral.

(6) Soil amendments

Various soluble soil amendments, such as gypsum, sulfuric acid, lime, and soluble resins, can be applied through sprinkler systems. In the San Joaquin Valley of California, gypsum must be applied on many soils to reduce the percentage of soluble sodium that can cause poor infiltration by dispersing the soil particles. In this area, it is common practice to introduce gypsum through sprinkle irrigation systems. The methods used are generally the same as those used to add soluble fertilizers.

(7) Applying pesticides

Pesticides include herbicides, insecticides, fungicides, rodenticides, fumigants, and similar substances. The sale and use of these materials is regulated by State and Federal laws. Many of the materials have been used effectively by growers and researchers; however, unless the chemicals have been cleared for use by the specific application method and under the specific conditions, they should not be used in sprinkler systems. There is great potential for this method of pest control, especially through center-pivot and fixed systems, but more research is needed.

Diluted solutions of the basic fertilizers and herbicides can be applied throughout the irrigated area during the ordinary irrigation operations. The program for foliar applications of trace elements and most pesticides is similar to the foliar cooling operation with fixed systems. The chemicals are added in precise quantities to the irrigation water to form diluted solutions. The system is then cycled so that the application time is just enough to wet thoroughly the foliage and the off time is sufficient for each application to dry. This process, which coats the leaves with thin layers of the chemical, is repeated until the desired amount of chemical is applied.

(8) Disposing of wastewater

Land application of wastewaters by sprinkle irrigation can be a cost-effective alternative to conventional wastewater treatment. Wastewaters are divided into

municipal, industrial, and agricultural categories. Wastewaters from most cities require rather extensive treatment before discharge. Industrial wastewaters can require extensive pretreatment, ranging from simple screening to primary and secondary treatment for removing oils, greases, metals, and harmful chemicals, pH adjustment, and chlorination. Agricultural wastewaters include effluents from animal production systems and food processing plants. For land application through sprinkle irrigation, most animal wastes must undergo some treatment, such as removal of large fibrous solids. Wastewater from food processing plants generally requires more extensive pretreatment such as removal of solids, greases and oils, and adjustments in pH.

(9) Design considerations

Major concerns for land application of wastewaters with sprinkler systems are that the wastewater be of good quality and applied in such a fashion that it will not destroy or render ineffective the disposal site or pollute ground and surface water in neighboring areas. Oils, greases, and heavy metals can harm the soil and the vegetative cover. Furthermore, excessive solids can build up a mat on the surface that will destroy the vegetative cover.

In designing a sprinkle irrigation system, the effluent vegetative cover, soil type, and frequency of application should be considered. Well-drained, deep sandy or loamy soils are often suitable for land application of wastes. Some soils may require subsurface drainage. The application rate should not exceed the infiltration rate of the soil, and most recommendations are for a maximum application rate of 0.25 inch per hour (6.4 mm/h). The total application per week can vary between 1 to 4 inches (25 to 100 mm), with the higher application during the summer months. Nevertheless, there should be a rest period between applications.

Woodlands can be a good disposal site for wastewaters. In woodlands, the soil surface is stable and the surface cover is effective for digesting organic matter. If grassland is used, select a grass that is specific for the site. Corn can also be grown on a disposal site, but effluent can be applied only at selected times of the year. Rates of nitrogen that can be applied will range from approximately 200 pounds per acre (224 kg/ha) per year for corn to 700 pounds per acre (785 kg/ha) per year for coastal Bermuda grass. Nitrogen applica-

tion in excess of plant use can result in leaching of nitrate and pollution of the groundwater.

(10) Hardware

Most land disposal sprinkler systems use single nozzle sprinklers, which reduces nozzle clogging problems and results in a lower application rate. If systems are designed to operate during freezing temperatures, select sprinklers that will operate under those conditions. Either portable aluminum or buried pipe may be used for main and lateral lines of periodic-move or fixed systems; however, noncorrosive buried pipe is recommended. For fixed systems designed to operate continuously, automation is recommended. Automatic valves can be operated by air, water, or electricity. However, the most desirable are either air or water valves with water from a clean source. Solids in the wastewater tend to clog the electric solenoid valves.

Valves for fixed systems should be located in a valve box, numbered, and color coded. If the site is in a freezing climate, drain valves should be installed to drain the pipe system. The most positive freeze protection system is an air purge system that can be used to clear the pipe of water. When the system is operated, only part of the time and the wastewater is corrosive or has a high solids content, the system should be flushed with fresh water after each use. Effluents left in the pipes will become septic and create a nuisance. Also, suspended solids will settle and harden at low points in the lines and may cause severe clogging.

Center-pivot and traveling sprinklers are sometimes used in addition to portable aluminum pipe and fixed irrigation systems for land application of wastewaters. Both of these systems have fairly high application rates. Effluent with high levels of suspended solids may clog the turbine or piston on water-drive traveling gun sprinklers. Furthermore, the operation of large impact sprinklers during windy weather can create severe drifting problems. For this reason, many center-pivot effluent disposal systems are now equipped with spray nozzles directed downward. Traction problems can also occur in center pivot systems, because of the large amounts of water applied.

The design of a sprinkle irrigation system for land application of wastewater is similar to the design of other types of sprinkle irrigation systems. The designer must follow the rules of good design, keeping in mind that the effluent is not water, but a mixture of water

and solids, and that wastewaters that are abrasive or corrosive will shorten the life of the system. Therefore, special equipment may be required.

(11) Frost protection

Sprinkle irrigation can be used for frost protection. However, an ordinary system is limited because of the area it can cover at any one setting of the lateral lines. Therefore, for adequate protection of most areas, it is necessary to add capacity so that the entire field can be watered simultaneously. The application rate and system capacity requirements for different levels of protection were presented earlier. Since an application rate of about 0.1 inch per hour is usually sufficient, small single-nozzle sprinklers are satisfactory; however, double-nozzle sprinklers can be used by plugging one nozzle. Nozzle sizes from three thirty-seconds to a quarter inch have been successfully used for overhead frost protection, with the size depending on the spacing.

Short-duration, light-radiant frosts (28 to 29 °F, or -2.2 to -1.7 °C) can be protected against with under-tree misting or by cycling an overhead system with 2- to 4-minute applications every 4 to 8 minutes, so that half the system is always operating. Such systems require about 26 to 30 gallon per minute per acre (4 – 5 l/s/ha), half as much water as is needed through continuously operating full-coverage systems.

Usually, wind speeds are low during periods when frost protection is possible. Therefore, wetted diameters taken from manufacturers' catalogues can be used with the standard reduction for developing sprinkler spacing criteria. Typical single-nozzle sprinklers recommended for frost protection systems produce D profiles and can be spaced at 75 percent of the wetted diameter and still give adequate coverage. Sprinkler pressures should be maintained on the high side of the recommended operating range, and rotation speeds of impact sprinklers should be 1 revolution per minute (rpm) or faster for best results.

(12) Frost control operation

For complete frost control, a continuous supply of water must be available. The water supply capacity must exceed the atmospheric potential to freeze the water; in other words, some water should always be left on the plants. The mechanics of frost control depend upon the fact that water freezes at a higher temperature than do the fluids in the plant. Therefore, as long

as there is liquid water available to be frozen, the temperature will be held at approximately 32 degrees Fahrenheit (0 °C), above the freezing point of the plant fluids.

The temperature of a wet surface will equal the wet bulb or dew point temperature, which is lower than the air temperature. Therefore, frost control systems should be turned on when the air temperature approaches 33 degrees Fahrenheit. The field becomes a mass of ice and yet the ice remains at a temperature above the freezing point of the plant liquid as long as water is being applied. Damage also can occur if the water is turned off too soon after the temperature climbs above 32 degrees Fahrenheit (0 °C). Therefore, for adequate protection, continue to apply water until the air temperature is above 32 degrees Fahrenheit (0 °C), and all the ice has melted off the plants.

Some type of electric alarm system should be installed so that the farmer will know when to get up at night to turn on the system. A thermo-switch set in the field at plant level with wires to the house and a loud bell alarm will serve this purpose. The switch should be set so that the bell sounds when the plant-level temperature reaches 34 degrees Fahrenheit (1 °C). The system should be laid out and tested well in advance of the time that it may have to be used.

Frost protection with sprinklers has been used successfully on trees, bushes, vines, and low growing vegetable crops, such as tomatoes, cucumbers, peppers, beans, cranberries, and strawberries. During low temperature frosts, the ice that accumulates on trees can be heavy enough to break the branches. Similar ice accumulation could break down sweet corn, celery, pole beans, and tall flowers. For this reason, tall, thin plants are not generally adapted to frost protection by ice encasement.

(13) Bloom delay

In the fall, deciduous trees, vines, and bushes lose their leaves and enter a condition known as dormancy. Plants are normally incapable of growth during this period, and fruit buds do not develop until they break dormancy sometime between midwinter and early spring. The rate of bud development depends on the air temperature around the buds. If the early spring temperatures are cool, blossoming is delayed; however, when spring temperatures are above normal, bud development accelerates and the trees blossom early.

If early bud development is followed by a sudden cold spell, the potential for freeze damage becomes serious. For example, Utah fruit growers suffered losses due to freeze damage 9 of the years between 1959 and 1973 as a result of freezes occurring after warm early spring temperatures caused the buds to develop to a vulnerable stage.

In the past, the common practice has been to use sprinklers to supply heat to the orchard for protection from freezing that occurs after the buds have developed to a sensitive stage. A new procedure is to cool the trees by sprinkling before the buds develop and thus to keep them dormant until after the major danger of freeze damage is past.

After dormancy, any time the temperature rises above 40 degrees Fahrenheit (4.4 °C), the buds will show signs of development. The rate of development increases as the temperature increases until the ambient air temperature reaches 77 degrees Fahrenheit (25 °C). Thereafter, the rate of development does not change appreciably with increasing temperature. The energy accumulation associated with bud development over a period of days is called growing-degree hours. As the buds continue to develop in the spring their susceptibility to damage from low temperatures increases.

Tests have shown that each fruit species has different chill unit requirements to complete dormancy and different growing degree hour accumulations to reach the various stages of phenological development. The system capacity required for bloom delay is described in the section on capacity requirements for fixed systems.

The amount of evaporative cooling that takes place on bare limbs depends on the temperature of the tree buds, the difference in vapor pressure between the bud surface and the air, and the rate at which evaporated water is removed by convective mass transfer (due to air movement). Therefore, for maximum cooling with the least amount of water application, it is necessary to completely wet the buds periodically and to allow most of the water to evaporate before rewetting.

The design and operation of bloom delay systems are still in the development stage. However, the current state of the art indicates the following for the Great Basin area of the western United States:

- Over-tree sprinkling to provide evaporative cooling will delay budding of deciduous fruit trees. Tests indicate that over 80 percent of the damage from early spring freezes can be prevented.
- Starting the sprinkler on the day when the mathematical model predicts winter rest is completed minimizes guesswork, provides maximum protection, and saves water.
- Shrub-type sprinkler heads can be programmed to cycle on and off as a means of saving water; however, the installation costs are greater than for impact-type sprinklers.
- In the early spring, less water is required to provide adequate cooling and protection. Water can be saved if:
 - the off portion of the watering cycle is long in the early spring and decreased as daytime temperatures rise
 - a smaller nozzle is used in impact sprinklers in the early spring
 - pump output is low in the early spring and is increased as daytime temperatures rise
- Impact sprinklers, with 9/64-inch nozzles on spacings of 40 by 50 feet (12 × 15 m) operating at 40 pounds per square inch (275 kPa) and cycled on and off each 2 minutes have given good protection under most conditions.
- Sprinkling for bloom delay can be combined with ice encasement sprinkling for freeze protection. The former can be used in the early spring and the latter in late spring.

(14) Microclimate control

Crop or soil cooling can be provided by sprinkle irrigation. Soil cooling can usually be accomplished by applications once or twice every 1 or 3 days. Therefore, ordinary-fixed systems, with or without automatic controls and center pivot systems with high speed drives are suitable for soil cooling. Foliar cooling requires two to four short applications every hour; therefore, only automated fixed systems can be used for this purpose. The small amounts of water intermittently applied cool the air and plant, raise the humidity, and in theory improve the production quality and yield. By supplying water on the plant surfaces, the plant is cooled and the transpiration rate reduced so that a plant that would wilt on a hot afternoon can

continue to function normally. More study is needed to better understand the application of sprinkle irrigation to crop cooling.

On low crops and vines, a 3-minute application at 0.1 inch per hour (2.4 mm/h) every 15 minutes has usually been adequate to reduce the temperature by 10 to 20 degrees Fahrenheit (−12 to −7 °C) when the humidity is 20 to 40 percent and the air temperature is over 95 degrees Fahrenheit (35 °C). On larger trees, a 6-minute application every 30 to 36 minutes has been shown to be satisfactory. Foliar cooling is feasible only with high quality water. The capacity requirements and system design procedures of fixed systems that are designed for foliar cooling are described in the section on capacity requirements for fixed systems.

(c) Advantages

Some of the most important advantages of the sprinkle method are:

- Small, continuous streams of water can be used effectively.
- Runoff and erosion can be eliminated.
- Problem soils with intermixed textures and profiles can be properly irrigated.
- Shallow soils that cannot be graded without detrimental results can be irrigated without grading (fig. 11-3).
- Steep and rolling topography can be irrigated.
- Light, frequent waterings can be efficiently applied.
- Crops germinated with sprinkler irrigation may later be surface irrigated with deeper applications.
- Labor is used for only a short period daily in each field.
- Mechanization and automation are practical to reduce labor.
- Fixed systems can eliminate field labor during the irrigation season.
- Unskilled labor can be used because decisions are made by the manager, rather than by the irrigator.

- Weather extremes can be modified by increasing humidity, cooling crops, and alleviating freezing by use of special designs.
- Plans for intermittent irrigation to supplement erratic or deficient rainfall or to start early grain or pasture can be made with assurance of adequate water.
- Salts can be effectively leached from the soil.
- High application efficiency can be achieved by a properly designed and operated system.
- Tall, dense crops can be adequately watered with sprinklers.
- Chemigation and fertigation (application of agricultural chemicals) is convenient.
- The effective land application of treated animal, municipal, and industrial effluent is possible.

(d) Disadvantages

Important disadvantages of sprinkle irrigation are:

- Relatively high initial costs, compared to surface irrigation methods, must be depreciated. For simple systems (such as hand-move sprinklers), these costs, based on 2008 prices, range approxi-

mately from \$300 to \$500 per acre; for mechanized and self-propelled systems, from \$750 to \$1,200 per acre; and, for semi-automated and fully automated fixed systems, \$800 to \$1,000 or more per acre.

- Cost of pressure development (pumping), when necessary, is about \$0.20 per acre-foot of water for each pound per square inch of pressure, based on \$0.06 per kilowatt hour for electricity, and assuming a pump efficiency of E_p is 70 percent; the equation is:

$$\text{cost per acre-ft per lb/in}^2 = \frac{2.36 (\$/\text{kWh})}{E_p} \quad (\text{eq. 11-1})$$

where:

the required pumping energy, in per kilowatt hour, for 1 acre-ft of water and 1 pound per square inch is $2.36/E_p$, or,

$$\text{energy} = \frac{(2.31 \text{ ft/lb/in}^2)(0.746 \text{ kW/HP})(43,560 \text{ ft}^3/\text{acre-ft})(7.481 \text{ gal/ft}^3)}{(3,960 \text{ gal/min-ft/HP})(60 \text{ min/h})E_p} \quad (\text{eq. 11-2})$$

where:

\$0.20 per acre-feet of water per pound per square inch is equivalent to \$0.024 per thousand cubic meters per kPa

- Large flows intermittently delivered are not economical without a reservoir, and even a minor fluctuation in rate causes difficulties.
- Sprinklers are not well adapted to soils having an intake rate of less than 0.15 inches per hour.
- Windy and excessively dry locations appreciably lower sprinkler irrigation efficiency.
- Irregular field shapes are not convenient to irrigate with mechanized sprinkler systems (hand-move laterals are much more adaptable, since each individual pipe section is moved separately and, therefore, adding or removing pipes to fit the field shape is easy).
- Cultural operations must be coordinated with the irrigation cycle.
- Surface irrigation methods on suitable soils and slopes may have higher potential irrigation efficiency.

Figure 11-3 Hand-move sprinklers operating on rocky ground with shallow soils and difficult topography



- Water supply must be capable of being cut off at odd hours when the soil moisture deficiency is satisfied.
- Careful management and maintenance must be exercised to obtain the high potential efficiency of the method.
- Systems must be designed by a competent specialist with full consideration for efficient irrigation, economics of pipe sizes and operation, and convenience of labor.
- Water quality can introduce problems.
 - When used in overhead sprinklers on fruit crops, irrigation water that has high concentrations of bicarbonates may affect the production quality.
 - Saline water may cause problems because salt may be absorbed by the leaves of some crops.
 - Careful filtration of surface water supplies is necessary to prevent clogging.
 - Corrosion of metal components and resultant clogging can be problematic.
- Some types of sprinkle irrigation systems, when not in operation, are susceptible to movement by wind.
- Pressure regulation and or flow control nozzles are required to achieve adequate water application uniformity on significantly undulating topographies.
- There may be increased evaporation losses from wet soil and plant surfaces due to more frequent irrigation.

Sprinkle irrigation can be adapted to most climatic conditions where irrigated agriculture is feasible. However, extremely high temperatures and wind velocities present problems in some areas, especially where irrigation water contains large amounts of dissolved salts. Crops such as grapes, citrus, and most tree crops are sensitive to relatively low concentrations of sodium and chloride and, under low humidity conditions, may absorb toxic amounts of these salts from sprinkle-applied water falling on the leaves. Because water evaporates between rotations of the sprinklers, salts concentrate more during this alternate wetting and drying cycle than if sprayed continuously. Plants may be damaged when these salts are absorbed.

Toxicity shows as a leaf burn (necrosis) on the outer leaf edge and can be confirmed by leaf analysis. Such injury sometimes occurs when the sodium concentration in the irrigation water exceeds 70 parts per million (ppm) or the chloride concentration exceeds 105 ppm. Irrigating during periods of high humidity, as at night, often greatly reduces or eliminates this problem.

Annual and forage crops, for the most part, are not sensitive to low levels of sodium and chloride. Recent research indicates, however, that they may be more sensitive to salts taken up through the leaf during sprinkling than to similar water salinities applied by surface or trickle methods. Under extremely high evaporative conditions, some damage has been reported for more tolerant crops such as alfalfa when sprinkled with water having an electrical conductivity (EC_w) of 1.3 dS/m and containing 140 parts per million sodium and 245 parts per million chloride. In contrast, little or no damage has occurred from the use of waters having an EC_w as high as 4.0 dS/m and respective sodium and chloride concentrations of 550 and 1,295 ppm when evaporation is low. Several vegetable crops have been tested and found fairly insensitive to foliar effects at high salt concentrations in the semi-arid areas of California. In general, local experience will provide guidelines to a crop's salt tolerance.

Damage can occur from spray of poor quality water drifting downwind from sprinkler laterals. Therefore, for periodic-move systems in arid climates where saline waters are being used, the laterals should be moved downwind for each successive set. Thus, the salts accumulated from the drift will be washed off the leaves. Sprinkler heads that rotate at one rpm or faster are also recommended under such conditions.

If overhead sprinklers must be used, certain sensitive crops, such as beans or grapes may not be possible to grow. A change to another irrigation method, such as furrow, flood, basin, or trickle, may be necessary. Under-tree sprinklers have been used in some cases, but lower leaves, if wetted, may still show symptoms due to foliar absorption.

The same guidelines used for furrow and border irrigation should also be used for sprinkle irrigation when determining allowable levels of soil salinity for various crops, water qualities, and soils. However, leaching requirements under sprinkle irrigation are not neces-

sarily the same as for other irrigation methods due to the direction of water movement in the soil, which is mostly vertical under sprinkler irrigation, but can have significant lateral components under micro irrigation and some type of surface irrigation.

(e) Installation and operation of sprinkler systems

(1) Installation and operation

The best prepared plan contributes little or nothing toward obtaining the objective of conservation irrigation and maximum yields of high-quality crops unless the farmer purchases substantially the equipment specified in the plan, installs the equipment properly, and operates it according to design. The installation of sprinkle irrigation systems may be the responsibility of the engineer, dealer, farmer, or any combination of the three depending on the financial and physical arrangements made by the farmer.

A plan of the system should be furnished to the farmer which includes a map of the design area or areas showing the location of the water supply and pumping plant; location of supply lines, mainlines, and sub-mains; location and direction of movement of lateral lines; spacing of sprinklers; and pipe sizes and length of each size required. While it is not necessary to furnish a complete list of materials, minimum equipment specifications should be furnished. These include the discharge, operating pressure, and wetted diameter of the sprinklers; the capacity of the pump at the design dynamic head; and the horsepower requirements of the power unit. Fittings for continuous operation should be specified where applicable.

Farmers may receive sprinkle-system plans prepared by NRCS engineers and then purchase equipment that is entirely different from that specified in the plans. While NRCS personnel do not have any responsibility for or control over the purchase of sprinkler equipment by the farmer, it is important, nevertheless, to emphasize the necessity of purchasing a satisfactory system. A sprinkler system should give suitable uniformity, have the capacity to supply crop water requirements throughout the season, and be designed to conserve energy.

The farmer should be given instruction in the layout of mainlines and laterals, spacing of sprinklers, movement of lateral lines, time of lateral operation, and maintenance of design operating pressures.

(2) Irrigation scheduling

The farmer should also be shown how to estimate soil-moisture conditions to determine when irrigation is needed and how much water should be applied. Ideally, irrigation scheduling should be managed so that optimum agricultural production is achieved with a minimum of expense and water use. Nearly perfect irrigation should be possible with fixed and center pivot systems. The soil moisture, stage of crop growth, and climatic demand should be considered in determining the depth of irrigation and interval between each irrigation. For each crop-soil-climate situation, there is an ideal irrigation management scheme.

Irrigation scheduling should be guided either by devices that indicate the soil-plant water status or by estimations of climatic evaporative demand. For example, soil-water sensors can be installed at representative field sites and connected to a data logger or telemetry system for recording and or real-time monitoring of field conditions. Computerized and internet-based scheduling services based on climatic demand prove to be an ideal tool for managing sprinkler systems.

(3) Screens and sand traps

When water is pumped directly from rivers, lakes, or canals, the intakes should be equipped with self-cleaning screens. The stainless steel screens should be about twice the diameter of the attached pipeline and a mesh opening of about 0.25 inch (6 mm) or less. Cleaning is often accomplished with internal pressurized water jets that rotate inside the intake screen and push debris away from the mesh openings. For center-pivot and linear-move systems, the lateral inlet point should also have a stainless steel or galvanized screen with a mesh size of 0.1 inch (3 mm) or less to keep debris, algae, weed seeds, and so on, from plugging nozzles. There needs to be a way to hydraulically isolate the screen from the rest of the system. These screens can be self cleaning or manually cleaned. There should be a pressurized water supply for a hose to manually wash the screen in both cases.

Because sand and small gravel tend to collect at the distal end of pipelines, sand traps should also be placed at the distal ends of center-pivot and linear-move systems. On a pipeline, these typically consist of a short section of 4 inch (100 mm) pipe pointing downward from a tee near the end of the mainline. On a center-pivot or linear-move lateral, longer pipes are hung from a tee near the end of the lateral (near the end gun) with a valve within reach from the ground. These pipes have a 4-inch (100 mm) spring-loaded valve or other method to quickly flush the collected sand from the system. Sometimes a special hose and large diameter (0.25 in or 6 mm) nozzle spray plate arrangement is used to continuously flush the sand while the system is operating.

623.1101 Types of sprinkler systems

There are 10 major types of sprinkler systems and several versions of each type. The major types of periodic-move systems are hand-move, end-tow, and side-roll laterals; side-move laterals, with or without trail lines; and gun and boom sprinklers. Fixed systems typically use either small or gun sprinklers. The major types of continuous-move systems are center-pivots, traveling-gun or boom sprinklers, and linear move (sometimes referred to as lateral move). Microspray systems are also technically sprinkler systems. However, the hydraulics, design, and operation of microspray systems are similar to those of drip or trickle systems. Therefore, their design is covered in Title 210 National Engineering Handbook (NEH) Part 623 Chapter 7, Microirrigation.

(a) Periodic move sprinkler systems

(1) Hand-move lateral

Hand-move laterals are composed of separate lengths of aluminum tubing with quick couplers that have either center-mounted or end-mounted riser pipes with sprinkler heads. Hand-move laterals are often referred to as hand lines. Water is conveyed to them with portable or buried mainline pipe with valve outlets at constant spacings. Systems are composed of one or more laterals. In previous years, this type of system was used to irrigate more area than any other system, and is still used on almost all crops and types of topography. Major disadvantages of the system are its high labor and high pressure requirements. This system is the basis from which all of the mechanized systems were developed.

Typical lengths of hand-move laterals are 1,280 feet (390 m) and typical lateral spacings, the distance the lateral is moved each time, are 50 and 60 feet (15 and 18 m). Spacing of sprinklers along laterals is generally 30 to 40 feet (9 to 12 m), which normally corresponds to the separate lengths of pipe. Laterals are generally constructed of aluminum for ease of movement. Some lateral systems use polyethylene (PE) pipe. Mainline systems are often buried, with risers extending to the ground surface each 50 to 200 feet (15 to 60 m) to which laterals are connected. Typical sprinkler operat-

ing pressures are 40 to 60 pounds per square inch (270 to 410 kPa). Crops irrigated using hand-move systems may need to have sufficiently deep roots or high-soil water-holding capacity, such that the laterals do not have to be returned to a specific location within less than about 5 days, but this depends on the availability of sprinkler pipe, labor, and water supply flow rate.

The job of moving a hand-move system requires more than twice the amount of time per irrigated acre and is not nearly as easy as the job of moving an end-tow, side-roll, or side-move system. If the wet soil is soft or sticky, even more labor is required to move each section of a hand-move system. Nevertheless, a major inconvenience of mechanical move systems occurs when the laterals reach the end of an irrigation cycle. When this happens with a hand-move system, the laterals at the field boundaries can be disassembled, loaded on a trailer, and hauled to the starting position at the opposite boundary. A mechanical-move lateral cannot be disassembled so easily, so an irrigator might decide to deadhead it back to its starting position. This operation is time consuming, especially when trail tubes are involved. However, in practice it is not uncommon to disassemble side-roll laterals after each irrigation, especially when labor costs are not prohibitive.

(2) End-tow lateral

An end-tow lateral system is similar to one with hand-move laterals except the system consists of rigidly coupled lateral pipe connected to a mainline. The mainline should be buried and positioned in the center of the field for convenient operation. Laterals are towed lengthwise over the mainline from one side to the other (fig. 11-4). After draining the pipe through automatic quick drain valves, a 20- to 30-horsepower tractor can easily pull a quarter-mile, 4-inch (100 mm) diameter lateral.

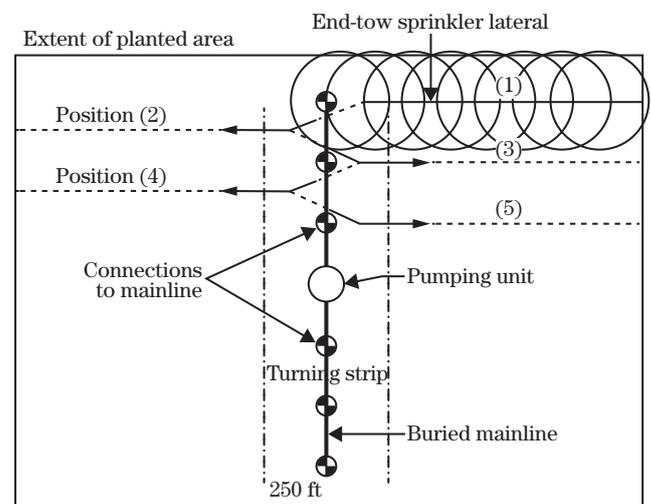
Two carriage types are available for end-tow systems. One is a skid plate attached to each coupler to slightly raise the pipe off the soil, protect the quick drain valve, and provide a wear surface when towing the pipe. Two or three outriggers are required on a quarter-mile lateral to keep the sprinklers upright. The other type uses small metal wheels at or midway between each coupler to allow easy towing on sandy soils.

End-tow laterals are the least expensive mechanical move systems; however, they are not well adapted to small or irregular areas, steep or rough topography,

row crops planted on the contour, or fields with physical obstructions. They work well in grasses, legumes, and other close-growing crops and fairly well in row crops, but the laterals can be easily damaged by careless operation such as moving them before they have drained, making too sharp an “S” turn, or moving them too fast. They are not, therefore, recommended for projects where the quality of the labor is undependable.

When used in row crops, a 200- to 250-foot-wide turning strip is required along the length of the mainline (fig. 11-4). The turning strip can be planted in alfalfa or grass. Crop damage in the turning areas can be minimized by making an offset equal to one-half the distance between lateral positions each time the lateral is towed across the mainline instead of a full offset every other time. Irrigating a tall crop such as corn requires a special crop planting arrangement such as 16 rows of corn followed by four rows of a low growing crop that the tractor can drive over without causing much damage.

Figure 11-4 Schematic of the move sequence between lateral positions for end-tow sprinklers with a buried mainline, and a pumping unit in the center of the field



A relatively new type of end-tow sprinkler system uses sprinklers in pods, spaced evenly along a line with skid plates which help hold the pods in an upright position. The line is pulled by a tractor or other vehicle to each irrigating position, but it is not moved while in operation. The pods can be designed to prevent damage due to livestock or horses stepping on the sprinklers, and they are typically used in pasture irrigation.

(3) Side-roll lateral

A side-roll lateral system, often referred to as wheel lines, is similar to a system with hand-move laterals. The lateral pipes are rigidly coupled together, and each pipe section is supported by a large wheel (fig. 11–5). The lateral line forms the axle for the wheels, and when a torque is applied the line rolls sideways. This unit is moved mechanically by an engine mounted at the center of the line or by an outside power source at one end of the line.

Side-roll laterals work well in low-growing crops. They are best adapted to rectangular fields with fairly uniform topography and no physical obstructions, but are often used on irregular field shapes. The diameter of the wheels should be selected so that the lateral pipe clears the mature crop and so that the specified lateral move distance is a whole number of rotations of the line. For example, for a 60 foot (18 m) move, use three rotations of a 76.4-inch (1.9 m) diameter wheel,

and for a 50 foot (15.3 m) move, use three rotations of a 64-inch (1.6 m) diameter wheel. In some cases a 6-foot-wheel diameter is used to provide sufficient crop clearance, whereby one rotation of the wheel is approximately 20 feet (6 m), so that five revolutions is approximately 100 feet. Then, in one irrigation the sets are in alternating moves of two and three revolutions, and in the next irrigation they are alternating sets of three and two revolutions, thereby providing an effective lateral spacing of about 50 feet (15.3 m) for each pair of irrigations.

Side-roll laterals up to 2,000 feet or longer can be satisfactory for use on close-planted crops and smooth topography. For rough or steep topography and for row crops with deep furrows, such as potatoes, laterals up to a quarter-mile (400 m) long are recommended, but the maximum length depends on many factors, such as the crop density, field topography, and pipe strength. Spacing of sprinklers along laterals is generally 30 to 40 feet (9–12 m). Typically, 4- or 5-inch-diameter aluminum tubing is used for laterals. For a standard quarter-mile lateral on a close-spaced crop at least three lengths of pipe to either side of a center power unit should be 0.072-inch heavy walled aluminum tubing to prevent the pipe from twisting and collapsing during changes in set. For longer lines and in deep-furrowed row crops or on steep topography heavier walled tubing should be used, enabling the laterals to roll more smoothly and uniformly, and with less chance of breaking. Mainline systems and operating pressures are as previously described for hand lines.

Figure 11–5 Side-roll sprinkler lateral (with drag lines, or trail tubes) in operation



A well designed side-roll lateral should have quick drains at each coupler so that it can be turned off, drained, and moved within 30 minutes. All sprinklers should be provided with a self leveler so that each sprinkler will be upright, regardless of the position at which the lateral pipe is stopped. In addition, the lateral should be provided with at least two wind braces, one on either side of the power mover and with a flexible or telescoping section to connect the lateral to the mainline hydrant valves.

Trail tubes, or drag lines, are sometimes (although infrequently) added to heavy walled 5-inch side-roll laterals. With sprinklers mounted along the trail tubes, the system has the capacity to irrigate more land than the conventional side-roll laterals. Special couplers with a rotating section are needed so the lateral can be rolled forward. Quick couplers are also required at the

end of each trail tube so they can be detached when a lateral reaches its last operating position. The lateral must be rolled back to the starting location where the trail tubes are, then reattached for the beginning of a new irrigation cycle.

(4) Side-move lateral

Side-move laterals, relatively rare, are moved periodically across the field in a manner similar to side-roll laterals. An important difference is that the pipeline is carried above the wheels on small A-frames instead of serving as the axle. Typically, the pipe is carried 5 feet (1.5 m) above the ground and the wheel carriages are spaced 50 feet (15 m) apart. A trail tube with 11 sprinklers mounted at 30 foot (9 m) intervals is pulled behind each wheel carriage. Thus, the system can wet a strip 320 foot (100 m) wide, allowing a quarter-mile-long line to irrigate approximately 11 acres at a setting. This system produces high uniformity and low application rates.

Side-move lateral systems are suitable for most field and vegetable crops. For field corn, however, the trail tubes cannot be used, and the A-frames must be extended to provide a minimum ground clearance of 7 feet. Small gun sprinklers (60 to 100 gpm, or 4 to 6 lbs) mounted at every other carriage will irrigate a 150-foot- (45 m) wide strip, and a quarter-mile-long lateral can irrigate 4.5 acres (1.8 ha) per setting. Application rates, however, are relatively high (approximately 0.5 in/h, or 1.3 cm/h).

(5) Fixed sprinklers

A fixed-sprinkler system has enough lateral pipe and sprinkler heads so that none of the laterals need to be moved for irrigation purposes after being placed in the field. Thus, to irrigate the field, the sprinklers only need to be cycled on and off. The three main types of fixed systems are those with solid-set portable hand-move laterals, buried or permanent laterals, and sequencing valve laterals. Most fixed-sprinkler systems have small sprinklers spaced 30 to 80 feet (9–24 m) apart, but some systems use small gun sprinklers spaced 100 to 160 feet (30–50 m) apart.

Solid-set portable—Solid-set portable systems (fig. 11-6) are often used for potatoes and other high-value crops where the system can be moved from field to field as the crop rotation or irrigation plan for the farm is changed. These systems are sometimes moved from field to field to germinate such crops as lettuce that

require irrigation up to three times per day, but that are then furrow irrigated following germination and root establishment. Moving the laterals into and out of a field requires much labor, although this requirement can be reduced by the use of special trailers on which the portable lateral pipe can be stacked by hand. After a trailer has been properly loaded, the pipe is banded in several places to form a bundle that is lifted off the trailer at the farm storage yard with a mechanical lifter. The procedure is reversed when returning the laterals to the field for the next season. In some cases where fields are flat and furrows are large, such as in the Imperial Valley of California, the laterals can be floated out of the germinated field using furrow irrigation. The laterals are disassembled section by section at the field edge. This reduces the need for foot traffic in wet fields and reduces labor requirements.

Buried laterals—Permanent, buried laterals are placed underground 18 to 30 inches (45–75 m) deep with only the riser pipe and sprinkler head above the surface. Many systems of this type are used in citrus groves, orchards, vineyards, and other crops of relatively high value. The sequencing valve lateral may be buried, laid on the soil surface, or suspended on cables above the crop. The heart of the system is a valve on each sprinkler riser that turns the sprinkler on or off when a control signal is applied. Some systems use a pressure change in the water supply to activate the valves. The portable lateral, buried (or permanent) lateral, and sequencing valve lateral systems can be

Figure 11-6 Hand-move sprinkler laterals in a solid-set portable configuration on rolling topography



automated by the use of electric or pneumatic valves which are activated by controllers. These automatic controllers can be programmed for irrigation, crop cooling, and frost control and can be activated by soil moisture measuring and temperature sensing devices.

Gun and boom sprinklers—Gun (giant, or big gun) sprinklers have 5/8 inch (1.6 cm) or larger nozzles attached to long (12 or more inches) discharge tubes. Most gun sprinklers are rotated by means of a rocker-arm drive and most can be set to irrigate a part circle (fig. 11-7).

Boom sprinklers have a rotating 110- to 250-foot (35–75 m) boom supported in the middle by a tower mounted on a trailer. The tower serves as the pivot for the boom that is rotated once every 1 to 5 minutes by jets of water discharged from nozzles. The nozzles are spaced and sized to apply a fairly uniform application of water to a circular area over 300 feet (90 m) in diameter. Tower movement is periodic and manual.

Gun or boom sprinkler systems can be used in many similar situations and are well adapted to supplemental irrigation and for use on irregularly shaped fields with obstructions. Each has its comparative advantages and disadvantages. Gun sprinklers are considerably less expensive and are simpler to operate; consequently, there are many more gun than boom sprinklers in

use. However, guns require high pressure (80–150 lb/in², 500–1,000 kPa) and therefore energy costs are higher. Gun and boom sprinklers usually discharge more than 100 gallons per minute (6.3 lps) and are operated individually rather than as sprinkler-laterals. A typical sprinkler discharges 500 gallons per minute (30 lps) and requires 80 to 100 pounds per square inch (550–700 kPa) or higher operating pressure.

Gun and boom sprinklers can be used on most crops, but they produce relatively high application rates and large water drops that tend to compact and seal the soil surface and create runoff problems. Therefore, these sprinklers are most suitable for coarse-textured soils having high infiltration rates and for relatively mature crops that need only supplemental irrigation. Gun and boom sprinklers are usually not recommended for use in extremely windy areas because their distribution patterns may become too distorted. Large gun sprinklers are usually trailer or skid mounted and like boom sprinklers are towed from one position to another by a tractor. A disadvantage of boom sprinklers is that they are unstable and can tip over when being towed over rolling or steep topography.

(b) Continuous-move sprinkler systems

Center-pivots—Center pivot systems sprinkle water from a moving lateral pipeline. The center pivot lateral is fixed at one end and rotates to irrigate a large circular area (or portion thereof). The fixed end of the lateral, called the pivot point, is connected to the water supply. The lateral consists of a series of spans with steel trusses ranging in length from 90 to 250 feet (25 to 75 m) and carried about 10 feet (3 m) above the ground by drive units (sometimes referred to as towers). A drive unit consists of an A-frame supported on motor-driven wheels (fig. 11-8). The last downstream drive unit moves continuously or intermittently to set the rotation speed, and all other drive units move intermittently to maintain the lateral pipe in an approximately straight alignment.

The most common center-pivot lateral uses 6 or 6-5/8 inch pipe, is nearly a quarter of a mile long (1,320 ft, or 400 m), and irrigates the circular portion (126 acres plus 2 to 10 acres more depending on the range of the end sprinklers) of a quarter section (160 acres). However, laterals, as short as 220 feet and as long as a half mile (800 m), are available. Laterals longer than

Figure 11-7 Part-circle gun sprinkler with rocker-arm drive



a quarter mile generally have one or more initial pipe spans of 8 or even 10 inch pipe. A guidance system composed of devices installed at each drive unit keep the lateral in a line between the pivot and end-drive unit, and the end-drive unit is set to control the speed of rotation. Mainlines supplying center pivots are buried and may be comprised of networks that supply multiple center pivot systems or single pipelines connecting the water source (well, pond, or canal) to a single center-pivot system.

The moving lateral pipeline is fitted with sprinklers to spread the water evenly over the circular field. The area to be irrigated by a nozzle along the lateral becomes progressively larger toward the moving end, and the lateral speed becomes progressively faster. Therefore, to provide uniform application, the sprinklers must be designed to have progressively greater discharges, closer spacing, or both, toward the moving end. Typically, the application rate near the moving end is about 2.5 inches per hour (64 mm/h). This exceeds the intake rate of many soils except during the first few minutes at the beginning of each wetting event. To minimize runoff, the laterals are usually timed to rotate once every 14 to 84 hours depending on the soil's infiltration characteristics, the system's capacity, and the maximum desired soil moisture deficit.

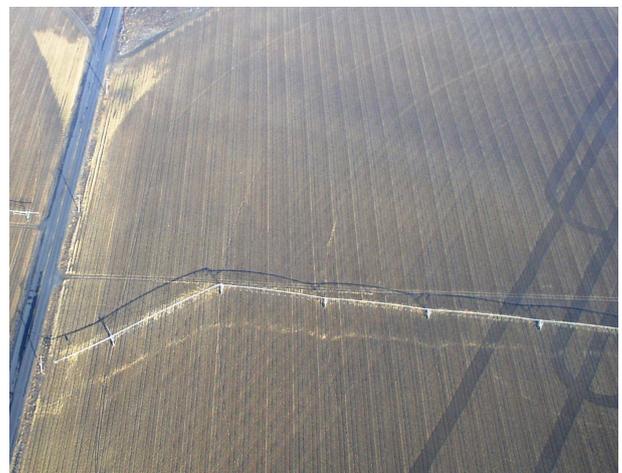
Five types of power units commonly used to drive the wheels on center pivots are electric motors, hydraulic oil motors, water pistons, water spinners and turbines, and air pistons. The first pivots were powered by water pistons; however, electric motors are by far most common today because of their speed, reliability, and ability to run backwards and forwards. Electric and hydraulic oil motors allow the system to be operated dry (while not irrigating).

Self-propelled, center-pivot sprinkler systems are suitable for almost all field crops, but require fields free from any obstructions above ground, such as telephone lines, electric power poles, buildings, and trees. They are best adapted for use on soils having high intake rates and on uniform topography. When used on soils with low intake rate and irregular topography, any runoff can cause erosion and puddles that may interfere with the uniform movement of the lateral and traction of wheels. If these systems are used on square fields, some means for irrigating the four corners must be provided, or other uses made of the area not irrigated. In a 160-acre quarter-section field, about 30 acres are not irrigated by the center-pivot system unless the pivot is provided with a special corner irrigating apparatus (fig. 11–9). With some corner systems only about 8 acres are left unirrigated.

Figure 11–8 Outer end of a center-pivot lateral in operation



Figure 11–9 Corner system in operation on a center pivot



Most pivot systems are permanently installed in a given field. However, in supplemental irrigation areas or for dual cropping, it may be practical to move a standard quarter-mile center-pivot lateral back and forth between two 130 acre fields. Many modern center pivot systems are equipped with remotely operated controls that use radio transmission and often internet delivery. Some systems provide audio and visual alarms upon system or water supply malfunction, including calling operators via radio or mobile phone. Some locations also have control centers for monitoring many center pivots and coordinating operations and maintenance activities (fig. 11–10).

Traveling sprinkler—The traveling sprinkler, or traveler, is a high-capacity sprinkler fed with water through a flexible hose, mounted on a self-powered chassis, and travels along a straight line while watering. The most common type of traveler used for agriculture in the United States has a 150 to 500 gallons per minute (10 to 30 lps) gun sprinkler that is mounted on a moving vehicle and wets a diameter of more than 400 feet (120 m). The unit is often equipped with a water piston or turbine-powered winch that reels in the cable. The cable guides the unit along a path as it tows a flexible high-pressure hose (lay-flat or round) that is connected to a pressurized water supply system. The typical hose is often 4 inches (100 mm) in diameter and approximately 660 feet long (200 m), allowing the unit to travel up to 1,320 feet (400 m) unattended (fig. 11–11).

In some systems, after use, the hose can be drained, flattened, and wound onto a reel. In other cases the plastic hose does not flatten when empty, and the reel assembly is parked at one end of the field and a tractor or truck pulls the gun-sprinkler carriage to the other end of the field, in a straight line. Then, the water is turned on and the reel slowly rotates, pulling the gun sprinkler in. When the carriage the gun is mounted on arrives at the reel assembly, a mechanism shuts off the system. The unit is moved to the next row and the process repeats until the entire field area is irrigated. The reel assembly rotates using a hydraulic motor which is driven by the water entering the unit, reducing the pressure substantially. The long hose also causes a significant pressure loss. Thus, sufficient supply-line pressure is needed to operate such a system, and it is most convenient to have the water supply at one end of the field, not in the middle of the field. The operator can use controls to adjust the rotation speed of the reel assembly and apply the desired depth of irrigation water.

Some traveling sprinklers have a self-contained pumping plant mounted on the vehicle that pumps water directly from an open ditch while moving. The supply ditches replace the hose. Travelers can also be equipped with boom sprinklers instead of guns. Boom sprinklers can be fixed (fig. 11–12) or have rotating arms 60 to 120 feet (18 to 36 m) long from which water is discharged through nozzles as described.

Figure 11–10 Computer screens at a control center for managing several hundred center pivots

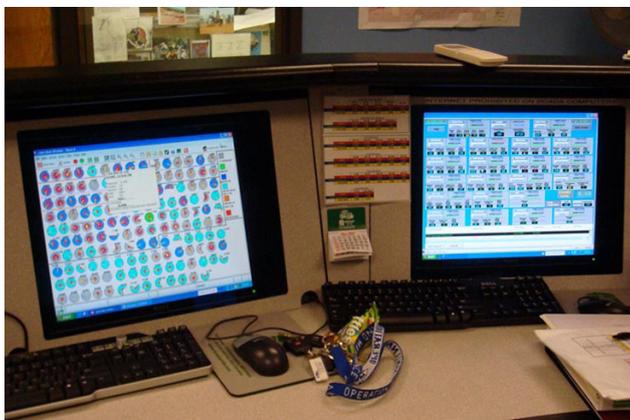


Figure 11–11 Hose-fed traveling gun type sprinkler



As the traveler moves along its path, the sprinkler wets a strip of land about 400 feet (120 m) wide rather than the circular area wetted by a stationary sprinkler. After the unit reaches the end of a travel path, it is moved and set up to water an adjacent strip of land. The overlap of adjacent strips depends on the distance between travel paths and on the diameter of the area wetted by the sprinkler. A part-circle sprinkler is frequently used so that the dry part of the pattern is over the tow path. That ensures the unit travels on dry ground (fig. 11–13).

Figure 11–13 shows a plan view of a typical traveling sprinkler layout for an 80 acre (32 ha) field. The entire field is irrigated from 8 tow paths, each 1,320 feet (400 m) long and spaced 330 feet (100 m) apart. Traveling sprinklers require the highest pressures of any system. In addition to the 65 to 100 pounds per square inch required at the sprinkler nozzles, hose friction losses add another 20 to 40 pounds per square inch to the required system pressure. Therefore, travelers are best suited for supplemental irrigation where seasonal irrigation requirements are small, thus mitigating the high power costs associated with high operating pressures.

Traveling sprinklers can be used in tall field crops such as corn and sugarcane and have even been used in orchards. They have many of the same advantages and disadvantages described under gun and boom sprinklers; however, because they are moving, traveling sprinklers have a higher uniformity and lower application rate than guns and stationary booms. The

application uniformity of travelers is only fair in the central portion of the field, and 100- to 200-foot-wide strips along the ends and sides of the field are usually poorly irrigated.

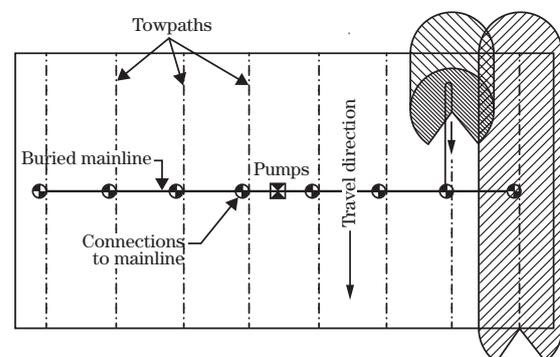
Linear-move lateral—Self-propelled linear-move laterals combine the structure and guidance system of a center-pivot lateral with a traveling water feed system similar to that of a traveling sprinkler. Linear-move laterals require rectangular fields free from obstructions. Measured water distribution from these systems has shown the highest application uniformity coefficients for single irrigations under both calm and windy conditions.

Some linear-move systems pump water from open ditches, but some are supplied by a flexible hose so that some undulation in ground elevation can exist (fig. 11–14). Other systems utilize automated coupling mechanisms in which the water is supplied through evenly-spaced hydrant valves along a buried mainline pipe. The automated coupling systems use swing arms with swivel joints to connect to the hydrants as the system moves down the field, and they are suitable for application in undulating topographies, but are much more expensive (and mechanically complex) than linear-move systems that take water from a ditch or a flexible hose. In any case, the guidance system must be robust to avoid shutdowns. Common guidance systems utilize an elevated cable or furrow along one side of the field. Other systems use global positioning satellite (GPS) technology to guide lateral movement.

Figure 11–12 Fixed-arm boom assembly with low-pressure spray nozzles for a traveler system



Figure 11–13 Typical layout for a traveling sprinkler with a buried mainline in the center of a rectangular field



Linear-move systems that pump from ditches must have a self-contained pump and motor, usually powered by an on-board diesel engine or motor fed via an auxiliary electrical cable. Hose-pull systems generally obtain necessary water pressure from the water source. An auxiliary electrical cable is often used to provide power for drive towers.

A major disadvantage of linear-move systems, as compared to center-pivot systems, is the problem of bringing the lateral back to the starting position. Since the center-pivot lateral operates in a circle, each irrigation cycle automatically ends at the beginning of the next, but because the linear-move lateral moves from one end of the field to the other, the ending position is the maximum distance away from the starting position; down time results if the machine is returned dry (not applying water). Sometimes, linear-move systems are operated in both directions, applying half of the maximum soil water deficit during each pass. However, the linear-move system can irrigate all of a rectangular field, whereas center-pivot systems can irrigate only an essentially circular area.

A relatively new type of linear-move system can pivot at one end when reaching the end of the field, so that the lateral is half as wide as the irrigated area. On one pass the lateral irrigates half of the field, and on the re-

turn pass it irrigates the other half. When the irrigation is complete, the lateral again pivots to return to the starting position. But while irrigating the lateral moves linearly just as with traditional linear-move systems. This type of system combines some features of linear moves and center pivots.

(c) Other sprinkler systems

Concerns about the availability and cost of energy has been increasing interest in the use of perforated pipe, hose-fed sprinklers operating on a grid pattern, and micro sprinklers. These systems afford a means of irrigating with low pressure (5–20 lb/in², or 30–140 kPa). Often, gravity (elevation difference) pressure is sufficient to operate these systems without pumps. Furthermore, inexpensive low-pressure pipe such as unreinforced concrete and thin-wall plastic can be used to distribute the water. These systems do have the disadvantage of a high labor requirement if moved periodically rather than being fixed in place.

Perforated pipe—This type of sprinkle irrigation is not commonly used for agricultural irrigation, though they can be inexpensive compared to other types of sprinkler systems. Perforated pipe systems spray water from one-sixteenth-inch-diameter or smaller holes drilled at uniform distances along the top and sides of a lateral pipe or hose. The holes are sized and spaced so as to apply water uniformly between adjacent lines of perforated pipeline (fig. 11–15). Such systems can operate effectively at pressures between 5 and 30 pounds per square inch, but can be used only on coarse-textured soils such as loamy sands with a high capacity for infiltration because the application rate is quite high. The application rate tends to change rapidly along the length of the lateral, so the water application uniformity is relatively low, compared to most sprinkler systems.

Hose-fed sprinkler grid—These systems use hoses to supply individual small sprinklers that operate at pressures as low as 5 to 10 pounds per square inch. They can also produce if the sprinklers are moved in a systematic grid pattern with sufficient overlap. However, these systems are not in common use except in home gardens and turf irrigation, although they do hold promise for rather broad use on small farms in developing countries where capital and power resources are limited and labor is relatively abundant.

Figure 11–14 Linear-move system with a flexible hose water supply



Orchard sprinklers—Orchard sprinklers are small spinners or impact sprinklers designed to cover the space between adjacent trees with little or no overlap between the areas wetted by neighboring sprinklers. Orchard sprinklers operate at pressures between 10 and 30 pounds per square inch (70 and 200 kPa), and typically the diameter of coverage is between 5 and 30 feet (2 and 10 m). Discharge rates range from 5 to 100 gallons per hour (20 to 375 lph). Orchard sprinklers are located under the tree canopies to provide approximately uniform volumes of water for each tree, but without wetting the tree foliage. Water should be applied fairly evenly to areas wetted, although some soil around each tree may receive little or no irrigation (fig. 11–16). Individual sprinklers can be supplied by aluminum laterals or hoses and periodically moved to cover several positions or an orchard sprinkler can be provided for each position on lateral lines that are similar to those used for drip irrigation. Orchard sprinklers are typically fixed to reduce labor costs and to provide some degree of frost protection.

Figure 11–15 A perforated-pipe lateral in operation



623.1102 Planning concepts

Planning for complete farm sprinkler systems includes consideration of crops and crop rotations, water quality, and the types of soils found in the specified design area. A farm sprinkle-irrigation system includes sprinklers and related hardware: laterals, submains, mainlines, pumping plant and boosters, filtration equipment, operation control equipment, and other accessories required for the effective application of water. Farm systems may also experience other changes, such as expansion in irrigated area or change in cropping patterns. For this reason, many experienced system designers choose to install supply and mainlines of larger than required capacity, allowing for possible future expansions or increased flow rate requirements. This approach can prevent the need to install additional pipe capacity later, saving costs in the long run. Figure 11–17 shows a periodic-move system with buried mainlines and multiple sprinkler laterals operating in rotation around the mainlines.

Large farm systems are usually made up of several field systems. Considerations of distribution efficiency, labor utilization, and power economy may be entirely different for field systems than for complete farm systems. Field systems can be fully portable, semiportable, or permanent. Inability to recognize the funda-

Figure 11–16 Orchard sprinklers operating from a lateral line



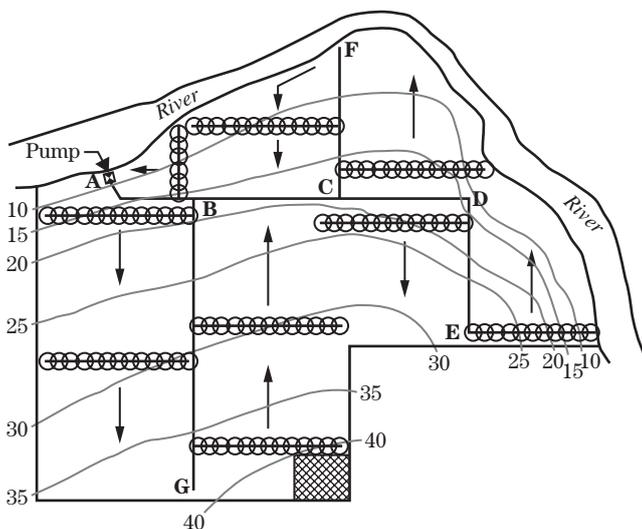
mental difference between field and farm systems, either by the planner or the owner (or both), has led to poorly planned systems of both kinds.

Failure to anticipate the required capacity of the ultimate layout has led to many piecemeal systems with poor distribution efficiencies, excessive initial costs, and high annual water application charges. This situation is not always the fault of the system planner, who may not always be informed as to whether future expansion is intended; however, the planner has a responsibility to inform the owner of possible considerations for future development when preparing a field system plan.

(a) Sprinkle irrigation system design

Sprinkle irrigation design can involve many steps, as shown, and several of these involve iterations to produce acceptable design alternatives. The first six steps of the design procedure are often referred to as the preliminary design factors. Some of these steps are described in more detail in other NRCS handbooks.

Figure 11-17 Layout of a periodic-move sprinkler system with several laterals for irrigating pastures. Some of the laterals will have changing lengths for different positions to accommodate the irregular field areas.



Also, some aspects of sprinkler system design and evaluation are covered in the American Society of Agricultural and Biological Engineers (ASABE) Standards and Practices, including S263, S435, S436, S447, S491, and EP409.

Step 1: Make an inventory of available resources and operating conditions. Include information on soils, topography, water supply, source of power, crops, and farm operation schedules.

Step 2: From the local irrigation guide or alternative, determine the maximum depth or quantity of water to be applied for the design scenario. Follow the instructions in 210-NEH, Part 652, Chapter 2, Soil-Plant-Water Relations, to compute this depth.

Step 3: Determine from the local irrigation guide the design period daily consumptive use rates and the annual irrigation requirements for the crops to be grown. System design is normally based on peak irrigation requirements. The procedure is described more fully in 210-NEH, Part 652, Chapter 3, Crops.

Step 4: Determine the maximum irrigation frequency of irrigation based on the maximum net depth to apply and the peak crop consumptive use rate. The procedure is described more fully in 210-NEH, Part 652, chapter 4. However, this step is often unnecessary for fully automated fixed systems or for center-pivot systems which may be designed to apply water more frequently than that which is required by the water storage capacity of the soil.

Step 5: Determine capacity requirements of the system as described in 210-NEH, Part 652, chapter 4.

Step 6: Assess the potential for water-application rate issues. Estimate maximum (not necessarily optimum) rates.

Step 7: Consider several alternative types of sprinkler systems. The landowner should be given alternatives from which to make a selection.

Step 8: For periodic-move and fixed sprinkler systems:

- Determine sprinkler spacing, discharge, nozzle size, and operating pressure for the optimum water-application rate.

- Estimate number of sprinklers operating simultaneously, required to meet system capacity requirements.
- Determine the best layout of main and lateral lines for simultaneous operation of the approximate number of sprinklers required.
- Make necessary final adjustments to meet layout conditions.
- Determine sizes of lateral line pipe required.
- Compute maximum total pressure required for individual lateral lines.

Step 9: For continuous-move sprinkler systems:

- Select the type of sprinkle nozzle desired.
- Set the minimum allowable nozzle pressure.
- Determine the desired system flow rate.
- Select the type of system drive (i.e., electric or hydraulic).
- Determine the maximum elevation differences that will be encountered throughout the movement of the system.
- Select the system pipe (or hose) diameter based on economic considerations.
- Calculate the system inlet pressure required to overcome friction losses and elevation differences and provide the desired minimum nozzle pressure.

Step 10: Determine required size of mainline pipe.

Step 11: Check mainline pipe sizes for power economy.

Step 12: Determine maximum and minimum operating conditions.

Step 13: Select pump and power unit for maximum operating efficiency within range of operating conditions. The selection of a pump and power plant is described in 210-NEH, Part 623, Chapter 8, Irrigation Pumping Plants.

Step 14: Prepare plans, schedules, and instructions for proper layout and operation.

Figure 11-18 is useful for organizing the information and data developed through carrying out these steps. The figure contains four columns that can be used for different crops or for different fields or zones on the same farm. Section VI of the figure is set up specifically for periodic-move and fixed-sprinkler systems. It can be used for continuous-move systems (fig. 11-19) by slight modifications and including:

- maximum application rate (in/h)
- time per revolution (center pivot), or per single run (h)
- speed of end tower (center pivot), or of the machine or sprinkler (ft/min)

The farmer should be consulted concerning financial, labor, and management capabilities. The system selection, layout, and hydraulic design process can proceed once the data on farm resources have been assembled.

(b) Application depth requirements

210-NEH, Section 15, chapters 1 and 2, provide detailed information about crop water requirements and required irrigation application depths. However, it is appropriate to include some of the basic calculations here for completeness. For irrigation system design purposes, the required net application depth per irrigation has traditionally been taken to be a function of a management allowed deficit (MAD), the soil water-holding capacity (W_a), and the crop root depth (Z), as:

$$AD = \frac{MAD}{100} W_a Z \quad (\text{eq. 11-3})$$

where:

- AD = the maximum net depth of water to apply per irrigation, in or mm, also referred to as allowable depletion
- MAD = management allowed deficit (usually 25 to 60 percent)
- W_a = the water-holding capacity, in/ft or mm/m, a function of soil texture and structure, equal to field capacity minus wilting point
- Z = the effective crop root depth, ft or mm

Figure 11–18 Sprinkle irrigation system design data sheet

	Variable name	Section, table, or equation	Zone 1	Zone 2
I. General				
(a) Pressure regulation (Y/N)				
(b) Estimated surface storage of water				
(c) Estimated preseason residual soil water				
II. Crop				
(a) Root depth (ft)	Z	Table 11–3		
(b) Growing season (days)		external data		
(c) Peak water use rate (in/d) over maximum interval	u_d	external data		
(d) Seasonal water use (in)	U	external data		
III. Soils				
(a) Surface texture				
Depth (ft)	Z_1	external data		
Available water-holding capacity (in/ft)	Wa_1	Table 11–2		
(b) Subsurface texture				
Depth (ft)	Z_2	external data		
Available water-holding capacity (in/ft)	Wa_2	Table 11–2		
(c) Management allowable depletion (%)	MAD	Table 11–3		
(d) Allowable depletion (in)	AD	Eq. 11–3		
(e) Maximum intake rate (in/h)	I_x	Table 11–5		
IV. Irrigation				
(a) Maximum interval during peak-use period (days)	f^*	Eq. 11–13		
(b) Days off each irrigation interval (days)	days off			
(c) Operating time to complete irrigation cycle (days)	f	Eq. 11–14		
(d) Net depth (in)	d_n	Eq. 11–5		
(e) Design uniformity coefficient (%)	CU	Table 11–6		
(f) Percent of field adequately irrigated (%)	pa	external data		
(g) Distribution efficiency (%)	DE_{pa}	Table 11–9		
(h) Effective portion of applied water to ground (%)	R_e	Fig. 11–28 Eq. 11–28		
(i) Application efficiency (%)	E_{pa}	Eq. 11–37		
(j) Leaching requirement	LR	Eq. 11–8		
(k) Gross depth (in)	d_g	Eq. 11–9		
V. Water requirements				
(a) Net seasonal (in)	Pe	external data		
(b) Effective rain (in)		external data		
(c) Stored moisture (in) for season		external data		
(d) Net irrigation (in) for season	U	external data		

Figure 11-18 Sprinkle irrigation system design data sheet—continued

	Variable name	Section, table, or equation	Zone 1	Zone 2
(e) Gross irrigation (in) for season				
(f) Number of irrigations	N_{IS}	Eq. 11-11		
VI. System capacity				
(a) Time to move set (h)	t_m	external data		
(b) Set time (h)—decimal	t_s	Eq. 11-53		
(c) Set time (h)—integer	t_s	Eq. 11-59		
(d) Average application rate (in/h)	I	Eq. 11-57		
(e) Revised gross depth (in)	d_g	Eq. 11-55		
(f) Settings per day	n_s	Eq. 11-58		
(g) Days of operation per interval	f	Eq. 11-14		
(h) Area irrigated (ac)	A	external data		
(i) Operating time per day (h)	T	Eq. 11-60		
(j) Preliminary system capacity (gpm)	Q	Eq. 11-12		

Figure 11–19 Center-pivot design data sheet.

	Variable name	Section or equation number	Zone 1	Zone 2
I. General				
(a) Pressure regulation (Y/N)				
(b) Estimated surface storage of water				
(c) Estimated preseason residual soil water				
II. Crop				
(a) Root depth (ft)	Z	Table 11–3		
(b) Growing season (days)		external data		
(c) Peak water use rate (in/day) over maximum interval	u_d	external data		
(d) Seasonal water use (in)	U	external data		
III. Soils				
(a) Surface texture				
Depth (ft)	Z_1	external data		
Available water-holding capacity (in/ft)	W_{a1}			
(b) Subsurface texture				
Depth (ft)	Z_2			
Available water-holding capacity (in/ft)	W_{a2}			
(c) Management allowable depletion (%)	MAD	Table 11–3		
(d) Allowable depletion (in)	AD	Eq. 11–3		
(e) Maximum intake rate (inch per hour)	I_x	Table 11–4		
IV. Irrigation				
(a) Maximum interval during peak-use period (days)	f^r	Eq. 11–13		
(b) Days off each irrigation interval (days)	days off			
(c) Operating time to complete irrigation cycle (days)	f	Eq. 11–14		
(d) Net depth (in)	d_n	Eq. 11–5		
(e) Design uniformity coefficient (%)	CU	ASABE S436		
(f) Percent of field adequately irrigated (%)	pa	external data		
(g) Distribution efficiency (%)	DE_{pa}	Table 11–9		
(h) Effective portion of applied water to ground (%)	R_e	Fig. 11–28, Eq. 11–37		
(i) Application efficiency (%)	E_{pa}	Eq. 11–48		
(j) Gross depth (in)	d_g	Eq. 11–9		
V. Water requirement				
(a) Net seasonal (in)				
(b) Effective rain (in)	P_e	external data		
(c) Stored moisture (in) for season		external data		
(d) Net irrigation (in) for season	U	external data		
(e) Gross irrigation (in) for season				

Figure 11–19 Center-pivot design data sheet—continued

	Variable name	Section or equation number	Zone 1	Zone 2
(f) Number of irrigations	N_{is}	Eq. 11–11		
VI. System capacity				
(a) Average application rate (in/h)	I	Eq. 11–228		
(b) Time per revolution (h)	$t_{rotation}$	external data		
(c) Approximate distance of end tower from pivot (ft)				
(d) End-tower speed (ft/min)	Speed _R	Eq. 11–232		
(e) Maximum radius (w/corner and/or end gun)	R	external data		
(f) Total area irrigated (ac)	A	external data		
(g) Maximum application rate at end of lateral (in/h)	$(I_x)_{r=R}$	Eq. 11–229		
(h) Maximum nozzle elevation difference along circular path (ft)				
(i) Estimated design nozzle pressure (lb/in ²)				
(j) Use pressure regulators? (yes or no)				
(k) Surface storage of water (in)		Table 11–41		
(l) Operating time per day (h)	T	Eq. 11–60		
(m) Preliminary system capacity (gpm)	Q	Eq. 11–12		

For most agricultural soils, field capacity (FC) is attained about 1 to 4 days after a complete (leaving zero water deficit in the rootzone) irrigation. The actual water depth applied may be less than AD if irrigation frequency is higher than needed during the peak-use period, but the context is for system design. MAD can also serve as a safety factor because many values (soil data, crop data, weather data, and others) are not precisely known. It may be assumed that crop yield and crop ET begins to decrease below maximum potential levels when actual soil water is below MAD (for more than about 1 day).

Water-holding capacity for agricultural soils is usually between 10 and 20 percent by volume. W_a is sometimes called total available water (TAW), water-holding capacity (WHC), available water-holding capacity (AWHC). Note that it may be more appropriate to base net irrigation depth calculations on soil-water tension rather than soil-water content, also taking into account the crop type. This is a common criterion for scheduling irrigations through the use of tensiometers.

In the case of layered soils having different values for W_a , AD can be calculated by summing the W_a values according to thickness of each layer within the effective rootzone and applying the same MAD to each layer:

$$AD = \frac{MAD}{100} [W_{a1}Z_1 + W_{a2}(Z - Z_1)] \quad (\text{eq. 11-4})$$

where:

- W_{a1} and W_{a2} = the water-holding capacities of layers 1 and 2
- Z_1 = the depth of the top soil layer
- Z = the effective root zone depth, assuming that $Z \leq Z_1 + Z_2$

In the case of three or more layers, equation 11-4 can be further expanded.

Typically in design of periodic-move systems, the time between irrigations during the peak water use period is maximized to reduce the number of laterals required, lowering capital cost, and to reduce labor requirements. Therefore, the maximum net application depth, d_n , used for the initial iteration of hardware design, is generally set equal to the allowable depletion, AD:

$$d_n = AD \quad (\text{eq. 11-5})$$

where:

- d_n = allowable net water depletion from soil between irrigations, in (mm)

In the design of continuous-move systems, like center-pivots, or fixed systems, such as solid set, d_n applied each irrigation may be less than AD to reduce runoff potential and to reserve a buffer in the soil reservoir to capture any significant rainfall that might occur during irrigation period.

Water-holding capacity

Soils of various textures and structures have varying abilities to retain water. Except in the case of required periodic leaching, any irrigation beyond the field capacity of the soil in the crop root zone is usually considered an economic loss and a potential water quality issue. Table 11-2 gives typical ranges of available water-holding capacities (defined as the field capacity minus permanent wilting point) of soils of different textures and is presented here for convenience. If local data are not available, the listed averages may be used as a guide. For conservative system design purposes, the total amount of soil water available for plant use in any soil is taken to be the sum of the available water-holding capacities of all horizons occupied by plant roots.

(c) Root depth

Typical plant feeder root and total root depth are given in many references; however, the actual depths of rooting of the various crops are affected by soil conditions and should be checked at the site. Where local data are not available and there are no expected root penetration restrictions, table 11-3 can be used as a guide to estimating the effective root depths of various crops, taken primarily from the FAO-24 and FAO-56 publications. The values given are expected, average values of maximum rooting depths and are reached by annual crops near the time of peak water use (and peak crop coefficient). The values represent the depth at which crops will obtain most of the needed water when grown in a deep, well drained, and adequately

irrigated soil. During periods of less root depth, irrigation frequency should be increased, using proportionally smaller application depths at each irrigation.

(d) Management-allowed deficit (MAD)

For periodic-move, and low frequency continuous-move systems, such as traveling sprinklers and linear moves, it is desirable to irrigate as infrequently as practical to reduce labor costs. A general rule of thumb for crops in arid and semiarid regions is that the soil moisture deficit or allowable depletion (AD) within the rootzone should not fall below about 50 percent of the total available water-holding capacity. This percentage is termed the management allowed deficit (MAD). Generally, it is desirable to bring the moisture level back to field capacity with each irrigation, especially with periodic-move systems. The duration of each wetting event is identical. Typical MAD values by crop are listed in table 11-3. Because these are MAD percentages, the planner or designer are encouraged to determine values locally based on local usage and production practices. Generally, a MAD of 40 percent is used for high-value crops or crops having shallow rooting depth, although values of 20 percent or less are sometimes used for high-value, water-sensitive crops. A MAD of 60 percent may be used for some low-value crops with deep roots. A MAD of 50 percent is frequently used.

Local soil conditions, soil management, water management, and economic considerations determine the amount of water used for irrigation and the rate of water application. The standard design approach has been to determine the amount of water needed to fill the entire rootzone to field capacity and, then, to apply at one application a larger amount to account for evaporation, leaching, and efficiency of application. The traditional approach to the frequency of application is to assign a value for MAD, calculate the equivalent depth of water in the rootzone reservoir that can be extracted with no moisture stress and, using the daily consumptive use rate of the plant, determine how long this supply will last. Such an approach is useful as a guide to irrigation requirements and system operation. However, many other factors may affect the amount of irrigation water and the timing of applications for optimal design and operation of a system. In humid regions, it may be necessary to manage soil moisture to capture rainfall during the irrigation period; however, the MAD limitation on soil moisture depletion should be followed for design purposes.

Table 11-2 Available water-holding capacity (W_a) of soils of different texture

Soil texture	Inches of water per foot of depth			Millimeters of water per meter of depth		
	Range		Avg.	range		Avg.
	Min.	Max.		Min.	Max.	
Very coarse sands	0.4	0.8	0.5	30	60	40
Coarse sand, fine sand, and loamy sand	0.8	1.3	1.0	60	100	80
Sandy loam	1.3	1.8	1.5	100	150	130
Very fine sandy loam, loam, and silt loam	1.5	2.3	2.0	130	200	170
Clay loam, silty clay loam, sandy clay loam	1.8	2.5	2.2	150	210	180
Sandy clay, silty clay, clay	1.6	2.5	2.3	130	210	190
Peat and muck soils	2.0	3.0	2.5	170	250	210

Table 11-3 Ranges of effective maximum crop root depths and typical values for management allowed depletion (MAD) for deep, uniform, well-drained soil profiles

Crop	Rooting depth range			Crop	Rooting depth range		
	(ft)	(m)	MAD (%)		(ft)	(m)	MAD (%)
Alfalfa	3.5–6.5	1.0–2.0	55	Maize (grain, silage)	3.5–5.5	1.0–1.7	55
Artichoke	2.0–3.0	0.6–0.9	45	Maize (sweet)	2.5–4.0	0.8–1.2	50
Asparagus	4.0–6.0	1.2–1.8	45	Melons	3.0–5.0	0.9–1.5	40
Avocado	2.0–3.0	0.6–0.9	60	Mint	1.5–2.5	0.4–0.8	40
Banana	1.5–2.5	0.5–0.8	40	Oats	3.5–5.0	1.0–1.5	55
Barley	3.5–5.0	1.0–1.5	55	Olives	4.0–5.5	1.2–1.7	65
Beans (green)	1.5–2.5	0.5–0.7	45	Onions	1.0–1.5	0.3–0.5	30
Beans (dry)	2.0–3.0	0.6–0.9	45	Palm trees	2.5–3.5	0.7–1.0	65
Beets	2.0–3.5	0.6–1.0	50	Parsnip	2.0–3.0	0.6–0.9	40
Berries	2.0–4.0	0.6–1.2	50	Passion fruit	1.0–1.5	0.3–0.5	35
Broccoli	1.5–2.0	0.4–0.6	40	Peas	2.0–3.5	0.6–1.0	40
Brussels sprout	1.5–2.0	0.4–0.6	40	Peppers	1.5–3.5	0.5–1.0	30
Bermuda hay	3.5–5.0	1.0–1.5	55	Pineapple	1.0–2.0	0.3–0.6	50
Cabbage	1.5–2.5	0.5–0.8	45	Pistachios	3.5–5.0	1.0–1.5	40
Canola	3.5–5.0	1.0–1.5	60	Potatoes	1.5–2.0	0.4–0.6	35
Cantaloupe	2.0–4.0	0.6–1.2	40	Pumpkin	3.0–4.0	0.9–1.2	40
Carrots	1.5–3.5	0.5–1.0	35	Radish	1.0–1.5	0.3–0.5	30
Celery	1.0–1.5	0.3–0.5	20	Safflower	3.5–6.5	1.0–2.0	60
Chard	2.5–3.5	0.7–1.0	30	Sisal	1.5–3.5	0.5–1.0	80
Citrus	4.0–5.0	1.2–1.5	50	Sorghum (grain, sweet, millet)	3.5–6.5	1.0–2.0	55
Clover	2.0–3.0	0.6–0.9	50	Sorghum (silage)	3.5–6.5	1.0–2.0	50
Coffee	3.0–5.0	0.9–1.5	60	Soybeans	2.0–4.5	0.6–1.3	55
Conifers	3.5–5.0	1.0–1.5	70	Spinach	1.0–1.5	0.3–0.5	20
Cotton	3.5–5.5	1.0–1.7	60	Squash	2.0–3.0	0.6–0.9	50
Cucumber	2.5–4.0	0.7–1.2	50	Strawberries	0.5–1.0	0.2–0.3	20
Dates	5.0–8.0	1.5–2.5	50	Sugar beets	2.5–4.0	0.7–1.2	55
Deciduous orchards	3.5–6.5	1.0–2.0	50	Sugarcane	4.0–6.0	1.2–1.8	65
Eggplant	2.5–4.0	0.7–1.2	45	Sunflower	2.5–5.0	0.8–1.5	45
Fig	2.5–3.5	0.8–1.0	50	Sweet potatoes	3.5–5.0	1.0–1.5	65
Flax	3.5–5.0	1.0–1.5	50	Switch grass	5.0–6.5	1.5–2.0	60
Grapes	3.5–6.5	1.0–2.0	35–45	Tomatoes	2.0–5.0	0.6–1.5	40
Grass hay	2.0–3.5	0.6–1.0	60	Turf grass	1.5–3.5	0.5–1.0	40
Grass pasture	1.5–5.0	0.5–1.5	60	Turnip (white)	1.5–3.0	0.5–0.9	40
Groundnuts	2.0–3.5	0.6–1.0	50	Walnuts	5.5–8.0	1.7–2.4	50
Hops	3.5–4.0	1.0–1.2	50	Watermelon	3.0–5.0	0.9–1.5	40
Lettuce	1.0–1.5	0.3–0.5	30	Wheat (spring)	3.5–5.0	1.0–1.5	55
Lentils	1.5–3.5	0.5–1.0	50	Wheat (winter)	5.0–6.0	1.5–1.8	55

Soil and plant environmental factors often affect root development. Soil density, pore shapes and sizes, soil-water status, aeration, nutrition, texture and structure modification, soluble salts, and plant-root damage by organisms must all be taken into account. Many of these values are traceable to Doorenbos and Pruitt (1977), Keller and Bliesner (1990), or Allen et al. (1998).

(e) Irrigation interval

The maximum irrigation frequency is:

$$f_x = \frac{d_n}{U_d} \quad (\text{eq. 11-6})$$

where:

f_x = the maximum interval (frequency) in days

U_d = the average daily crop water requirement during the peak use period

The range of f_x values for agricultural crops is usually:

$$0.25 < f_x < 8 \text{ d} \quad (\text{eq. 11-7})$$

Then nominal irrigation frequency, f' , is the value of f_x rounded down to the nearest whole number of days. In some cases, it is acceptable to round up if the values are conservative and f_x is near the next highest integer value. Also, f' can be fractional if the sprinkler system is automated, and it can be further reduced to account for nonirrigation days, whereby $f \leq f'$.

Irrigation system design is usually for the most demanding conditions, and the crop water requirements during the peak-use period depends on the crop type and weather. Thus, crop water requirements can be different from year to year for the same crop type. Some crops may have the peak water requirement at the beginning of the season due to land preparation requirements, but these crops are normally irrigated by surface systems.

When a system is to irrigate different crops (in the same or different seasons), the crop with the highest peak evapotranspiration (ET) should be used to determine system capacity. Consider design probabilities for ET during the peak use period, because peak ET for the same crop and location will vary from year-to-year due to weather variations. Also consider deficit irrigation, which may be feasible when water supply is limited or expensive (relative to the crop value).

(f) Leaching requirement and gross depth

Leaching may be necessary if annual rains and or snowmelt are not enough to flush the rootzone, or if deep percolation from irrigation is small (i.e., good application uniformity and or efficiency). Leaching may also be necessary if the electrical conductivity of the irrigation water, EC_w , is relatively high. If the electrical conductivity of the irrigation water is low, it may not be necessary to consider leaching in the design (system capacity). The design equation for leaching is:

$$LR = \frac{EC_w}{5EC_e - EC_w} \quad (\text{eq. 11-8})$$

where:

LR = leaching requirement

EC_w = EC of the irrigation water, dS/m or mmho/cm

EC_e = estimated saturation extract EC of the soil rootzone for a given yield reduction value.

Equation 11-8 is taken from FAO Irrigation and Drainage Paper 29. When $LR > 0.1$, the leaching ratio increases the depth to apply by $1/(1-LR)$; otherwise, LR does not need to be considered in calculating the gross depth to apply per irrigation, nor in calculating system capacity. Gross application depth, d_g , is calculated when $LR \leq 0.1$:

$$d_g = 100 \left(\frac{d_n}{E_{pa}} \right) \quad (\text{eq. 11-9})$$

And, when $LR > 0.1$,

$$d_g = \frac{90 d_n}{(1-LR)E_{pa}} \quad (\text{eq. 11-10})$$

The coefficient, 90, in equation 11-10 is 100 multiplied by 0.9, where the 0.9 value is meant to take into account the unavoidable deep percolation that results from nonuniformity for a complete irrigation. When the calculated value of LR is a negative value, the irrigation water is too salty, and the crop would either die or suffer severely.

(g) Irrigations per season

The number of irrigations per season is estimated as:

$$N_{is} = \frac{U - P_e}{d_n} \quad (\text{eq. 11-11})$$

where:

N_{is} = the approximate number of irrigations per season

U = seasonal crop water requirement, in or mm

P_e = effective precipitation during the irrigation season, in or mm

The net depth has units of inches per irrigation or millimeters per irrigation. N_{is} represents the approximate number of irrigations per season. The value of N_{is} can be useful to estimate labor requirements for nonautomated sprinkler systems and to perform other economic analyses when comparing alternate designs.

(h) System capacity requirements

The required capacity of a sprinkler system depends on the size of the area irrigated (design area), amount of water to be applied, and amount of time allowed to apply that amount of water. Stated another way, minimum capacity depends on total area irrigated, gross depth of water applied during the design irrigation, and the net operating time allowed to apply this depth. The required minimum capacity of a sprinkler system can be computed by equation 11-12, which is derived from a volume balance in which the product of average flow rate and duration is equal to the product of area and application depth (210-NEH, Part 652):

$$Q = K \frac{Ad_g}{fT} \quad (\text{eq. 11-12})$$

where:

Q = required minimum system discharge capacity, gpm or lps

A = design area, a or ha

d_g = gross application depth, in or mm

f = irrigation interval or frequency, days

T = actual operating time per day, h/d

K = 453 for English units, or 2.78 for metric units

In later sprinkle system design stages, the number of laterals (or sprinklers) operating at the same time will be determined. Multiplying the nominal sprinkler flow rate by the number of sprinklers will give a more accurate estimate of the required system capacity, which will be greater than, or equal to, that calculated by equation 11-12. With a periodic-move sprinkle system, the calculated number of laterals may be rounded up to a whole number, increasing the required system capacity. Also, the required capacity for a fixed (solid-set) sprinkle system will be the number of sprinklers needed to cover the entire field area, multiplied by the nominal sprinkler flow rate, and this will almost always give a larger value of Q than equation 11-12. When the actual required system capacity is greater than that calculated by equation 11-12, the irrigations can be completed in less than f days.

Parameter f is less than or equal to f' , the maximum interval between irrigation events, determined by allowable net water depletion from soil between irrigations (d_n) and the design rate of daily water use (u_d):

$$f' = \frac{d_n}{u_d} \quad (\text{eq. 11-13})$$

where:

d_n = net application depth, in (mm)

u_d = design rate of daily water use, in/d (mm/d)

Following calculation of f' , the operating time for completion of one irrigation is calculated by subtracting any days off from system operating to cover downtime from system malfunction, days without availability of a sufficient water supply, or days where the system is not operated:

$$f = f' - \text{days off} \quad (\text{eq. 11-14})$$

Parameter f should be consistent with the type of irrigation system. For continuous-move systems partial days (e.g., 4.7 days) are practical, but for periodic-move systems, f must be rounded down to the nearest set interval of the system. For example, f must be rounded down to a whole day (an integer, such as 6 days) for hand lines that will be moved only once per

day, or down to the nearest half-day (e.g., 6.5 days) for lines that will be moved twice per day.

Parameter T must be less than 24 hours per day if down time is required for moving laterals, cleaning filters, or other maintenance and or repairs. In designs, the value of T is almost always less than 24 hours per day because of the need to perform maintenance and occasional emergency repairs, even during the peak-use period. Also, the power supply can sometimes be interrupted during an irrigation, particularly when the source is from electrical lines. Finally, in some cases the value of T can be substantially lowered to take into account the time-of-day billing rates for electrical consumption by comparing annualized fixed costs to uniform annual operating costs (including power for pumping) over the expected useful life of the system. See the section on life-cycle costs.

For center pivot systems and fully automatic fixed systems, it is often best to let d equal the gross depth required per day and f equals 1.0. To allow for some breakdown or moving of systems, T can be reduced by 6 to 10 percent from the potential value of 24 hours. Figure 11–19 can be used for center-pivot preliminary design calculations. In addition, with center-pivot systems, the system capacity is greater when a corner system or end gun, if present, is operating. A better estimate of Q is:

$$Q = K_2 \frac{d_g \pi R^2}{fT} \quad (\text{eq. 11-15})$$

where:

K_2 = 0.0104 for English units, 0.000278 for metric units

R = effective wetted radius of the irrigated area of the center-pivot system (ft or m) when the corner system is full extended or the end gun is operating

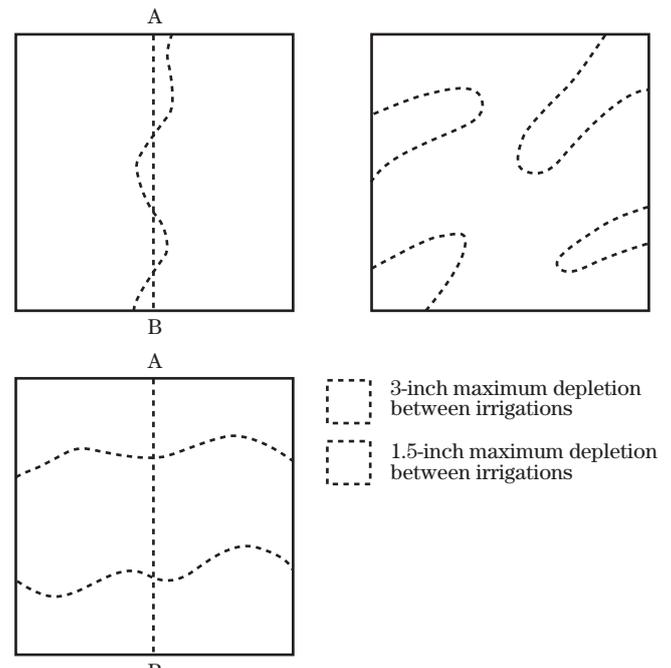
The actual operating time, T , is of major importance because it has a direct bearing on the capital investment and labor requirement per acre required for equipment, especially for Periodic move systems. From equation 11–12 it is obvious that the longer the operating time, the smaller the required system capacity for a given depth of application. A smaller system capacity reduces the capital cost for irrigating a given acreage. Conversely, where the farmer wishes to irrigate an acreage in a minimum number of days and

has labor available only for operation during daylight hours, the equipment costs per acre will be high. With center-pivot and automated field systems, light, frequent irrigations are practical because labor requirements are minimal and the equipment layout and design are not greatly affected. In fact, center-pivot and linear-move system operation is often dictated towards light, frequent irrigations in order to minimize runoff.

Before a sprinkler system is planned, the designer should thoroughly acquaint the owner with these facts and the number of operating hours that can be allowed for completing one irrigation during the design irrigation period. Also, the farmer should understand the amount of labor required to run the sprinkler system so that this operation interferes minimally with other farming operations.

Areas that have several soil zones (fig. 11–20) that vary widely in water-holding capacity and infiltration rate can be subdivided on the basis of the water needed at each irrigation d , f' , and f) for all systems except center pivots. It is easier to operate center-pivot sprinklers

Figure 11–20 Subdivision of design areas having different soil zones



as though the entire field has the soil with the lowest water-holding capacity coupled with the soil having the lowest infiltration rate.

Sample calculation 11–1 has been prepared as an example of the use of the formula where a single crop is irrigated in the design area. The design moisture use rate and irrigation frequency can be obtained from irrigation guides where available. Many land-grant universities have irrigation water guides available that generally include seasonal water requirements and peak irrigation demands. Otherwise, they may be computed from 210–NEH, Part 623, Chapter 2, Irrigation Water Requirements, and 210–NEH, Part 623, Chapter 1, Soil-Plant-Water Relationships.

Sample calculation 11–1—Computing capacity requirements for a single crop in the design area.

Given:

- 40 acres of sugar beets to be irrigated with wheel-lines (A)
- design moisture use rate (U_C): 0.26 inches per day
- peak rooting depth (Z) of 3 feet
- management allowed depletion (MAD) of 50 percent
- soil-water-holding capacity W_{a1} of 2.0 inches per foot
- soil-water-holding capacity W_{a2} of 1.6 inches per foot
- irrigation efficiency (E_{pa}) 75%.

Calculations:

- Allowable depletion (AD) for soil 1 = 2.0 in/ft \times 3 ft \times 50/100 = 3.0 in
- Allowable depletion (AD) for soil 2 = 1.6 in/ft \times 3 ft \times 50/100 = 2.4 in
- Moisture to be replaced in soil at each irrigation: minimum of 3.0, 2.4 = 2.4 in
- Gross depth of water applied (d): 2.4/0.75 or 3.2 in at 75% efficiency
- Irrigation interval (f'): = 2.4/0.26 = 9.2 days, truncated to 9 days

- Days of operation per interval (f): 9 days–1 day off is 8 days in a 9-day interval
- System to be operated 20 h/d (T)

The design area can be served by a mainline as indicated by the dotted A-B line in figure 11–20. Line A-B has a length of 1,320 feet. The 620-foot laterals can operate on both sides of the mainline, and can be managed to run 25 percent longer on the 3.0 inch zone and 25 percent more often on the 2.4 inch zone. Alternatively, separate laterals may be designed for each zone with different water application rates, but with different return times. However, this type of management can be complicated for users and, typically, all laterals are designed and operated the same, with consideration given to the soil having the smallest AD. Also, the irrigation water requirement is not impacted by the soil texture; instead, it depends on the crop type, adequacy of available soil water, and weather conditions.

Laterals operating on soil 2 could be sized and operated differently from those on soil 1. However, typically, all laterals are designed and operated the same, with consideration given to the soil having the smallest AD.

The two soils lay in a mixed spatial pattern. The system will be designed for the 2.4 inch application. For deep-rooted crops, the entire area might be given a 3.0 inch application for the first irrigation in the spring. However, this would mean some sacrifice in water-application efficiency.

Calculation using equation 11–12:

$$\begin{aligned} Q &= 453 \frac{Ad_g}{fT} \\ &= 453 \frac{(40 \text{ ac})(3.2 \text{ in})}{(8 \text{ d})(20 \text{ h/d})} \\ &= 362 \text{ gal/min} \end{aligned}$$

Where two or more areas with different crops are being irrigated by the same system and peak design-use rates for the crops occur at about the same time of the year, the capacity for each area is computed as shown in sample calculation 11–1 and capacities for each area are summed to obtain the required capacity

of the system. The time allotted for completing one irrigation over all areas (f) must not exceed the shortest irrigation-interval as shown in the local irrigation guide or determined by the procedure in 210-NEH, Part 652, chapter 3.

System-capacity requirements for an area in a crop rotation and under a common irrigation system are calculated to satisfy the period of water use. Allowances must be made for the differences in time when the peak-use requirements for each crop occur (sample calculation 11-2).

Sample calculation 11-2—Computing capacity requirements for a crop rotation.

Given:

- Design area of 90 acres in California with crop acreages as:
 - 10 acres Irish potatoes, last irrigation May 31
 - 2.6 inches application, last 12 days in May (peak period)
 - 30 acres corn, last irrigation August 20
 - 2.9 inches application, last 12 days in May
 - 3.4 inches application, last 12 days in July (peak period)
 - 50 acres alfalfa, irrigated through frost-free period
 - 3.6 inches application, last 12 days in May
 - 4.3 inches application, last 12 days in July (peak period)
 - Irrigation period (f), 10 days in 12-day irrigation interval (f')
 - System is to be operated 16 hours per day (T)

Calculations:

Using equation 11-12, capacity requirements for May is calculated when all three crops are being irrigated.

Irish potatoes:

$$Q = \frac{(453)(10)(2.6)}{(10)(16)} \\ = 74 \text{ gal/min}$$

Corn:

$$Q = \frac{(453)(30)(2.9)}{(10)(16)} \\ = 246 \text{ gal/min}$$

Alfalfa:

$$Q = \frac{(453)(50)(3.6)}{(10)(16)} \\ = 510 \text{ gal/min}$$

Total for May = 74 + 246 + 510 = 830 gal/min

Capacity requirements for July when potatoes have been harvested but corn and alfalfa are using moisture at the peak rate.

Corn:

$$Q = \frac{(453)(30)(3.4)}{(10)(16)} \\ = 289 \text{ gal/min}$$

Alfalfa:

$$Q = \frac{(453)(50)(4.3)}{(10)(16)} \\ = 609 \text{ gal/min}$$

Total for July = 289 + 609 = 898 gal/min

Although only two of the three crops are being irrigated, the maximum capacity requirement of the system is in July.

The quality of most water is good enough that no extra system capacity is required for leaching during the peak use period. Leaching requirements can usually be adequately satisfied before or after the peak use period and by deep percolation associated with nonuniformity that is imbedded in the efficiency term. In some areas, the off-season rainfall and/or snowmelt will provide adequate annual leaching, but this depends on the irrigation water salinity.

If highly saline irrigation water is to be used on salt-sensitive crops, a portion of the annual leaching requirement should be provided during each irrigation. The system capacity should be increased by an amount equal to the annual leaching requirement divided by the number of irrigations per year. The procedure for determining leaching requirements is presented in 210-NEH, Part 623, chapters 1 and 2.

It is not recommendable to irrigate under extremely windy conditions because of poor application uniformity, relatively high drift, and evaporation losses. This is especially true with periodic-move systems on low infiltration soils that require low application rates. When these conditions exist, system capacities must be increased proportionately to offset the reduced number of sprinkling hours per day or sprinkling days per irrigation interval.

In water short areas, it is sometimes practical to purposely underirrigate to conserve water at the expense of some reduction in potential yields. Yields per unit of water applied are sometimes optimum with system capacities about 20 percent lower than are specified for conventional periodic-move systems in the same area. Deficit irrigation is best achieved by using a longer interval between irrigations than is normally recommended for optimum yields, by the same interval with lower water application, or a combination of the two.

(i) Fixed systems

Additional advantages for fixed systems are that they can be used for ordinary irrigation, high-frequency irrigation, crop cooling, and frost protection. All fixed systems are ideal for applying water-soluble fertilizers and other agricultural chemicals. However, special consideration is required when estimating the system capacity required by each of these uses.

Ordinary irrigation—Some fixed systems are installed in permanent crops, and relatively long irrigation intervals are often used due to substantial crop root development and for long-term crop health considerations. The capacity of such systems can be 5 to 10 percent less than conventional periodic-move systems in the same area because there is no down time during lateral moves. The capacity should be sufficient to apply the peak net crop water requirements for low frequency (1 or 2 week interval) irrigations when the system is operated on a 24 hour per day, 7 days per week basis. These systems may be used to apply fertilizers and other chemicals and can be controlled by hand valves or may be automated.

High frequency—If the system is designed to apply irrigations once or twice a day to control soil temperatures during germination, for example, and to

hold the soil-moisture content within a narrow band, a greater system capacity is required. The net system capacity should be increased by 10 to 20 percent over a conventional periodic-move system because the crop will potentially be consuming water at the peak daily potential ET rate. By contrast, under lower frequency irrigation, the average consumptive use rate over the longer period is lower than the peak daily potential rate due to averaging in days having somewhat lower potential ET. A major purpose for such a system may be to keep the crop delivering a peak ET rate to increase crop quality and yield. Clearly, crops that do not respond favorably to consistently high soil moisture conditions (due to disease, molds, and other problems) are not particularly good candidates for solid-set (fixed) sprinkler systems. High-frequency systems can be hand-valve operated, but are normally automated. Automatic valve systems are typically used to apply water-soluble fertilizers and other agricultural chemicals.

Crop cooling—High-frequency systems used for foliar cooling must have automatic valving, use high quality water, and have up to double the capacity of ordinary high frequency systems. Foliar cooling systems are sequenced so that the leaves are kept wet. Water is applied until the leaf surfaces are saturated, shut off until nearly dry, then reapplied. This generally requires having one-quarter to one-sixth of the system in operation simultaneously and cycling the system once every 15 to 40 minutes depending on system capacity, crop size, and climatic conditions. For example, a system for cooling trees might be operated 6 out of every 30 minutes so that one-fifth of the area is being sprinkled at any one time. Foliar cooling systems must have sufficient capacity to satisfy the evaporation demand on a minute-by-minute basis throughout the peak use hours during the peak use days. To accomplish this, the system capacity must be 1.5 to 2.5 times as great as is required for a conventional periodic-move system. Such systems are capable of all the previously listed uses except providing full frost protection.

Frost protection—System capacity requirements for frost protection depend on lowest expected temperature, type of frost (radiant or advective), relative humidity, wind movement, crop height, and cycle time (or turning speed) of the sprinklers. The basic process of overhead freeze control requires that a continuous

supply of water be available at all times. The protective effect of sprinkling comes mainly from the 144 British thermal unit (BTU) of latent heat released per pound (334 kJ/kg) of water during the actual freezing of the water. In addition, a small amount of heat (1 BTU per pound of water per degrees Fahrenheit temperature drop, or 4.2 kJ/kg/ °C) comes from the water as it cools to the freezing point. By using dew point temperature, humidity and temperature effects can be combined. As a general rule, with sprinklers turning faster than 1.0 RPM and winds up to 1 miles per hour (0.45 m/sec), an application rate of 0.15 inch per hour (4 mm/h), equivalent to 65 gallons per minute per acre (10 l/sec/ha), should provide overhead freeze protection down to a dew point temperature of 20 degrees Fahrenheit (−6.7 °C). For every degree above or below a dew point temperature of 20 degrees Fahrenheit (−6.7 °C) the application rate can be decreased or increased by 0.01 inch per hour (0.25 mm/h), equivalent to 4.3 gallons per minute per acre (0.67 lps/ha).

It is essential that frost protection systems be turned on before the dew point temperature drops below freezing and left operating until all the ice has melted the following morning. Where the dew point temperatures are apt to be low for long periods of time on consecutive days, the potential damage to trees from the ice load may be so great that overhead freeze control is impractical.

To protect against minor frosts having dew point temperatures of 28 or 29 degrees Fahrenheit (−2 °C), use under-tree sprinkler systems with every other sprinkler operating and over-crop systems having limited capacity where they are rapidly sequenced. Such systems may require only 25 to 30 gallons per minute per acre (4 to 5 lps/ha). However, even these rates are 4 to 5 times larger than systems designed for irrigation only. Therefore, pump, mainline, and lateral sizes are significantly larger.

Bloom delay—Bloom delay is a means of cold protection where woody plants are cooled by sprinkling during the dormant season to delay budding until there is less probability of a damaging frost. Such systems are similar to crop cooling systems, but they are generally cycled so that half of the system is operating simultaneously. The system capacity to do this is governed by equipment and distribution uniformity considerations.

An application rate of 0.10 to 0.12 inch per hour (2.5 to 3 mm/h) is about as low as can be practically achieved with ordinary impact sprinklers. Operating half of such a system simultaneously over a field may require 22 to 26 gallons per minute per acre (3.4 to 4 lps/ha).

(j) Continuous-move systems

Because center-pivot systems are completely automatic, it is relatively easy to carefully manage soil-moisture levels.

Ordinary irrigation—Center-pivot systems have the same attributes for ordinary irrigation as fixed systems. However, mechanical breakdown is more likely. In center-pivot designs, it is typical to assume irrigation 90 percent of the time (21.6 h/d), allowing 10 percent of the time for maintenance and repairs, as necessary, during the peak-use period. The assumption that a center pivot will operate 100 percent of the time during the peak-use period, decrease the system capacity, but it runs the risk of not being able to apply the needed water if (for mechanical, electrical, or other reasons) the system cannot actually operate 24 hours per day during this period.

High frequency—Where high-frequency irrigation is used for the same purposes, both fixed and center-pivot systems should have similar capacities. These comments also hold true where high-frequency irrigation is used in arid areas to reduce runoff if the soil-crop system has a low water-holding capacity. The maximum speed of the system and the area of coverage will limit the allowable irrigation frequency.

Limited irrigation—On crop-soil systems where there is 5 inches (125 mm) or more water storage capacity, irrigation rates that are about 10 percent lower than the peak-use rate can be used during the peak-use period without appreciably affecting the yields of many crops. The use of light, frequent irrigation makes it practical to gradually deplete deep soil moisture during peak-use periods when the system capacity is inadequate to meet crop moisture withdrawal rates. However, when subsoil moisture storage is inadequate, light, frequent irrigation can result in significant water loss from evaporation from wet soil and vegetation and may be an inefficient use of a limited supply of

water. Frequent irrigation may, in some cases, also increase salinity problems. Under these conditions, deeper, less frequent irrigations may produce better yields.

(k) Intake and optimum application rates

The rate at which water should be applied depends on:

- The time required for the soil to absorb the calculated depth of application without runoff for the given conditions of soil, slope, and cover. The depth of application divided by this required time is the maximum application rate.
- The minimum application rate that will result in uniform distribution and satisfactory efficiency under prevalent climatic conditions, or that is practical with the system selected. For most irrigated crops, the minimum rate of application to obtain reasonably good distribution and high efficiency under favorable climatic conditions is about 0.15 inch per hour (4 mm/h). If high temperatures and high wind velocities are common, the minimum application rate must be higher to reduce problems associated with wind drift. The establishment of minimum application rates for local conditions requires both experience and judgment.
- The amount of time it takes for irrigation to achieve efficient use of available labor in coordination with other operations on the farm.
- The application rate adjusted to the number of sprinklers operating in the best practical system layout.

The infiltration rate of soil generally reduces with time of wetting. The rate of application should be planned so that it is no higher by the end of an irrigation than the capacity of the soil to absorb water. Ideally, intake versus time of application information should be developed by applying water at the expected sprinkling intensity of the system selected on crops, soils, and slopes similar to the expected site conditions. This information can often be obtained by examining an existing system, but it is difficult to set up an experiment to observe it. Intake curves for sprinkle irrigation are not necessarily the same as those derived from ponding studies due to impacts of surface sealing by

sprinkler drops and due to the sprinkle application rate generally being less than that of a ponded infiltration rate.

On bare soils, drop impact causes surface sealing and reduces infiltration. The kinetic energy of a falling drop is the product of one-half its mass and the square of its velocity. Drop sizes range from 0.5 to 5.0 mm and have terminal falling velocities ranging from about 6 to 30 feet per second (2 to 10 m/sec), respectively. With a typical fall distance equivalent to about 10 to 20 feet (3 to 6 m), most drops from impact sprinklers come close to reaching their respective terminal velocities. Table 11-4 presents terminal velocities and kinetic energies associated with different drop sizes.

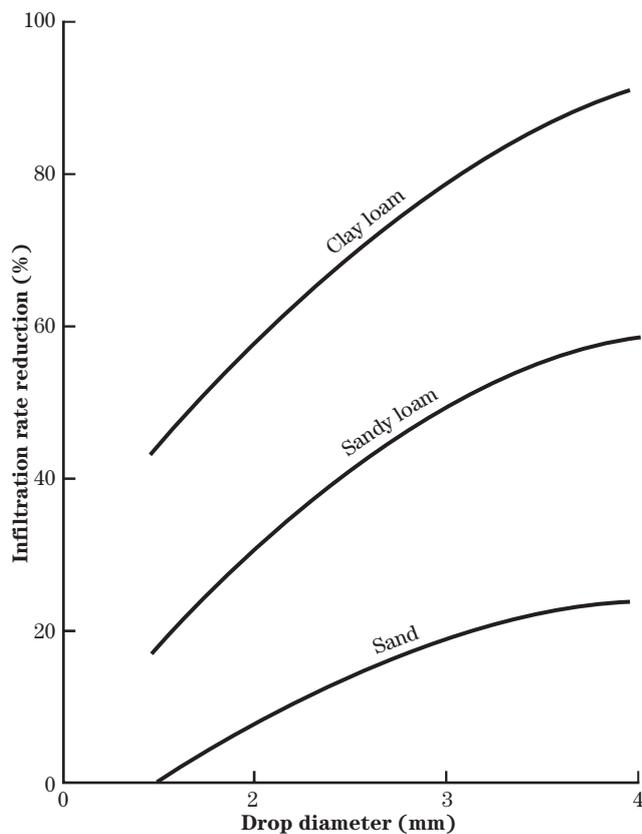
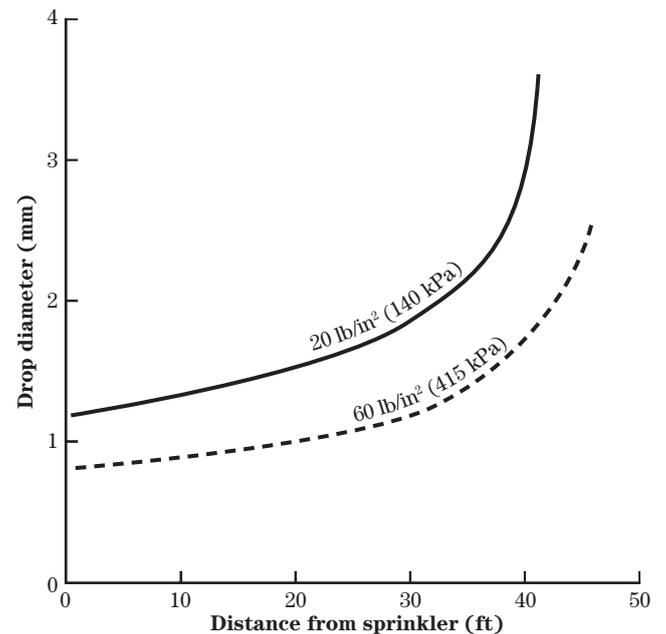
The surface sealing and reduction in infiltration caused by drop impact depends on the soil texture and structure, amount and type of crop cover, and the application rate. Figure 11-21 shows the general relation between drop size and reduction in infiltration rate on three different bare soils with an application rate of approximately 0.5 inch per hour (13 mm/hr). The reduction in infiltration rate on the freshly tilled, heavy-textured soil approached the maximum level about 20 minutes after the beginning of the application.

Drop size is reduced as pressure increases (fig. 11-22) or as nozzle size decreases due to increased velocity and turbulence inside the nozzle orifice and in the jet. Drop sizes can also be reduced using means other than high pressure to cause jet breakup. For example, some nozzle designs include pins that protrude into the jet near the nozzle orifice; some use sharp orifices or triangular, rectangular, or oval orifices instead of tapered, circular nozzles; and some use impinging jets of water. Low pressure nozzles used on continuous-move systems often use fixed or rotating plates to break up and deflect drops. Because of high energy costs, creation of smaller (i.e., medium) drop size with low pressure has become desirable.

Impact sprinklers produce a circular wetted area. At any one moment, however, all of the water in the jet lands in a small segment of the total wetted area. The application rate on the concentrated area exceeds the instantaneous infiltration capacity of the soil. The excess water momentarily ponds, forming a film on the soil surface that lubricates the surface soil particles and reduces to zero surface tension forces that

Table 11-4 Terminal velocities and kinetic energies associated with different size raindrops

Drop size (in)	Volume (mm ³)	Terminal velocity (ft/sec)	Terminal velocity (m/sec)	Kinetic energy values		
				in relation to a 1.0-mm drop	per inch of rain (ft-lb/ft ²)	
0.020	0.5	0.07	5.9	1.80	0.032	2.8
0.039	1.0	0.52	12.6	3.84	1.0	12.7
0.059	1.5	1.8	17.4	5.30	6.5	24.5
0.079	2.0	4.2	21.2	6.46	22.8	36.3
0.098	2.5	8.2	24.0	7.32	57.0	46.4
0.118	3.0	14.1	25.9	7.89	116	54.2
0.138	3.5	22.4	27.4	8.35	205	60.6
0.157	4.0	33.5	28.5	8.69	332	65.5
0.177	4.5	47.7	29.3	8.93	499	69.3
0.197	5.0	65.4	29.8	9.08	708	71.7

Figure 11-21 Infiltration rate reduction due to sprinkling on three different soil types at an application rate of approximately 0.5 in/h (13 mm/h)**Figure 11-22** Drop sizes at various distances from a standard 5/32-in (4 mm) nozzle operating at 20 and 60 lb/in² (140 and 415 kPa)

might otherwise help hold the surface soil grains in place. Thus, droplets striking the wet surface tend to dislodge soil particles which then become suspended and settle out on the soil surface. Some of these particles are carried into the soil by the infiltrating water, causing surface sealing, and compaction. Spray and rotating plate nozzles used on center pivots generally distribute water in all directions and therefore do not concentrate drop energy as much as do impact sprinklers. However, some nozzle systems produce large drop sizes, in an effort to increase distance of drop travel, and therefore can have relatively large amounts of energy per individual water drop. As shown in figure 11-21, large drops can increase surface sealing, resulting in a reduced infiltration rate.

The average application rate from a sprinkler operated in a rectangular grid of similar sprinklers (fig. 11-23) is computed by dividing the discharge by the mean area per sprinkler, as:

$$I = K \left(\frac{q}{S_e S_l} \right) \quad (\text{eq. 11-16})$$

where:

- I = average application rate, in/h or mm/h
- q = sprinkler discharge, gpm or lpm
- S_e = uniform spacing of sprinklers along the laterals, ft or m
- S_l = spacing of laterals along the mainline, ft or m
- K = 96.3 for English units or 60 for metric units

Typically, an impact sprinkler with a five-thirty-second-inch (4 mm) nozzle operating at 50 pounds per square inch (345 kPa) and discharging 5 gallons per minute (19 lpm) might be spaced on a 30 by 50 foot spacing (30 ft between sprinklers along the lateral, and 50 ft between parallel lateral positions). From equation 11-16, the average application rate is 0.32 inch per hour (8 mm/h).

To compute the average instantaneous application rate (I_i) for a rotating sprinkler stream having a given radius of throw (R_j) and wetted angular segment (S_a), in degrees, equation 11-16 may be modified to the following, where q is the discharge of an individual sprinkler:

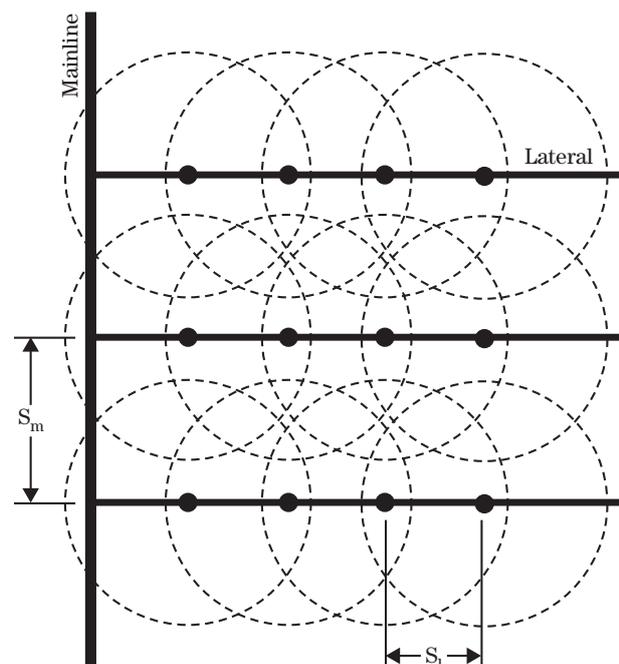
$$I_i = K \left(\frac{q}{\pi (R_j)^2 \left(\frac{S_a}{360^\circ} \right)} \right) \quad (\text{eq. 11-17})$$

where:

- I_i = average instantaneous application rate
- K = 96.3 for English units or 60 for metric units
- q = discharge of an individual sprinkler, gpm (lpm)
- R_j = given radius of throw, ft (m)
- S_a = wetted angular segment, in degrees

Figure 11-24 shows a sketch of the area covered by the average instantaneous application rate. If the sprinkler produced a wetted radius of $R_j = 45$ feet (13.7 m) and the jet stream wetted an angular segment of S_a is 6 degrees, then I_i is 4.5 inches per hour (114 mm/h). This is considerably higher than the infiltration rate of most agricultural soils, except during the first mo-

Figure 11-23 Sprinkler and lateral spacing for a rectangular sprinkler layout (plan view)



ments of irrigation on a dry soil. It is important to consider, however, that the sprinkler will rotate 354 degrees (in this example) before the jet of water passes over the same segment again, during which time some or all of the applied water will have infiltrated into the soil. Equation 11-17 applies to impact sprinklers having one or two (usually opposing) nozzles. For multiple-jet spray nozzles, the number of jets must be taken into consideration.

Increasing sprinkler pressures or applying other means to reduce drop size also tends to decrease the instantaneous application rate by increasing the area of jet distribution. The smaller drops and lower I_i work together to reduce surface sealing. A jet of water rotating quickly over the soil surface will cause less sealing than a slower moving stream. The greatest drop impact and highest I_i is toward the periphery of throw and downwind from the sprinkler. For impact sprinklers, a good rotational speed for the jet at the periphery of the wetted area is 5 feet per second (1.5 m/sec), which is a typical walking speed of 3.5 miles per hour (5.6 kph). A typical impact sprinkler that produces a

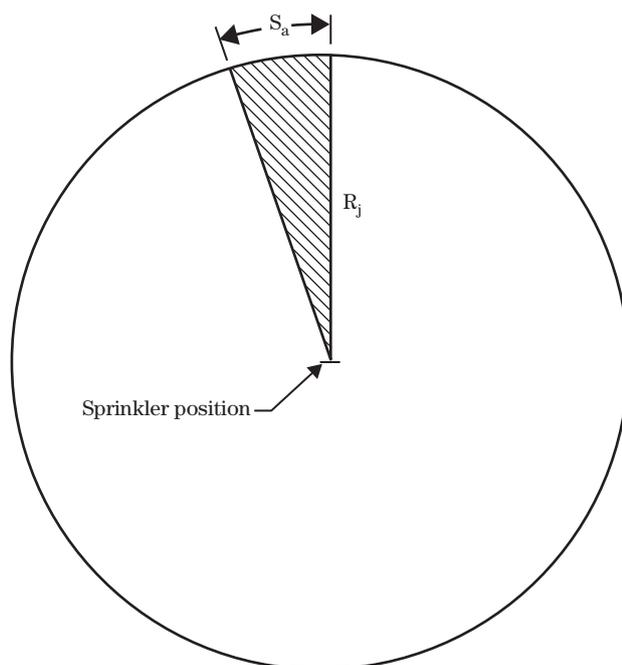
90- to 100-foot wetted diameter should rotate about once a minute. However, a gun sprinkler that wets an area over 400 feet (120 m) in diameter should turn only once every 4 to 5 minutes. Also, it is important to consider that the applied water will not necessarily have infiltrated into the soil by the time the sprinkler completes a rotation; thus, the soil infiltration rate is an important consideration.

Periodic-move and fixed systems—Many local irrigation guides give suggested values for maximum water-application rates for different soils and for different slopes and cover. Maximum application rates for good ground cover should be used only when such cover can be established and maintained. Table 11-5 can be used for suggested maximum application rate values for periodic-move systems. The table is based on average soil conditions for the irrigation of all crops, except grasses and alfalfa, on various slopes. For bare ground and poor soil conditions, the values should be reduced by about 25 percent. For grasses and alfalfa, the values may be increased by about 25 percent. In addition, application rates should be reduced 25 percent for gun sprinklers because an abundance of large water droplets are produced and high instantaneous application rates are present, both of which increase surface sealing. Large droplets and high application rates also effectively reduce surface storage by smoothing surface microtopography and decreasing the size of local depressions. In all cases, the selected water-application rate should fall somewhere between these maximum values and minimum values.

Once maximum and minimum rates of application have been determined, the designer needs to arrive at a rate that requires a time of setting that fits into the farm operation schedule. For periodic-move systems, it is generally desirable to have intervals that give one, two, or at most three changes per day and that avoid nighttime changes. Changes just before or after meal-times leave most of the day for other work. For fixed systems (especially when automated), any number of changes per day can be made.

Continuous-move systems—Traveling sprinklers, such as hose-pull systems, like periodic-move systems, are generally managed to apply relatively deep irrigations to reduce labor and relative reset times. Furthermore, drop sizes tend to be large due to large nozzle bores, so that values from table 11-5 should be reduced by 25

Figure 11-24 Plan view of a circular sprinkler-irrigated area and instantaneous wetted area.



percent when used as a guide to selecting maximum application rates for traveling sprinklers.

It is practical and often necessary to apply frequent, light applications with center-pivot and linear-move systems. Automation allows for light, frequent irrigation and intensities of application rates generally requires light applications to reduce runoff. With light applications, up to 0.1 to 0.5 inch (3 to 13 mm) of the applied water can sometimes be stored in small depressions on the soil surface for later infiltration. The amount of surface storage depends on the roughness of tillage operations, slope, time since tillage, and whether implements that create small reservoirs, or depressions, are employed. Careful management of the use of surface storage is needed, because once the storage is exceeded, runoff will begin and erode the microstorage structure.

If surface storage is properly managed, and center pivot laterals or linear move laterals are operated to apply light applications that do not create runoff, then often these systems can be operated to apply applications more than 100 percent greater than those specified in table 11-5 on ground slopes of less than

5 percent. It is difficult to nozzle center-pivot systems that have a maximum application rate of much less than 1.0 inch per hour (25 mm/h). The rates in table 11-5 represent long-term infiltration rates for applications lasting 4 hours or longer, whereas a center-pivot may wet a specific location for only 5 to 20 minutes. This is another reason why application rates from center-pivot and linear-move systems may be able to exceed those shown in table 11-5. Local observation of application rates and times to surface ponding until runoff should be made under the types of soil surface (tillage) conditions and slopes that will be experienced by the irrigation system to be designed. These observations are described in the design section on center-pivot systems.

Table 11-5 Suggested maximum application rates for sprinklers for average soil, slope, and tilth

Soil texture and profile		Ground slope			
		0-5% (in/h)	5-8% (in/h)	8-12% (in/h)	12-16% (in/h)
1	Coarse, deep sandy soil	2.00	1.50	1.00	0.50
2	Coarse sandy soils over more compact soils	1.50	1.00	0.75	0.40
3	Light, deep sandy loam soils	1.00	0.80	0.60	0.40
4	Light sandy loams over more compact soils	0.75	0.50	0.40	0.30
5	Deep silt loam soils	0.50	0.40	0.30	0.20
6	Silt loams over more compact soils	0.30	0.25	0.15	0.10
7	Heavy-textured clays or clay loam soils	0.15	0.10	0.08	0.06

623.1103 System layout

Figure 11–25 shows general types of periodic-move sprinkler system layouts. The layout of a system will often be simple, as in the case of small regularly shaped areas. Large odd-shaped tracts with broken topography may present a complex engineering problem requiring alternate layouts and careful pipe-size analyses. This section describes the most important points that must be considered in planning a system layout and the general rules to follow. These rules provide only general guidance to the planner and designer. In the more complex layouts, considerable judgment must be exercised.

(a) Number of sprinklers operating

A system layout must provide for simultaneous operation of the average number of sprinklers that will satisfy the required system capacity determined by equation 11–12. This average number is computed as:

$$N_n = \frac{Q}{q_a} \quad (\text{eq. 11-18})$$

where:

N_n = minimum average number of sprinklers operating

Q = required system capacity from equation 11–12, gal/min (l/m)

q_a = average sprinkler discharge, gal/min

The variation in the number of sprinklers operated from time to time during an irrigation cycle should be kept to a minimum to facilitate lateral routing and maintain a more nearly constant load on the pumping plant. Because no variation will be needed in a rectangular area, farmers should be encouraged to relocate fences, drainage ditches, roads, and other field boundaries, where practicable, to obtain a rectangular area.

Pipe lengths are generally standardized, and sprinklers on portable systems are normally spaced at 30-, 40-, and 60-foot intervals on the laterals. Furthermore, the spacing between laterals is usually at 40-, 50-, 60-, and 80-foot intervals along the mainline. Since whole later-

als must be operated simultaneously, the preliminary system capacity determined by equation 11–12 may be lower than the required capacity, even on rectangular fields. However, the depth per irrigation (d) or the length of actual operating time per irrigation (f) can usually be adjusted to optimize the fit.

On odd-shaped fields where it is sometimes necessary to operate less than the average required number of sprinklers for one or more lateral settings, the engine is throttled down to reduce the discharge. Where two or more laterals (each containing different numbers of sprinklers) are operating simultaneously, valves in the lateral lines must be used to control the pressure at the sprinklers. For most odd-shaped tracts, the number of sprinklers will exceed the theoretical minimum number computed, and extra equipment will be necessary to serve parts of the tract most distant from its center. If the design area is subdivided, the number of sprinklers required for each subdivision must be computed separately.

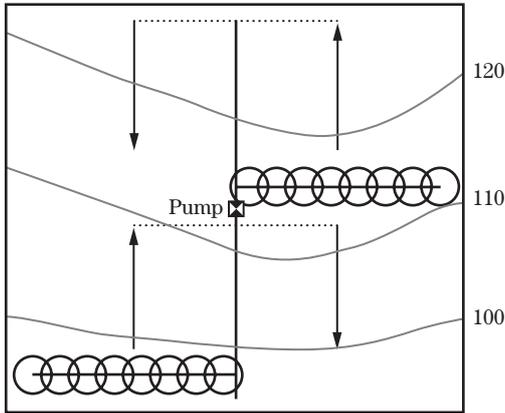
(b) Number of laterals required

The required number of laterals and the number of settings required for each lateral depends on the number of allowable sets per day and maximum number of days allowed for completing an irrigation during the peak-use period. The required number of settings per lateral must not exceed the product of these two factors. If the system layout provides for at least the minimum number of sprinklers required, then the number of settings required per lateral will not exceed this allowable limit. Long, narrow, or irregularly shaped parts of a tract may require additional lateral settings. More equipment is necessary if such areas are to be served within the allowable irrigation time period.

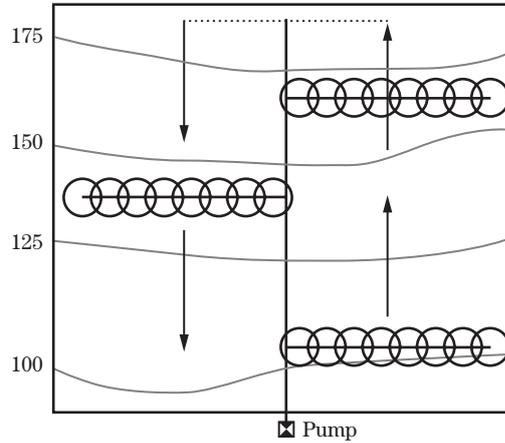
(c) Lateral layout

Figure 11–26 shows the effects of topography on lateral layout. To obtain near-uniform application of water throughout the length of a lateral, the line must be of a pipe diameter and length and follow an alignment that will result in a minimum acceptable variation in the discharge of individual sprinklers along the line. Normally, this discharge variation should not exceed 10 percent unless long-term economic justification exists.

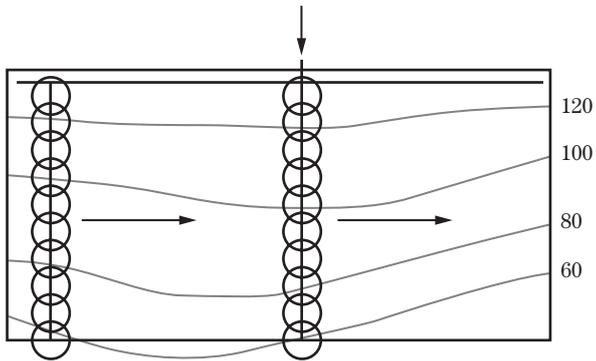
Figure 11-25 Sample layouts of periodic-move sprinkler systems that account for topography



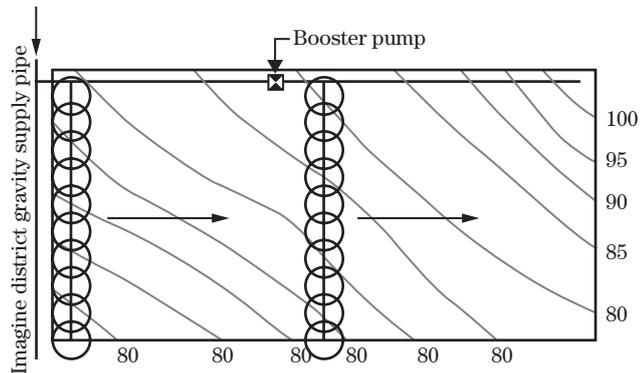
A. Moderate, uniform topography with water supply in the center of the field



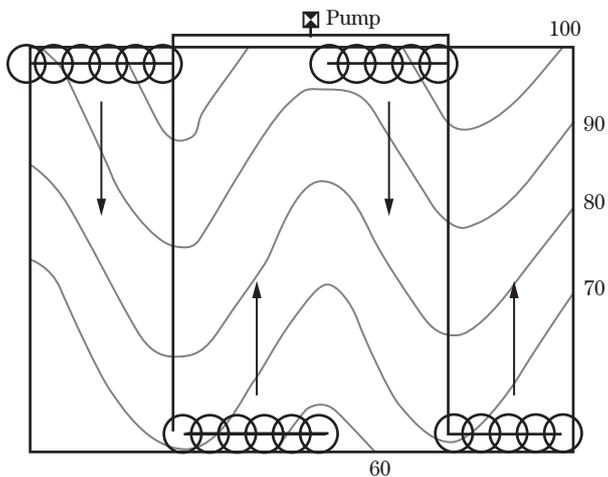
B. Use of odd number of laterals layout running cross slope to reduce pressure variation



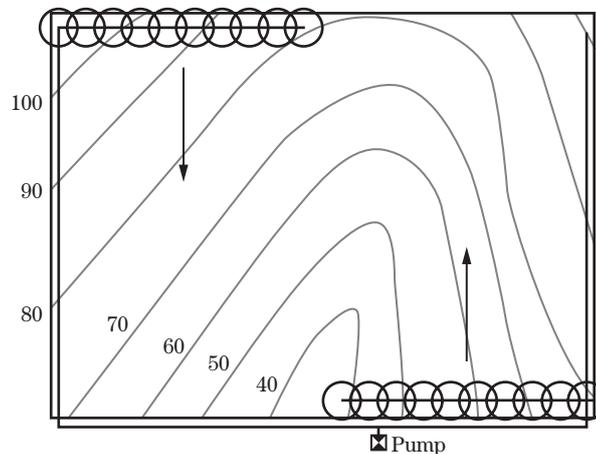
C. Gravity-fed system with laterals running in the downhill direction



D. Laterals running downhill to avoid excessive pressure variation from running them uphill

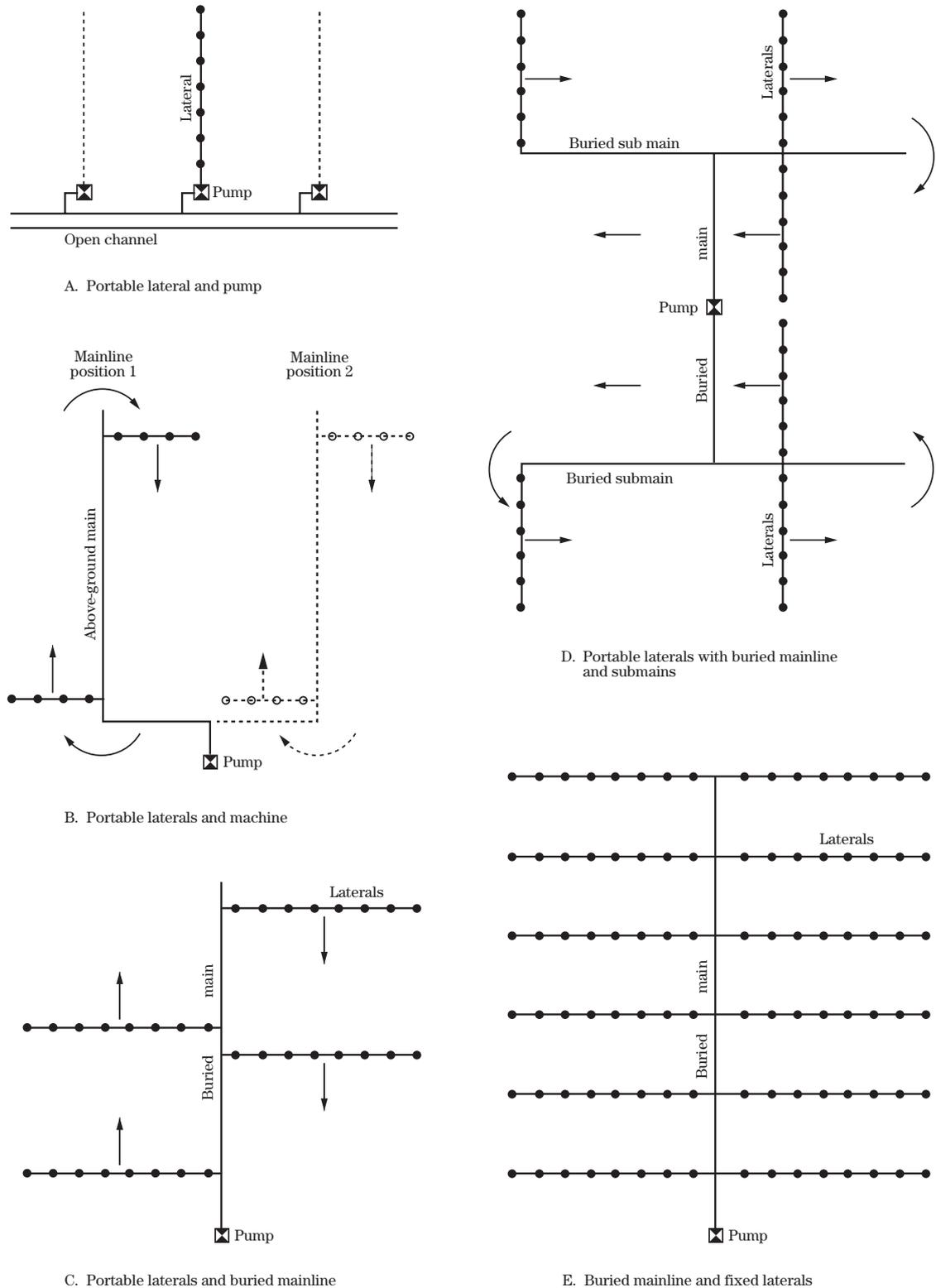


E. Two sub-mains on ridges with laterals running in the downhill direction



F. Two sub-mains at the left and right field boundaries to avoid running laterals uphill

Figure 11-26 General types of periodic-move sprinkler systems



Based on the orifice equation relationship between q and P , either pressure (or flow) regulation must be provided for each sprinkler, or laterals must be located and pipe sizes selected so that the total losses in the line, due to both friction and elevation change, will not exceed 20 percent of the average design operating pressure at the sprinkler nozzles (P_a).

To meet this pressure-variation criterion, it is generally necessary to lay laterals across prominent land slopes (fig. 11–26, A and B). Laid on level land or the contour, a hand-move lateral of a given pipe size with a fixed average sprinkler-discharge rate (q_s) will be limited only to that length in which 20 percent of P_a is lost as a result of friction. One must also consider structural issues when using wheel-move systems.

Running laterals uphill should be avoided wherever possible because the combined effects of elevation change and friction loss on pressure decrease can significantly reduce discharge uniformity. Where used, the laterals need to be materially shortened unless pressure or flow regulators are used. Such a lateral that goes uphill of a given pipe size and fixed average discharge rate, q_{a1} , is limited to that length in which the loss due to friction is equal to the difference between 20 percent of P_a and the loss due to static head (elevation). For example, if the static head caused by the difference in elevation between ends of the lateral amounts to 12 percent of P_a , then the line is limited to the length in which only 8 percent of P_a is lost due to pipe friction.

Running laterals downslope is often a distinct advantage, provided the slope is fairly constant and not too steep (fig. 11–26, C, D, and E). Because the difference in elevation between the two ends of the lateral contributes to a gain in pressure head, laterals running downslope may be longer than those laid on level ground, without compromising pressure uniformity along the lateral. But, while downhill slopes may permit longer laterals for a given pipe size or a smaller pipe size for a given lateral length, such a layout does not generally permit a split-line layout or lateral rotation about the mainline or submain.

When the slope of the ground along the lateral is approximately equal to the friction loss gradient, the pressure along the lateral will be nearly constant. When the slope along the lateral increases with suc-

cessive settings, pressure regulation valves may be required at the lateral inlets to avoid excessive pressures and exceeding the design pressure variation limit.

Hand-move lateral lines need to be limited to one or two pipe sizes for simplicity of operation. Many irrigators prefer the use of a single pipe size for ease in handling, even though a dual pipe size lateral might be cheaper to purchase and might provide better uniformity (on laterals running downhill).

Lateral lines should be located at right angles to the prevailing wind direction where possible and moved in the direction of the wind if the water contains more than 1,000 parts per minute of salts.

If hand-move lateral pipelines are to remain in a single design area and are not to be moved from field to field, they can be located so that they are rotated around the mainline, thereby minimizing the hauling of pipe back to the starting point for subsequent irrigations (fig. 11–25B). However, in some cases this may not be a significant issue, but could represent a design alternative for the farmer to consider.

Farming operations and row directions often influence the layout of laterals. Contoured row crops are normally sprinkle irrigated only with hand-move or solid-set systems, which presents special problems, such as difficulty in placing and moving lateral lines and achieving uniform coverage.

Where the land is terraced and the topography broken, curves in the alignment of the rows may be sharper than can be turned with the limited deflection angle of the coupling devices on portable irrigation pipe. This difficulty may be overcome in the following ways: soil profiles permitting, land grading may be used to improve terrace and row alignment; short lengths of flexible hose may be used in the line at the sharpest bends. Some growers prefer to run the laterals parallel and downhill on a slope somewhat steeper than the grade of the terraces even though both rows and terraces must be crossed by the pipelines. In such cases, several plants are removed or left out of each row at points crossed by the lateral lines.

Where sloping land is terraced and the slopes are not uniform, lateral lines laid between crop rows will not be parallel. Thus, the lateral spacing (Sl) will be vari-

able between two adjacent lines. This variation adversely affects uniform application and efficient water use. Where topography permits their use, parallel terraces will help overcome this problem. Perforated-pipe laterals may be used when irrigating low-growing crops, such as small vegetables. In such cases, lines are laid on the contour between crop rows.

(d) Mainline layout

Figures 11–25 and 11–26 also show various mainline configurations. Normally, the mainline layout is dictated by lateral layout rather than vice-versa. Mainlines, or submains where used, should usually run up and down predominant land slopes. Where laterals are downslope, the mainline will often be located along a ridge, with laterals sloping downward on each side. Different pipe sizes should be used along the mainline for pressure control and to maintain a reasonably balanced load on the pumping plant.

Mainlines should be located, where possible, so that laterals can be rotated in a split-line operation as illustrated in figure 11–25D. This minimizes both pipe friction losses and the labor needed for hauling lateral pipe back to the starting point. The planting, cultural, and harvesting operations do not always permit a split-line operation, however. Water is usually applied to part of a field immediately after a priming (removing ripened leaves from the stalk), and most growers object to priming in several parts of the field simultaneously as would be necessary to stay ahead of the lateral moves in a split-line operation. The situation is similar for haying operations.

(e) Location of water source and pump

If a choice in location of the water-supply source is possible, the source should be placed near the center of the design area as this is typically the most hydraulically efficient and, therefore, most economical. This results in the least cost for mainline pipe and pumping. A choice of location of the water supply is usually possible only when a groundwater well is the source.

When the source is surface water, the designer must often select a location for the pumping plant. Wherever possible, the pumping plant should be located at a central point for delivery to all parts of the design area

when the area is relatively flat. If the field has large elevation changes, it is preferable to have the pumping plant at an uphill location, when possible. Figure 11–17 illustrates the choice of pump locations between points A and F. With the pump at location A, line BC will carry water for 30 acres (12 ha) and line CF will carry water for 15 acres (6 ha); with the pump at F, BC will carry water for 40 acres (16 ha); and CF will carry water for 72 acres (29 ha). In this example, pump location A provides the least cost of mainline pipe.

On flat or gently sloping lands where water is to be pumped from gravity ditches, mainline costs will be reduced if water is run in a ditch to the center of the design area. On steeper topographies where water and pressure are obtained from a gravity line above the design area, cost is least if the gravity line enters the design area at the center of the top boundary.

Booster pumps should be considered when small parts of the design area demand higher pressures than does the main body of the system. The use of booster pumps avoids supplying unnecessarily high pressures at the main pumping plant to meet the pressure required by small fractions of the total discharge. Booster pumps are sometimes used where the static head is so great that two pumps prove more economical than a single unit. A careful analysis of pumping costs is required in such cases. Booster pumps are described in more detail in NEH, section 15, chapter 8.

(f) Adjustments to meet layout conditions

After completing the layout of mainlines and laterals it is usually necessary to adjust one or more of the following:

- number of sprinklers operating, N_n
- water-application rate, I
- gross depth of each irrigation, d
- sprinkler discharge, q_a
- spacing of sprinklers, $S_e \times S_l$
- actual operating time per day, T
- days to complete one irrigation, f
- total operating time per irrigation, fT

- total system capacity, Q

Experienced designers can foresee these adjustments during the layout process. On regular tracts, the layout can be determined early by using the design procedure presented herein, and the subsequent steps developed on the basis of fixed layout requirements.

The application rate (I) can be adjusted according to the flexibility in time allowed for applying the required gross depth of water (d), but this is limited by the maximum water-application rates, determined by the water infiltration rate of the soil, and by the minimum water application rates practical for the design.

Since I is a function of q and spacing, the discharge can be modified only to the extent that the spacing or I , or both, can be modified if d is held constant. However, d and the irrigation frequency can also be adjusted if further modification is needed. Spacing can be adjusted within limits to maintain a fixed value of I . Changes in sprinkler spacing (S_l or S_e) can be made in 10-foot intervals to alter the number of operating sprinklers for a fixed length of lateral or the number of lateral positions across the field. Major adjustments in I to fit the requirements of a good layout must be compensated for by modifying the operating period, fT , to fit d .

Before the layout is finalized, T and f are assumed in computing Q by equation 11–12. If the total time of operation (fT) is increased, Q may be proportionately reduced. The actual system capacity is the product of the maximum number of operating sprinklers (N_x and q_a). Rewriting equation 11–18 and replacing N_n with N_x :

$$Q = N_x q_a \quad (\text{eq. 11-19})$$

Therefore, the final adjustment is to compute the total system capacity needed to satisfy maximum demands. Sample calculation 11–3 illustrates the problem of adjusting system capacity to meet layout requirements.

Sample calculation 11–3—Determine system capacity and adjust operating conditions to meet layout requirements.

Given:

- An 80-acre potato field with 1,320- by 2,640-foot dimensions.
- Assume that d is 2.79 inches and q_a is 4.78 gallons per minute.
- There will be an 8-day irrigation interval with 7-day operating time during the peak-use period.
- There will be two 11.5-hour sets per day, and a 40- by 50-foot sprinkler spacing.

Layout:

Preliminary system capacity by equation 11–12:

$$\begin{aligned} Q &= 453 \frac{Ad}{fT} \\ &= 453 \frac{(80)(2.7)}{(8)(2)(11.5)} \\ &= 532 \text{ gpm} \end{aligned}$$

The minimum number of sprinklers is determined using equation 11–18:

$$\begin{aligned} N_n &= \frac{Q}{q_a} \\ &= \frac{532}{4.78} \\ &= 112 \text{ sprinklers} \end{aligned}$$

Design the layout with one mainline 1,320 feet long, through the center of the field, with laterals 1,320 feet long to either side. With S_e is 40 feet, the number of sprinklers per lateral is 33. The minimum whole number of laterals required is 4. The number of lateral settings on each side of the mainline with S_l being 50 feet is 27 settings.

There are two sides of the mainline and 27 positions per side, giving 54 lateral positions. Then, dividing 54 by 4 laterals is 13.5, which is rounded up to 14 for 2 laterals, one on each side of the mainline. The time required to complete one irrigation is 14 positions divided by 2 sets per day is 7 days. This value equals the 7 days calculated earlier from the AD and the consumptive use rate, which is acceptable.

Adjustments:

With all four laterals operating, the maximum number of sprinklers running is:

$$N_x = 4(33) = 132 \text{ sprinklers}$$

The actual system capacity computed by equation 11-19 is:

$$\begin{aligned} Q &= N_x q_a \\ &= 132(4.78) \\ &= 631 \text{ gal/min} \end{aligned}$$

This is higher than the preliminary capacity that was based on an 8-day irrigation interval. The final system capacity could be reduced to more nearly equal the preliminary Q as 532 gallons per minute by letting d equal 2.45 inches and reducing the irrigation interval to 7 days (no down time). This would require changing q to about 4.25 gallons per minute (depending on the effect of the equation). However, it was decided to leave the 8-day interval to provide a margin of safety since the water supply was sufficient. Furthermore, the savings in system costs afforded by a lower application rate would likely be more than offset by the added labor cost due to more frequent irrigations.

623.1104 Sprinkler irrigation efficiency

Irrigation efficiency is a concept that is used extensively in system design and management. It can be divided into two components; application uniformity and water losses. Water losses include evaporation, leakage, and deep percolation from over-application. If either uniformity is poor or losses are large, water-use efficiency will be low. Several factors affect the water-application efficiency of sprinkle irrigation systems:

- Variation of individual sprinkler discharge along lateral lines can be held to a minimum by proper lateral layout and hydraulic design and, in some cases, pressure regulation.
- Variation in moisture distribution within the sprinkler-spacing area is caused primarily by wind movement and individual sprinkler pattern. For periodic-move, fixed, and traveling sprinklers, this can be partially overcome by closely spacing sprinklers along laterals and closely spacing laterals or tow paths to meet adverse wind conditions. In addition to the variation caused by wind, there is always variability in the distribution pattern of individual sprinklers. The extent of this variability depends on sprinkler design, operating pressure, and sprinkler rotation. For center-pivot and linear-move systems, wind distortion is not as serious a problem because the sprinklers are spaced closely together along the lateral, and the lateral is continuously moving.
- In addition to losses by lack of uniformity, water can be lost by direct evaporation from the spray (before the drops hit the ground or crop canopy) and by evaporation from wet soil and plant canopy surfaces. Spray or droplet evaporation increases as temperature and wind velocities increase, and as average drop size, water application rate, and relative humidity of the air decrease. Evaporation from the soil surface, before the water can be extracted by plant roots, decreases proportionally as greater depths of water are applied per irrigation event.

(a) Uniformity

Distribution uniformity (DU) is a useful term for assigning a numerical value to the uniformity of application. The DU represents the uniformity of water application throughout the field and is calculated by comparing average application depths on the quarter of the field (statistically) receiving the lowest application depths against the average depth for the entire field:

$$DU = 100 \left(\frac{\text{Average low-quarter depth of water received}}{\text{Average depth of water received}} \right) \quad (\text{eq. 11-20})$$

where:

the average low-quarter depth of water received is the average of the lowest quarter of the measured values in a specified area, and each value represents an equal surface area. The specified area may be a complete field, however, generally, for periodic-move and fixed systems, the specified area is the rectangular area between four adjacent sprinklers, with consideration of application overlap by sequential lateral operation or positioning.

Another parameter that is used to evaluate sprinkle irrigation uniformity is the uniformity coefficient developed by Christiansen:

$$CU = 100 \left(1.0 - \frac{\sum X}{mn} \right) \quad (\text{eq. 11-21})$$

where:

- X = absolute deviation of the individual observations from the mean, in or mm
- m = mean depth of observations, in or mm
- n = number of observations

Test data for CU > 70 percent usually conform closely to a normal distribution and are reasonably symmetrical around the mean application depth. Therefore, CU can be approximated by:

$$CU = 100 \left(\frac{\text{Average low-half depth of water received}}{m} \right) \quad (\text{eq. 11-22})$$

and the relationship between DU and CU can be approximated by (Keller and Bliesner 1990):

$$CU \approx 100 - 0.63(100 - DU) \quad (\text{eq. 11-23})$$

or

$$DU \approx 100 - 1.59(100 - CU) \quad (\text{eq. 11-24})$$

DU and CU have a maximum value of 100 percent, which implies perfect uniformity. In practice, values are less than 100 percent.

DU and CU are determined through field procedures utilizing catch can tests, which measure the water applied at discrete points. For center pivots, the calculation of CU must account for the variation in field area covered by each sprinkler along the lateral. The center-pivot CU as defined by Heermann and Hein is presented in ASABE Standard S436.1, along with other test procedures for the evaluation of center-pivot and linear-move application uniformity.

General CU target values—In terms of the different types of sprinkle irrigation systems, the design CUs listed in table 11-6 are recommended as minimum values. In general, economic and production criteria suggest a target CU of at least 85 percent for delicate and shallow-rooted crops such as potatoes and most other vegetables. Deep-rooted field crops such as alfalfa, corn, cotton, and sugar beets and tree and vine crops that have deep spreading root systems can generally be adequately irrigated using the values also listed in table 11-6.

A design uniformity of CU less than 95 percent is not normally warranted for any type of sprinkler system because the increased system cost may be more than the benefits of such a high uniformity. Thus, the target uniformity for system design should not be unreasonably high. Also, it should be recognized that the effective uniformity of sprinkle irrigation is usually higher than the application uniformity, at least in the absence of ponding and runoff, because of spatial water redistribution within the crop root zone, both during and immediately following an irrigation.

Some of the factors that affect uniformity tend to average out during multiple irrigation applications. Therefore, the DU and CU following a series of irriga-

tion applications is often higher than from a single irrigation if there is some randomness in areas that are under or over-irrigated. This may occur from variation in wind speed and direction over time or from variation in sprinkler head orientation (level) from irrigation to irrigation. Other aspects of non-uniformity tend to concentrate, that is, the same areas tend to be over or under irrigated during each irrigation application, for example, due to poor distribution of water within the grid among sprinklers even with no wind, or pressure variation along a lateral. Obviously, the major concern is with those aspects that concentrate in the problem areas.

Components of nonuniformity in sprinkle irrigation systems that tend to even out with multiple irrigations are:

- Uneven operation of sprinklers or nozzles—This includes variations in turning speed regularity, variations in discharge between sprinklers caused by differences in nozzle size and wear, and irregularity of trajectory angle caused by riser straightness.
- Uneven travel speed for moving sprinklers, or set time for periodic-move systems—When the lack of uniformity in moving systems is caused by steep slopes or the weight of hose being dragged, there will be little tendency for this unevenness to smooth out. On the other hand, the lateral line set time for periodic-move systems will generally smooth out randomly over multiple irrigations, especially if care is taken to alternate between day and night sets.

- Variation in wind speed and direction from irrigation to irrigation.
- Redistribution of soil water within the crop root-zone to relatively dry regions during and after an irrigation.

These factors tend to concentrate unevenness:

- Differences in sprinkler discharges throughout the system caused by elevation and friction loss.
- Surface movement of water (both micro and macrorunoff)—Normally, one thinks of all the water infiltrating into the soil where it falls. This is not always the case. For example, along the outer edges of center-pivot irrigated fields the application rate is often greater than 1 inch per hour (25 mm/h), which is excessive for many soils and therefore localized or even larger scale surface transfer of water can occur.
- Poor water distribution around field boundaries—This is especially true for giant sprinklers that by necessity have a poor watering pattern around all boundaries, and for center pivots where an effort is made to irrigate a substantial distance past the end of the hardware. For example, the last 100 feet (30 m) past the end of a 1,320-foot (400-m) center-pivot lateral constitutes more than 13 percent of the area wetted of the system if irrigated all the way around the circle. The outer 100 feet (30 m) of a 160-acre (65 ha) field irrigated with a giant sprinkler constitutes 15 percent of the field area. Tipping sprinkler risers inward along the outer lateral sets of periodic-move and fixed systems and using part-circle sprinklers on lateral ends where medium and small sprinklers are used can greatly improve the uniformity along the field edges.

Table 11-6 Recommended design CU values for different sprinkler systems

Sprinkler system or application	Recommended minimum design CU
Hand move	70%
Side roll (wheel line)	75%
Fixed (solid set)	85%
Traveler	85%
Center pivot	90%
Linear move	95%
Disposal of effluent	70%

Uneven aerial distribution of water has both a tendency to smooth out and a tendency to concentrate over multiple irrigations. Uneven distribution results from insufficient overlap, sprinkler pattern shape, and wind effects on the overlap and pattern shape. Because the wind is usually different during each irrigation, there is some tendency for uniformity to improve over several irrigations. Also, alternating day and night sets and changing the lateral positions for each irrigation smooth out some unevenness. Generally, close sprinkler spacings give higher uniformities regardless

of wind conditions. Continuously moving a sprinkler is similar to having infinitely close sprinkler spacing along the direction of travel. Continuous-move systems have potential for quite high uniformities regardless of winds, if the sprinkler spacing at right angles to the direction of movement is sufficiently close.

Most of the effort to evaluate sprinkle irrigation system uniformity and efficiency is done with can tests. Such tests typically measure only the uniformity problems associated with aerial distribution. With close sprinkler spacings on fixed systems and along moving laterals, a high level of uniformity with DU values above 90 percent is practical in the test area. However, the other problems causing lower uniformity reduce the highest practical overall DU to about 85 percent. A low DU or CU value indicates that losses due to deep percolation will be excessive if adequate irrigation is applied to all areas.

Sprinkler physical characteristics, as well as nozzle size and pressure, affect performance. Therefore, the DU or CU values used for final design computations should be based on field or test facility data. Field evaluation techniques for estimating the uniformity of periodic-move, traveling, and center-pivot sprinklers are presented in this chapter. However, when test data are not available in general planning for the most common periodic-move sprinkler, spacings can be used to obtain estimated value of CU for various wind conditions and application rates. The average uniformity of the catch data of two irrigations is always higher than the average uniformities of the two irrigations measured individually, because of changes in wind and water jets. Uniformity can be further improved by positioning the laterals midway between the previous settings for alternate irrigations. This practice is called alternate sets, and it halves the effective lateral spacing for the pair of irrigations. The uniformity of a pair of irrigations using alternate sets can be approximated by (Keller and Bliessner 1990):

$$CU_a = 10\sqrt{CU} \quad (\text{eq. 11-25})$$

and

$$DU_a = 10\sqrt{DU} \quad (\text{eq. 11-26})$$

For gun or boom sprinklers, CU values of 60 to 75 percent are typical for low and moderate wind conditions. These sprinklers are not recommended for use in high winds. By using alternate sets along the lateral or between laterals when practical, CU_a values of about 80 percent can be obtained in the central portion of a field.

For traveling sprinklers, the effective spacing along the tow path that corresponds to the lateral is zero. The expected CU in the central portion of the field and in low to moderate winds should be similar or slightly better than the CU_a of 80 percent for periodic-move, gun, or boom sprinklers.

Center-pivot and linear-move systems produce high uniformities because the sprinklers are usually relatively close together on the moving laterals and pressure regulators (fig. 11-27) are often used at each sprinkler to reduce variation caused by topography. With correct nozzling, CU greater than 94 percent, DU greater than 90 percent can be expected in the area under the system hardware in relatively level fields. For well-designed center-pivot systems, the DU should range from 93 to 96 percent for systems outfitted with impact sprinklers and, with spray nozzles, from 91 to 95 percent. The same high uniformities can be maintained even on steep, undulating fields if pressure regulators or flow-control-nozzle sprinklers are used to counter elevation effects and to regulate pressure variation when a periodically operated end gun or corner system is activated. When large end-gun sprinklers are used on center-pivots, the average CU of the whole irrigated area drops about 1 percent for each 1 percent of area covered past the end of the hardware.

(b) Water loss

Although performance evaluation efforts often focus on uniformity problems, loss of water from leakage, runoff, or overirrigation also reduces system efficiency. Frequently, designers assume that systems will be perfectly managed and losses will almost be eliminated, but this is seldom the case. Overwatering is generally the greatest cause of loss in any irrigation system. Other major causes of losses associated with sprinkle irrigation are:

- direct evaporation from droplets and from wet soil surfaces and plant canopy and transpiration from unwanted vegetation
- wind drift
- leaks and system drainage

Evaporation losses from wet soil and plant canopies increase as a percentage of the application depth and frequency of irrigation increases, because individual depths of application are less with frequent irrigation and the soil and canopy are wet more of the time. Wind drift and evaporation losses may be less than 5 percent when irrigating a crop with a full vegetative canopy in low winds, especially with low pressure nozzles on center pivots or linear move systems where the nozzles are placed in or near tops of crop canopies. More commonly, wind drift and evaporation losses range between 5 and 10 percent. However, under severe conditions the losses can be considerably greater. Figure 11–28 was developed by Keller-Bliesner (1990) as a guide for estimating the effective portion of the water applied that reaches the soil-plant surface (R_e). The values given for effectiveness for different potential evapotranspiration rates are based on an assumed full plant canopy and 24-hour applications. The fine-spray curves are based on three-sixteenth-inch (4.8 mm) nozzles operating at 60 pounds per square inch (410 kPa) in a 40- by 60-foot (12 by 18 m) spacing.

Figure 11–27 Preset pressure regulators for sprinklers



The coarse spray is for three-sixteenth-inch nozzles operating at 30 pounds per square inch (210 kPa) in a 30- by 60-foot (9 by 18 m) spacing.

To use figure 11–28, it is necessary to know whether the spray from a sprinkler is coarse, fine, or somewhere in between. To make this determination, a coarseness index (CI) is used. This index can be calculated by this method:

$$CI = K \frac{P^{1.3}}{B} \quad (\text{eq. 11-27})$$

where

CI = Coarseness index

K = coefficient equal to 1.0 for English units and equal to 0.032 for metric units

P = nozzle operating pressure (lb/in² or kPa)

B = nozzle bore diameter, 64ths of an in or mm

If the value of CI less than or equal to 7, then the spray is considered to be coarse, and the lower portion of figure 11–28 should be used to find R_e . If CI greater than 17, then the spray is considered to be fine, and the upper portion of the figure should be used. When the value of CI falls between 7 and 17, the R_e value may be interpolated by the formula:

$$R_e = \frac{(CI-7)}{10}(R_e)_c + \frac{(17-CI)}{10}(R_e)_f \quad (\text{eq. 11-28})$$

where:

R_e = effective portion of applied water (fraction)

$(R_e)_c$ = R_e value when the coarse spray curves are used

$(R_e)_f$ = R_e value when the fine spray curves are used

Keller and Bliesner (1990) provided a regression equation that reproduces the curves in figure 11–28:

$$R_e = 0.976 + 0.005 ET_o - 0.00017 ET_o^2 + 0.0012 W - 0.00043 (CI)(ET_o) - 0.00018 (CI)(W) - 0.000016 (CI)(ET_o)(W)$$

(eq. 11–29)

where:

R_e = fraction (0 to 1)

ET_o = reference ET in mm/day (grass-based)

CI = coarseness index ($7 \leq CI \leq 17$)

W = wind speed, m/h, km/h (1 m/h = 1.6 km/h)

For equation 11-38, if $CI < 7$, then set it equal to 7; if $CI > 17$, then set it equal to 17.

Keller and Bliesner (1990) suggested modifications to values for CI, P, and B used in equation 11-27 or figure 11-28 for low-pressure nozzles used on center pivots and for modifications made to impact sprinklers:

For low-pressure, fixed-spray nozzles:

With smooth plates let $CI = 17$

With narrow-groove serrated plates let $CI = 12$

With wide-groove serrated plates let $CI = 7$

For impact-sprinklers use equation 11-27 to compute CI. Then adjust values for the nozzle operating pressure, P, and nozzle diameter, B, to compensate for impacts of flow distortion on drop size by:

For ordinary nozzles:

P = actual P

B = actual B

For diffusing nozzles:

P = $1.5 \times$ actual P

B = the equivalent B for a standard nozzle

For nozzles with flexible flow-control orifices:

P = $1.1 \times$ actual P

B = the equivalent B at normal operating pressure (must be calculated from an orifice equation)

For nozzles with straightening values:

P = $0.9 \times$ actual P

B = actual B

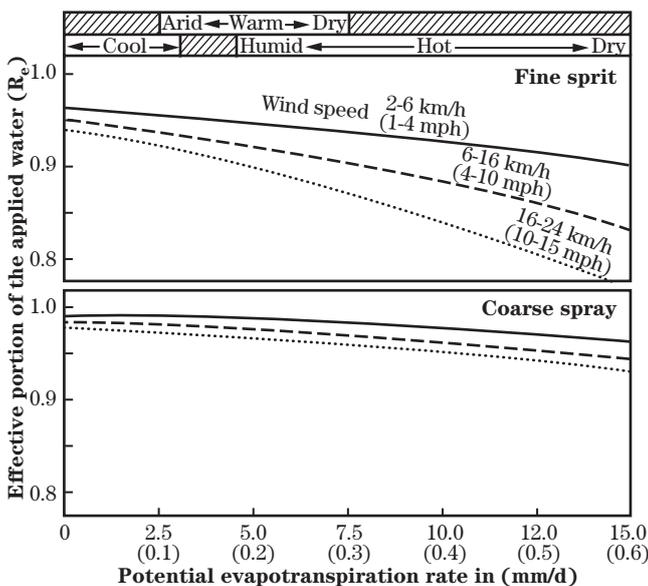
For orifice-type (or ring) nozzles:

P = $1.2 \times$ actual P

B = the equivalent B for a tapered nozzle or about $0.85 \times$ actual B

For well maintained systems, leaks and drainage losses can be held to less than 1 percent of system capacity or even eliminated by using antidrain valves at the sprinklers. However, poorly maintained systems can have leakage and drainage losses of up to 10 percent or more.

Figure 11-28 Effective portion of water applied, R_e , by sprinkling with fine and coarse sprays in different wind conditions and with different potential evapotranspiration rates on crops with full canopies (Keller and Bliesner 1990)



(c) Application efficiency

Perhaps the most often used irrigation efficiency term has been application efficiency (E_a). Application efficiency is generally defined as the ratio of the average depth of irrigation water stored in the rootzone to the average depth of irrigation water applied.

The E_a parameter reflects the impacts of losses of water caused by deep percolation, wind drift, and evaporation losses. However, because E_a only reflects the fraction of applied water stored within the rootzone that is potentially accessible for evaporation and transpiration, it does not indicate the adequacy of the irrigation. Therefore, under exaggerated under-irrigation, E_a can equal 100 percent. To be more useful, the application efficiency term needs to combine some measure of uniformity, adequacy of irrigation, and losses. An example of such a concept is the application efficiency of the low quarter (E_q). The E_q is the application efficiency that occurs when a field is irrigated with sufficient water depth so that the average depth of water infiltrated to the rootzone on the quarter of

the field that (statistically) receives the lowest portion of water just equals the soil moisture deficit at the time of irrigation. When this occurs, seven-eighths (87%) of the field has been watered to field capacity or higher and one-eighth of the field receives some amount of under irrigation. Therefore, seven-eighths of a field will have some amount of deep percolation, depending on the degree of water application uniformity. The seven-eighths (over irrigation) minus one-eighth (under irrigation) concept is generally well understood and widely used by the agricultural community and is considered to represent an economic balance for high-value crop production. The E_q is a useful term for placing a numerical value on irrigation efficiency for medium to high value crops. For design purposes, the ratio of the average low-quarter depth of irrigation water available to the plant to the average depth of irrigation water applied can be estimated by:

$$E_q = DU(R_e O_e) \quad (\text{eq. 11-30})$$

where:

E_q = application efficiency of the low quarter (%)

DU = distribution uniformity (%)

R_e = effective portion of applied water from figure 11-28

O_e = fraction of water effectively discharged through sprinklers or nozzles

The difference $1 - O_e$ represents the fraction of leakage, and in well-maintained systems, O_e is 0.99 or greater.

When the soil moisture deficit (SMD) is divided by E_q to determine the gross depth of irrigation, d , only about 10 percent of the area (one-eighth) will remain below field capacity, as illustrated in a later section. Conversely, about 90 percent of the area will be adequately irrigated and will receive varying amounts of overirrigation. While this is practical for medium- to high-value crops, it may be extravagant for low-value field and forage crops. For such crops an application efficiency based on the average low-half depth is more appropriate.

Similar to E_q , an application efficiency of the low half (E_h) can be estimated as:

$$E_h = CU(R_e O_e) \quad (\text{eq. 11-31})$$

When E_h is used to estimate the gross depth, d , needed to replace a given SMD, about 20 percent of the area (field) will remain below field capacity and about 80 percent of the field will experience some deep percolation. Some of the deep percolation is useful for maintaining a low salt balance within the rootzone. However, deep percolation represents a loss in energy investment, a potential loss of soil nutrients, and, depending on the local and regional hydrology and recycling of groundwater, a potential loss of water. Whether deep percolation is considered to be a loss to the resource depends on whether downstream users, in space and time, are able to capture and use the deep percolation after it enters groundwater. Another aspect of deep percolation is that some agricultural chemicals will move with the water and possibly contaminate groundwater or surface water bodies. Some deep percolation may be periodically necessary to maintain a favorable salt balance in the crop rootzone. More coverage on application efficiency, including how to estimate E_a for other levels of irrigation adequacy, besides the average of the low-quarter, and average of the low half, is given in the following section on design of periodic-move systems. The range of target E_q and E_h values for various types of sprinkler systems are shown in table 11-7.

These application efficiency values are based on full-canopy crops and the assumption that the systems are well designed and carefully maintained. The values should be considered only as estimates. Considerably lower values would be obtained with poor management or where systems are poorly designed or ill suited to the prevailing conditions. When DU or CU can be measured, E_q and E_h can be calculated for specific field conditions using equations 11-30 or 11-31.

Table 11-7 Ranges of target E_q and E_h values for different types of sprinkler systems

Type	E_q	E_h
Periodic-move lateral	60–75%	70–85%
Gun or boom sprinklers	50–60%	60–75%
Fixed lateral	60–85%	70–88%
Traveling sprinklers	55–67%	65–77%
Center pivot	75–85%	80–88%
Lateral move	80–87%	85–90%

Sprinkler system operation and maintenance should include periodic evaluation to determine efficiency and to locate potential areas for upgrading performance. With scheduling and careful management, improvements in irrigation efficiency of older systems are possible by updating systems using state-of-the-art hardware and management:

- Increases of 20 percent to 40 percent, or more, are possible when current system uniformities are low, there is supplemental rain, and soils have low water-holding capacities.
- Increases of 5 to 15 percent are often possible for high water-holding capacity soils and 10 to 25 percent for low water-holding capacity soils when maximum production per unit of land is desired in arid zones with abundant water supplies.
- In arid zones where water supplies are scarce and maximum productivity per unit of water used is desired, fields are often underirrigated. In such instances, scheduling can at best increase efficiencies by 10 percent, since deep percolation losses are already likely to be small. Scheduling may be useful, however, in determining the best time to apply the limited water available. This can be done by watering at the most strategic crop phenological development stage that results in maximum profit. By carefully analyzing and selecting the crops and planting dates, water requirements may be further reduced.

623.1105 Design procedure

Designing a sprinkler system involves many decisions based on measured and/or estimated data, engineering calculations, designer experience, and farmer preferences. In general, a design process involves the production of two or more alternatives from which the client (or farmer) can choose, after considering the pros and cons of each. In most cases it is not advisable to present a single design to a client. An important part of the design process is to include operational and maintenance guidelines for the implementation of the design.

The first step in the design procedure is to collect basic farm resource data. This information includes a topographic map showing obstacles and farm and field boundaries, as well as data on water resource quality, quantity, and dependability; weather; crops; and soils. The farmer should be consulted about financial, labor, and management capabilities, plus any specific cultural practices or constraints that may impact the system design or operation. Once the data on farm resources have been assembled, the system selection, layout, and hydraulic design process may proceed. Of these, the first task is to consider the different types of sprinkle irrigation system that might be feasible for the given conditions, including the preferences of the farmer (who in some cases might already have decided to use a particular type of sprinkler system). This can be a process of elimination, and or it can be a listing of the types of systems that would be considered potentially appropriate.

The major components in a sprinkler system (sprinklers, laterals, mainline, pump, and other hardware) are shown in figure 11–29. Some sprinkler systems will not have all of these components, while others can have additional hardware not indicated in the figure. The design process should begin with the sprinkler selection and then continue with the system layout, followed by the design of the lateral, supply line, mainline, and pumping plant. Typically, some iteration is required. To make an appropriate system selection, it may be necessary to design and analyze two or more systems, and the farmer should carefully study the alternative before ultimately selecting a system.

(a) Periodic-move and fixed systems

Periodic-move and fixed sprinkler systems are known as set systems because the sprinklers do not move during operation, instead, they are moved from one position to another after the pump (valve) is shut off and the pipes have drained. The basic strategy for designing all periodic-move and fixed systems is the same as for hand-move systems (which is one type of periodic-move system). Much of the design described in this section also applies to continuous-move systems. For example, the design of mainlines and pumping plants is similar for all systems. There are also many similarities between the sprinkler-head characteristics of periodic-move and continuous-move systems. Because of this overlap, the sections on the continuous-move sprinklers will only contain material that is unique to those systems. Sprinklers are classified according to their operating pressure range, means of rotation, jet deflection and breakup, and their position in relation to irrigated crops. The different classifications of impact sprinklers, with the characteristics and adaptability of each, are given in table 11–8. Classification of characteristics of spray and rotation nozzles typically used with center-pivot and linear-move systems are included later in that section.

(1) Sprinkler selection for periodic-move and fixed systems

Sprinkle irrigation system design would be significantly simplified if there were only one sprinkler on the market. But there can actually be a great variety of different sprinklers available on the market in any given location, from different manufacturers, and the selection of a sprinkler can be one of the most difficult aspects of a system design. Sprinklers have been designed for various applications, are made of different materials (metals and plastics), sometimes with special features (low pressure, pressure compensation, wind compensation), and have widely differing purchase prices. The designer must use experience and judgment, as well as information from vendors and manufacturers, to develop a list of sprinklers and nozzles that would fit a given design scenario. In some cases, reconsider the list of sprinklers depending on whether pressure regulating valves will be used in the design. A thorough design will typically involve the (computational) evaluation of a number of different sprinklers.

Impact sprinklers have the benefit over low-pressure nozzles typically used on center-pivot and linear-move systems of longer throw distance and typically fewer plugging problems. The longer throw allows larger spacing between sprinklers and laterals reducing required number of laterals and pipe costs. The longer throw does come at the expense of typically larger pressure and energy requirements. For systems using impact, gear-drive, or plate-rotating single jet sprinklers, actual sprinkler head selection is based on the discharge rate, height of trajectory, and sprinkler distribution characteristics desired. Sprinklers for periodic-move differ little from those for fixed-sprinkler systems. The main difference is that in fixed systems, pipe lengths are not necessarily a multiple of 10 feet (3.3 m).

By keeping sprinkler discharge rates as low as possible while still using wide sprinkler spacings, the size and amount of pipe, as well as labor, are kept to a minimum. However, in periodic-move systems, higher sprinkler discharge can result in fewer laterals, since laterals can be moved more frequently. The sprinkler giving the most economical overall system should be selected if soil surface sealing, wind, and infiltration are not limiting factors. When bare soil surfaces are sprinkled, to meet minimum discharge requirements and to reduce soil sealing and runoff potential, select

Figure 11–29 Basic sprinkler system components

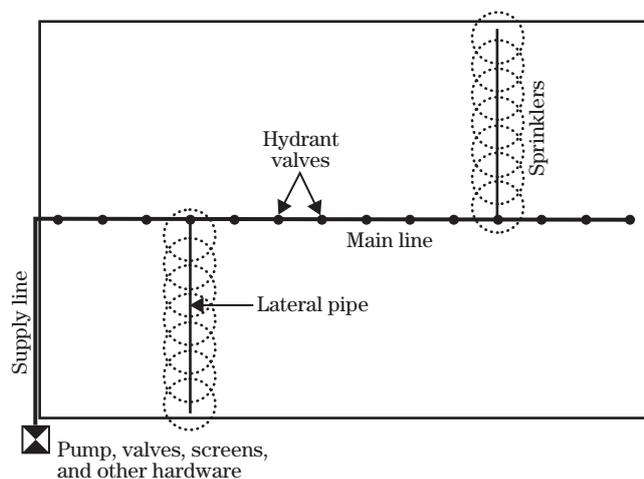


Table 11-8 Classification of impact and similar sprinklers and their adaptability

Type of sprinkler	Low pressure	Moderate pressure	Medium pressure	High pressure	Hydraulic or giant (gun)	Undertree long-angle	Perforated pipe
General characteristics	Special thrust springs or reaction-type arms	Usually, single-nozzle oscillating or long-arm dual-nozzle design	Either single- or dual-nozzle design	Either single- or dual-nozzle design	One large nozzle with smaller supplemental nozzles to fill in pattern gaps. Small nozzle rotates the sprinkler	Designed to keep stream trajectories below fruit and foliage by lowering the nozzle angle	Portable irrigation pipe with lines of small perforations in upper third of pipe perimeter
Pressure range	5–15 lb/in ² 35–100 kPa	15–30 lb/in ² 100–210 kPa	30–60 lb/in ² 200–415 kPa	50–100 lb/in ² 350–690 kPa	80–120 lb/in ² 550–830 kPa	10–50 lb/in ² 70–350 kPa	4–20 lb/in ² 30–140 kPa
Range of wetted diameters	20–50 ft 6–15 m	60–80 ft 20–25 m	75–120 ft 20–35 m	110–230 ft 30–70 m	200–400 ft 60–120 m	40–90 ft 12–30 m	10–50-ft wide strips 3–15-m wide strips
Recommended minimum application rate	0.40 in/h 10 mm/h	0.20 in/h 5 mm/h	0.25 in/h 6 mm/h	0.50 in/h 12 mm/h	0.65 in/h 17 mm/h	0.33 in/h 8 mm/h	0.50 in/h 12 mm/h
Jet characteristics (assuming proper pressure-nozzle size relations)	Water drops are large due to low pressure	Water drops are fairly well broken	Water drops are well broken over entire wetted diameter	Water drops are well broken over entire wetted diameter	Water drops are extremely well broken	Water drops are fairly well broken	Water drops are large due to low pressure
Water distribution pattern (with proper spacing, pressure, and nozzle)	Fair	Fair to good at upper limits of pressure range	Very good	Good except where wind velocities exceed 4 mph (6 kph)	Acceptable in calm air. Severely distorted by wind	Fairly good diamond pattern. Recommended where laterals are spaced more than one tree apart	Good rectangular pattern

Table 11–8 Classification of impact and similar sprinklers and their adaptability—continued

Type of sprinkler	Low pressure	Moderate pressure	Medium pressure	High pressure	Hydraulic or giant (gun)	Undertree long-angle	Perforated pipe
Adaptations and limitations	Small acreages. Confined to soils with intake rates exceeding 0.50 in/h (12 mm/h) and good ground cover on medium- to coarse-textured soils.	Primarily for undertree sprinkling in orchards. Also for field crops and vegetables.	For all field crops and most irrigable soils. Well adapted to overtree sprinkling in orchards and groves.	Same as for medium-pressure sprinklers, except where wind is excessive.	Adaptable to close-growing crops that provide a good ground cover. For rapid coverage and for odd-shaped areas. Limited to soils with high intake rate.	For orchards and citrus groves. In orchards where wind will distort overtree sprinkler patterns. In orchards where available pressure is insufficient for operation of overtree sprinklers.	For low-growing crops only. Unsuitable for tall crops. Limited to soils with relatively high intake rates. Best adapted to small areas of high-value crops.

nozzles sizes between 5/64th inch (2 mm) and 9/64th inch (3.6 mm). Also operating pressures over 50 pounds per square inch (345 kPa) should be used to create a finer spray (smaller drop size).

Under-tree systems may require low trajectory sprinklers having 10 to 25 degree trajectories to reduce foliar wetting and interference. Under-tree sprinkling is required when the irrigation water is of such low quality that it will cause significant leaf burn or when micro sprays are used. Under-tree sprinkling is also recommended rather than over-tree sprinkling to reduce evaporation losses from wet-tree canopies and sprinkler drift. Variations in sprinkler design imposed by tree spacings and shapes are not detailed here. Generally, however, where sprinkler spacing is larger than tree spacings, sprinklers that throw a greater volume of water to the outer perimeter of the wetting pattern produce the best under-tree results because tree interference tends to cause excess water application close to the sprinklers.

On over-crop systems in windy areas, low-angle sprinklers with a trajectory of 18 to 21 degrees produce better results than high-angle sprinklers with 25 to 28 degrees trajectories. Many sprinkler manufacturers have compromised on a trajectory angle of between 223 and 247 degrees to achieve reasonable performance under varying wind conditions. Where winds are always very low, high-angle sprinklers give the best results with a minimum of pressure.

Once the type of sprinkler has been determined, based on pressure limitations, application rates, cover conditions, crop requirements, and availability of labor, the next step is to determine the combination of sprinkler spacing, operating pressure, and nozzle sizes that will most nearly provide the optimum water-application rate with the greatest uniformity of distribution and low operating costs. This determination is based on pressure limitations, application rates constrained by soil infiltration limits, cover conditions, crop requirements, and availability of labor.

(2) Factors affecting distribution uniformity

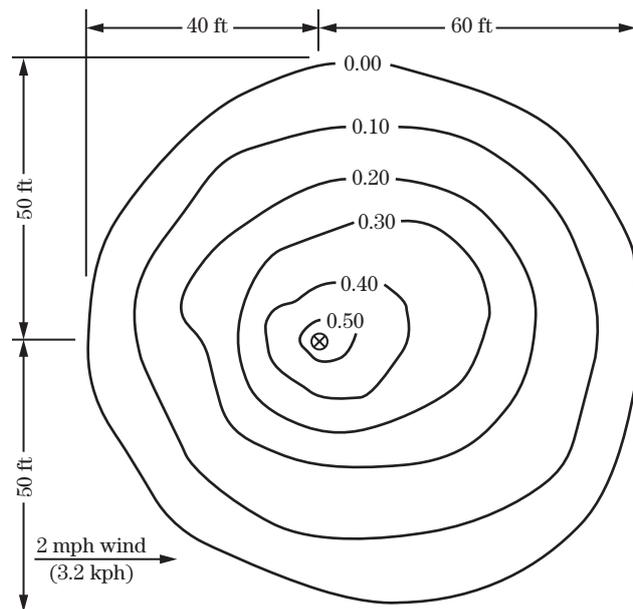
The degree of uniformity obtainable depends primarily on the water distribution pattern of from the sprinkler and on the spacing of the sprinklers. Figure 11-30 shows the distribution pattern and precipitation pro-

files obtained from a typical double-nozzle sprinkler operating at the correct pressure with only a slight wind.

Each type of sprinkler has certain precipitation profile characteristics that typically change as nozzle size and operating pressure change. Each has an optimal range of operating pressures for each nozzle size. Most sprinkler manufacturers recommend operating pressures or ranges of pressures that will result in the most desirable application pattern for each type of sprinkler and nozzle size. In selecting nozzle sizes and operating pressures for a required sprinkler discharge, the different pressures generally affect the profile from impact sprinklers.

- At the lower side of the specified pressure range for any nozzle, the average water droplet size is relatively large. When pressure falls too low, the water from the nozzle falls in a ring a short distance away from the sprinkler, giving a poor precipitation profile (fig. 11-31A), and increasing losses due to wind drift and evaporation.

Figure 11-30 Distribution pattern and precipitation profiles from a typical double-nozzle sprinkler operating under low-wind conditions



- Within the desirable range, the sprinkler should produce the precipitation profile shown in figure 11-31B.
- On the high side of the pressure range, the water from the nozzle breaks up into fine drops and settles around the sprinkler (fig. 11-31C). Under such conditions the profile is easily distorted by wind.

Wind distorts the application pattern, and the higher the wind velocity, the greater the distortion. Figure 11-32 shows test results of an intermediate double-nozzle sprinkler operating under a wind velocity of 10.7 miles per hour (17.2 kph). This distortion must be considered when selecting the sprinkler spacing.

The depth of water applied to an area surrounding a sprinkler varies with distance from the sprinkler. Thus, to obtain a reasonably high uniformity of application, water from adjacent sprinklers must be added. Figure 11-33 illustrates the depth of distribution obtained by overlap from sprinkler to sprinkler along the lateral. While figure 11-34 overlap from lateral to lateral.

Figure 11-32 Effect of wind on distribution pattern and precipitation profiles from a typical intermediate double-nozzle sprinkler

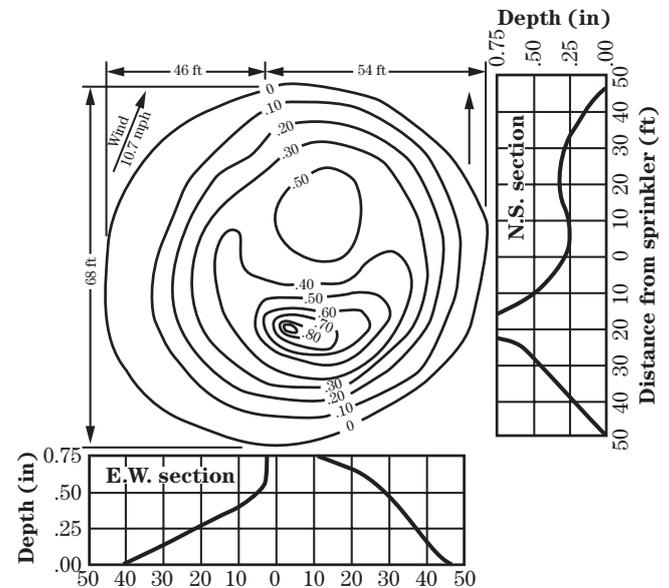


Figure 11-31 Effect of different pressures on precipitation profiles for a typical double-nozzle sprinkler (the sprinkler is located at position zero, in the center)

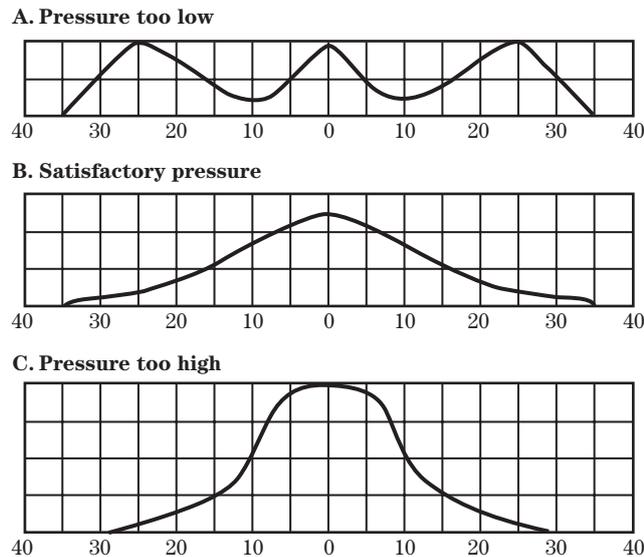
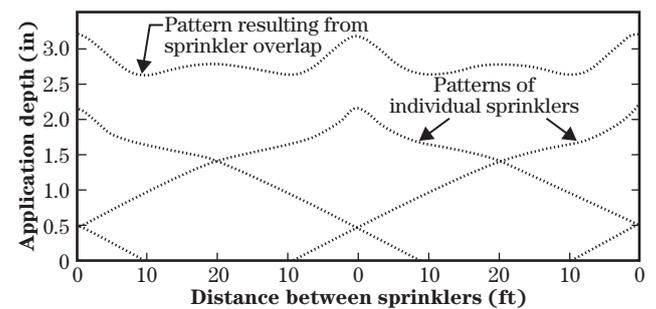


Figure 11-33 Example of the water distribution pattern between adjacent sprinklers along a lateral



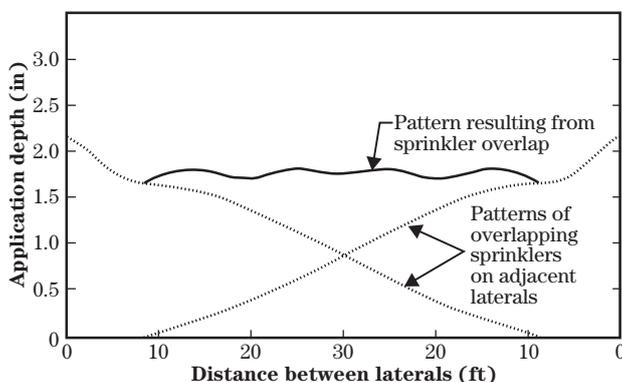
(b) Wetted diameter and recommended spacings

Manufacturers of sprinklers specify a wetted diameter and discharge data for all nozzle sizes and operating pressure combinations for each type of sprinkler in their line. Since sprinkler-spacing recommendations commonly are made on the basis of these diameters, the planner must carefully consider them. The precipitation profile is also important when making sprinkler spacing recommendations. Different sprinkler nozzle, pressure, and physical characteristics produce different precipitation profiles. Figure 11–35 shows a stylized set of potential sprinkler profiles and optimum spacings.

Certain sprinklers under specific conditions produce a typical precipitation profile as shown in figure 11–35. Each profile type has its spacing recommendations based on the diameter of effective coverage under the particular field conditions of operation. Conditions that affect both the diameter and profile characteristics are:

- direction and velocity of the wind measured from the ground level to the top of the jet trajectory
- angle of stream trajectories
- height and angle of risers
- turbulence in the stream of water entering and leaving the nozzle
- pressure at the nozzle

Figure 11–34 Example of the water distribution pattern between overlapping sprinkler patterns between adjacent laterals



- size of the nozzle
- speed and uniformity of rotation and characteristics of the driving mechanism such as the shape,
- angle frequency of the spoon and lever action
- nature of other turning mechanism (gears or viscous deflecting plate)

With such a complex set of conditions the practical way of determining the profile type and diameter is by placing catchment gages in the precipitation area and evaluating the results.

Profiles A, B, and C (fig. 11–35) are characteristic of sprinklers having two or more nozzles. Profiles C and D are characteristic of single-nozzle sprinklers at the recommended pressures. Profile E is generally produced with gun sprinklers or sprinklers whose pressure at the nozzle or nozzles is lower than those recommended for the nozzle sizes concerned. Sprinklers with straightening vanes just upstream from the range nozzle also tend to produce an E profile. The vanes increase the diameter of throw by creating larger drop sizes, but pressures often must be increased by 10 to 16 pounds per square inch (70 to 110 kPa) to keep the dip in the center of the profile from becoming too low. Profile E is also common to some types of spray devices used on center pivots. For these devices and center-pivot designs, the irregularity of the E pattern can be overcome by using close nozzle spacings of only 15 to 30 percent of the effective wetted diameter.

Figure 11–35 Christiansen's geometrical sprinkler profiles and optimum spacings as a percentage of the effective wetted diameter

Sprinkler profile		Recommended spacing as a percentage of diameter		
Type	Shape	Square	Triangular equilateral	Retangular short × long
A		50	50	40×60 to 65
B		55	66	40×60
C		60	65	40×60 to 65
D		40 70 (Fair)	70 to 75	40×70 to 75
E		40 80 (Fair)	80	40×80

The spacing recommendations in figure 11–35 should give acceptable application uniformities for gridded systems when a realistic effective wetted diameter is used. Operating conditions in the field affect both the diameter and the precipitation profile. Wind is the chief modifier reducing the diameter of throw and changing profiles to a mixed type such as a short A or B type on the upwind side of the sprinkler, a D or E type downwind, and a C type crosswind (fig. 11–32).

The wetted diameter of a sprinkler as listed in the many manufacturer's brochures is often for no wind and to the farthest droplet from the sprinkler. Under field operating conditions with 0 to 3 mph wind, such diameters should be reduced by 10 percent from the reported values to obtain a relative effective diameter, d_{eff} . Effective diameters should be further reduced for winds exceeding 3 miles per hour (5 kph). Therefore,

$$d_{\text{eff}} = 0.9d_{\text{manf}} \quad \text{if } u_2 \leq 3 \text{ m/h} \quad (\text{eq. 11-32})$$

and

$$d_{\text{eff}} = [0.9 - 0.025 \times (u_2 - 3)] d_{\text{manf}} \quad \text{if } u_2 > 3 \text{ m/h} \quad (\text{eq. 11-33})$$

where:

d_{manf} = diameter reported in manufacturer literature
 u_2 = average expected wind speed during operation at 2 m height above the ground, in mph (3 mph is equivalent to 1.3 m/sec)

A reduction of 2.5 percent for each miles per hour over 3 miles per hour (1.3 m/sec or 5 kph) is a fair estimate for the usual range of wind conditions under which sprinklers are operated. For set sprinkler systems, the spacing of laterals along a mainline should not exceed 65 percent of the wetted diameter, and should be limited to 60 percent for 1 to 5 miles per hour winds, 50 percent for 6 to 10 miles per hour winds, and 45 percent for winds exceeding 10 miles per hour. For high pressure and gun sprinklers, the sprinkler spacing should not exceed 65 percent of the wetted diameter in the absence of wind and should be limited to 50 percent for 5 to 10 miles per hour winds, or 30 percent when winds are greater than 10 miles per hour.

Generally, highest uniformities are obtained at spacings of 40 percent or less of the diameter so that many areas receive application from two or more sprinklers, but such close spacings raise both precipitation rates and costs. Overly conservative (close) or optimistic (too large) spacings between lines sprinklers and laterals can result in poor uniformities of coverage. Certain profile types, notably D and E, require a narrow range in spacing to obtain a narrow range at high uniformity for extended spacing between lines. The uniformity with these profiles can change drastically with changes in wind speed. Unfortunately, the uniformity can actually decrease with D and E profiles as wind velocity decreases because of too much overlap. The E profile is often called a donut pattern and can occur when pressure or bore turbulence is insufficient to break up the water jet so that the proportion of large drops, with relatively large throw distance, is large.

Under field operating conditions, a variety of wind speeds and directions usually occur during the irrigation set. Therefore, a mixture of profiles is produced. As a general recommendation, moderate and intermediate-pressured sprinklers should be spaced as (CPS-442):

- Rectangular spacing of 40 by 65 percent of the effective diameter based on the average wind speed during the setting.
- Square spacing of 50 percent of the effective diameter based on average wind speed during the setting.
- Equilateral triangular spacing of 65 percent of the effective diameter based on average wind speed during the setting.

(c) Effects of system pressure on uniformity

Nozzle discharge varies with the nozzle pressure unless special flexible orifice nozzles are used to control the flow. Figure 11–36 shows the relationship between discharge and pressure for a typical fixed 5/32 inch nozzle that gives 5 gallons per minute at 48 pounds per square inch and for a flexible orifice nozzle designed to give 5 gallons per minute (0.32 l/sec), regardless of

pressure. But it is difficult to manufacture the flexible orifice nozzles precisely, and they are apt to have up to ± 5 percent variation in flow, even with uniform pressures. The same variation is also typical for almost all the flow or pressure control devices that can be used at the base upstream of each sprinkler. Therefore, unless the difference in pressures throughout the system is expected to exceed 15 to 20 percent of the desired average operating pressure, it is best to use standard fixed nozzles and no flow-control devices. The 15 to 20 percent pressure range stems from the standard orifice relationship where discharge is proportional to the square-root of pressure. The square root of 1.15 is 1.07 and the square root of 1.20 is 1.10, meaning the 15 to 20 percent pressure variation with fixed orifice nozzles will cause 7 to 10 percent variation in discharge.

An energy advantage of flexible orifice nozzles is that they maintain relatively constant flow without causing the pressure drops associated with other types of pressure regulators of at least 5 pounds per square inch (35 kPa), which is a typical characteristic of the flow or pressure control regulation devices used at the base of sprinklers. This is an important advantage when operating pressures are lower than 50 pounds per square inch (345 kPa) and maintaining a reasonably high nozzle pressure is necessary to have adequate jet breakup and range of throw. However, when pressures are above 80 pounds per square inch (550

kPa), the jet breakup and wind drift may be excessive and the sprinklers may turn erratically. Therefore, for such high-pressure operation, pressure control devices should be used at the base of each sprinkler, or total lateral pressure should somehow be reduced. Recommended operating pressures are typically provided by the manufacturer.

(d) Systemwide application uniformity

When pressure or flow controls, such as flexible-orifice nozzles, are used, the DU and CU test values should be multiplied by approximately 0.95 to obtain the systemwide (field) uniformity. This accounts for impacts of field edges, manufacturing variation, and the imperfections of pressure and flow control devices.

When pressure control and or flow control are not used, the pressure variations throughout the system can cause the overall uniformity of the system to be substantially lower than the uniformity in the test area. An estimate of the system DU and CU can be computed from according to the maximum, minimum, and average system pressures by:

$$\text{System DU} = \text{DU} \left(1 - \frac{P_x - P_n}{5P_a} \right) \quad (\text{eq. 11-34})$$

and

$$\text{System CU} = \text{CU} \left(1 - \frac{P_x - P_n}{8P_a} \right) \quad (\text{eq. 11-35})$$

where:

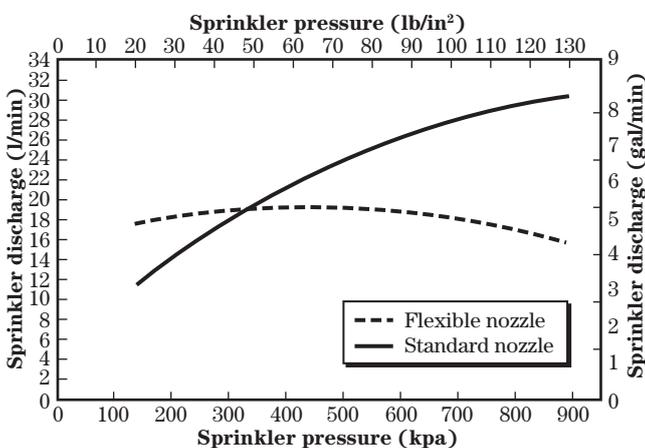
P_x = maximum sprinkler pressure in the system, lb/in² or kPa

P_n = minimum sprinkler pressure in the system, lb/in² or kPa

P_a = average sprinkler pressure in the system, lb/in² or kPa

These two relationships are approximate and were developed by Keller and Bliesner (2000). They can also apply to center-pivot and linear-move systems that do not use pressure control at the nozzles.

Figure 11-36 Comparison of pressure versus discharge relationship for a standard fixed nozzle and a special flexible orifice nozzle.



Using the data from the previous example on uniformity with a test DU of 82 percent:

$$\begin{aligned} \text{System DU} &= 82 \left(1 - \frac{45 - 39}{(5)(40)} \right) \\ &= 80\% \end{aligned} \quad (\text{eq. 11-34})$$

and with a test CU of 87 percent:

$$\begin{aligned} \text{System CU} &= 87 \left(1 - \frac{45 - 39}{(8)(40)} \right) \\ &= 85\% \end{aligned} \quad (\text{eq. 11-35})$$

The leading manufacturers of sprinklers are continually field testing their products and data are available on several sprinklers operating under various field conditions and from tests conducted indoors. When planning sprinkle irrigation systems, the user should not only seek data from online sources or printed material, but can also request data from the distributors or manufacturers. If available, the data should be used as a basis for selecting the combination of spacing, discharge, nozzle size, and operating pressure that will result in the highest practical uniformity coefficient for the existing various operating conditions being considered.

(1) Selection of spacing

The basic criterion governing the selection of spacing for any given sprinkler nozzle-pressure and wind combination is the desired distribution uniformity. Generally, the higher the value of the crop, water, or fertilizer, or the higher the damage caused by low uniformity, such as by water logging or soil salinity damage, the higher the recommended CU value. Higher values for CU generally require closer nozzle or lateral spacing, higher operating pressures, or both, which in turn require higher investment and perhaps operating costs. Some balance is required. Note that low CU can often be balanced by high application depth with more deep percolation. However, this may cause problems with water logging, negative water quality and quantity impacts, and economic losses from inefficient losses of income by leaching of nutrients. In areas where daytime wind speeds are substantially higher than those during nighttime or where nighttime wind speeds are substantially higher than those during daytime, for example in coastal areas or mountain valleys, sprinkler systems may need to be designed to operate during

only part of the day or night when wind speeds are lowest. This will require larger capacities for pipes and pump and larger nozzles or more laterals.

When applying chemicals through the system, a CU above 85 percent (DU > 76 percent) is recommended. When systems have low CU due to wind, chemicals should be applied only during calm periods.

(2) Distribution efficiency

Table 11-9 gives a more useful meaning to the concept of CU as paired against adequacy of irrigation. If a sprinkler system has a CU of 86 percent, then for each inch of average gross application received at the crop or field surface, 80 percent of the field area would receive at least 0.85 inch, and 50 percent of the area would receive at least 1.00 inch. If the CU were only 70 percent, then 80 percent of the area would only receive at least 0.68 inch or more water, and 20 percent of the field would receive 0.68 inch of water or less, even though, on average, the field receives 1.0 inch.

To apply a net application of 1.0 inch (25 mm) to at least 80 percent of the area using a system having a CU of 86 percent, a gross depth equal to 1.0 inch divided by 0.85 is 1.18 inches must be applied in addition to any wind drift and evaporation losses must be applied. With a CU of only 70 percent, a gross application, after drift and evaporation losses of equal to 1.0 inch divided by 0.68 is 1.47 inches, would be required in addition to drift and evaporation losses to apply a net application of 1.0 inches to 80 percent of the area.

Assuming that application depths follow a normal (symmetrical) distribution, table 11-9 provides data for constructing figure 11-37, which illustrates the relation between rainfall field area and depth of water applied at the CU values described. With 80 percent of the field adequately irrigated to 1 inch, both 70 and 86 percent CU values leave 20 percent of the area under-irrigated (to some degree), and 80 percent of the field area is adequately or overirrigated. However, the 70 percent CU requires a gross application of approximately 25 percent more water than does the 86 percent CU. Deep percolation losses from some portions of the field are substantial with the 70 percent CU, with 20 percent of the field having at least 0.8 inch of deep percolation (assuming that soil water depletion of the field is 1 in). Deep percolation on the wettest 20 percent of the field would be reduced to about 0.3 inch if the CU were increased to 86 percent.

When any given CU value is used as the irrigation application efficiency, the field area that receives the desired application depth, or more, will be approximately 80 percent. This is illustrated by the fact that the values under the 80 percent adequacy column in table 11–9 correspond well with the values under the CU column. The design irrigation application efficiency should be further reduced for wind drift and evaporation losses using equation 11–48. Often, for large fields, evaporation of drifting spray drops cools and humidifies the downwind layer of air above the crop, which in turn reduces ET in the downwind areas. The reduction in ET compensates in part for the evaporative losses, so estimates of R_e from figure 11–28 can often be increased on a field-wide basis. When three or more adjacent laterals are operated simultaneously in a fixed or block-move system, the wind drift and evaporation losses may be minimized to the extent that essentially all of the water is applied effectively. Table 11–9 can be used to approximate overall irrigation efficiency for block system layouts.

Table 11–10 provides a better understanding of CU and shows the relative productivity, based on percent adequacy of irrigation by field area, especially when dealing with shallow-rooted crops, such as forage crops. The derivation of table 11–10 assumes that crop yield reduces in proportion to reduction in water application below what is required. Almost optimum average field yields can be obtained with a system having a low CU, provided enough water is applied to ensure that a high percentage of the field is adequately irrigated. For example, with a CU of 90 percent, and 90 percent of the area adequately irrigated, 99 percent of the potential crop yield might be obtained by applying gross irrigations of 1.19 times the adjusted net requirements after allowing for wind drift and evaporation losses (fig. 11–28). With a CU of only 70 percent, 97 percent of the potential crop yield might be obtained if 90 percent of the area were adequately irrigated. The gross irrigation requirements, however, would be 1.92 times the adjusted net requirement because of deep percolation. If only 1.19 times the adjusted net application were applied with a CU of 70 percent, then only 65 percent of the area would be adequately irrigated and

Table 11–9 Ratios of the target (desired) depth of water applied to the gross average application for various values of CU and percentages of land area adequately irrigated.

CU %	Percent area adequately irrigated (pa)									
	95	90	85	80	75	70	65	60	55	50
94	0.88	0.90	0.92	0.94	0.95	0.96	0.97	0.98	0.99	1.00
92	0.84	0.87	0.90	0.92	0.93	0.95	0.96	0.98	0.99	1.00
90	0.79	0.84	0.87	0.89	0.92	0.93	0.95	0.97	0.98	1.00
88	0.75	0.81	0.84	0.87	0.90	0.92	0.94	0.96	0.98	1.00
86	0.71	0.78	0.82	0.85	0.88	0.91	0.93	0.96	0.98	1.00
84	0.67	0.74	0.79	0.83	0.87	0.90	0.92	0.95	0.98	1.00
82	0.63	0.71	0.77	0.81	0.85	0.88	0.91	0.94	0.97	1.00
80	0.59	0.68	0.74	0.79	0.83	0.87	0.90	0.94	0.97	1.00
78	0.55	0.65	0.71	0.77	0.81	0.86	0.89	0.93	0.97	1.00
76	0.51	0.61	0.69	0.75	0.80	0.84	0.88	0.92	0.96	1.00
74	0.46	0.58	0.66	0.73	0.78	0.83	0.87	0.92	0.96	1.00
72	0.42	0.55	0.64	0.70	0.76	0.82	0.87	0.91	0.96	1.00
70	0.38	0.52	0.61	0.68	0.75	0.80	0.86	0.91	0.95	1.00

only 90 percent of optimum yields might be expected on a field-wide average. The difference between 90- and 99 percent yield may be more than enough to pay for improving the CU from 70 percent to 86 percent.

The same values in table 11-9 can be transformed into what is termed the distribution efficiency, DE, by multiplying by 100, and are shown in table 11-11. The distribution efficiency is defined as the ratio of the depth of water required to refill the average soil moisture depletion to the depth of infiltration water needed to be applied, assuming no runoff. DE is expressed as a percentage and usually some level of adequacy of irrigation is specified, so that DE is generally subscript-

ed as DE_{pa} , where pa represents the percent adequacy. For example, DE_{80} is the distribution efficiency when 80 percent of the field is fully (adequately) irrigated. The DE_{pa} term describes both impacts of application uniformity and irrigation adequacy. In equation form:

$$DE_{pa} = 100 \left(\frac{d_n}{d_i} \right) \tag{eq. 11-36}$$

where:

d_n = allowable net water depletion from soil between irrigations, in (mm)

d_i = water required at the ground surface to satisfy d_n on pa percent of the field

Figure 11-37 Relationships between surface field area and depth of water applied

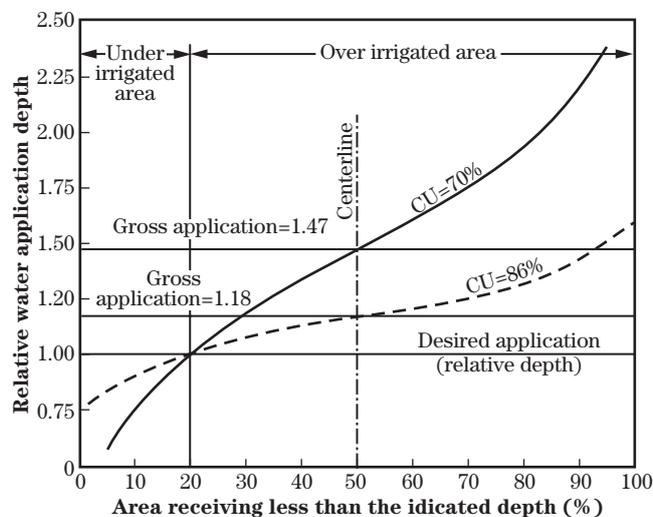


Table 11-10 Relative percentages of optimum productivity

CU (%)	Percent area adequately irrigated							
	95	90	85	80	75	70	65	60
90	100	99	99	98	98	97	97	96
86	100	99	98	98	97	96	96	95
82	99	99	98	97	96	95	94	93
78	99	98	97	96	95	94	93	91
74	98	97	96	95	94	93	91	90
70	98	97	95	94	92	91	90	88

Because sprinkler systems should be designed to eliminate or minimize surface runoff, d_i does not include any runoff. As shown in table 11-9, DE_{pa} has a direct relationship to CU and pa. To account for drift, evaporation, and system leakage losses, DE_{pa} is transformed into the application efficiency, E_{pa} , using the principle introduced in equations 11-30 and 11-31:

$$E_{pa} = DE_{pa} R_e O_e \tag{eq. 11-37}$$

Table 11-11 Distribution efficiency, DE_{pa} , used for system design

CU (%)	Percent area adequately irrigated							
	95	90	85	80	75	70	60	50
94	88	90	92	94	95	96	98	100
92	84	87	90	92	93	95	98	100
90	79	84	87	89	92	93	97	100
88	75	81	84	87	90	92	96	100
86	71	78	82	85	88	91	96	100
84	67	74	79	83	87	90	95	100
82	63	71	77	81	85	88	94	100
80	59	68	74	79	83	87	94	100
78	55	65	71	77	81	86	93	100
76	51	61	69	75	80	84	92	100
74	46	58	66	73	78	83	92	100
72	42	55	64	70	76	82	91	100
70	38	52	61	68	75	80	91	100

where:

R_e and O_e = effective fraction of discharged water reaching the surface and fraction of diverted water reaching the nozzle

These are defined for equations 11–30 and 11–31. Equation 11–37 is equivalent to equations 11–30 and 11–31, except that DE_{pa} is used in place of DU or CU. DE_{pa} is determined from table 11–9 or equation 11–36) as a function of CU and pa. Equations 11–30 and 11–31 represent special cases of equation 11–37, where pa is 90 percent and 80 percent respectively. Where calculation of DE_{pa} is desired, it can be calculated from using the selected value for CU and pa as:

$$DE_{pa} = 100 + \left(606 - 24.9 pa + 0.349 pa^2 - 0.00186 pa^3 \right) \left[1 - \frac{CU}{100} \right] \quad (\text{eq. 11-38})$$

The use of equations 11–48 and 11–49 allow the designer to determine DE_{pa} for any value for CU and pa selected for the design and using specific estimates for R_e that can vary with climate, nozzle selection, and design pressure.

To summarize, the use of CU to estimate application efficiency via equation 11–30 will result in about 80 percent adequacy of irrigation and an application efficiency approximating the application efficiency of E_h , where, by definition, adequacy of irrigation is 75 percent. A similar calculation results from equations 11–48 and 11–49, using pa equal to 80 percent and CU. The use of DU to estimate application efficiency via equation 11–39 will result in about 85 to 90 percent adequacy of irrigation and an application efficiency approximating the application efficiency of E_q , where, by definition, adequacy of irrigation is 88 percent. A similar calculation results from equations 11–39 and 11–40 using pa equals 90 percent and CU.

(e) Application efficiency

The design application efficiency is based on the expected potential performance of the sprinkler system, before installation, based on an analysis of a proposed system layout and configuration. But the calculated design application efficiency also presupposes correct operation (pressures, set durations, and other factors)

and maintenance of the system. In contrast, the actual application efficiency is measured in the field on an existing sprinkler system for the purpose of comparisons and the identification of changes that could be made to improve the system performance.

The definition for the DE_{pa} used for system design is given by equation 11–38. This definition uses the ratio of d_n to d_i and is useful during system design for estimating the gross water requirement, where d_n is known from the average net depth of water needed to refill the rootzone, and d_i is the water required at the ground surface. The variable d_i is related to d_g as d_i equals $d_g R_e O_e$. In system evaluations, the application efficiency is calculated differently from the design application efficiency. In system evaluation, the “actual” application efficiency, denoted as E'_{pa} is defined as:

$$E'_{pa} = 100 \left(\frac{d_r}{d_g} \right) = DE'_{pa} R_e O_e \quad (\text{eq. 11-39})$$

where:

d_r = average depth of added water that actually resides in the rootzone following the completion of the irrigation event
 DE'_{pa} = actual distribution efficiency

By definition, d_r does not include any deep percolation, and because 100 minus pa percent of the field receives less than the required d_n depth, then d_r will always be less than or equal to d_n ; therefore, E'_{pa} will always be less than or equal to E_{pa} . Actual application efficiency, E'_{pa} , is used in system performance evaluation, whereas design application efficiency, E_{pa} is used in design. E'_{pa} is not used in design because depth d_r is not generally known before the system is installed. In practice, E'_{pa} can be estimated by multiplying E_{pa} by the ratio of DE'_{pa} to DE_{pa} , where DE_{pa} is calculated from equation 11–38 or table 11–10 using CU and pa. DE'_{pa} can be calculated from DE_{pa} using pa and CU using the following regression relationship derived by taking ratios of equations for DE'_{pa} and DE_{pa} :

$$E'_{pa} = E_{pa} (0.514 + 0.00367 \times CU + 0.00187 \times pa) \quad (\text{eq. 11-40})$$

where:

CU and pa are in percent

Similarly:

$$DE'_{pa} = DE_{pa} (0.514 + 0.00367 \times CU + 0.00187 \times pa) \quad (\text{eq. 11-41})$$

where:

in application of equations 11-40 and 11-41, the multiplier of E_{pa} and DE_{pa} , needs to be limited to ≤ 1.0 so that $E'_{pa} \leq E_{pa}$ and $DE'_{pa} \leq DE_{pa}$.

(f) Design application rate and set time

For fixed and periodic-move systems, the design application rate must be limited to less than the minimum soil infiltration rate. The soil infiltration rate of soils generally declines with time of wetting, so that the minimum soil infiltration rate will occur at the end of the irrigation set. The longer the set, the lower the infiltration rate, until a near long-term rate is reached. Information on soil infiltration rates generally needs to be based on local observations. Rates can be higher with crops that cover the soil since soil sealing is less of a problem.

The design application rate and the set time should be determined simultaneously, with the set time adjusted upward to fit convenient cultural practices or, alternatively, the gross application depth reduced to less than the allowable, such as to permit an integer number of set changes each day. Equations 11-42 to 11-45 can be applied, where the maximum set time is first calculated:

$$t'_s = \frac{R_e d_g}{I_s} + t_m \quad (\text{eq. 11-42})$$

where:

t'_s = decimal set time (hours)

R_e = effective portion of applied water to ground (decimal)

d_g = gross application depth

I_s = maximum soil infiltration rate expected at the end of the set, typically the long-term rate

t_m = time required to move the lateral (while off), h

R_e is used in equation 11-42 to adjust d_g to the depth of water that reaches the ground. Parameter t_m is generally 0 for automated fixed systems and may range

from 0.5 hour for side-roll (wheel line) systems to 1.0 hour for quarter-mile (400 m) hand lines. The prime (') on t'_s indicates that this is a real (decimal) value that will be modified by generally rounding to a value that can be divided evenly into 24 hours. t'_s can be rounded down, which indicates that, to adhere to the maximum infiltration rate, the gross application depth and irrigation interval will both be decreased. This may result in more lateral moves per irrigation interval and more irrigations, meaning more labor. Alternatively, t'_s can be rounded up, which means using an application rate that is less than that allowed by the soil infiltration rate. In addition, rounding t'_s up will generally mean that more laterals will be required for a Periodic move system, which means higher investment cost. In most cases t'_s will be set to a value that can be divided evenly into 24 hours. To round t'_s down:

$$t_s = \max(2, 3, 4, 6, 8, 12, 24) \leq t'_s \quad (\text{eq. 11-43})$$

where:

the max function selects the maximum value in the parentheses that fulfills the less than or equal to conditional.

Then, the gross application depth to adhere to the I_s limitation is:

$$d_g = \frac{(t_s - t_m) I_s}{R_e} \quad (\text{eq. 11-44})$$

This new value for d_g will be less than or equal to the initial d_g . If t'_s is rounded up, it is calculated as:

$$t_s = \min(2, 3, 4, 6, 8, 12, 24) \geq t'_s \quad (\text{eq. 11-45})$$

In the case of rounding t'_s up, the gross depth remains unchanged because it is limited by AD divided by the application efficiency. The mean gross application rate is reduced because of the longer set time. The mean design application is calculated as:

$$I = \frac{d_g}{(t_s - t_m)} \leq \frac{I_s}{R_e} \quad (\text{eq. 11-46})$$

where:

I will be $\leq I_s/R_e$

I_s is divided by R_e to adjust to the gross rate that can be discharged from the sprinkler.

The number of settings per day is:

$$n_s = \frac{24}{t_s} \quad (\text{eq. 11-47})$$

If t_s is calculated from equation 11-43, n_s will have an integer value. If, for some reason, t_s is not constrained to a value that is divisible into 24 hours, then n_s may not be an integer. In that case, the designer may wish to round n_s to an integer value for ease and consistency of system operation. In that case, t_s can be adjusted (lengthened) by rearranging equation 11-47 as:

$$t_s = \frac{24}{n_s} \quad (\text{eq. 11-48})$$

Usually, unless it is supplied by groundwater, the system should be designed to operate continuously to match the continuous water supply. Therefore, the product of n_s and t_s should total 24. In the case of a groundwater supply under complete control of the operator, the product of n_s and t_s can be less than or equal to 24. The operating time per day, T , is, at a maximum:

$$T = 24 - n_s t_m \quad (\text{eq. 11-49})$$

The value for T may be reduced if additional down time is desired during the day. However, if the water source is from surface water that is continuously delivered to the system, then T should be maximized so that on-farm reservoir storage volume can be minimized.

(g) Sprinkler discharge rate

The discharge, q , of a sprinkler in a fixed or Periodic move system is a function of the design application rate, I , and the sprinkler spacing. It can be calculated by solving equation 11-22 for q :

$$q = \frac{I S_e S_l}{K} \quad (\text{eq. 11-50})$$

where:

q = sprinkler discharge, g/m or l/m

I = average design application rate, in/h or mm/h

S_e = uniform spacing of sprinklers along the laterals, ft, m

S_l = spacing of laterals along the mainline, ft or m

K = 96.3 for English units, 60 for metric units

(1) Guideline spacing tables

For preliminary design purposes, tables 11-12 through 11-15 may be used as a guide for estimating the anticipated CU for various sprinkler spacing and application rate combinations for periodic-move and fixed grid systems. The CU estimates presented in the tables were derived from an analysis of numerous tests of impact sprinklers having 1/2- or 3/4-inch bearings, standard 22 to 28 degree trajectory angles, and nozzles without vanes. The tables are separated into 4 sections according to wind speeds (up to 4 m/h (2 m/sec), 4 to 10 mph (2 to 4.5 m/sec), 10 to 15 m/h (5 to 7 m/sec), and 15 to 20 m/h (7 to 9 m/sec)). Using vanes or angles from 18 to 21 degrees may improve uniformities in the higher wind speeds, and under these conditions, table 11-14 can be used for 10 to 15 miles per hour winds or table 11-15 can be used with caution for 15 to 20 miles per hour winds.

The nozzle sizes and pressures given in the tables for each spacing will give application rates (I) that fall within 0.02 inch per hour (0.51 mm/h) of rates indicated by the column headings. Equation 11-50 should be used to compute the precise flow rate needed for a given I and the manufacturer's sprinkler tables used to determine the required operating pressure. Pressures for standard nozzles should be selected to fall within the ranges shown in table 11-16.

The low side of the pressure ranges given above should be increased by 5 to 10 pounds per square inch (35 to 70 kPa) when sprinkling bare soils that tend to seal. High pressures should be avoided to save energy and eliminate excessive drift and evaporation losses.

(2) Risers

A straight riser pipe, located between the sprinkler head and the lateral-line pipe, must be provided with hand line, solid-set, and big-gun systems to remove the turbulence setup when the direction of flow is changed by diversion of a part of the flow in the lateral to an individual sprinkler. If not removed, this turbulence

Table 11-12 A guide to recommended nozzle sizes and pressures with expected average CU values for different application rates and sprinkler spacings under low wind conditions (0–4 m/h, or 0–m/sec)

Sprinkler		Water application rate, in/h \pm 0.02 in/h (mm/h \pm 0.5 mm/h)						
Spacing ft \times ft (m \times m)	Operation	0.10 (2.5)	0.15 (3.8)	0.20 (5.1)	0.25 (6.4)	0.30 (7.6)	0.35 (8.9)	0.40 (10.2)
30 \times 40 (9 \times 12)	Nozzle	3/32	3/32	7/64	1/8	9/64	5/32	9/64 \times 3/32
	Pressure	30 lb/in ²	50 lb/in ²	45 lb/in ²	45 lb/in ²	45 lb/in ²	40 lb/in ²	40 lb/in ²
	CU	82%	83%	82%	83%	83%	85%	88%
30 \times 50 (9 \times 15)	Nozzle	3/32	7/64	1/8	9/64	5/32	11/64	11/64
	Pressure	40 lb/in ²	40 lb/in ²	45 lb/in ²	50 lb/in ²	45 lb/in ²	45 lb/in ²	50 lb/in ²
	CU	83%	88%	86%	86%	84%	85%	86%
30 \times 60 (9 \times 18)	Nozzle		1/8	9/64	5/32	11/64	3/16	3/16
	Pressure		40 lb/in ²	45 lb/in ²	45 lb/in ²	45 lb/in ²	45 lb/in ²	50 lb/in ²
	CU		88%	88%	89%	88%	85%	87%
40 \times 40 (12 \times 12)	Nozzle	7/64	1/8	9/64	1/8 \times 3/32	5/32 \times 3/32	5/32 \times 3/32	5/32 \times 1/8
	Pressure	30 lb/in ²	35 lb/in ²	35 lb/in ²	40 lb/in ²	35 lb/in ²	40 lb/in ²	35 lb/in ²
	CU	78%	82%	86%	87%	88%	89%	90%
40 \times 50 (12 \times 15)	Nozzle			5/32	5/32 \times 3/32	5/32 \times 3/32	11/64 \times 3/32	3/16 \times 3/32
	Pressure			35 lb/in ²	35 lb/in ²	45 lb/in ²	40 lb/in ²	40 lb/in ²
	CU			78%	83%	84%	88%	89%
40 \times 60 (12 \times 18)	Nozzle			5/32	11/64	3/16	13/64	7/32
	Pressure			50 lb/in ²				
	CU			83%	85%	85%	84%	86%
60 \times 60 (18 \times 18)	Nozzle			3/16	13/64	7/32	7/32	1/4
	Pressure			60 lb/in ²	65 lb/in ²	65 lb/in ²	80 lb/in ²	88 lb/in ²
	CU			88%	88%	88%	88%	88%

1 lb/in² = 6.89 kPa; 1/64 in = 0.40 mm; nozzle sizes, inches.

Table 11-13 A guide to recommended nozzle sizes and pressures with expected average CU values for different application rates and sprinkler spacings under high wind conditions (10-15 mph, or 5-7 m/sec).

Sprinkler		Water application rate, in/h \pm 0.02 in/h (mm/h \pm 0.5 mm/h)						
Spacing		0.10	0.15	0.20	0.25	0.30	0.35	0.40
ft \times ft	Operation	(2.5)	(3.8)	(5.1)	(6.4)	(7.6)	(8.9)	(10.2)
(m \times m)	Nozzle	3/32	3/32	7/64	1/8	9/64	5/32	9/64 \times 3/32
30 \times 40	Pressure	30 lb/in ²	50 lb/in ²	45 lb/in ²	45 lb/in ²	45 lb/in ²	40 lb/in ²	45 lb/in ²
(9 \times 12)	CU	75%	80%	80%	84%	84%	85%	86%
30 \times 50	Nozzle		7/64	1/8	9/64	5/32	11/64	11/64
(9 \times 15)	Pressure		40 lb/in ²	45 lb/in ²	50 lb/in ²	45 lb/in ²	50 lb/in ²	55 lb/in ²
	CU		70%	81%	82%	87%	88%	88%
30 \times 60	Nozzle			9/64	5/32	11/64	3/16	3/16
(9 \times 18)	Pressure			45 lb/in ²	45 lb/in ²	45 lb/in ²	45 lb/in ²	50 lb/in ²
	CU			72%	75%	81%	84%	86%
40 \times 40	Nozzle		1/8	9/64	5/32	11/64	11/64	3/16
(12 \times 12)	Pressure		35 lb/in ²	35 lb/in ²	35 lb/in ²	35 lb/in ²	50 lb/in ²	45 lb/in ²
	CU		80%	82%	81%	80%	86%	85%
40 \times 50	Nozzle			5/32	5/32	11/64	3/16	13/64
(12 \times 15)	Pressure			35 lb/in ²	50 lb/in ²	50 lb/in ²	50 lb/in ²	50 lb/in ²
	CU			77%	78%	80%	80%	82%
40 \times 60	Nozzle			5/32	11/64	3/16	13/64	7/32
(12 \times 18)	Pressure			50 lb/in ²				
	CU			68%	74%	78%	81%	82%
60 \times 60	Nozzle			3/16	13/64	7/32	7/32	1/4
(18 \times 18)	Pressure			60 lb/in ²	65 lb/in ²	65 lb/in ²	80 lb/in ²	68 lb/in ²
	CU			64%	66%	68%	80%	82%

1 lb/in² = 6.89 kPa; 1/64 in = 0.40 mm; nozzle sizes in in

Table 11-14 A guide to recommended nozzle sizes and pressures with expected average CU values for different application rates and sprinkler spacings under extreme wind conditions (15–20 mph, or 7–9 m/sec)

Sprinkler		Water application rate, in/h \pm 0.02 in/h (mm/h \pm 0.5 mm/h)						
Spacing								
ft \times ft		0.10	0.15	0.20	0.25	0.30	0.35	0.40
(m \times m)	Operation	(2.5)	(3.8)	(5.1)	(6.4)	(7.6)	(8.9)	(10.2)
	Nozzle	3/32	3/32	7/64	1/8	9/64	5/32	5/32
30 \times 40	Pressure	30 lb/in ²	50 lb/in ²	45 lb/in ²	45 lb/in ²	45 lb/in ²	40 lb/in ²	45 lb/in ²
(9 \times 12)	CU	69%	72%	73%	75%	76%	82%	85%
	Nozzle			1/8	9/64	5/32	11/64	11/64
30 \times 50	Pressure			45 lb/in ²	50 lb/in ²	45 lb/in ²	50 lb/in ²	55 lb/in ²
(9 \times 15)	CU			74%	77%	80%	81%	84%
	Nozzle			9/64	5/32	11/64	3/16	3/16
30 \times 60	Pressure			45 lb/in ²	45 lb/in ²	45 lb/in ²	45 lb/in ²	50 lb/in ²
(9 \times 18)	CU			60%	65%	75%	80%	83%
	Nozzle			9/64	5/32	11/64	11/64	3/16
40 \times 40	Pressure			35 lb/in ²	35 lb/in ²	35 lb/in ²	50 lb/in ²	45 lb/in ²
(12 \times 12)	CU			70%	72%	76%	81%	84%
	Nozzle			5/32	5/32	61/64	3/16	13/64
40 \times 50	Pressure			35 lb/in ²	50 lb/in ²	50 lb/in ²	50 lb/in ²	50 lb/in ²
(12 \times 15)	CU			55%	60%	70%	75%	77%
	Nozzle			5/32	11/64	3/16	13/64	7/32
40 \times 60	Pressure			50 lb/in ²				
(12 \times 18)	CU			64%	70%	73%	74%	75%
	Nozzle						7/32	1/4
60 \times 60	Pressure						80 lb/in ²	68 lb/in ²
(18 \times 18)	CU						66%	75%

1 lb/in² = 6.89 kPa; 1/64 in = 0.40 mm; nozzle sizes, in

Table 11-15 Pressure ranges for standard sprinkler nozzles

Nozzle sizes		Pressure range	
(in)	(mm)	(lb/in ²) ^{1/}	(kPa) ^{1/}
5/64 to 3/32	2.0 to 2.4	20–45	140–310
7/64 to 9/64	2.8 to 3.6	25–50	170–340
5/32 to 11/64	4.0 to 4.4	30–55	210–380
3/16 to 7/32	4.8 to 5.6	35–60	240–410

1 Add 5 lb/in² (35 kPa) when straightening vanes are used.

Table 11-16 Recommended minimum sprinkler riser heights for set systems

Discharge (gpm)		Riser height	
(gpm)	(l/sec)	(in)	(m)
Under 10	Under 0.6	6	0.15
10–25	0.6–1.6	9	0.23
25–50	1.6–3.2	12	0.30
50–120	3.2–7.5	18	0.45
more than 120	more than 7.5	36	0.90

can carry through the nozzle and cause a premature stream breakup, a reduced diameter of coverage, and a poorer distribution pattern. In the case of wheel lines, articulated levelers are placed upstream of each sprinkler and risers are not required. The length of pipe needed to remove turbulence varies with sprinkler discharge. Recommended minimum riser heights (above the lateral pipe) are given in table 11–17.

Most crops exceed 12 inches (0.3 m) in height, so, except for clean cultivated orchards where low-riser pipes are desirable for undertree sprinkling, the choice of riser height will be depend on the minimum height to clear the crop height, availability, and issues related to moving the lateral pipe. Although some research studies indicate that 12 to 24 inches (0.3–0.6 m) of

additional height improve the sprinkler distribution efficiency, there are obvious disadvantages, such as wind drift and awkward handling of the lateral line. Farmers usually prefer 18- to 24-inch (0.5–0.6 m) risers, except when irrigating tall crops, such as cotton and maize.

Not all sprinkler systems use risers. For example, side-roll sprinklers (wheel lines) have the sprinklers mounted on swivel joints at the lateral pipe, and some older center pivots have impact sprinklers mounted directly on the lateral. Most linear-move and center pivot systems have dropdown sprayer sprinklers which can be considered to be the opposite of risers but with similar hydraulic characteristics.

Table 11–17 A guide to recommended nozzle sizes and pressures with expected average CU values for different application rates and sprinkler spacings under moderate wind conditions (4–10 mph, or 2–5 m/sec)

Sprinkler		Water application rate, in/h \pm 0.02 in/h (mm/h \pm 0.5 mm/h)						
Spacing ft \times ft (m \times m)	Operation	0.10 (2.5)	0.15 (3.8)	0.20 (5.1)	0.25 (6.4)	0.30 (7.6)	0.35 (8.9)	0.40 (10.2)
30 \times 40 (9 \times 12)	Nozzle	3/32	3/32	7/64	1/8	9/64	5/32	9/64 \times 3/32
	Pressure	30 lb/in ²	50 lb/in ²	45 lb/in ²	45 lb/in ²	45 lb/in ²	40 lb/in ²	40 lb/in ²
	CU	82%	85%	85%	82%	83%	84%	85%
30 \times 50 (9 \times 15)	Nozzle	3/32	7/64	1/8	9/64	5/32	11/64	11/64
	Pressure	40	40	45	50	45	45	50
	CU	70%	75%	84%	84%	84%	87%	85%
30 \times 60 (9 \times 18)	Nozzle		1/8	9/64	5/32	11/64	3/16	3/16
	Pressure		40 lb/in ²	45 lb/in ²	45 lb/in ²	45 lb/in ²	45 lb/in ²	50 lb/in ²
	CU		80%	84%	84%	84%	85%	86%
40 \times 40 (12 \times 12)	Nozzle	7/64	1/8	9/64	1/8 \times 3/32	5/32 \times 3/32	5/32 \times 3/32	5/32 \times 1/8
	Pressure	30 lb/in ²	35 lb/in ²	35 lb/in ²	40 lb/in ²	35 lb/in ²	40 lb/in ²	35 lb/in ²
	CU	80%	83%	83%	83%	84%	87%	86%
40 \times 50 (12 \times 15)	Nozzle			5/32	5/32 \times 3/32	5/32 \times 3/32	11/64 \times 3/32	3/16 \times 3/32
	Pressure			35 lb/in ²	35 lb/in ²	45 lb/in ²	40 lb/in ²	40 lb/in ²
	CU			76%	76%	76%	83%	84%
40 \times 60 (12 \times 18)	Nozzle			4/32	11/64	3/16	13/64	7/32
	Pressure			50 lb/in ²				
	CU			77%	81%	83%	84%	85%
60 \times 60 (18 \times 18)	Nozzle			3/16	13/64	7/32	7/32	1/4
	Pressure			60 lb/in ²	65 lb/in ²	65 lb/in ²	80 lb/in ²	68 lb/in ²
	CU			80%	82%	83%	84%	84%

1 lb/in² = 6.89 kPa; 1/64 in = 0.40 mm; nozzle sizes in inches.

(h) Discharge requirement

The required average discharge (q) of a sprinkler is a function of the water application rate (I) and the sprinkler spacing. The desired I depends on time per set, net depth to be applied per irrigation, the allotted time per set, and the application efficiency. The upper limit for I is constrained by soil intake to avoid runoff. The lower limit on I is constrained by drop size and wind distortion considerations, as discussed earlier. It is practical to change positions of Periodic move laterals only once or twice, or perhaps three times, per day unless they are automated. For one change per day, the time per set will be 24 hour minus the length of time required to change the lateral position, leaving a total of 23 to 23.5 hour. For two changes per day, set times will range between 11 and 11.5 hour.

Figure 11–38 shows a copy of figure 11–18 completed for example 40-acre fields of alfalfa and potatoes. Sample calculations 11–4 and 11–5 illustrate the procedure for determining the desired application rate (I) and related average sprinkle discharge (q) for the alfalfa field and the potato field, respectively.

Sample calculation 11–4—Determine the net depth per irrigation, irrigation interval, irrigation efficiency, application rate, and sprinkler discharge requirement.

Given:

- Information in parts I and II of figure 11–38 for alfalfa
- An average wind of 4 to 10 miles per hour

Assume:

- Soil moisture depletion is $MAD = 50$ percent
- Maximum soil infiltration rate is 0.4 inch per hour for the alfalfa cover
- There will be one change per day
- The desired sprinkler spacing is 40 by 60 feet
- Moderate-pressure, moderate-sized sprinklers are desired, assuming a coarseness index half-way between coarse and fine, $CI = 12$.
- The system will have a target uniformity coefficient, CU of 84 percent (table 11–13 suggests

a $CU = 84\%$ for a 40×60 ft spacing and 0.35 in/h application rate).

- The system will require 1.0 hrs to move laterals in between sets.

Calculations:

The depth of soil layer 1 (8 ft) exceeds the mature rooting depth of 6 feet, so for an MAD of 50 percent, where the allowable soil water depletion is 50 percent of the total available water-holding capacity in the root zone, which in this case is:

$$AD = \frac{MAD}{100} [WHC_1 Z_1 + WHC_2 (Z - Z_1)] \Rightarrow \frac{50}{100} (2.0)(6) \quad (\text{eq. 11-4})$$

To calculate the design application efficiency, first the effective portion of the applied rate (R_e) is calculated from figure 11–28 using a potential ET rate of 0.3 inch per day and wind speed range of 4 to 10 miles per hour. For a nozzle having fine spray, from figure 11–28, the R_e is about 0.91 and for a nozzle having coarse spray, from figure 11–28, the R_e is about 0.97. Therefore, from equation 11–28 and assuming a droplet size halfway between fine and coarse (i.e., $CI = 10$):

$$\begin{aligned} R_e &= \frac{(CI - 7)}{10} (R_e)_c + \frac{(17 - CI)}{10} (R_e)_f \\ &= \frac{(10 - 7)}{10} 0.97 + \frac{(17 - 10)}{10} 0.91 \\ &= 0.94 \end{aligned} \quad (\text{eq. 11-28})$$

Because alfalfa is a relatively low-value crop, an applied efficiency (E_h) based on the average low-half depth is appropriate:

$$\begin{aligned} E_h &= CU (R_e O_e) \\ &= 84 (0.94)(1.0) \\ &= 79\% \end{aligned} \quad (\text{eq. 11-31})$$

assuming that leakage losses are 0, so that O_e is 1.00. Note that some iteration may be required to determine the best estimate for CU after the design application rate is determined. Alternatively to equation 11–31, use equation 11–37 with $DE_{pa} = 83$ percent, taken from table 11–11 for $pa = 80$ percent, to estimate E_{pa} :

Figure 11–38 Sprinkler irrigation system data design sheet

	Variable name	Section, table, or equation	Zone 1	Zone 2
I. General				
(a) Pressure regulation (Y/N)	—	—		
(b) Estimated surface storage of water				
(c) Estimated preseason residual soil water				
II. Crop				
			Alfalfa	Potato
(a) Root depth (ft)	Z	Table 11–3	6	2.5
(b) Growing season (days)			165	135
(c) Peak water use rate (in/day) over maximum interval	ud	external data	0.3	0.25
(d) Seasonal water use (in)	U	external data	30	19
III. Soils				
(a) Surface texture			Loam	Sandy loam
Depth (ft)	Z ₁	field data	8	4
Available water-holding capacity (in/ft)	Wa ₁	Table 11–2	2	1.6
(b) Subsurface texture		—	—	—
Depth (ft)	Z ₂	field data	—	—
Available water-holding capacity (in/ft)	Wa ₂	Table 11–2	—	—
(c) Management allowable depletion (%)	MAD	Table 11–3	50	30
(d) Allowable depletion (in)	AD	Eq. 11–3	6	1.2
(e) Maximum intake rate (inch per hour)	Ix	Local data or table 11–5	0.40	0.25
IV. Irrigation				
(a) Maximum interval during peak-use period (days)	f ^ˆ	Eq. 11–13	20	8
(b) Days off each irrigation interval (days)	days off		2	1
(c) Operating time to complete irrigation cycle (days)	f	Eq. 11–14	0.4	0.25
(d) Net depth (in)	d _n	Eq. 11–5	6	1.2
(e) Design uniformity coefficient (%)	CU	Table 11–7	84	78 (88) ¹
(f) Percent of field adequately irrigated (%)	pa		80	80 (90)
(g) Distribution efficiency (%)	DE _{pa}	Table 11–11, Eq. 11–36	83	76 (80)
(h) Effective portion of applied water to ground (%)	Re	Fig. 11–28, Eq. 11–28	0.94	0.92 (0.92)
(i) Efficiency (%)	E _{pa}	Eq. 11–37	78.0	69.9 (73.6)
(j) Leaching requirement	LR	Eq. 11–8	0.0	0.0
(k) Gross depth (in)	dg	Eq. 11–9	7.7	1.5

Figure 11-38 Sprinkler irrigation system data design sheet—continued

	Variable name	Section, table, or equation	Zone 1	Zone 2
V. Water requirements				
(a) Net seasonal (in)				
(b) Effective rain (in)	P_e	external data		
(c) Stored moisture (in) for season		external data		
(d) Net irrigation (in) for season	U	external data		
(e) Gross irrigation (in) for season				
(f) Number of irrigations	N_{is}	Eq. 11-11		
VI. System capacity				
(a) Time to move set (h)	t_m	external data	1	0.5
(b) Set time (h)—decimal	t'_s	Eq. 11-42	19.1	6.8
(c) Set time (h)—integer	t_s	Eq. 11-48	242	82
(d) Average application rate (in/h)	I	Eq. 11-46	0.33	0.23
(e) Revised gross depth (in)	d_g	Eq. 11-44	7.7	1.7
(f) Settings per day	n_s	Eq. 11-47	1	3
(g) Days of operation per interval	f	Eq. 11-14	18	4
(h) Area irrigated (ac)	A	external data	40	40
(i) Operating time per day (h)	T	Eq. 11-49	23	22.5
(j) Preliminary system capacity (gpm)	Q	Eq. 11-12	337	346

1 The value in parentheses for CU and pa for crop 2 are if alternate sets are used.

2 (eq. 11-45 was applied).

$$\begin{aligned} E_{pa} &= DE_{pa}R_eO_e \Rightarrow E_{80} \\ &= 83(0.94)(1.0) \\ &= 78\% \end{aligned}$$

which is essentially the same as $E_h = 79$ percent.

Assuming an E_h of 75 percent, the gross application would be calculated in equation 11-9. Also assuming that d_n equals AD, as given by equation 11-5, to maximize the time between irrigations, then gross application depth, from equation 11-9, is:

$$\begin{aligned} d_g &= 100 \left(\frac{d_n}{E_{pa}} \right) \\ &= 100 \left(\frac{6.0}{75} \right) \\ &= 8.0 \text{ in} \end{aligned}$$

Assuming it will take 1 hour to change the position of a hand-move lateral ($t_m = 1.0$ hour) and a maximum soil infiltration rate of 0.4 inch per hour, the maximum set time from equation 11-42 is:

$$\begin{aligned} t'_s &= \frac{R_e d_g}{I_s} + t_m \\ &= \frac{(0.94)(7.7 \text{ in})}{0.4 \text{ in/h}} + 1 \\ &= 19.1 \text{ h} \end{aligned}$$

This reveals that only one set per day is practical.

Round t'_s up as:

$$t_s = \min(2, 3, 4, 6, 8, 12, 24) \geq t'_s \Rightarrow 24 \geq 19.1 \Rightarrow 24 \text{ h} \quad (\text{eq. 11-45})$$

In the case of rounding t'_s up, the gross depth remains unchanged because it is limited by AD divided by application efficiency. The designer could: continue the design with the current configuration (nozzles, spacings, pressures, and so on) and manage the system operating time to accomplish good irrigation water management; or, change the configuration and iterate. To change the configuration, the user could start

by reducing the mean design application rate because several hours of operation time are unused with the current configuration ($24 - 19.1 = 4.9$ h). The revised mean design application is calculated from equation 11-46:

$$\begin{aligned} I &= \frac{d_g}{(t_s - t_m)} \leq \frac{I_s}{R_e} \Rightarrow \frac{8.0}{24 - 1} \\ &= 0.35 \text{ in/h} \leq \frac{0.4}{0.94} \end{aligned}$$

where: $I = 0.33$ inch per hour is $\leq I_s/R_e = 0.43$ inch per hour.

The number of settings per day from equation 11-47 is:

$$\begin{aligned} n_s &= \frac{24}{t_s} \\ &= \frac{24}{24} \\ &= 1 \end{aligned}$$

The discharge, q , of each sprinkler in the periodic-move system, from equation 11-50 is:

$$\begin{aligned} q &= \frac{I S_e S_l}{K} \\ &= \frac{0.35(40)(60)}{96.3} \\ &= 8.72 \text{ gal/min} \end{aligned}$$

The maximum allowable irrigation interval during the peak use period, from equation 11-13 is:

$$\begin{aligned} f' &= \frac{d_n}{u_d} \\ &= \frac{6.0}{0.3} \\ &= 20 \text{ d} \end{aligned}$$

Assuming two days of down time per irrigation cycle, the days of operation per interval, from equation 11-14 is:

$$\begin{aligned} f &= f' - \text{days off} \\ &= 20 - 2 \\ &= 18 \text{ d} \end{aligned}$$

$$\begin{aligned} I &= \frac{7.6 \text{ in}}{23 \text{ h}} \\ &= 0.33 \text{ in/h} \end{aligned}$$

(eq. 11-51)

These are the maximum allowable depletion and corresponding maximum interval during the peak use period that will give the desired level of productivity. The actual depletion between irrigations and f' can be reduced to fit the final system design. The operating time per day, T , from equation 11-49 is:

$$\begin{aligned} T &= 24 - n_s t_m \\ &= 24 - (1)(1) \\ &= 23 \text{ h} \end{aligned}$$

Assuming it will take 1 hour to change the position of a hand-move lateral, the time per set with one change per day will be 23 hours. The preliminary application rate is:

$$\begin{aligned} I' &= \frac{8.0 \text{ in}}{23 \text{ h}} \\ &= 0.35 \text{ in/h} \end{aligned} \quad (\text{eq. 11-51})$$

Application rate (I) is the application depth (D_c) divided by application time (T).

From table 11-15 (4-10 mph winds) the anticipated CU = 84 percent on a 40 by 60 foot spacing and 0.35 inch per hour. A more specific estimate of CU can often be obtained directly from a supplier. The expected application efficiency can now be estimated by equation 11-8:

$$\begin{aligned} E_h &= \text{CU}(R_e O_e) \\ &= 84(0.94)(1.0) \\ &= 79\% \end{aligned} \quad (\text{eq. 11-31})$$

The required gross application can now be more accurately computed as:

$$\frac{6.0}{79/100} = 7.6 \text{ in} \quad (\text{eq. 11-9})$$

and the required application rate is:

The required sprinkler discharge can now be calculated by equation 11-50:

$$\begin{aligned} q &= \frac{I(S_e S_1)}{96.3} \\ &= \frac{(0.33)(40)(60)}{96.3} \\ &= 8.22 \text{ gal/min} \end{aligned}$$

Sample calculation 11-5—Determine irrigation efficiency and application rate.

Given:

- Information in parts I and II of figure 11-38 for potatoes
- An average wind of 10 to 15 miles per hour

Assume:

- Maximum soil infiltration rate is 0.25 inch per hour.
- Soil moisture depletion is MAD = 30 percent.
- Side-roll laterals will be used, and two changes per day will be made with the assumption that it will take 0.5 hour to move each lateral.
- The desired sprinkler spacing is 40 by 50 feet.
- Moderate pressure, moderate sized sprinklers are used having a coarseness index half-way between coarse and fine (i.e., CI = 10).
- The system will have a target uniformity coefficient, CU of 78 percent (table 11-16 suggests a CU = 78 percent for a 40 by 50 ft spacing and 0.25 in/h application rate).

Calculations:

The depth of soil layer one (4 ft) exceeds the rooting depth of 2.5 feet so that, for an MAD of 30 percent, where the allowable soil water depletion is 30 percent of the total available water-holding capacity of the root zone, equation 11-4 yields:

$$\begin{aligned} AD &= \frac{MAD}{100} [WHC_1 Z_1 + WHC_2 (Z - Z_1)] \\ &= \frac{30}{100} [(1.6)(2.5)] \\ &= 1.2 \text{ in} \end{aligned}$$

To calculate the design application efficiency, first the effective portion of the applied rate (R_e) is calculated from figure 11-28 using a potential ET rate of 0.25 inch per day and wind speed range of 10 to 15 miles per hour. For a nozzle having fine spray, from figure 11-28, the R_e is about 0.89, and for a nozzle having coarse spray, from figure 11-28, the R_e is about 0.96. From equation 11-28 and assuming a droplet size halfway between fine and coarse (i.e. $CI = 10$):

$$\begin{aligned} R_e &= \frac{(CI-7)}{10} (R_e)_c + \frac{(17-CI)}{10} (R_e)_f \\ &= \frac{(10-7)}{10} 0.96 + \frac{(17-10)}{10} 0.89 \\ &= 0.92 \end{aligned}$$

Because potatoes are a relatively high-value, shallow-rooted crop, an application efficiency (E_q) based on the average low-quarter depth, is appropriate, so one would use DU as the measure of uniformity. This will leave approximately 10 percent of the area under-watered. Assuming an E_q of 67 percent, the gross application would be:

$$\frac{1.2}{(67/100)} = 1.8 \text{ in} \quad (\text{eq. 11-9})$$

Assuming it will take 30 minutes to change the position of a side-roll lateral, the time per set with two changes per day will be 11.5 hours. The preliminary application rate is:

$$\begin{aligned} I' &= \frac{1.8 \text{ in}}{11.5 \text{ h}} \\ &= 0.16 \text{ in/h} \quad (\text{eq. 11-84}) \end{aligned}$$

From table 11-16, (10-15 mph winds) read the anticipated $CU = 78$ percent. If alternate sets are used the improved uniformity can be estimated by equation 11-34 as:

$$\begin{aligned} CU_a &= 10\sqrt{CU} \\ &= 10\sqrt{78} \\ &= 88\% \end{aligned}$$

These are two processes that can be used to develop the expected E_q . An estimated DU_a can be determined by equation 11-25 as:

$$\begin{aligned} DU_a &= 100 - 1.59(100 - CU_a) \\ &= 100 - 1.59(100 - 88) \\ &= 81\% \quad (\text{eq. 11-86}) \end{aligned}$$

and from equation 11-30:

$$\begin{aligned} E_{(90\% \text{ adequate})} &= 81(0.92)(1.0) \\ &= 75\% \quad (\text{eq. 11-87}) \end{aligned}$$

The other method is to determine E_{pa} using DE_{pa} from table 11-10 with $CU_a = 88$ percent and find that for 90 percent of the area adequately irrigated 0.81 inch (21 mm) is the minimum depth of water applied per 1.0 inch (25 mm) of effective application so:

$$\begin{aligned} E_{(90\% \text{ adequate})} &= 81(0.92) \\ &= 75\% \quad (\text{eq. 11-88}) \end{aligned}$$

The equivalent E_{90} can be determined for $pa = 90$ percent by calculating $DE_{pa} = 65$ percent from table 11-11 using $CU = 78$ percent, assuming that leakage losses are zero, so that O_e is 1.00. Using equation 11-37 with $DE_{pa} = 65$ percent:

$$\begin{aligned} E_{pa} &= DE_{pa} R_e O_e \Rightarrow E_{90} \\ &= 65(0.92)(1.0) \\ &= 60\% \end{aligned}$$

which is the same value as determined using E_q .

This application efficiency is unsatisfactorily low due to a combination of the high wind speed, moderately low application rate, and high value for pa . Consider whether side-roll sprinklers should be used for potatoes in this windy climate. To obtain an application efficiency of at least 70 percent, one would need to increase the DE_{pa} to 76 percent, which, from table 11-10 would require a CU of about 85 percent, given

the $p_a = 90$ percent, or, given the estimated CU of 78 percent for the 40- by 50-foot spacing, would require p_a to be reduced to 80 percent. The p_a equals 80 percent is probably a reasonable expectation, given the high wind speeds. The estimated yield is 96 percent at p_a is 80 percent and CU is 78 percent, but only for forage types of crops. In the case of potatoes, where tuber quality is equally important to bulk yield, and where tuber quality generally suffers under soil water stress, the estimated yield may be only 90 percent on the field average, given the particular p_a and CU combination.

Assuming that p_a will be reduced to 80 percent, then the application efficiency is recalculated as E_{80} :

$$\begin{aligned} E_{p_a} &= DE_{p_a} R_e O_e \Rightarrow E_{80} \\ &= 76(0.92)(1.0) \\ &= 70\% \end{aligned}$$

from equation 11-37 so that $d_g = 1.7$ inches.

If alternate sets are used, the improved CU_a can be estimated by equation 11-25 as:

$$\begin{aligned} CU_a &= 10\sqrt{CU} \\ &= 10\sqrt{78} \\ &= 88\% \end{aligned}$$

Using $p_a = 90$ percent, from table 11-9, $DE_{90} = 81$ percent, so that:

$$\begin{aligned} E_{p_a} &= DE_{p_a} R_e O_e \Rightarrow E_{90} \\ &= 81(0.92)(1.0) \\ &= 75\% \end{aligned} \quad (\text{eq. 11-37})$$

If alternate sets had not been used, the efficiency would have been much lower, or the target p_a would have to be lowered to about 90 percent adequacy. Also, if an efficiency of 75 percent is assumed and alternate sets not used, the area adequately irrigated will only 75 percent. This was determined by noting that 0.81 inch is the minimum depth of water applied per in of effective application with a CU of 78 percent and 75 percent adequacy in table 11-7. Because the CU_a estimate from equation 11-25 may be overstated, it is probably reasonable to use the $E_{80} = 70$ percent in the system design.

Assuming $d_n = AD$ to maximize the time between irrigations, then gross application depth, from equation 11-9 is:

$$\begin{aligned} d_g &= 100 \left(\frac{d_n}{E_{p_a}} \right) \\ &= 100 \left(\frac{1.2}{70} \right) \\ &= 1.7 \text{ in} \end{aligned}$$

Assuming it will take 0.5 hour to change the position of a side-roll lateral ($t_m = 0.5$ h), and a maximum soil infiltration rate of 0.25 inch per hour, the maximum set time from equation 11-42 is:

$$\begin{aligned} t'_s &= \frac{R_e d_g}{I_s} + t_m \\ &= \frac{(0.92)(1.7)}{0.25} + 0.5 \\ &= 6.8 \text{ h} \end{aligned} \quad (\text{eq. 11-94})$$

Round t'_s up using equation 11-45:

$$t_s = \min(2, 3, 4, 6, 8, 12, 24) \geq t'_s \Rightarrow 8 \geq 6.8 \Rightarrow 8 \text{ h} \quad (\text{eq. 11-95})$$

In the case of rounding t'_s up, the maximum gross depth remains unchanged because it is limited by AD divided by application efficiency. The mean application rate, however, is reduced, because of the longer set time. The mean design application is calculated from equation 11-46:

$$\begin{aligned} I &= \frac{d_g}{(t_s - t_m)} \leq \frac{I_s}{R_e} \Rightarrow \frac{1.7}{8 - 0.5} \\ &= 0.227 \text{ in/h} \leq \frac{0.25}{0.92} \end{aligned}$$

where:

$$I = 0.227 \text{ in/h is } \leq I_s/R_e = 0.27 \text{ in/h}$$

The number of settings per day from equation 11-58 is:

K_d = discharge coefficient for the sprinkler and nozzle combined
 P = sprinkler operating pressure (lb/in² or kPa).

The value for K_d changes with nozzle size.

The value of K_d can be determined for any combination of sprinkler and nozzle if a P and a corresponding q are known. Because of the nonlinear nature of friction and miscellaneous losses internal inside the sprinkler friction losses, and K_d decreases slightly as q and P increases; however, over the normal operating range of most sprinklers, it can be assumed to be constant. The average values of K_d over the recommended range of operating pressures for each nozzle size are given in table 11-18.

The discharge coefficient, K_d , in equation 11-52 is actually equal to the product of an orifice coefficient, K_o , and the effective orifice cross-sectional area, A :

$$\begin{aligned} q &= K_d \sqrt{P} \\ &= K_o A \sqrt{P} \\ &= K_o \left(\frac{\pi d_{noz}^2}{4} \right) \sqrt{P} \end{aligned} \quad (\text{eq. 11-53})$$

where:

d_{noz} = nozzle orifice diameter, in (mm), assuming a circular orifice cross section

The value for K_o can be determined from q versus P tables and is relatively constant for the same type and manufacturer of sprinkler and nozzle, as shown in table 11-18. A typical value for K_o is 36 to 37 for q in gallons per minute and P in pounds per square inch. Table 11-19 gives values for K_o for brass nozzles from a leading sprinkler manufacturer. Values for specific nozzle designs and manufacturers may differ by a few percent.

A first estimate for nozzle diameter can be determined by solving equation 11-53 for d_{noz} :

$$d_{noz} = \sqrt{\frac{4q}{\pi K_o \sqrt{P}}} \quad (\text{eq. 11-54})$$

The value for d_{noz} will have to be rounded to the nominal value for d_{noz} that is available from manufacturers.

The value for operating pressure can then be adjusted to produce the desired q .

Equation 11-52 can be rearranged to give:

$$q = q' \sqrt{P/P'} \quad (\text{eq. 11-55})$$

or,

$$P = P' (q/q')^2 \quad (\text{eq. 11-56})$$

where:

P' and q' = corresponding values that are known (from table 11-18 or a manufacturer's table) and either q or P is unknown.

Sample calculation 11-6 illustrates the procedure for determining the nozzle size and pressure required to obtain a given sprinkler discharge.

Sample calculation 11-6—Determination of nozzle size and average operating pressure.

Given:

Sprinkler spacing of 40 by 60 feet and an average sprinkler discharge of q_a is 8.22 gallons per minute.

Calculations:

Use equation 11-50 to calculate the desired intake rate.

$$\begin{aligned} I &= \frac{96.3q}{S_e S_l} \\ &= 96.3 \frac{(8.22)}{(60 \times 40)} \\ &= 0.33 \end{aligned}$$

Then from table 11-15 a sprinkler with a 13/64-inch nozzle should be appropriate application rate of (0.35 + 0.02 in/h). Furthermore, from table 11-18 (or from appropriate manufacturers' information) a 13/64-inch nozzle will discharge 8.00 gallons per minute at 45 pounds per square inch and 8.445 gallons per minute at 50 pounds per square inch. Thus, the average sprinkler pressure (P_a) which will give the required discharge can be interpolated as $P_a = 47$ pounds per square inch (324 kPa). Another way to estimate P_a is:

Table 11-18 Nozzle discharge and wetted diameters for typical 1/2- and 3/4-inch bearing impact sprinklers with trajectory angles between 22 and 28 degrees and standard nozzles without vanes

Sprinkler pressure lb/in ²	Nozzle diameter - inch																	
	3/32		7/64		1/8		9/64		5/32		11/64		3/16		13/64		7/32	
	gpm	ft	gpm	ft	gpm	ft	gpm	ft	gpm	ft	gpm	ft	gpm	ft	gpm	ft	gpm	ft
20	1.14	63	1.55	73														
25	1.27	64	1.73	76	2.25	76	2.88	79	3.52	82	2							
30	1.40	65	1.89	77	2.47	77	3.16	80	3.85	85	4.64	88	5.50	91	6.50	94	7.58	96
35	1.51	66	2.05	77	2.68	78	3.40	81	4.16	87	5.02	90	5.97	94	7.06	97	8.25	100
40	1.62	67	2.20	78	2.87	79	3.64	82	4.45	88	5.37	92	6.40	96	7.55	99	8.82	102
45	1.72	68	2.32	79	3.05	80	3.85	83	4.72	89	5.70	94	6.80	98	8.00	101	9.35	104
50	1.80	69	2.45	80	3.22	81	4.01	84	4.98	90	6.01	95	7.17	100	8.45	103	9.88	106
55	1.88	70	2.58	80	3.39	82	4.25	85	5.22	91	6.30	96	7.52	101	8.85	104	10.34	107
60	1.98	71	2.70	81	3.54	83	4.42	86	5.45	92	6.57	97	7.84	102	9.24	105	10.75	108
65					3.68	84	4.65	87	5.71	93	6.83	98	8.19	103	9.60	106	11.10	109
70					3.81	84	4.82	88	5.92	94	7.09	99	8.49	104	9.95	107	11.40	110
K_d^3	0.255		0.346		0.453		0.575		0.704		0.849		1.012		1.1983		1.394	
K_d^4	36.9		36.8		36.9		37.0		36.7		36.6		36.7		36.8		37.1	

1 The use of straightening vanes or special long discharge tubes increases the wetted diameter by approximately 5 percent.

2 Lines represent upper and lower recommended pressure boundaries.

$$q = K_d \sqrt{P}$$

3 for P in lb/in² and q in gal/min.

4 The apparent orifice coefficient for equation 11-33 based on the value given for K_d .

Table 11-19 Typical values for the orifice coefficient, K_o , as applied in equation 11-106

Unit for q	Unit for P (or H)	Unit for d	K_o
gal/min	lb/in ²	inch	36.8
gal/min	ft	inch	24.2
l/sec	kPa	mm	0.00137
l/sec	m	mm	0.0043
liter/min	kPa	mm	0.0824
liter/min	m	mm	0.258

$$\begin{aligned} n_s &= \frac{24}{t_s} \\ &= \frac{24}{8} \\ &= 3 \text{ settings per day} \end{aligned} \quad (\text{eq. 11-97})$$

The discharge, q , of each sprinkler in the periodic-move system, from equation 11-61 is:

$$\begin{aligned} q &= \frac{IS_t S_m}{K} \Rightarrow \frac{0.227(40)(50)}{96.3} \\ &= 4.7 \text{ gal/min} \end{aligned} \quad (\text{eq. 11-98})$$

The maximum allowable irrigation interval during the peak use period, from equation 11-13 is:

$$\begin{aligned} f' &= \frac{d_n}{u_d} \\ &= \frac{2.0}{0.25} \\ &= 8 \text{ d} \end{aligned}$$

Assuming one day of down time per irrigation cycle, the days of operation per interval, from equation 11-14 is:

$$\begin{aligned} f &= f' - \text{days off} \\ &= 8 - 1 \\ &= 7 \text{ d} \end{aligned}$$

These are the maximum allowable depletion and corresponding maximum interval during the peak use period that will give the desired level of productivity. The actual depletion between irrigations and f' can be reduced to fit the final system design. The operating time per day, T , from equation 11-49 is:

$$\begin{aligned} T &= 24 - n_s t_m \Rightarrow 24 - (3)(0.5) \\ &= 22.5 \text{ h} \end{aligned}$$

The required gross application, assuming $E_q = 75$ percent, can now be determined as:

$$\frac{2.0}{75/100} = 2.7 \text{ in} \quad (\text{eq. 11-9})$$

and the required application rate is:

$$\begin{aligned} I &= \frac{2.7 \text{ in}}{11.25 \text{ h}} \\ &= 0.24 \text{ in/h} \end{aligned} \quad (\text{eq. 11-51})$$

The required sprinkler discharge can now be computed by equation 11-50 as:

$$\begin{aligned} q &= \frac{0.24(40)(50)}{96.3} \\ &= 4.98 \text{ gal/min} \end{aligned}$$

The production value of having 90 percent adequacy by using alternate sets versus 75 percent adequacy can be demonstrated, assuming overwatering does not reduce yields. Table 11-9 gives relative percentages of optimum production for different CU and adequacy values. With a CU = 78 percent and 75 percent adequacy, the relative production is 95 percent and for a CU = 88 percent and 90 percent adequacy, is 98 percent. Thus, the use of alternate sets can be expected to improve yields by at least 4 percent. If, however, uneven watering decreases production or quality (due to leaching of fertilizer or water-logging), the gross income differences may be considerably larger than 4 percent.

(i) Nozzle size and pressure

Table 11-18 shows the expected typical discharge and wetted diameters in conditions of no wind from typical half- and three-quarter-inch bearing impact sprinklers with angles of trajectory between 22 and 28 degrees and having standard nozzles without vanes. The various values in the table are for different nozzle sizes between 3/32 and 7/32 inch and base of sprinkler pressures between 20 and 70 pounds per square inch.

In general the relationship between discharge and pressure from a sprinkler can be expressed by the orifice equation:

$$q = K_d \sqrt{P} \quad (\text{eq. 11-52})$$

where:

q = sprinkler discharge (gpm or lpm or lps)

$$P_a = 45 \left(\frac{8.22}{8.00} \right)^2$$

$$= 47 \text{ lb/in}^2 \quad (\text{eq. 11-56})$$

rearranging equation 11-52:

$$P_a = \left(\frac{q_a}{K_d} \right)^2$$

$$= \left(\frac{8.22}{1.1983} \right)^2$$

$$= 47 \text{ lb/in}^2 \quad (\text{eq. 11-52})$$

$$P_a = \left(\frac{q_a}{K_o} \left(\frac{4}{\pi d_{\text{noz}}^2} \right) \right)^2$$

$$= \left(\frac{8.22}{36.8} \left[\frac{4}{\pi \left(\frac{13}{64} \right)^2} \right] \right)^2$$

$$= 47.5 \text{ lb/in}^2 \quad (\text{eq. 11-53})$$

(j) Friction losses

The Darcy-Weisbach and Hazen-Williams equations are the most commonly used pipe friction loss equations for sprinkler irrigation design. Each is presented along with equations used to define some of the terms. In designs, it is important to estimate friction loss because it is one of two factors that affect pressure variations in pipes, the other being elevation change. Pressure variations have a direct effect on water application uniformity through a sprinkler system, as described in the section on sprinkle irrigation efficiency.

(1) Darcy-Weisbach Equation

This equation is written for circular pipe cross sections, which includes virtually all pipes used in sprinkler irrigation:

$$h_f = f \frac{L V^2}{D 2g} \quad (\text{eq. 11-57})$$

where:

h_f = friction loss (head of water), ft or m

f = friction factor
 L = pipe length, ft or m
 D = pipe inside diameter, ft or m
 V = average velocity at a cross-section, $4Q/\pi D^2$ ft/sec or m/sec, in which Q is the flow rate (ft³/sec or m³/sec)
 g = ratio of weight to mass on the surface of the Earth (32.2 ft/sec² or 9.81 m/sec²)

Darcy-Weisbach is a (usually) more accurate pipe friction-loss equation, compared to alternative equations.

The Moody diagram, as found in hydraulics books, can be used with the Darcy-Weisbach equation to determine the friction factor, f , but with calculators and computers it is more convenient to use the Swamee-Jain equation to determine the f value:

$$f = \frac{0.25}{\left[\log_{10} \left(\frac{\epsilon}{3.75 D} + \frac{5.74}{N_R^{0.9}} \right) \right]^2} \quad (\text{eq. 11-58})$$

where:

ϵ = roughness height of the pipe material, ft or m
 D = inside diameter of the pipe, ft or m
 N_R = Reynolds number

The Swamee-Jain equation is valid for turbulent flow in the range: 4,000 less than or equal to N_R less than or equal to $1.0(10)^8$. The flow in sprinkler pipes is almost always turbulent.

The ratio ϵ/D is called relative roughness. The roughness height, ϵ , varies widely according to pipe material, condition, and age. Typical values are listed in table 11-20. Parameters ϵ and D must have the same units (in or mm). The Blasius equation can be applied to determine the value of f , in some cases, for smooth pipes (plastic pipes).

(2) Hazen-Williams equation

This is a simple, completely empirical pipe friction-loss equation, also for circular pipe cross sections:

$$h_f = \frac{JL}{100} \quad (\text{eq. 11-59})$$

where:

J = friction loss gradient (ft/100 ft or m/100 m),
defined as:

$$J = K \left(\frac{Q}{C} \right)^{1.852} D^{-4.87} \quad (\text{eq. 11-60})$$

in which C is a roughness coefficient. The value of K in this equation is:

$$\begin{aligned} K &= 1,050 && \text{for } Q, \text{ gal/min and } D, \text{ in} \\ K &= 16.42(10)^6 && \text{for } Q, \text{ l/s and } D, \text{ cm} \\ K &= 1.217(10)^{12} && \text{for } Q, \text{ l/sec and } D, \text{ mm} \end{aligned}$$

Typical values of C are given in table 11-21. The value of C depends also on the pipe size and Reynolds number, but complete relationships with those two parameters are not available. Uncertainties in the value of C tend to make the Hazen-Williams equation less accurate than Darcy-Weisbach.

(3) Blasius equation

This empirical equation can be used to estimate the f value for smooth (plastic (PVC and PE)) pipes of the typical diameters found in sprinkle irrigation systems:

$$f = 0.32 N_R^{-0.25} \quad (\text{eq. 11-61})$$

Table 11-20 Suggested values of the roughness height for use in the Darcy-Weisbach and Swamee-Jain equations for typical sprinkle-system pipe materials.

Pipe material	Pipe roughness height in ft [m]		
	New	Average	Old
Smooth-drawn tubing (glass, brass)	$5.0(10)^{-6}$ [0.000015 ^{b,c}]		
PVC and PE pipe	$6.6(10)^{-6}$, $5.0(10)^{-6}$ [0.000002 ^e , 0.0000015 ^g]	$4.3(10)^{-5}$ [0.000013 ^f]	
Aluminum (with couplers)	$3.3(10)^{-4}$ [0.0001]	$4.3(10)^{-4}$ [0.00013 ^f]	
Butt-welded steel			
New	$1.3(10)^{-4}$ [0.00004 ^{b,c,d}]		
Light rust	$4.9(10)^{-4}$ [0.00015 ^a]	$6.6(10)^{-4}$ [0.0002 ^f]	$1.2(10)^{-3}$ [0.00037a]
Hot-asphalt-dipped	$2.0(10)^{-4}$ [0.00006 ^a]	$2.6(10)^{-4}$ [0.00008 ^f]	$4.9(10)^{-4}$ [0.00015a]
Heavy brush-coated enamels/tars	$1.2(10)^{-3}$ [0.00037 ^a]	$3.1(10)^{-3}$ [0.00095 ^a]	
With incrustation or tuberculation		$3.1(10)^{-3} - 8.2(10)^{-3}$ [0.00095-0.0025 ^a]	$8.2(10)^{-3} - 2.0(10)^{-2}$ [0.0025-0.006 ^a]
Epoxy-enameled steel		$1.6(10)^{-5} - 1.6(10)^{-4}$, $9.8(10)^{-5}$ [0.000005 - 0.00005 ^a , 0.00003 ^f]	
Galvanized iron	$5.0(10)^{-4}$ [0.00015 ^{b,c,d}]		
Wrought iron	$1.5(10)^{-4}$ [0.000045 ^a]	$4.3(10)^{-4}$ [0.00013 ^a]	$3.0(10)^{-3} - 8.2(10)^{-3}$ [0.0009 - 0.0025 ^a]

a Brater and King (1976)

b Morris and Wiggert (1972)

c Streeter and Wylie (1979)

d Binder (1973)

e Flammer et al. (1982)

f Keller and Bliesner (1990)

g Uni-Bell Plastic Pipe Association (1980)

where 2,000 is equal to or less than N_R which is equal to or less than 100,000. When the Reynolds number is less than about 2,000, the flow is laminar and the f factor is defined as:

$$f = \frac{64}{N_R} \quad (\text{eq. 11-62})$$

(4) Reynolds number

The dimensionless Reynolds number is used in the Swamee-Jain and Blasius equations. For circular pipe cross sections:

$$\begin{aligned} N_R &= \frac{VD}{\nu} \\ &= \frac{4Q}{v\pi D} \end{aligned} \quad (\text{eq. 11-63})$$

where ν is kinematic viscosity (m^2/sec), which is a function of water temperature.

Kinematic viscosity is a function of water temperature, and over the range of temperatures in irrigation systems it can be estimated as:

$$\nu = \frac{1}{21,460 + 855.9T + 2.749T^2} \quad (\text{eq. 11-64})$$

for ν in ft^2/sec and T in degrees Fahrenheit, or,

$$\nu = \frac{1}{556,633 + 19,828T + 99.55T^2} \quad (\text{eq. 11-65})$$

for ν in m^2/sec and T in degrees Celcius.

(5) Local losses

Valves, elbows, couplers, screens, and other hardware found in sprinkler irrigation systems cause local, or "minor," hydraulic losses. In some cases, these losses are a significant part of the total losses, especially for short lengths of pipe, and in other cases they can be negligible. Local losses are usually estimated based on a dimensionless coefficient, K_r , which is multiplied by the velocity head, $V^2/2g$, yielding a hydraulic loss in terms of head of water, as from the Darcy-Weisbach and Hazen-Williams equations.

$$(h_f)_{\text{local}} = K_r \frac{V^2}{2g} \quad (\text{eq. 11-66})$$

The value of the coefficient depends on the type of hardware and usually on its size and condition, as well. Values of K_r can be found in most hydraulic handbooks, and some values are given in tables 11-22 through 11-24.

When determining the velocity head at a reducing fitting, the diameter and flow that gives the highest head should be used. As an example, assume an 8 by 6 by 6-inch reducing side outlet tee has an inflow of 1,000 gallons per minute, outflows of 400 gallons per minute from the side outlet, and 600 gallons per minute through the body. The three respective velocity heads are 0.64 foot for the inlet, 0.32 foot for the side outlet, and 0.69 foot for the line flow (flow going past) through the body. Therefore, when estimating hour for the side outlet flow, use the velocity head of 0.64 foot (because it is larger than 0.32 ft) and $K_r = 1.0$ from table 11-22 to obtain $h_f = 1.0(0.64) = 0.64$ ft (eq. 11-66) for the line flow $h_f = 0.5(0.69) = 0.35$ ft.

Table 11-24 gives velocity heads for inside diameters in whole-inch increments. Actual inside pipe diameters are usually different, but these table values give

Table 11-21 Typical values of the Hazen-Williams C for different pipe sizes and materials

Pipe material	C
Plastic (4 in diameter or larger)	150
Plastic (2 to 3 in diameter)	140
Aluminum (with couplers every 30 ft)	130
Galvanized steel	130
Epoxy-coated steel	145-150
Polyethylene lined steel	135-145 ¹
Steel (new)	130
Steel (15 years old)	100
Butyl rubber drop tubes	150
Rigid drop tubes	145

¹ With polyethylene-lined steel pipe having bulk head fittings at each outlet and with outlets spaced at 30 inches, the C value may decrease to 135 due to the effects of the additional roughness elements.

Table 11–22 Values of the local loss coefficient (K_r) for irrigation pipe fittings and valves

Fitting or valve	Diameter (in)							
	2	3	4	5	6	8	10	12
Couplers								
ABC	1.2	0.8	0.4	0.3				
Hook latch	0.6	0.4	0.3	0.2	0.2			
Ring lock				0.2	0.2	0.2	0.2	0.2
Elbows								
Long radius	0.4	0.3	0.3	0.3	0.2	0.2	0.2	0.2
Mitered	0.8	0.7	0.6	0.6	0.6	0.6	0.6	0.5
Tees								
Hydrant (off)		0.6	0.5	0.4	0.3	0.3	0.3	0.3
Side outlet	1.6	1.3	1.2	1.1	1.0	0.9	0.8	0.8
Line flow	0.8	0.7	0.6	0.6	0.5	0.5	0.4	0.4
Side inlet	2.4	1.9	1.7	1.5	1.4	1.2	1.1	1.1
Valves								
Butterfly					0.8	0.6	0.5	0.5
Plate type	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Ames check			1.8		1.5	1.3	1.2	
Hydrant with opener		8.0	7.5	7.0	6.7			
Special								
Strainer	1.5	1.3	1.0	0.9	0.8	0.7	0.6	0.5
“Y” (Long rad.)	0.8	0.6	0.6	0.6	0.4	0.4	0.3	0.3

1 Source: Ames Irrigation Handbook. W.R. Ames Company, Milpitas, CA

Table 11–23 Values of the local loss coefficient (K_f) for standard pipe fittings and valves.

Fitting, valve, or other	Nominal diameter (in)						
	3	4	5	6	7	8	10
Elbows:							
Regular flanged 90°	0.34	0.31	0.30	0.28	0.27	0.26	0.25
Long radius flanged 90°	0.25	0.22	0.20	0.18	0.17	0.15	0.14
Long radius flanged 45°	0.19	0.18	0.18	0.17	0.17	0.17	0.16
Regular screwed 90°	0.80	0.70					
Long radius screwed 90°	0.30	0.23					
Regular screwed 45°	0.30	0.28					
Bends:							
Return flanged	0.33	0.30	0.29	0.28	0.27	0.25	0.24
return screwed	0.80	0.70					
Tees:							
Flanged line flow	0.16	0.14	0.13	0.12	0.11	0.10	0.09
Flanged branch flow	0.73	0.68	0.65	0.60	0.58	0.56	0.52
Screwed line flow	0.90	0.90					
Screwed branch flow	1.20	1.10					
Valves:							
Globe flanged	7.00	6.30	6.00	5.80	5.70	5.60	5.50
Globe screwed	6.00	5.70					
Gate flanged	0.21	0.16	0.13	0.11	0.09	0.075	0.06
Gate screwed	0.14	0.12					
Swing check flanged	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Swing check screwed	2.10	2.00					
Angle flanged	2.20	2.10	2.00	2.00	2.00	2.00	2.00
Angle screwed	1.30	1.00					
Foot	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Strainers (basket type)	1.25	1.05	0.95	0.85	0.80	0.75	0.67
Inlets or entrances:							
Inward projecting	0.78				Same for all diameters		
Sharp cornered	0.50				Same for all diameters		
Slightly rounded	0.23				Same for all diameters		
Bell-mouth	0.04				Same for all diameters		

Table 11–24 Values of velocity head ($V^2/2g$) for different diameters and flow rates

Flow (gal/min)	Inside diameter (mm)								Flow (l/sec)					Inside diameter (mm)					
	2	3	4	5	6	7	8	10	12	12	50	75	100	125	150	175	200	250	300
50	0.405	0.080	0.025							2	0.053	0.010	0.003						
100	1.619	0.320	0.101	0.041	0.020					5	0.331	0.065	0.021	0.008	0.004				
150	3.643	0.720	0.228	0.093	0.045	0.024				10	1.322	0.261	0.083	0.034	0.016	0.009	0.005		
200		1.279	0.405	0.166	0.080	0.043	0.025			15		0.588	0.186	0.076	0.037	0.020	0.012	0.005	
250		1.999	0.633	0.259	0.125	0.067	0.040	0.060		20			0.331	0.135	0.065	0.035	0.021	0.008	
300			0.911	0.373	0.180	0.097	0.057	0.023		25			0.516	0.212	0.102	0.055	0.032	0.013	0.006
350			1.240	0.508	0.245	0.132	0.077	0.032	0.015	30				0.305	0.147	0.079	0.046	0.019	0.009
400				0.663	0.320	0.173	0.101	0.041	0.020	35				0.331	0.200	0.108	0.063	0.026	0.012
450				0.839	0.405	0.219	0.128	0.052	0.025	40					0.261	0.141	0.083	0.034	0.016
500				1.036	0.500	0.270	0.158	0.065	0.031	45					0.331	0.178	0.105	0.043	0.021
550					0.605	0.326	0.191	0.078	0.038	50						0.220	0.129	0.053	0.026
600					0.720	0.388	0.228	0.093	0.045	55						0.266	0.156	0.064	0.031
650					0.845	0.456	0.267	0.109	0.053	60							0.186	0.076	0.037
700					0.980	0.529	0.310	0.127	0.061	65							0.218	0.089	0.043
750						0.607	0.356	0.146	0.070	70						0.253	0.104	0.050	
800						0.691	0.405	0.166	0.080	75							0.119	0.057	
850						0.780	0.457	0.187	0.090	80							0.035	0.065	
900						0.874	0.512	0.210	0.101	85							0.153	0.074	
950							0.571	0.234	0.113	90							0.171	0.083	
1000							0.633	0.259	0.125	95							0.191	0.092	
1100							0.765	0.313	0.151	100							0.212	0.010	
1200							0.911	0.373	0.180	105							0.233	0.112	
1300								0.438	0.211	110							0.123		
1400								0.508	0.248	115							0.135		
1500								0.583	0.281	120							0.147		
1600								0.663	0.320	125							0.159		
1700								0.749	0.361	130							0.175		
1800								0.839	0.405	135							0.186		
1900								0.935	0.451	140							0.200		
2000									0.500	150							0.230		
2500									0.781	160							0.261		

satisfactory results for most practical purposes. The values of K_r are only approximations for the fittings in general, inasmuch as the inside diameters of fittings vary as well.

For an abrupt enlargement in pipe cross section, the local loss coefficient can be estimated as:

$$K_r = \left(1 - \left(\frac{D_{\text{small}}}{D_{\text{large}}} \right)^2 \right)^2 \quad (\text{eq. 11-67})$$

where:

- D_{small} = inside diameter of the upstream pipe, ft or m
 D_{large} = inside diameter of the downstream pipe, ft or m

Similarly, for a sudden reduction in pipe diameter:

$$K_r = 0.7 \left(1 - \left(\frac{D_{\text{small}}}{D_{\text{large}}} \right)^2 \right)^2 \quad (\text{eq. 11-68})$$

For gradually diverging sections, the local loss coefficient can be estimated as:

$$K_r = \frac{\alpha}{45} \left(0.84 \left(1 - \frac{D_{\text{small}}}{D_{\text{large}}} \right) + 0.488 \left(1 - \frac{D_{\text{small}}}{D_{\text{large}}} \right)^2 \right) \quad (\text{eq. 11-69})$$

for α is less than 45 degrees, where α is the angle of the divergence ($\alpha=180^\circ$ represents an abrupt expansion), and,

$$K_r = 0.84 \left(1 - \frac{D_{\text{small}}}{D_{\text{large}}} \right) + 0.488 \left(1 - \frac{D_{\text{small}}}{D_{\text{large}}} \right)^2 \quad (\text{eq. 11-70})$$

for $\alpha \geq 45^\circ$.

For gradually converging sections, the local loss coefficient can be estimated as:

$$K_r = 0.038 + 0.0052 \alpha \ln \left(2 - \frac{D_{\text{small}}}{D_{\text{large}}} \right) \quad (\text{eq. 11-127})$$

These equations for diverging sections were developed from tables presented by Sneed and Allen (2009).

(6) Friction losses in laterals

Friction loss is less for flow through a pipe with multiple outlets than for constant discharge through the length of a pipeline of a given diameter because the flow rate decreases each time an outlet is passed. The method developed by Christiansen for computing pressure losses in multiple-outlet pipelines has been widely accepted and is presented here. It involves first computing the friction loss in the line without multiple outlets and then multiplying by a factor, F , based on the number of outlets (e.g., the number of sprinklers, N , along the lateral).

Table 11-25 Reduction coefficients (F) for computing friction loss in pipes with multiple outlets having nearly the same discharge

Number of outlets	$F^{1/}$ (end)	$F^{2/}$ (mid)
1	1.00	1.00
2	0.64	0.52
3	0.53	0.44
4	0.49	0.41
5	0.46	0.40
6	0.44	0.39
7	0.43	0.38
8	0.42	0.38
9	0.41	0.37
10-11	0.40	0.37
12-14	0.39	0.37
15-20	0.38	0.36
21-35	0.37	0.36
> 35	0.36	0.36

1 $F(\text{end})$ is for first sprinkler SI from main (end-riser pipe).

2 $F(\text{mid})$ is for first sprinkler SI/2 from main (mid-riser pipe).

Christiansen's equation for computing the reduction coefficient (F) for pipes with multiple, equally spaced outlets where the first outlet is SI from the mainline is:

$$F = \frac{1}{m+1} + \frac{1}{2N} + \frac{\sqrt{m-1}}{6N^2} \quad (\text{eq. 11-72})$$

and where the first outlet is SI/2 (for example, when laterals are connected to both sides of a mainline) from the mainline:

$$F = \left(\frac{2N}{2N-1} \right) \left(\frac{1}{m+1} + \frac{\sqrt{m-1}}{6N^2} \right) \quad (\text{eq. 11-73})$$

where:

m = 1.852 for the Hazen-Williams equation

m = 2.0 for the Darcy-Weisbach equation

N = number of outlets along the pipe

The value of F approaches 0.36 when N is greater than 35, which is often the case with sprinkler laterals (table 11-25). Note that the equations 11-72 and 11-73 for F are for pipes that have no flow past the last outlet (sprinkler); they cannot be directly applied to the estimation of friction losses only partway down the lateral pipe. Also, the calculation of F assumes that each outlet has a constant discharge, which is not exactly correct because of inevitable pressure variations along a lateral. Equations 11-72 and 11-73 are for use with laterals having nearly constant discharge per outlet, such as for hand lines, wheel-lines, solid-set (fixed), and linear-move systems. For center-pivot laterals, outlet discharge varies with distance from the center pivot, and where there are more than about 35 sprinklers on a center pivot (which is the usual case), F is 0.555. For more than 35 sprinklers, the F value is higher on a center-pivot lateral than on laterals for other types of sprinkler systems because the flow rate in the pipe decreases more slowly at the downstream end, so that the average velocity along the length of the lateral is higher.

With the adjustment for the outlet factor, F, the friction loss for lateral pipes having outlets with nearly the same discharge is:

$$h_f = \frac{JFL}{100} \quad (\text{eq. 11-74})$$

In terms of pressure loss, in the English system (lb/in² and ft):

$$P_f = \frac{JFL}{100(2.31)} \quad (\text{eq. 11-75})$$

and in the metric system (kPa and m):

$$P_f = \frac{JFL}{100(9.81)} \quad (\text{eq. 11-76})$$

623.1106 Lateral design

Lateral-line pipe sizes should be chosen so that the total pressure variation in the line, due to both friction head and elevation, meets the criteria outlined in lateral layout.

(a) Laterals on level ground

A standard design criterion of the NRCS is that the allowable pressure loss due to friction in a lateral line on level ground will be 20 percent of the average design operating pressure for the sprinklers (P_a). Therefore, the allowable head loss gradient (J_a), will be:

$$J_a = \frac{0.20 P_a (2.31)}{F(L/100)} \quad (\text{eq. 11-77})$$

To design lateral size using J_a , select the smallest pipe size that has J equal to or less than J_a . For example, using table 11-26 for aluminum lateral pipe, find the flow rate corresponding to the total lateral discharge. Moving along that line to the right, find the pipe size column that contains a value just equal to, or less than, J_a . This is the pipe size required. Reverse the procedure to determine the actual pressure loss due to friction (P_f). Determine the pressure required at the mainline for single pipe size laterals:

$$P_m = P_a + 0.75P_f + P_r \quad (\text{eq. 11-78})$$

and for dual pipe size laterals:

$$P_m = P_a + 0.67P_f + P_r \quad (\text{eq. 11-79})$$

where:

P_m = pressure required at the mainline end (lateral inlet pressure) (lb/in²)

P_f = pressure loss due to pipe friction (lb/in²) calculated using eq. 11-75

P_r = pressure required to lift water up the riser, riser height/2.31 (lb/in²)

Table 11-26 Friction loss rate in ft/100 ft (J) in portable aluminum pipe with 0.050 in wall and couplings every 30 ft¹

Flow rate (gpm)	2-in	3-in	4-in	5-in
10	0.40	0.05		
20	1.44	0.18		
30	3.05	0.39		
40	5.20	0.66		
50	7.85	1.00		
60	11.01	1.40	0.33	
70	14.65	1.87	0.44	
80	18.76	2.39	0.57	0.19
90	23.33	2.98	0.70	0.23
100	28.36	3.92	0.85	0.28
120		5.07	1.20	0.39
140		6.74	1.59	0.52
160		8.64	2.04	0.67
180		10.74	2.54	0.83
200		13.06	3.08	1.01
220		15.58	3.68	1.21
240		18.30	4.32	1.42
260		21.22	5.01	1.65
280		24.35	5.75	1.89
300			6.54	2.15
320			7.37	2.42
340			8.24	2.71
360			9.16	3.01
380			10.13	3.33
400			11.14	3.66
420			12.19	4.01
440			13.28	4.37
460			14.42	4.75
480			15.61	5.14
500			16.83	5.54
520				5.96
540				6.39
560				6.83
580				7.29
600				7.76

¹ Based on the Hazen-Williams equation with $C = 130$

(b) Laterals laid uphill

In figure 11–39, where the lateral runs uphill, P_f must equal or exceed 20 percent of P_a minus the pressure required to overcome elevation P_e , which is the difference in elevation divided by 2.31 inches.

$$J_a = \frac{(0.20 P_a - P_e)(2.31)}{F(L/100)} \quad (\text{eq. 11-80})$$

Where P_a and P_e are in pound per square inch and J_a and L in foot per 100 feet and feet.

For single pipe size laterals on uniform uphill slopes:

$$P_m = P_a + \frac{3}{4}P_f + \frac{1}{2}P_e + P_r \quad (\text{eq. 11-81})$$

and for dual pipe size laterals:

$$P_m = P_a + \frac{2}{3}P_f + \frac{1}{2}P_e + P_r \quad (\text{eq. 11-82})$$

Sample calculation 11–7 illustrates this procedure.

(c) Laterals laid downhill

In figure 11–40, where the lateral runs downhill, the allowable P_f is $0.20 P_a + P_e$ and for relatively mild slopes:

$$J_a = \frac{(0.20 P_a + P_e)(2.31)}{F(L/100)} \quad (\text{eq. 11-83})$$

However, on steep slopes where P_e is greater than $0.4P_a$, pressure increase due to elevation fall may be more than desirable. The design should minimize the pressure variation along the line by reducing pipe sizes. For these conditions, pipe sizes are selected on the basis of friction loss equaling elevation gain, P_f equals P_e .

For single pipe size laterals on uniform downhill slopes:

$$P_m = P_a + \frac{3}{4}P_f - \frac{1}{2}P_e + P_r \quad (\text{eq. 11-84})$$

and for dual pipe size laterals:

$$P_m = P_a + \frac{2}{3}P_f - \frac{1}{2}P_e + P_r \quad (\text{eq. 11-85})$$

Figure 11–39 A lateral running uphill

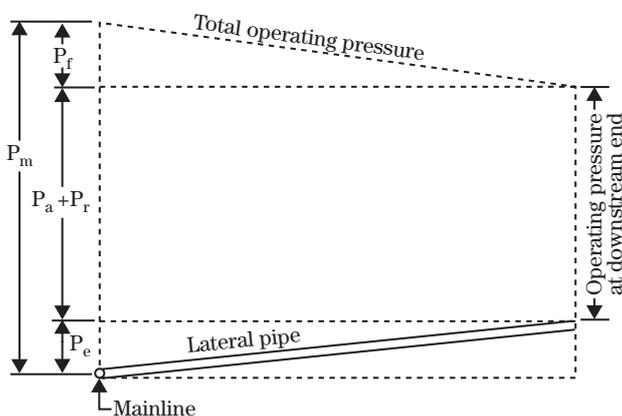
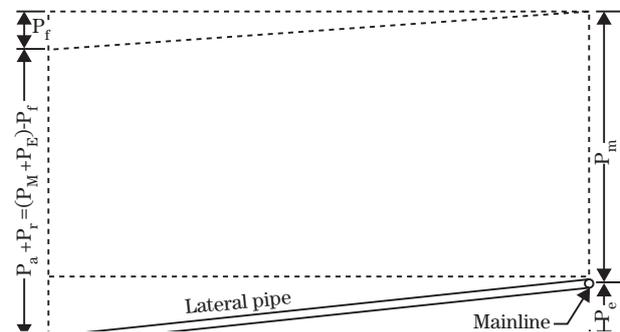


Figure 11–40 A lateral running downhill



Sample calculation 11–8 illustrates this procedure for laterals running downhill.

(d) Laterals with two pipe sizes

Lateral lines of a single pipe size are preferred for convenience. The use of two pipe sizes will reduce initial costs. Portable laterals containing more than two pipe sizes should never be considered; however, permanently buried laterals of multiple pipe sizes are practical.

Tables 11–25 and 11–26 can be used to find the nearest uniform pipe size for a lateral line that will result in a friction loss equal to or less than the allowable P_f . The tables may also be used to obtain the lengths of each of two pipe sizes on a lateral line, by using these steps:

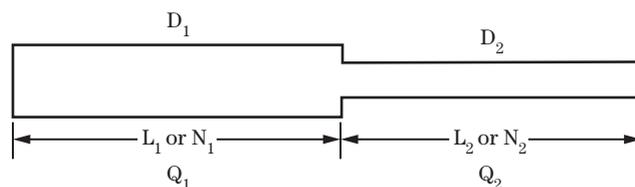
Step 1: Compute the allowable P_f for the total length of the line as described.

Step 2: Convert this allowable P_f to J_a by using equations 11–77, 11–80, or 11–83, as appropriate for the slope conditions.

Step 3: With the total lateral line capacity (Q) and the J_a known, use table 11–26 to find the two required pipe sizes.

Step 4: Determine the specific lengths of each of the two pipe sizes required by trial and modification. First estimate lengths L_1 and L_2 , where L_2 is the length of smaller diameter pipe, and then compute the total pressure loss due to friction for these lengths. The closed end of the multioutlet line must be considered in all friction-loss calculations using equations 11–74, 11–75, or 11–76. If this loss falls above or below the allowable h_f or P_f , choose different values of L_1 and L_2 and repeat the procedure.

Figure 11–41 Schematic of a dual-pipe-size sprinkler lateral



Step 5: Assume that pipe diameter (D_1) extends for the full length of the lateral line and find the loss for length ($L_1 + L_2$) containing ($N_1 + N_2$) sprinklers and discharging Q_1 plus Q_2 .

Step 6: Find the loss in length (L_2) for pipe diameter (D_1) containing (N_2) sprinklers and discharging Q_2 .

Step 7: Then find the loss in length (L_2) of pipe diameter (D_2) containing (N_2) sprinklers and discharging Q_2 .

Step 8: Combine the losses as:

$$P_{f(1+2)}(\text{for } D_1) - P_{f(2)}(\text{for } D_1) + P_{f(2)}(\text{for } D_2) \quad (\text{eq. 11-86})$$

Sample calculation 11–7—Laterals laid uphill with two pipe sizes.

Given:

- lateral consisting of 960 feet of portable aluminum irrigation pipe with 24 sprinklers spaced 40 foot apart, discharging at a rate of 12.5 gallons per minute, and operating at 44 pounds per square inch
- lateral capacity: $Q = 300$ gpm
- elevation difference = 9.0 ft (uphill) or $P_e = 9.0/2.31 = 3.9$ lb/in²
- height of risers for corn: 8.0 ft

Find:

- The smallest pipe sizes that will limit pressure loss due to both friction and elevation difference to 20 percent of P_a
- Pressure requirements at the mainline, P_m

Calculations:

Referring to figure 11–39, determine the allowable J_a by equation 11–80:

$$J_a = \frac{(0.20 \times 44 - 3.9) \times 2.31}{960 / 100 \times 0.37} = 3.19$$

Using the lateral capacity of Q equals 300 gallons per minute and J_a is 3.19, table 11-26 indicates that some 5 and 4 inch pipe should be used. Assuming an initial estimate of 480 feet:

$$\begin{array}{ll} D_1 = 5 \text{ in} & D_2 = 4 \text{ in} \\ L_1 = 480 \text{ ft} & L_2 = 480 \text{ ft} \\ N_1 = 12 & N_2 = 12 \\ Q_1 = 150 \text{ gpm} & Q_2 = 150 \text{ gpm} \end{array}$$

Using tables 11-25 and 11-26, and assuming D_1 equals 5 inches for the entire length of the lateral, find the loss in $(L_1 + L_2) = 960$ feet containing $(N_1 + N_2) = 24$ sprinklers and discharging $(Q_1 + Q_2) = 300$ gallons per minute, using equation 11-75:

$$\begin{aligned} P_{f(1+2)}(\text{for } D_1) &= \frac{(2.15)(0.37)(960)}{100(2.31)} \\ &= 3.31 \text{ lb/in}^2 \end{aligned}$$

Find the loss in $L_2 = 480$ feet of $D_1 = 5$ inch pipe containing $N_2 = 12$ sprinklers and discharging $Q_2 = 150$ gallons per minute:

$$\begin{aligned} P_{f(2)}(\text{for } D_1) &= \frac{0.59 \times 0.39 \times 480}{100(2.31)} \\ &= 0.48 \text{ lb/in}^2 \end{aligned} \quad (\text{eq. 11-75})$$

and in a similar manner find the loss in the 4 inch pipe:

$$\begin{aligned} P_{f(2)}(\text{for } D_2) &= \frac{1.81 \times 0.39 \times 480}{231} \\ &= 1.47 \text{ lb/in}^2 \end{aligned} \quad (\text{eq. 11-75})$$

The friction loss for the dual pipe size line can now be determined by equation 11-86:

$$\begin{aligned} P_f &= 3.31 - 0.48 + 1.47 \\ &= 4.3 \text{ lb/in}^2 \end{aligned}$$

This value is slightly lower than the allowable $P_f = 0.20$ $P_a - P_e = 0.20 \times 44 - 3.9 = 4.9$ pounds per square inch. Therefore, less 5 inch pipe and more 4 inch pipe can be used. By assuming 400 feet of 5 inch pipe containing 10 sprinklers and 560 feet of 4 inch pipe containing 14 sprinklers, a repetition of the procedure results in:

$$\begin{aligned} P_f &= 3.31 - 0.75 + 2.28 \\ &= 4.8 \text{ lb/in}^2 \end{aligned} \quad (\text{eq. 11-86})$$

The pressure requirement at the mainline can now be determined by equation 11-82:

$$\begin{aligned} P_m &= 44.0 + \left(\frac{2}{3} \times 4.8\right) + \left(\frac{1}{2} \times 3.9\right) + \frac{8.0}{2.31} \\ &= 52.6 \text{ lb/in}^2 \end{aligned}$$

Sample calculation 11-8—Laterals laid downhill.

Given:

- lateral consisting of 960 feet of portable aluminum irrigation pipe with 24 sprinklers spaced 40 foot apart, discharging at a rate of 12.5 gallons per minute, and operating at 44.0 pounds per square inch
- lateral capacity: $Q = 300$ gallons per minute
- average downhill slope: 3.5 percent and 33.6 feet in total length of line
- height of risers for corn = 8 feet
- owner desires only one pipe size

Find:

- the smallest pipe size that will result in an approximate balance between pressure loss due to friction and pressure gain due to elevation decrease
- pressure requirements at the mainline

Calculations:

Assume the allowable P_f to be equal to the pressure gain due to elevation, which is $P_e = 33.6/2.31 = 14.5$ pounds per square inch. Convert the pressure gain due to elevation to an allowable head loss gradient (J_a) using equation 11-83 and letting $P_a = 0$:

$$\begin{aligned} J_a &= \frac{(14.5)(2.31)}{0.37 \left(\frac{960}{100}\right)} \\ &= 9.43 \text{ ft/100 ft} \end{aligned}$$

Using a lateral capacity of 300 gallons per minute, table 11-26 indicates some 3 and 4 inch pipe will be required. If only one pipe size is used, it should be all 4 inch pipe. The pressure loss due to friction resulting from the use of 4 inch pipe by equation 11-75 is:

$$P_f = \frac{(0.37)(6.54)(960)}{231}$$

$$= 10.1 \text{ lb/in}^2$$

The percent pressure variation in the line is:

$$\frac{P_e - P_f}{P_a} = \frac{14.5 - 10.1}{44.0}$$

$$= 10.0\% \quad (\text{eq. 11-87})$$

If only 3 inch pipe were used, the pressure loss due to friction would be 42.5 pounds per square inch, and the resulting pressure variation would be:

$$\frac{P_e - P_f}{P_a} = \frac{42.5 - 14.5}{44.0}$$

$$= 64.0\% \quad (\text{eq. 11-87})$$

This is outside the 20 percent limit, therefore, a line consisting of 3 inch pipe should not be used. Using equation 11-84, to compute the pressure required at the mainline for a 4 inch lateral:

$$P_m = 44.0 + \frac{3}{4}(10.1) - \frac{1}{2}(14.5) + \frac{8.0}{2.31}$$

$$= 47.8 \text{ lb/in}^2$$

(e) Laterals with flow-control devices

Flow or pressure control devices are used in lateral lines where the topography is too broken or steep to permit the pressure variation in the line to be controlled within the 20 percent limit by the selection of practical pipe sizes. These devices are either valves placed between the lateral and sprinkler head at each sprinkler outlet, or special flow-control nozzles as described earlier, designed to provide equal discharge at all sprinklers.

When flow or pressure control devices are used at the base of each sprinkler, the pressure that must be

provided at the distal end of the lateral will be P_a plus P_r plus the pressure required to overcome friction loss in the control valves, P_{cv} (fig. 11-42). However, when flexible orifice nozzles are used to maintain constant flow, P_{cv} is effectively zero. Since the valves control the discharge of the sprinklers, the selection of lateral pipe sizes becomes less a problem of maintaining a specified pressure variation between sprinklers and more a problem of economics. The allowable P_f should be that which will result in the lowest annual pumping cost. For most conditions, P_f may be assumed to be about $0.20 P_a$, or 10 pounds per square inch.

The pressure requirement at the mainline for level (zero slope) laterals is:

$$P_m = P_a + P_f + P_r + P_{cv} \quad (\text{eq. 11-88})$$

For uphill laterals it is:

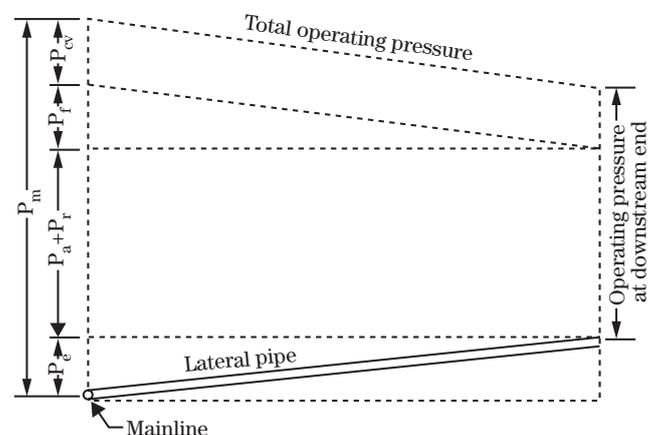
$$P_m = P_a + P_f + P_e + P_r + P_{cv} \quad (\text{eq. 11-89})$$

For downhill laterals it is:

$$P_m = P_a + P_f - P_e + P_r + P_{cv} \quad (\text{eq. 11-90})$$

Valve manufacturers furnish data on the pressure losses for different discharges through their valves. Sample calculation 11-9 illustrates the procedure involved in the design of a sprinkler lateral with flow control nozzles.

Figure 11-42 A lateral running uphill with flow-control valves



Sample calculation 11-9—Design of lateral with flow control nozzles**Given:**

- A lateral, 1,320 feet long, running up and down slopes on broken (irregular) topography
- The highest point in the line is 33 feet above the lateral inlet from the mainline
- The lateral contains 44 sprinklers spaced at $S_1 = 30$ feet with $q_a = 5.0$ gallons per minute
- The first sprinkler is $1/2 S_1$ from the mainline.
- Sprinklers with flexible orifice nozzles designed to discharge about 5 gallons per minute between 40 and 80 pounds per second as shown in figure 11-36 will be used.
- The system will have 3 foot risers, and the owner desires single pipe size laterals.

Find:

- Pipe size and P_m required.

Calculations:

Pressure required to overcome elevation is:

$$P_e = \frac{33}{2.31} \\ = 14.3 \text{ lb/in}^2$$

Let the allowable $P_f = 10$ pounds per square inch, which is about 20 percent of the pressure that would be required for a standard 5/32-inch nozzle discharging 5.0 gallons per minute. The allowable head loss gradient for $P_f = 10$ pounds per square inch is:

$$J_a = \frac{(10.0)(2.31)}{0.36 \left(\frac{1,320}{100} \right)} \\ = 4.86 \text{ ft/100 ft} \quad (\text{eq. 11-75})$$

From table 11-26 for $Q_1 = 44(5.0) = 220$ gallons per minute it is determined that 4 inch pipe will satisfy J_a . Using equation 11-131:

$$P_f = \frac{(0.36)(3.68)(1,320)}{231} \\ = 7.6 \text{ lb/in}^2 \quad (\text{eq. 11-76})$$

Typically, sprinkler regulating valves have a P_{cv} of between 10 and 15 pounds per square inch; however, as mentioned above for flexible orifice nozzles, $P_{cv} = 0$. Substituting the lowest permissible operating pressure, 40 pounds per square inch, for P_a in equation 11-89:

$$P_m = 40.0 + 7.6 + 14.3 + \frac{3.0}{2.31} + 0 \\ = 63.2 \text{ lb/in}^2$$

(f) Hose-fed design

Hose-fed systems for overlapped sprinkler grids and for orchard sprinklers require special design considerations; however, the design strategies described earlier in this section can be used. Each hose may be fitted with 1 to 10 sprinklers and either periodically pulled to a new set position or left stationary.

If a manifold serves hoses operating with one or two sprinklers in every other tree row, the manifold should be treated as an ordinary sprinkler lateral. However, the average pressure along the manifold should be the average sprinkler pressure desired, P_a plus the friction head loss in the hose and hose bib (a hydrant). If each submain serves only one or two hose lines, with several sprinklers on each, the hose line should be treated as an ordinary sprinkler lateral. Equation 11-75 is used to find P_f and equations 11-88 to 11-90 are used to find P_m .

Friction losses in small diameter hoses can be estimated by:

$$J = \frac{100 h_f}{L} \\ = 0.133 \left(\frac{Q^{1.75}}{D^{4.75}} \right) \text{ for } D < 5 \text{ in} \quad (\text{eq. 11-91})$$

This equation is derived by combining the Blasius equation and the Darcy-Weisbach formula for smooth pipes. Equation 11-91 gives good results for 5 inch diameter and smaller plastic pipe. For larger plastic pipes, the Hazen-Williams equation with $C = 150$ can be used; however, slightly more accurate estimates of friction loss can be obtained from:

$$J = \frac{100 h_f}{L}$$

$$= 0.133 \left(\frac{Q^{1.83}}{D^{4.83}} \right) \quad \text{for } D > 5 \text{ in} \quad (\text{eq. 11-92})$$

Table 11-27 gives friction loss gradients for various sizes of hoses and hose bibs based on equation 11-91.

(g) Perforated-pipe laterals

Since perforated-pipe laterals have equally spaced multiple outlets, the general principles for design of laterals with impact sprinklers also apply to perforated-pipe laterals. Nevertheless, because of their low operating pressure, there are more restrictions on the design of perforated-pipe laterals. Laterals must be

laid very nearly on the level if pressure variation along the line is to be kept within acceptable limits. Pressure control valves cannot be used for this purpose, and only one pipe size should be used.

Perforated pipe is available for only a few rates of application. The most typical rates are 0.75 and 1.0 inch per hour. This limit in application rates materially reduces the flexibility in design. The manufacturers of perforated pipe have simplified the design of laterals by furnishing performance tables for each combination of pipe size and application rate. Knowing the length of the line makes the discharge, spread (width of the wetted area), and operating pressure from the tables easy to read. Table 11-28 is an example. The designer should request such tables from the manufacturer when making recommendations for the use of perforated pipe.

Table 11-27 Approximate friction loss gradients for plastic hoses and hose bibs ^{1/}

Flow (gal/min)	Friction loss lb/in ² /100 ft ^{2/}			Hydrant loss lb/in ²	
	5/8 in	3/4 in	1 in	3/4 in	1 in
2	1.81	0.76	0.19	0.1	
4	6.07	2.55	0.65	0.2	0.1
6	12.35	5.19	1.32	0.4	0.2
8	20.43	8.59	2.19	0.8	0.3
10	30.19	12.70	3.24	1.2	0.5
12	41.53	17.47	4.45	1.7	0.7
14		22.88	5.83	2.4	0.9
16		28.90	7.37	3.1	1.2
18		35.52	9.06	3.9	1.5
20			10.89	4.8	1.9
22			12.87	5.8	2.3
24			14.98	6.9	2.7
26			17.24	8.0	3.2
28			19.62	9.2	3.7
30			22.14	10.6	4.3

1 Nominal hose sizes and also inside diameters.

2 Friction losses in valves vary widely with different makes of equipment. These values should be used only as a guide in determining the size required.

To illustrate the use of table 11-28, assume a lateral 750 feet long with SI = 40 feet applying water at the rate of 1.0 inch per hour. Since this table includes lateral lengths of 750 feet for 5 inch pipe and an application rate of 1.0 inch per hour, this size pipe may be used. Find the 750 foot column and follow the column downward until a spread of 42 feet is reached. A spread of 2 feet greater than the lateral spacing is customarily used to provide a 1 foot overlap between laterals to prevent dry areas. With a 42 foot spread the lateral discharge is 364 gallons per minute. Following a horizontal line to the left, the inlet pressure or pressure required at the mainline, is $P_m = 15.0$ pounds per square inch (103 kPa).

(i) Buried laterals

The design of buried plastic laterals for permanent systems is essentially the same as for portable aluminum laterals. The main differences are due to the difference in pipe friction and the fact that up to four different pipe sizes are often used. To determine friction loss use equations 11-91 or 11-92 to compute the P_f of a multisized lateral either following a procedure similar to that outlined in this section or the procedures developed in 210-NEH, Part 623 chapter 7.

Table 11-28 Typical performance table for perforated pipelines^{1/}

Inlet pressure (lb/in ²)	Pipe size = 5 in diameter application rate = 1.0 in/h																		
	Length of line (ft)																		
Discharge and spread	50	100	150	200	250	300	350	400	450	500	550	600	650	700	750	800	850	900	950
6 gal/m	16	32	48	64	80	96	112	127	142	157	172	187	202	217	231	245	259	273	286
spread	30	30	30	30	30	30	30	29	29	29	29	28	28	28	27	27	26	26	25
7 gal/m	17	34	51	68	85	102	119	136	153	170	186	202	218	234	250	265	280	295	309
spread	33	33	33	33	32	32	32	32	32	31	31	31	31	30	30	29	29	28	27
8 gal/m	18	36	54	72	90	108	126	144	162	180	198	215	232	249	266	282	298	314	330
spread	35	35	35	35	35	35	34	34	34	34	33	33	33	33	32	32	31	30	30
9 gal/m	19	38	57	76	95	114	133	152	171	190	209	227	245	263	281	298	315	332	348
spread	37	37	37	37	37	37	37	37	36	36	36	35	35	35	34	34	33	32	32
10 gal/m	20	40	60	80	100	120	140	160	180	200	220	239	258	277	296	314	332	350	367
spread	39	39	39	39	39	39	38	38	38	38	37	37	37	36	36	35	35	34	33
11 gal/m	21	42	63	84	105	126	147	168	189	210	231	251	271	291	311	330	349	368	386
spread	40	40	40	40	40	40	40	40	40	39	39	39	38	38	37	37	36	36	35
12 gal/m	22	44	66	88	110	132	154	176	198	220	241	262	283	304	324	344	364	383	402
spread	41	41	41	41	41	41	41	41	41	41	40	40	40	39	39	39	38	37	37
13 gal/m	23	46	69	92	115	138	161	184	207	230	252	274	296	318	339	360	381	401	421
spread	43	43	43	43	43	43	42	42	42	42	42	41	41	41	40	40	39	39	38
14 gal/m	24	48	72	96	120	144	168	192	216	239	262	285	308	330	352	374	395	416	437
spread	44	44	44	44	44	44	44	43	43	43	43	42	42	42	41	41	40	40	39
15 gal/m	25	50	75	100	125	150	175	199	223	247	271	295	318	341	364	386	408	430	451
spread	45	45	45	45	45	45	45	45	45	44	44	44	43	43	42	42	41	41	40
16 gal/m	26	52	78	104	130	155	180	205	230	255	280	305	324	353	377	400	423	445	467
spread	46	46	46	46	46	46	46	46	46	46	45	45	44	44	43	43	42	42	41
17 gal/m	26	52	78	104	130	156	182	208	234	260	286	311	336	361	385	409	433	456	479
spread	48	48	48	47	47	47	47	47	47	47	46	46	46	45	45	44	43	43	42
18 gal/m	27	54	81	108	135	162	189	216	243	269	295	321	347	372	397	422	446	470	493
spread	49	49	49	48	48	48	48	48	48	47	47	47	47	46	46	45	44	44	43
19 gal/m	28	56	84	112	140	168	196	224	251	278	305	332	358	384	410	435	460	484	508
spread	49	49	49	49	49	49	49	49	49	49	48	48	48	47	47	46	45	45	44
20 gal/m	29	58	87	116	145	173	201	229	257	285	313	340	367	394	420	446	472	497	522
spread	50	50	50	50	50	50	50	50	50	49	49	49	49	48	48	47	46	46	45

^{1/} Furnished by a pipe manufacturer. Spread is in units of feet.

623.1107 Mainline design

Mainlines for sprinkler systems vary from short portable feeder lines to intricate networks of buried mains and submains for large systems. The principal function of mainlines and submains is to convey the quantities of water required to all parts of the design area at the pressure required to operate all laterals under maximum flow conditions. The principal design problem is the selection of pipe sizes that will accomplish this function economically. For the purposes here, the line running from the water source to the design area, usually called the supply line, will be treated as part of the mainline. The design of mainlines or submains requires an analysis of the entire system to determine maximum requirements for capacity and pressure.

Friction-loss tables—The Hazen-Williams equation is the most commonly used formula for computing friction loss in aluminum mainline pipes. Table 11–29 gives friction loss J values in foot per 100 feet for portable aluminum irrigation pipe with typical mainline coupler losses assuming 30-foot pipe lengths.

Tables 11–30 and 11–31 give J values for SDR 41 PVC, IPS, and PIP (Class 100 lb/in²) thermoplastic pipe used in typical sprinkle irrigation system mainlines. The values in these tables were computed using equation 11–163 which gives slightly more accurate estimates than the Hazen-Williams equation with C = 150 for smooth plastic pipe. Table 11–32 gives J values based on the Hazen-Williams equation with C = 100 for welded steel pipe.

Other types of pipe material are often available and practical for sprinkler system mainlines. As a general rule, each manufacturer of pipe material has friction loss tables available for the particular class of pipe offered. It is impractical to include all such tables in this handbook, and the designer should obtain from the manufacturers appropriate friction-loss tables for pipe materials other than those included here. Alternately, the designer can calculate friction loss using the Hazen-Williams or Darcy-Weisbach equation using C or roughness values from tables 11–17 and 11–18 and inner diameter of the pipe. Inside diameters for a range of PVC pipe are listed in appendix C for a range of pressure ratings.

Table 11–29 Friction loss J values in ft/100 ft of portable aluminum mainline pipe with couplers connecting 30-ft lengths^{1/}

Flow rate (gpm)	5 in ^{2/} (0.050) (4.900)	6 in (0.058) (5.884)	8 in (0.072) (7.856)	10 in (0.091) (9.818)	12 in (0.091) (11.818)
100	0.28	0.12			
150	0.60	0.24			
200	1.01	0.42	0.10		
250	1.53	0.63	0.15		
300	2.15	0.88	0.22		
350	2.86	1.17	0.29		
400	3.66	1.50	0.37	0.12	
450	4.56	1.87	0.46	0.15	
500	5.54	2.27	0.56	0.19	
550	6.61	2.71	0.66	0.22	
600	7.76	3.18	0.78	0.26	
650	9.00	3.69	0.90	0.31	
700		4.24	1.04	0.35	0.14
750		4.81	1.18	0.40	0.16
800		5.42	1.33	0.45	0.18
850		6.07	1.49	0.50	0.20
900			1.65	0.56	0.23
950			1.83	0.62	0.25
1,000			2.01	0.68	0.27
1,100			2.39	0.81	0.33
1,200			2.81	0.95	0.39
1,300			3.26	1.10	0.45
1,400			3.74	1.26	0.51
1,500			4.25	1.44	0.58
1,600			4.79	1.62	0.66
1,800			5.96	2.01	0.82
2,000			7.25	2.45	0.99
2,200			8.64	2.92	1.18
2,400				3.43	1.39
2,600				3.98	1.61
2,800				4.56	1.85
3,000				5.18	2.10
3,500					2.80
4,000					3.58

¹ Based on the Hazen-Williams equation with C = 130; 20 ft pipe increases by 7%, and 40 ft pipe decreases by 3%

² Outside diameter; wall thickness and inside diameter in parentheses

Table 11-30 Friction-loss J values in ft/100 ft of SDR 41, IPS, PVC (Class 100 psi) thermoplastic pipe used for sprinkle irrigation mainlines, based on eq. 11-91

Flow rate (gpm)	4 in ¹ (4.280)	6 in (6.301)	8 in (8.205)	10 in (10.226)	12 in (12.128)
100	0.42				
150	0.86				
200	1.42				
250	2.09				
300	2.88	0.47			
350	3.77	0.62			
400	4.77	0.80			
450	5.86	0.99			
500		1.20	0.33		
550		1.42	0.40		
600		1.67	0.47		
650		1.93	0.54		
700		2.22	0.62	0.21	
750		2.51	0.70	0.24	
800		2.83	0.79	0.27	
850		3.16	0.88	0.30	
900		3.51	0.98	0.34	
950		3.87	1.08	0.37	
1,000		4.25	1.19	0.41	0.18
1,100		5.07	1.41	0.49	0.21
1,200		5.94	1.66	0.57	0.25
1,300			1.92	0.66	0.29
1,400			2.20	0.76	0.33
1,500			2.50	0.86	0.38
1,600			2.81	0.97	0.43
1,800			3.48	1.20	0.53
2,000			4.23	1.46	0.64
2,200			5.03	1.74	0.76
2,400			5.90	2.04	0.89
2,600				2.36	1.03
2,800				2.70	1.18
3,000				3.06	1.34
3,500				4.06	1.78
4,000				5.19	2.28

1 Nominal pipe diameter; inside diameter in parentheses

Table 11-31 Friction loss J values in ft/100 ft of SDR 41, PIP, PVC (Class 100) thermoplastic pipe used for sprinkle irrigation mainlines. Based on eq. 11-92

Flow rate (gpm)	6 in ¹ (5.840)	8 in (7.762)	10 in (9.702)	12 in (11.642)	15 in (14.554)
300	0.68				
350	0.90				
400	1.15				
450	1.42				
500	1.73	0.44			
550	2.06	0.52			
600	2.41	0.61			
650	2.79	0.71			
700	3.20	0.81	0.28		
800	4.08	1.03	0.35		
900	5.06	1.28	0.44		
1,000	6.14	1.55	0.53		
1,100		1.85	0.63	0.26	
1,200		2.17	0.74	0.31	
1,300		2.51	0.86	0.35	
1,400		2.88	0.98	0.41	
1,600		3.67	1.25	0.52	0.18
1,800		4.56	1.55	0.64	0.22
2,000		5.52	1.88	0.78	0.27
2,200		6.58	2.24	0.93	0.32
2,400			2.63	1.09	0.37
2,600			3.04	1.26	0.43
2,800			3.48	1.44	0.49
3,000			3.95	1.64	0.56
3,500				2.17	0.74
4,000				2.77	0.94
4,500				3.44	1.17
5,000				4.17	1.42
5,500					1.69
6,000					1.98
6,500					2.29
7,000					2.63

1 Nominal pipe diameter; inside diameters are in parentheses.

Table 11-32 Friction loss in ft/100 ft (D), in mainlines of 8-to-12-year-old welded steel pipe. Based on Hazen-Williams with C = 100.

Flow (gpm)	4-inch OD		5-inch OD		6-inch OD		7-inch OD		8-inch OD		10-inch OD	
	16 gage	12 gage	14 gage	12 gage								
40	0.26	0.27	0.29	0.09	0.09							
50	0.39	0.41	0.44	0.13	0.14							
60	0.55	0.57	0.62	0.19	0.20							
70	0.74	0.76	0.82	0.25	0.26							
80	0.94	0.98	1.06	0.32	0.34	0.13	0.13					
90	1.17	1.22	1.31	0.40	0.42	0.16	0.17					
100	1.42	1.48	1.60	0.48	0.51	0.19	0.20	0.09	0.09			
125	2.15	2.23	2.41	0.73	0.77	0.29	0.31	0.14	0.14			
150	3.02	3.13	3.38	1.02	1.08	0.41	0.43	0.19	0.20			
175	4.01	4.17	4.50	1.35	1.44	0.54	0.57	0.25	0.26	0.13	0.13	
200	5.14	5.34	5.76	1.73	1.84	0.70	0.73	0.32	0.34	0.17	0.17	
250	7.77	8.07	8.70	2.62	2.78	1.05	1.11	0.49	0.51	0.25	0.26	0.08
300	10.89	11.31	12.20	3.67	3.90	1.47	1.55	0.68	0.71	0.35	0.37	0.12
350	14.49	15.04	16.23	4.89	5.19	1.96	2.06	0.91	0.95	0.47	0.49	0.16
400	18.55	19.26	20.79	6.26	6.65	2.51	2.64	1.16	1.22	0.60	0.62	0.20
450	23.07	23.96	25.85	7.78	8.27	3.12	3.28	1.45	1.51	0.75	0.77	0.25
500	28.04	29.12	31.42	9.46	10.05	3.80	3.99	1.76	1.84	0.91	0.94	0.30
600				13.26	14.08	5.32	5.59	2.47	2.58	1.27	1.32	0.42
700				17.64	18.74	7.08	7.44	3.28	3.43	1.69	1.76	0.56
800				22.59	24.00	9.07	9.53	4.20	4.39	2.17	2.25	0.72
900						11.28	11.86	5.23	5.46	2.69	2.80	0.89
1000						13.71	14.41	6.36	6.63	3.27	3.40	1.08
1200						19.21	20.20	8.91	9.30	4.59	4.76	1.52
1400								11.85	12.37	6.10	6.34	2.02
1600								15.18	15.84	7.82	8.11	2.59
1800										9.72	10.09	3.22
2000										11.82	12.27	3.91
2500										17.86	18.54	5.92
3000												8.29

Notes: 12 gage is 0.1046 inches thick; 14 gage is 0.0747 inches thick; and, 16 gage is 0.0598 inches thick.

Most friction loss tables furnished by manufacturers are for new pipe unless otherwise stated. The designer should allow for aging of the pipe by adding a percentage of the loss consistent with the type of material and the average life of the pipe.

(a) General design procedure

The loss in pressure caused by friction is the primary consideration in the design of any pipe system. The basic problems vary depending on the source of pressure. When the pressure required for sprinkler system operation is supplied by pumping, the problem is one of selecting mainline pipe sizes and pipe materials that will result in a reasonable balance between annual pumping costs and the capitalized cost of the pipe. The ultimate objective is to arrive at a design that results in the lowest annual water application cost.

Normal procedure is to assume, within a reasonable range, several values of allowable head loss due to friction in mainlines and submains and to compute the pipe size or sizes for each assumed value. The pipe sizes thus obtained are then checked for power economy and the most economical sizes are selected. Experience shows that head loss values assumed over a range of 10 to 40 feet (3.05 to 12.19 m), as in the first step in this procedure, will prove adequate.

If gravity pressure (pressure gained by elevation differences) is used, one of two problems may arise. When elevation differences are scarcely enough to provide adequate pressure for operation of the system, the problem becomes one of conservation of energy demanding larger than normal pipe sizes to reduce friction losses and to avoid booster pumping where possible. When elevation differences considerably exceed those required to provide normal operating pressure; the problem becomes one of reducing pressure gains, thus requiring small pipe sizes to increase friction losses. On steep slopes, this procedure is required to protect the mainline and other equipment in the system.

In addition to pressure loss considerations, the velocity of flow in mainlines should be restricted to eliminate possible water hammer damage. This is particularly important in PVC and other plastic pipelines that have relatively low pressure ratings. In PVC pipe design, mainline velocities should be limited to about

5.0 feet per second (1.5 m). With SDR-41 PVC pipe, the surge pressure is approximately equal to 12.4 pounds per square inch (85 kPa) for each 1.0 foot per second (0.305 m/s) velocity change. Appendix C describes a procedure for calculating pressure ratings of pipe, given SDR, thickness, and type of material.

(b) Design for a single lateral

When only one lateral is moved along one or both sides of a mainline, selecting the mainline pipe size is relatively simple. The pipe size may be selected directly from tables or from appropriate formulas that will result in a friction loss not exceeding the allowable limit when the lateral is operating from the distal end of the mainline.

If two laterals are being moved along a mainline, but are not rotated in a split-line operation, the problem is the same as if a single lateral were being used. The size of pipe selected will be that which will result in a friction loss within allowable limits when both laterals are discharging from the distal end of the main.

(c) Design for a split-line layout

The split-line layout consists of two or more laterals rotated around the mainline or submains. Its purpose is twofold:

- to equalize the load at the pump regardless of lateral position
- to minimize the haul back of lateral pipe to the beginning point

Figure 11-43 uses a split-line layout to illustrate the problem of mainline design. In this layout, one lateral is moved up one side of the mainline while the other lateral is moved down the other side. It is apparent that at times the full quantity of water (Q) will have to be conveyed from A to B. At such times there will be no flow beyond B. From B to C, the flow will never exceed $Q/2$, and when one lateral is operating at C, requiring a flow of $Q/2$ at that point, the other lateral will be at A. In this case the flow for the entire mainline length will be $Q/2$.

For any given total head at the pump, the smallest pipe sizes will be the ones that result in equal values for H_{f1} and H_{f2} plus E_2 . Note that the elevation difference between B and C (E_2) in figure 11-44 is positive for uphill and negative for downhill lines. After pipe sizes have been computed for any reasonable value for head loss, adjustments can be made to balance annual pumping costs and capitalized pipe costs. For mainlines fed from elevation difference pressure systems, the available head is fixed, and the smallest pipe sizes that will deliver the required flow to the laterals should be used.

A simple procedure to follow in determining minimum pipe sizes for a given limit of head loss:

Step 1: Find the pipe size from the appropriate table that will carry the flow in the first length of main (L_1) with a friction loss equal to or just larger than allowed.

Step 2: If the friction loss for length of pipe L_1 using the selected pipe size exceeds the H_{f1} limit, find the friction loss in the next larger size pipe.

Step 3: Determine the proportionate lengths for L_1 for the two pipe sizes as:

$$h_{r1} = XJ_2 + (L_1 - X)J_1 \quad (\text{eq. 11-93})$$

where:

- H_{f1} = limit of friction loss in a length of pipe, ft
- X = length of the smaller pipe, ft/100 ft
- J_2 = friction loss gradient in the smaller pipe, ft/100 ft
- $(L_1 - X)$ = length of the larger pipe, ft/100 ft
- J_1 = friction loss gradient in the larger pipe, ft/100 ft

Step 4: Solving equation 11-93 for X gives:

$$X = \frac{H_{f1} - J_1 L_1}{J_2 - J_1} \quad (\text{eq. 11-94})$$

Step 5: Determine the pipe size requirements for length L_2 by:

$$H_{f2} = J_1 L_{d1} + J_2 L_{d2} + J_3 (L_2 - Y) + J_4 Y \quad (\text{eq. 11-95})$$

where:

- H_{f2} = limit of friction loss in entire mainline, ft
- L_{d1} = length of pipe of diameter D_1 , ft/100 ft
- L_{d2} = length of pipe of diameter D_2 , ft/100 ft
- $(L_2 - Y)$ = length of pipe diameter D_3 , ft/100 ft
- Y = length of pipe of diameter D_4 ft/100 ft
- J_1, J_2, J_3, J_4 = friction loss gradients ft/100 ft, in pipe diameters, $D_1, D_2, D_3,$ and D_4 , respectively

Figure 11-43 Design of mainline running uphill with twin laterals (shown at position B), split-line operation

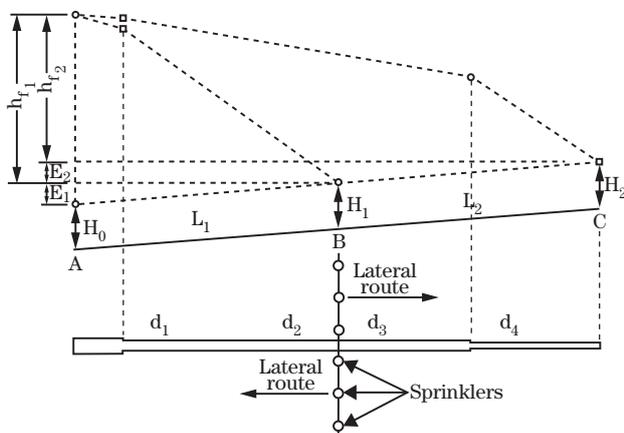
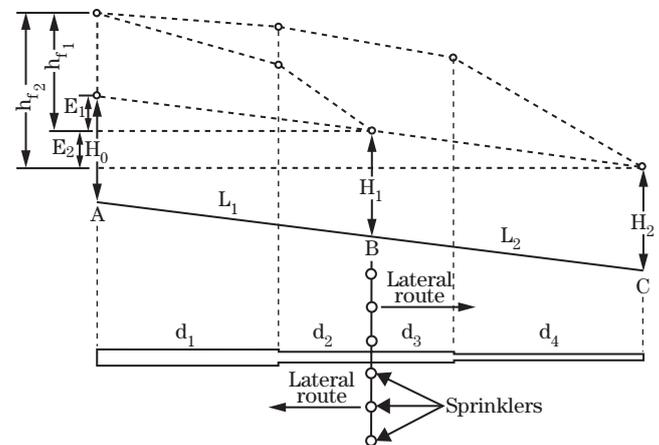


Figure 11-44 Design of mainline running downhill with twin laterals (shown at position B), split-line operation



Solving equation 11-166 for Y gives:

$$Y = \frac{H_{f2} - J_1 L_{d1} - J_2 L_{d2} - J_3 L_2}{J_4 - J_3} \quad (\text{eq. 11-96})$$

Sample calculation 11-10 illustrates the problem of mainline design when two laterals are operated in a split-line manner.

Sample calculation 11-10—Uphill mainline with twin lateral split-line operation.

Given:

Refer to figure 11-43

- Q, system capacity: 500 gallons per minute
- Length of supply line (water source to design area): 440 foot aluminum pipe (30 ft sections).
- L, length of mainline (within design area): 1,200 foot aluminum pipe (30 ft sections)
- $L_1 = 600$ feet, $L_2 = 600$ feet
- $H_0 = H_1 = H_2 = 125$ feet (head required to operate laterals)
- $E_1 = E_2 = 7.0$ feet (elevation difference in mainline assuming uniform slope).
- Total allowable head loss due to friction: 33.0 feet

Find:

- The smallest pipe sizes for both supply line and mainline that will limit friction head to 33.0 feet

Calculations:

Assume 6 inch diameter of supply line. From table 11-28, friction loss in 6 inch pipe for 500 gallons per minute equal 2.27 foot per 100 foot. Friction loss in the 440-foot supply line is 4.4 times 2.27 equals 10.0 feet. Then, H_{f2} is 33.0 minus 10.0 equals 23.0 feet and H_{f1} equals H_{f2} plus E_2 equals 23.0 plus 7.0 equals 30.0 feet.

H_{f1} is greater than H_{f2} by E_2 because when both laterals are operating at position B, the pump is not operating against static head E_2 . Thus, advantage can be taken of this by increasing the allowable friction loss in section A-B.

When both laterals are operating from position B, Q equal 500 gallons per minute and L_1 equals 600 feet. The average loss through length L_1 is H_{f1} divided $L_1/100$ equals $30.0/6$ equals 5.0 foot per 100 foot. From table 11-26, 5 and 6 inch pipe are indicated for D_2 , friction loss in 5 inch pipe, J_2 equals 5.54 feet per 100 foot and for D_1 , friction loss in 6 in pipe, J_1 equals 2.27 feet per 100 foot. Let X be the length of D_2 , then 600 minus X equals length of D_1 and by equation 11-94:

$$X = 100 \left[\frac{30.0 - 2.27 \left(\frac{600}{100} \right)}{5.54 - 2.27} \right] = 500 \text{ ft}$$

Use 500 feet of 5 inch pipe and 600 minus 500 equals 100 feet of 6 inch pipe. When one lateral is operating from position A and the other is operating from position C, Q equals 250 gallons per minute. The average loss through length L_2 equals H_{f2} divided by $(L_2/100)$ is $23.00/6$ equals 3.83 feet per 100 feet. From table 11-28, 4 and 5 inch pipe sizes are indicated. For D_4 , friction loss in 4 inch pipe, J_4 equals 4.66 feet per 100 feet; for D_3 and D_2 , friction loss in 5 inch pipe, J_3 equals J_2 equals 1.53 feet per 100 feet; and for D_1 , friction loss in 6 inch pipe, J_1 equals 0.63 feet per 100 feet. Let Y equal length of D_4 , then 600 minus Y equals length of D_3 pipe, and by equation 11-96:

$$Y = 100 \left[\frac{23.0 - 0.63 \left(\frac{100}{100} \right) - 1.53 \left(\frac{500}{100} \right)}{(4.66 - 1.53)} \right] = 177 \text{ ft}$$

Use 180 feet of 4 inch pipe, 600 minus 180 equals 420 feet of 5 inch pipe in L_2 . Thus, the mainline will consist of:

- 100 feet of 6 inch pipe
- 500 plus 420 equals 920 feet of 5 inch pipe
- 180 feet of 4 inch pipe

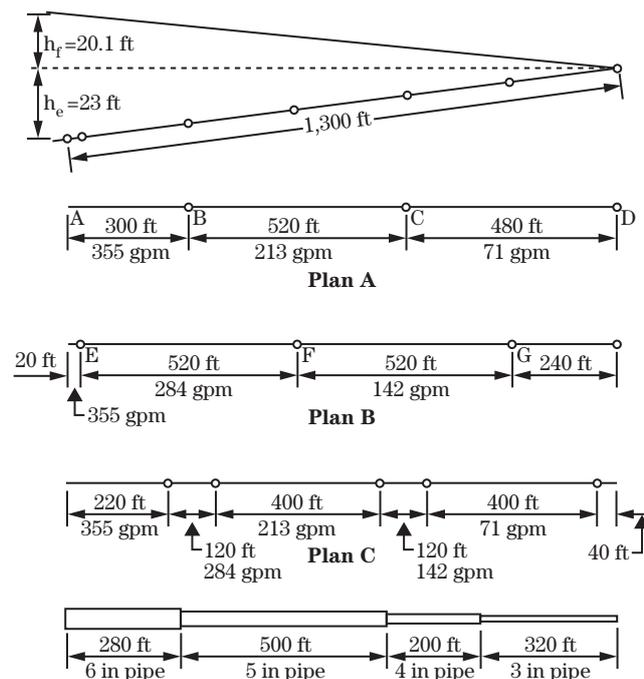
Similar calculations should be made for different assumed values of allowable friction head loss (h_f) to determine the most economical pipe sizes.

(d) Design with multiple laterals in rotation

If more than two laterals are operated and the flow in the mainline is split, with part of the first lateral taken out and the rest continuing in the mainline to serve other laterals, the design problem becomes more complex (fig. 11-45).

There are no simple equations that can be used to determine the minimum pipe sizes. However, approximations can be made by inspection and trial-and-error calculations. As a starting point, assume that the total allowable friction loss should be distributed in a straight line for flows reaching the far end of the main. The allowable loss for each reach of main will then be proportional to the length of the reach.

Figure 11-45 Design of an uphill mainline with five 71-gpm laterals, split-line operation assuming the allowable friction head loss is 20.1 ft, and an elevation difference of 23 ft



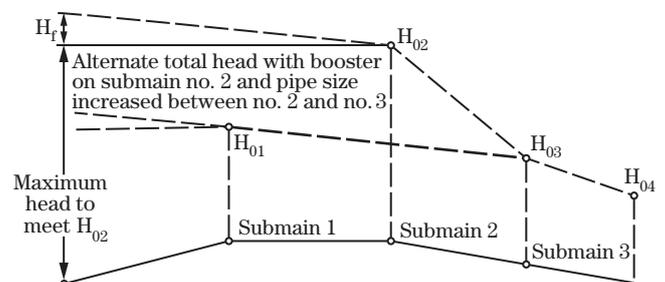
Using the method and formulas developed for the split-line design, minimum pipe sizes can be determined to fit the allowable head loss values for each reach of mainline. The resulting head loss will approximate a straight line and will coincide with the straight line at each control point as shown on the profile in figure 11-45.

The mainline designed will satisfy the requirements for operation with one lateral at the far end of the mainline. It must then be checked to see that it will satisfy the requirements for operation with laterals in other positions on the line. If the design does not satisfy the requirements for all operating conditions, it will have to be adjusted. After completing a design satisfactory for a given total allowable friction head loss, similar designs for other values of head loss can be used in balancing pipe and power costs.

(e) Main and submain layout

If several submains are used to operate laterals, the design of the mainline system is a series of individual problems where the maximum operating head requirements for each submain must be computed. The solution for minimum pipe sizes consistent with allowable head loss is similar to the mainline-design problem in sample calculation 11-10. Figure 11-46 illustrates how to determine the maximum head requirements at the pump on the basis of the maximum requirements for submain 2. In this case, if the submain serves a small part of the total area, a booster pump might be used, thus reducing the requirements at the main pump as shown by the alternate line.

Figure 11-46 Maximum operating conditions with submains



(f) Water hammer analysis

Water hammer is a type of severe hydraulic transient phenomenon in a pressurized conduit, such as a pipe, that can cause significant damage and should be considered in most irrigation system designs, as well as in operations. Hydraulic transients in pressurized pipes may be referred to as surges or water hammer, whereby surges are associated with relatively low pressure fluctuations compared to those of water hammer. Transients occur in pipelines due to many actions, such as:

- starting and stopping of pumps
- changes in valve openings
- operation of pressure relief valves
- filling and emptying of pipelines
- sudden movement of air pockets

When water hammer occurs, high-speed pressure waves move along the length of the pipeline, and by the time it is realized, it is usually too late to take preventive action. Water hammer wave speeds in pipelines can be up to 5,000 kilometers per hour, or more, in some cases. Damage due to water hammer can result from high-pressure waves that might burst a pipe or break a valve, for example. Damage can also occur due to low-pressure waves, where the pipe can suddenly collapse, even if it is made of a strong material, such as steel. The magnitude of the pressures due to water hammer depends on the velocity change, resulting wave speed, and geometry of the pipe.

The velocity change can be up to the velocity in the pipeline when a valve is suddenly slammed shut, that is, ΔV equals V_0 minus 0, where V_0 is the flow velocity in the pipeline before the valve is shut. The higher the velocity in the pipeline before water hammer occurs, the worse the potential problems will be. This is why irrigation system designers usually limit pipe velocities to about 7 feet per second (1.5 m/s). Water hammer issues can be lessened by adequate system design, but to avoid problems altogether requires operational consideration. A system should be designed that is not susceptible to water hammer and also provide operational guidelines to avoid water-hammer damage.

Water hammer is usually a concern in supply (conveyance) pipelines and in mainlines, so it should be

afforded at least a cursory analysis. Water hammer is not a concern in irrigation laterals because those pipes have multiple outlets (sprinklers or emitters) open to the atmosphere along their length. The outlets act as pressure relief valves when a pressure wave moves through the lateral pipe rapidly dampening the wave amplitude. Mainlines with multiple open outlets (multiple operating laterals), are not as susceptible to water hammer as supply lines, because in this case they behave (hydraulically) a little more like laterals.

(i) Acoustic wave speed

In most hydraulic calculations, the error associated with an assumption of incompressibility is negligible, but this is not the case when analyzing water hammer. The wave speed in a pipeline can be calculated based on:

$$a \approx \frac{\sqrt{K/\rho}}{\sqrt{1 + \left(\frac{K}{E}\right)\left(\frac{D}{t}\right)}} \approx \underbrace{\sqrt{K/\rho}}_{\text{when there is some air}} \quad (\text{eq. 11-97})$$

where:

- a = wave speed
- E = modulus of elasticity of the pipe material, lb/ft³ or kg/m³
- K = bulk modulus of water, lb/in² or MPa
- D = pipe inside diameter, ft or m
- t = pipe wall thickness, ft or m
- ρ = density of water, 62.4 lb/ft³ or 1,000 kg/m³

The far right-hand side of equation 11-97 is an acceptable approximation of the wave speed because all irrigation pipelines have some air mixed with the water. The bulk modulus accounts for the compressibility of water. Bulk modulus and compressibility are inversely proportional. The bulk modulus for water is about 294(10)³ pounds per square inch (2,025 MPa) for water at temperatures normally found in irrigation pipes.

$$a \approx \sqrt{K/\rho} \approx 4,600 \text{ ft/s (1,400 m/s)} \quad (\text{eq. 11-98})$$

The modulus of elasticity depends on the pipe material and tends to decrease with increasing temperature. According to equation 11-98, pipes of small diameter, thick walls, and rigid material (high modulus of elasticity) will result in the highest speeds. For example, wave speeds are relatively high in small diameter, thick steel pipes, which provide for little attenuation

of the wave amplitude. Large-diameter, flexible pipes cause relatively rapid pressure wave attenuation and are less susceptible to water hammer damage. The amount of air in the water also affects wave speed and the attenuation of pressure surges during a hydraulic transient. The presence of air tends to lessen the damaging effects of water hammer.

(ii) Maximum pressure change

The sudden increase in pressure head at the upstream side of a valve that is suddenly slammed shut can be estimated as:

$$\Delta H = -\frac{a\Delta V}{g} \left(1 + \frac{V_o}{a} \right) \quad (\text{eq. 11-99})$$

where:

ΔH = maximum change in head, ft or m

V_o = initial average velocity at a pipe cross section, ft/s or m/s

g = ratio of weight to mass, 9.81 m/s² or 32.2 ft/s²

The wave speed is usually much higher than the initial velocity, so equation 11-99 can often be approximated as:

$$\Delta H \approx -\frac{a\Delta V}{g} \quad (\text{eq. 11-100})$$

without the introduction of significant error.

When a valve is shut completely, ΔV is equal to the initial velocity, V_o . The maximum change in head, ΔH , is directly proportional to V_o in this case. For example, double V_o and the change in head, ΔH , is double when water hammer occurs. This is why sprinkler pipeline velocities should be limited to reasonable values (5–7 ft/s, or 1.5–2.0 m/s). Note also that ΔH is also directly proportional to the wave speed, a .

The high-pressure wave can cause the pipe to burst, or accessories (valves or vents) to blow off the pipe. The initial high-pressure wave lasts for about $2L/a$, then becomes a low-pressure wave for the next $2L/a$. After that ($4L/a$), the cycle repeats. The low-pressure wave can result in less-than-atmospheric pressure in the pipeline, possibly causing sections of it to suddenly collapse. Pipes can collapse due to the low-pressure

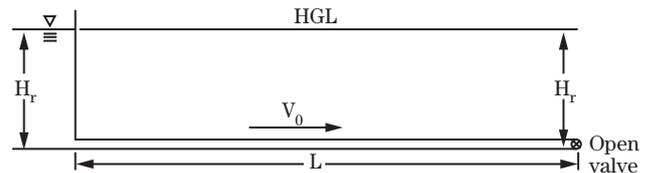
wave even when they are able to withstand the initial high-pressure wave.

(iii) Water hammer example

As a very simple example of water hammer, a level pipeline of length, L , is connected to a reservoir with a constant head, H_r . Initially, steady flow prevails with an open valve at the end of the pipeline and an average pipe cross section velocity of V_o . Note the hydraulic grade line (HGL), parallel to the pipeline (fig. 11-47).

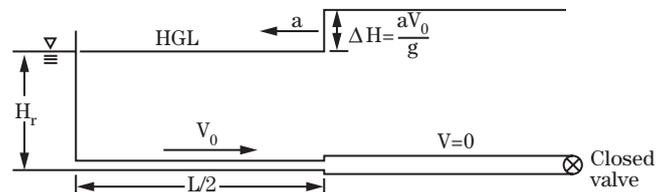
The valve is suddenly closed, causing unsteady flow and water hammer. First, a high pressure (aV_o/g) wave moves upstream from the valve at a velocity equal to “ a ,” arriving at the reservoir after a time equal to L/a . As the wave moves upstream, the flow rate in the pipeline goes to zero (fig. 11-48).

Figure 11-47 Water hammer example ($t = 0$)



(1) Steady flow, open valve ($t=0$)

Figure 11-48 Water hammer example ($t = L/2a$)



(2) Valve suddenly closed, wave moves upstream ($t=L/2a$)

(iv) Avoiding water-hammer damage

These steps can be taken to avoid or reduce the possibility of water-hammer damage in pipelines:

Step 1: Fill and empty pipelines slowly.

Step 2: Do not suddenly open or close valves (specify slowly closing valves).

Step 3: Limit operational velocities to 7 feet per second (1.5 m/s).

Step 4: Attempt to avoid suddenly starting or stopping a pump.

Step 5: Use spring-loaded check valves that close before flow reverses.

Step 6: Use manually operated valves that cannot close quickly.

Step 7: Use correctly sized and placed pressure-relief valves.

Step 8: Use correctly sized and placed vacuum-relief valves.

Step 9: Use some kind of surge protection device.

Step 10: Use a stronger pipe material.

Step 11: Use pipe with thicker walls.

Note that some of the steps can be taken during system design, but others depend on operations. The system designer will not be able to eliminate the possibility of water hammer, but should provide operational recommendations as part of the design.

(v) Sample supply line water hammer problem

In this example, these parameters are given: a 1,800-foot-long PVC 1120 supply pipe has a standard dimension ratio (SDR = outside diameter/wall thickness) of 64; the maximum operational pressure is 60 pounds per square inch, and the velocity is 7 feet per second. If a valve at the downstream end of the pipe is suddenly closed, will the pipe be in danger of failing?

The solution to the problem is according to the procedures and equations defined. If the valve closes within $2L/a$ equals $2(1,800 \text{ feet})/4,600 \text{ feet per second}$ which equals 0.78 seconds, it is essentially an instantaneous closure. Depending on the valve type, it may be impossible to close the valve so quickly (some valves are geared down to avoid fast operations), and this will

help avoid water hammer damage. From ASABE Standard S376.1, which deals with thermoplastic irrigation pipelines, the pressure rating for PVC 1120 with SDR equal to 64 is listed as 63 pounds per square inch, so our operational pressure of 60 is near the limit already, even without water hammer. This is not a good design.

Calculate the maximum change (eq. 11-100) in pressure as:

$$\begin{aligned}\Delta H &\approx -\frac{a\Delta V}{g} \\ &= \frac{(4,600 \text{ ft/s})(7 \text{ ft/s})}{32.2 \text{ ft/s}^2} \\ &= 1,000 \text{ ft} \left(433 \text{ lb/in}^2\right)\end{aligned}$$

The initial high-pressure wave moving upstream from the closed valve will be 60 plus 433 or 493 pounds per square inch, which is nearly eight times the pressure rating. The pipe may burst if the valve is suddenly closed, so it would be advisable to do one or more of these things:

- Use a larger pipe to reduce the operational velocity
- Specify a valve that cannot close very fast
- Select a pipe with a lower SDR

The third measure is needed in any case because the operational pressure is too close to the pipe pressure rating and does not allow for any surges or water hammer. Note that this is as simple as it gets for water hammer analysis, but it is much better than ignoring the possibility in the design.

The preceding is only an introduction to simple water hammer analysis. Some full-semester university courses are dedicated to the analysis of hydraulic transients, including water hammer, in pressurized pipelines. Also, there are a number of books, papers, and pamphlets dealing with water hammer analysis and the prevention of water hammer damage.

623.1108 Pipe sizing using life-cycle costs

The most economical size or combination of sizes of pipe in a mainline or submain is that which will result in a reasonable balance between the annual cost of owning the pipe and the annual pumping cost. The balance depends primarily on two factors: the seasonal hours of operation, and the cost of the power used. For example, in humid areas, a system may be operated for 500 hours per season or less, and power rates may be comparatively low. The annual cost of pumping to overcome friction losses is low and a reduction in mainline pipe sizes might be justifiable. In an area where full season operation is required and power costs are high, pumping against increased friction head is much more costly. In these cases, an increase in mainline pipe sizes is often required to achieve an economic balance.

To find the most economical life-cycle costs of a system, the designer must find the minimum sum of the fixed plus operating costs. To visualize this, think of selecting the diameter of a water supply line. If a small pipe is used, the fixed (materials and installation) cost will be low, but the annual operating cost of overcoming friction losses in the pipe will be large. As the pipe diameter is increased, the fixed cost will also increase, but the power costs will decrease. The optimum pipe size is the one for which the annualized fixed plus annual power costs are least.

The life-cycle cost analysis can be made on a present worth or on an annual basis. In either case the interest rate (i), the expected life of the item (n), and an estimate of the expected annual rate of escalation in energy costs (e) must be considered. The present worth of the escalating energy factor ($PW(e)$) and the equivalent annual cost of the escalating energy factor ($EAE(e)$) can be computed by these equations for e does not equal i :

$$PW(e) = \left[\frac{(1-e)^n - (1+i)^n}{(1+e) - (1+i)} \right] \left[\frac{1}{(1+i)^n} \right] \quad (\text{eq. 11-101})$$

where:

- e = decimal equivalent annual rate of energy escalation
- $PW(e)$ = present worth factor of escalating energy costs, taking into account the time value of money over the life cycle

$$EAE(e) = \left[\frac{(1-e)^n - (1+i)^n}{(1+e) - (1+i)} \right] \left[\frac{i}{(1+i)^n - 1} \right] \quad (\text{eq. 11-102})$$

where:

- $EAE(e)$ = equivalent annual cost factor of escalating energy, taking into account the time value of money over the life cycle

The standard capital recovery factor is computed by:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (\text{eq. 11-103})$$

where:

- CRF = uniform series annual payment (capital recovery factor), which takes into account the time value of money and depreciation over the life cycle
- i = time value of unsecured money to the developer or the decimal equivalent annual interest rate
- n = number of years in the life cycle

When considering life-cycle costs, the time value of unsecured money to the developer should be used as the appropriate interest rate (i). This is normally higher than bank interest rates because of the higher risks involved. Returns from unsecured agricultural developments should be about 10 percent higher than the interest rates on high grade, tax-free, long-term securities unless some special tax benefits are involved.

Table 11-33 gives the necessary factors for either a present worth or an annual life-cycle cost analysis. The table gives factors for 9 and 13.5 percent annual escalation in energy costs for 10 to 25 percent interest rates and for life cycles of 7 to 40 years. The value is the present worth [PW (0 percent)] factor of non-escalating energy, taking into account the time value of money over the life cycle.

The expected life of different mainline pipe materials is:

Portable aluminum	10 to 20 years
Coated welded steel	10 to 20 years
PVC plastic	20 to 40 years

However, because of obsolescence, life cycles of n equals 20 or less are frequently used for all pipes. The number of brake horsepower (BHP) hours per unit of fuel that can be expected from efficient, well-maintained power units is:

Diesel	15.0 BPH hours per U.S. gallon
Gasoline (water cooled)	10.5 BPH hours per U.S. gallon
Butane-propane	9.5 BPH hours per U.S. gallon
Natural gas	8.5 BPH hours per 100 cubic feet
Electric	1.20 BPH hours per kilowatthour at the meter

The factors presented in table 11–33 can be used with the present annual power costs, U , and the cost of the irrigation system, M , to estimate the:

- present worth of energy escalating at 9 percent per year is equal to U times PW (9 percent)
- equivalent annual cost (U') of energy escalating at 9 percent per year is U' equals U times EAE (9%)
- annual fixed cost of the irrigation system is M times CRF
- present worth of nonescalating energy is U times PW (0%)
- the annual cost of nonescalating energy is equal to U
- present worth of the irrigation system is equal to M

Although the selection of economical pipe sizes is an important engineering decision, it is often given insufficient attention, especially in relatively simple irrigation systems. Many designers use an arbitrary flow velocity or a unit friction loss to size pipe because they

consider the methods for selecting economic pipe size too time consuming, limited, or complex. The economic pipeline selection chart presented was developed to help remedy this situation. The chart can be constructed for a given set of economic parameters and used to select directly the most economical pipe sizes for nonlooping systems having a single pump station. The chart approach to economic design is particularly useful when technicians are employed to design a number of simple systems having the same economic parameters.

(a) Economic pipe selection chart

This example demonstrates how the chart is constructed:

Step 1: The necessary economic data must be obtained.

- For a 20 percent time value of money and expected life cycle of aluminum mainline pipe of 15 years from table 11–33, $CRF = 0.214$ and EAE (9 percent) = 1.485.

Nominal diameter (in)	Price/100 ft	Annual fixed cost/100 ft ($0.214 \times$ price/100 ft)
5	\$150	\$32.10
6	\$200	\$42.80
8	\$250	\$53.50
10	\$300	\$64.20
12	\$350	\$74.90

- Diesel fuel at \$1.05 per gallon gives \$0.07 per BHP-hr
- There are an estimated 1,000 hours of operation per year
- Hazen-Williams resistance coefficient for portable aluminum mainline pipe is $C = 130$

Step 2: Determine the yearly fixed cost difference between adjacent pipe sizes and enter this in table 11–34.

Step 3: Determine the equivalent annual cost per water horsepower (WHP) hour of energy escalating at 9 percent per year as follows, assuming a 75 percent pump efficiency:

Table 11-33 Present worth and annual economic factors for assumed escalation in energy costs of 9 and 13.6% and various interest rates and life cycles

Factor	Interest (i)	Life cycle (n) years					
	%	7	10	15	20	30	40
PW (13.5%)	10	7.004	10.509	17.135	24.884	44.547	71.442
EAE (13.5%)		1.439	1.710	2.253	2.923	4.726	7.306
PW (9%)		6.193	8.728	12.802	16.694	23.965	30.601
EAE (9%)		1.272	1.420	1.683	1.961	2.542	3.129
CRF		0.205	0.163	0.131	0.117	0.106	0.102
PW (0%)		4.868	6.145	7.606	8.514	9.427	9.779
PW (13.5%)	15	5.854	8.203	11.917	15.396	21.704	27.236
EAE (13.5%)		1.407	1.634	2.038	2.460	3.306	4.101
PW (9%)		5.213	6.914	9.206	10.959	13.327	14.712
EAE (9%)		1.253	1.378	1.574	1.751	2.030	2.215
CRF		0.240	0.199	0.171	0.160	0.152	0.151
PW (0%)		4.160	5.019	5.847	6.259	6.566	6.642
PW (13.5%)	20	4.967	6.569	8.712	10.334	12.490	13.726
EAE (13.5%)		1.378	1.567	1.863	2.122	2.509	2.747
PW (9%)		4.453	5.615	6.942	7.762	8.583	8.897
EAE (9%)		1.235	1.339	1.485	1.594	1.724	1.781
CRF		0.277	0.239	0.214	0.205	0.201	0.200
PW (0%)		3.605	4.192	4.675	4.870	4.979	4.997
PW (13.5%)	25	4.271	5.383	6.651	7.434	8.215	8.513
EAE (13.5%)		1.351	1.508	1.723	1.880	2.056	2.128
PW (9%)		3.854	4.661	5.449	5.846	6.147	6.224
EAE (9%)		1.219	1.305	1.412	1.479	1.539	1.556
CRF		0.316	0.280	0.259	0.253	0.250	0.250
PW (0%)		3.161	3.571	3.859	3.954	3.995	3.999

— The present annual cost of energy is:

$$U = \frac{(1,000 \text{ hr/yr})(\$0.07 \text{ per BHP-hr})}{0.75 \text{ WHP/BHP}} = \$93.33 \text{ per WHP-yr} \quad (\text{eq. 11-104})$$

— The equivalent annual cost of energy at EAE (9 percent) = 1.485 is:

$$U' = 1.485(\$93.33/\text{WHP-yr}) = \$138.60/\text{WHP-yr} \quad (\text{eq. 11-105})$$

Step 4: The WHP savings needed to offset the annual fixed cost difference between adjacent pipe sizes are equal to the fixed cost difference divided by U' . The required values are presented in table 11-34 and an example calculation for 6 to 8 in pipe is:

$$\text{WHP}(6-8) = \frac{\$10.70/100 \text{ ft-yr}}{\$138.60/\text{WPH-yr}} = 0.077 \text{ WHP/100 ft} \quad (\text{eq. 11-106})$$

Step 5: The head loss difference (ΔJ) between adjacent pipe sizes needed to obtain the WHP is presented in table 11-34 and an example calculation for an assumed system flow rate, $Q = 1,000$ gpm, is:

$$\Delta J(6-8) = \frac{0.077 \text{ WHP/100 ft} \times 3,960}{1,000 \text{ gal/min}} = 0.31 \text{ ft/100 ft} \quad (\text{eq. 11-107})$$

Step 6: The flow rates (q) that would produce the required ΔJ between adjacent pipe sizes are shown in table 11-34. These flow rates can be determined by trial and error using J values from pipe friction loss calculators or tables. For example, to get $\Delta J(8-10) = 0.31$ foot per 100 feet at $q = 450$ gallons per minute from table 11-29:

$$\begin{aligned} J(8) &= 0.46 \text{ ft/100 ft} \\ J(10) &= 0.15 \text{ ft/100 ft} \\ \Delta J(8-10) &= 0.31 \text{ ft/100 ft} \end{aligned}$$

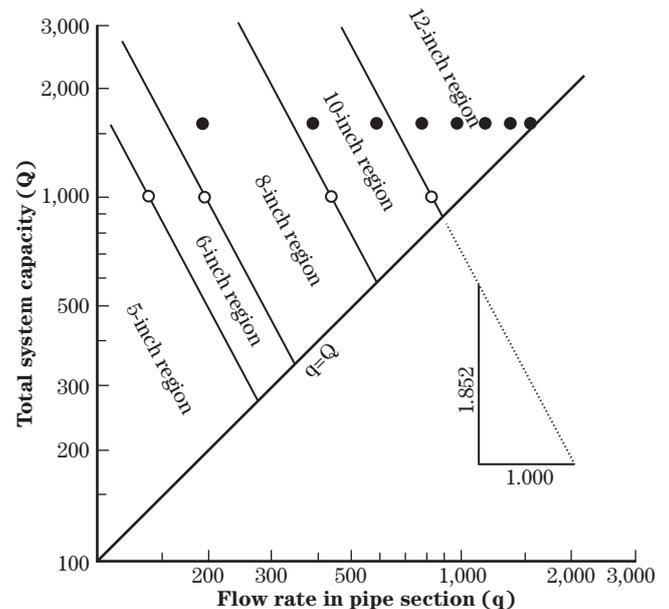
To obtain a J value directly, construct a log-log graph of flow versus head loss differences between adjacent pipe sizes.

Step 7: Plot the points representing the system flow used in step 5 ($Q = 1,000$ gpm) at the pipe flow rates determined in step 6, on log-log graph paper as in figure 11-53 (open circles).

Table 11-34 Sample data and procedure for locating economic pipe size regions on selection chart, $C = 130$, $\text{CRF} = 0.214$, $U' = \$138.60/\text{WHP-year}$, and $Q = 1,000$ gpm

Step	Item	Adjacent pipe sizes nominal diameters (in)			
		5-6	6-8	8-10	10-12
2	Yearly fixed-cost difference \$/100	10.70	10.70	10.70	10.70
4	Water horsepower (WHP)	0.077	0.077	0.077	0.077
5	ΔJ ft/100 ft	0.31	0.31	0.31	0.31
6	Q gpm	140	200	450	850

Figure 11-53 Economic pipe selection chart for portable aluminum pipe with $C=130$, $\text{CRF}=0.214$, and $U' = \$138.60/\text{WHP year}$.



Step 8: Draw lines through each of the points plotted in step 7. These lines should have a slope equal to the exponent for Q or V in the pipe friction equation used. In this case use a slope of -1.85 . These lines represent the set of pipe flow rates (q) that gives the same fixed plus operating cost with adjacent sizes of pipe for different system flow rates (Q). Each pair of lines defines the region in which the size common to both lines is the most economical pipe to use.

Figure 11-53 shows the complete economic pipe size selection chart, plotted with logarithmic scales. The circles on the graph at a system flow rate Q equals 1,000 gallons per minute represent the pipeline flow rates (q) found in step 6 and presented in the last line of table 11-34. Changing any of the economic factors will shift the lines in the chart shown in figure 11-53. Developing a new chart for a new set of economic factors is simple when the spacing between lines remains constant, such as for a new U' (CRF) or when the pipe prices all change proportionally. Construction of steps 1 through 6 needs to be repeated for only one pair of adjacent pipe sizes at a single Q . This Q versus q point locates the new position for the lines in question and all other lines can be shifted an equal distance and drawn parallel to their original positions. In practice, it is not always necessary to construct the chart as shown in figure 11-53 because the calculations can be easily redone, as necessary, for different system capacities, Q .

(b) Economical mainline design

The negative sloping lines on figure 11-53 represent all the possible Q versus q values for each of the adjacent pairs of pipe sizes that will give the same sum of fixed plus operational costs. The zone between adjacent lines defines the region of Q versus q values when the pipe size that is common to both lines is the most economical selection. The chart is universally applicable for the most economical pipe size selections in any sized series system for the economic boundary conditions assumed. Two example systems are given to demonstrate the use of the chart:

Sample calculation 11-11—Use of economic pipe selection chart.

Given:

- For system layouts refer to figure 11-54.
- For economic pipe selection chart refer to figure 11-53.

Find:

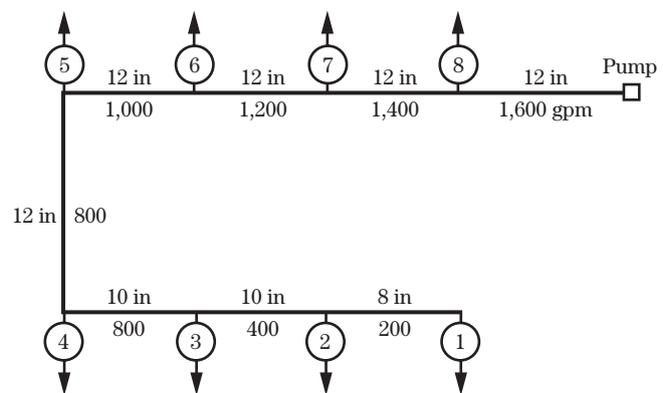
- The most economical pipe sizes for systems (a) and (b), using portable aluminum pipe with the economic parameters considered in developing figure 11-53.

Calculations:

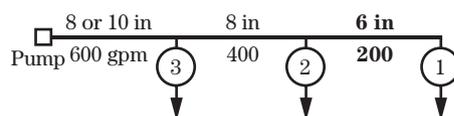
System (A)

A pipe system that is to deliver 200 gallons per minute to each of eight different hydrants as shown in figure 11-54(A). The pump discharge is Q equals 8 times 200 gallons per minute is 1,600 gallons per minute, which is also the flow rate in the first section of pipe. The flow rate in the pipe will decrease by 200 gallons per

Figure 11-54 Flow systems with pipe sizes selected from the economic pipe size selection chart shown in figure 11-38



A. 1,600-gpm system with eight 200-gpm outlets



B. 600-gpm system with three 200-gpm outlets

minute at each outlet, with the final section carrying only 200 gallons per minute. The solid dots plotted on figure 11–53 are the Q versus q points representing this system. The pipe size region where each point falls is the pipe size to use for that section. The pipe sizes and flow rates for each reach are shown on figure 11–54(A). Since 12 inch pipe is the largest size considered in setting up the chart, the 12 inch region is exaggerated. If 14 inch pipe had been considered, perhaps some of the flows would have fallen above the 12 inch region.

System (B)

Assume a system has three 200 gallons per minute outlets, so that Q equals 600 gallons per minute (38 l/s) as shown in figure 11–39(b). The flow rates and recommended pipe sizes for each reach are shown on figure 11–54(B). If q is 200 gallons per minute (13 l/s) in the smaller system, 6 inch pipe should be installed, and in the larger system 8 inch pipe is recommended. If q is 600 gallons per minute, the larger system should have 10 inch pipe; the smaller only requires 8 inch pipe. This is because the added power cost to offset friction for a given q increases with Q .

The preceding examples and solutions shown in figure 11–54(B) are applicable for the main branch of the pipeline system when that branch is uphill, level, or moderately downhill from the pump. Many practical system layouts involve boundary conditions that differ from those given. For these situations the trial-and-error solutions for determining the most economical pipe sizes become even more time consuming, and the chart method requires some adjustment. Some such instances are: subbranch, parallel, or branched series pipelines; and pipelines running down steep slopes where the pressure gain due to elevation differences is greater than pressure loss due to friction with the pipe sizes selected by the chart method. Although in these cases the pipe sizes selected using the chart method in figure 11–53 must be adjusted downward, the adjustments are direct and yield the most economical pipe sizes for the new conditions. Sample calculation 11–12 demonstrates the use of these adjustments.

(c) Pipe diameter selection

Various designers may use different methods to size sprinkler system mainlines. The recommended technique is:

- *Economic method*: Selection of the least amount of fixed plus power costs as described in the section on life-cycle costs.
- *Unit head-loss method*: Setting a limit on the head loss per unit length, for example 2.0 feet per 100 feet.
- *Velocity method*: Setting a limit on the velocity.
- *Percent head loss method*: Setting a limit on the friction head loss in the mainline network, This can be done by allowing mainline pressure to vary by 10 to 20 percent of the desired average sprinkler operating pressure.

For the economic method, construct an economic pipe selection chart such as figure 11–53 or by merely comparing the fixed plus power costs of the most reasonable combination of pipe sizes. In any case, the velocity method should be used to ensure that V is less than 7 feet per second (2 m/s) to avoid water-hammer problems. In sample calculation 11–12 all of the selection methods are compared. This sample problem demonstrates the value of the economic chart method.

Sample calculation 11–12—Comparison of pipe-size selection methods.

Given:

- For system layout, refer to figure 11–55.
- Aluminum pipe and cost data used in previous section on life-cycle costs.

Find:

Pipe size selection based on:

- economic method
- head loss gradient of 2 feet per 100 feet or less
- maximum flow velocity of 7 feet per second or less
- mainline friction head loss of 15 percent of P_a is 50 pounds per square inch or 17.3 feet.

Calculations:

Selection by head-loss gradient—Select pipe sizes from table 11–35 so that the head-loss gradient (J) will be less than, but as close to 2 feet per 100 feet as possible for each reach of pipe. This results in a total head lost of 21.4 feet due to pipe friction.

Selection by velocity method—Select pipe sizes so that the velocity of flow will be less than but as close to 7.0 feet per second as possible for each section of pipe. This results in a total head loss of 39.7 feet due to pipe friction as shown in table 11–35. Velocity limitations for each size of pipe were computed by:

$$V = 0.4085 \frac{Q}{D^2} \quad (\text{eq. 11-108})$$

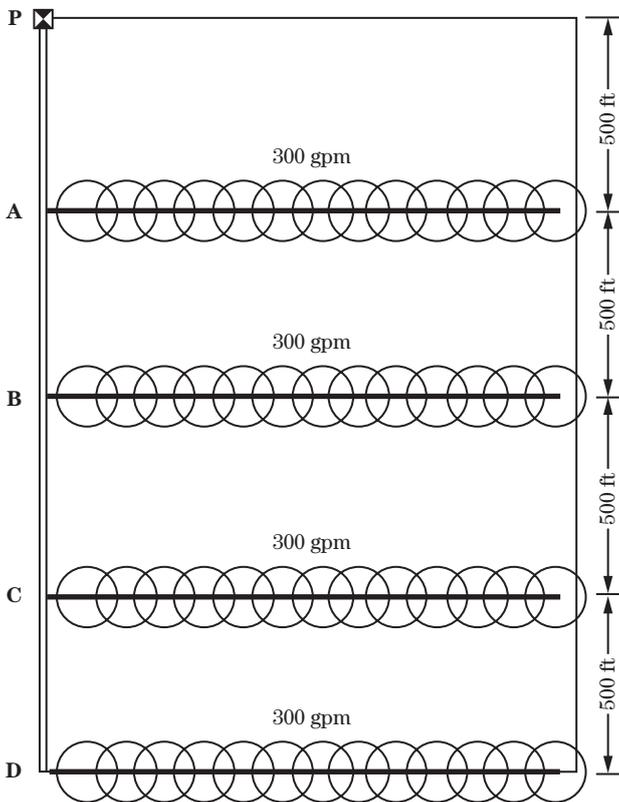
where:

- V = velocity of flow in pipe, ft/s (m/s)
- Q = flow rate, gpm (l/min)
- D = inside diameter of pipe, in (mm)

Selection by percent head-loss method—Select pipe sizes so that the total head loss does not exceed 17.3 feet. For a beginning point, let the maximum unit head loss be 2.0 pounds per square inch per 100 feet. This will be the same as for the head-loss gradient method in which the total head loss is 21.4 feet. Therefore, some pipe diameters must be increased to reduce the total head loss. First, the pipe size in the section having the greatest unit head loss should be increased; in this case the diameter in section A–B is increased from 8 to 10 inch pipe. If this had not decreased the total head loss sufficiently, the pipe diameter in the section with the next highest unit head should have been increased and so on. The results of this procedure give a total head loss of 15.9 feet, as shown in table 11–32.

Selection by the economic method—Select pipe sizes that will require the least amount of pumping (fuel) plus annual fixed (investment) costs as described earlier under life-cycle costs. In this simple example, the set of practical pipe diameter combinations that should be considered are:

Figure 11–55 System layout for sample calculation 11–12



Section	Flow (gpm)	Diameters (in)
P–A	1,200	12, 10, or 8
A–B	920	12, 10, or 8
B–C	600	10, 8, or 6
C–D	300	8, 6, or 5

This results in 28 iterations if all combinations are considered in which an upstream pipe diameter is never smaller than that in a downstream section. The economic pipe selection method can be used to simplify the selection process (if the economic parameters had been different from this problem, a new chart would have been required). This chart gives a total head loss of 5.6 feet due to pipe friction, as shown in table 11–35.

It may be surprising that such large pipe diameters are called for by the economic method in this problem. The validity of the economic method can be tested by comparing the total annual costs of the different sets of pipes. To accomplish this, the total pipe cost should be multiplied by the CRF to obtain the annual fixed cost. The annual energy cost (CE') is equal to the total head loss (h_f) multiplied by the annual energy cost per unit of head loss. Thus, CE' can be computed by:

$$CE' = h_f \left(\frac{EAE U Q_s}{3,960} \right) \quad (\text{eq. 11-109})$$

where:

CE' = annual energy cost of head loss (\$)

h_f = total head loss due to pipe friction, ft

EAE = the equivalent annual cost factor of escalating energy

U = present annual cost of energy from equation 29 (\$/WHP-year)

Q_s = total system capacity, gpm

Table 11-35 Data for sample calculation 11-12 showing the total pipe friction head loss obtained by different pipe size selection methods

Pipe section	Flow (gpm)	Length (ft)	Diameter (in)	J (ft/100 ft)	Loss (ft)
Selection by economic method					
P-A	1,200	500	12	0.39	2.00
A-B	900	500	12	0.23	1.20
B-C	600	500	10	0.26	1.30
C-D	300	500	8	0.22	1.10
Total =					5.60
Selection by head-loss gradient					
P-A	1,200	500	10	0.95	4.8
A-B	900	500	8	1.65	8.3
B-C	600	500	8	0.78	3.9
C-D	300	500	6	0.88	4.4
Total =					21.4
Selection by velocity method					
P-A	1,200	500	10	0.95	4.8
A-B	900	500	8	1.65	8.3
B-C	600	500	6	3.18	15.9
C-D	300	500	5	2.15	10.8
Total =					39.8
Selection by percent head-loss method					
P-A	1,200	500	10	0.95	4.8
A-B	900	500	10	0.56	2.8
B-C	600	500	8	0.78	3.9
C-D	300	500	6	0.88	4.4
Total =					15.9

Table 11-36 shows a comparison of the total annual costs for the different pipe size combinations presented in table 11-36. From table 11-36 it is apparent that the economic selection method gives the lowest total annual cost.

An alternative to constructing and using an economic pipe selection chart is to test a unit length of each section of pipe separately. This is demonstrated in table 11-36 for section C-D in figure 11-55 in which the flow rate is only 300 gallons per minute. However, the total system capacity must be used in equation 11-109 to determine the annual cost of the head loss in section C-D. This is necessary since the extra pressure head needed to compensate for the friction loss in any section of pipe must be provided at the pumping plant to the total system flow of Q is 1,200 gallons per minute.

For systems with downhill or branching mainlines the pipe size selection is more complex. As a beginning point, pipes should be sized by the economic method. Then the pressure at each lateral inlet point should be computed to find the inlet point that requires the

Table 11-36 Comparison of total annual costs for different pipe-size combinations for section C-D of sample calculation 11-13

Method (or size for C-D)	Initial capital (\$)	Annual fixed cost ¹ (\$)	Total H (ft)	Annual energy ² (\$)	Annual total (\$)
Gradient	5,000	1,070	21.4	899	1,969
Velocity	4,500	963	39.7	1,667	2,630
Percent	5,250	1,124	15.9	668	1,792
Economic	6,250	1,338	5.6	235	1,573
	\$/100 ft	\$/100 ft	$h_f/100$ ft	\$/100 ft	\$/100 ft
(10-inch)	300	64	0.07	3	67
(8-inch)	250	54	0.22	9	63
(6-inch)	200	43	0.88	37	80
(5-inch)	150	32	2.15	90	122

1 CRF = 0.214 from table 11-33 for n = 15 years and i = 20 percent
 2 CE' = \$42 for each foot of head loss as computed by equation 11-32 in which $Q_s = 1,200$ gpm, $h_f = 1.0$ ft; U = \$93.33/WHP-year from equation 11-29 for 1,000 h/yr, \$0.07/BHP-hr, and 75-percent pump efficiency; and EAE = 1.486 from table 11-33 for n = 15 yr, i = 20%, and r = 9%

highest pump discharge head. Pipe sizes can then be reduced for the rest of the system so that all lateral inlet pressures are the same as demonstrated in sample calculation 11–13.

Sample calculation 11–13—Mainline pipe selection for a system with submains.

Given:

- economic pipe selection chart presented in figure 11–53 for aluminum pipe
- project with four small center pivots as shown in figure 11–56
- flow rate to each center pivot is 200 gallons per minute

Find:

- most economical pipe sizes for the system

Calculations:

First select the pipe sizes from figure 11–53 and compute the friction loss in each pipe section as in table 11–37. Then, locate the critical lateral inlet point as demonstrated in the top portion of table 11–26. The critical point is the inlet requiring the largest h_f plus

ΔE , which in this case is point B. Excess pressure along the path from the pump to the critical inlet cannot be reduced by pipe-size reductions. The excess pressure in all other branches may be reduced if the velocity limitations are not exceeded. The excess head at C is equal to the difference between the h_f plus ΔE_1 , between P–B and P–C, which is 8.7 minus (–2.6) equals 11.3 feet. The same amount of excess head occurs at D.

Replacing the 6 inch pipe in sections E–C and E–D with 5 inch pipe still results in excess heads of 5.4 feet at C and D (see the center section of table 11–38). Therefore, a portion of the 8 inch pipe in section A–E can be reduced to 6 inch pipe. The length (X) of 6 inch pipe that will increase the head loss by 5.4 feet can be computed by equation 11–94 (This was referred to as 165, so I substituted eq. 94. Is that right?) as:

$$\begin{aligned} X &= 100 \left(\frac{H_{f1} - J_1 L_1}{J_2 - J_1} \right) \\ &= 100 \left(\frac{5.4}{1.50 - 0.37} \right) \\ &= 478 \text{ ft} \end{aligned} \quad (\text{eq. 11-110})$$

Figure 11–56 Project layout with four center-pivot sprinkler laterals

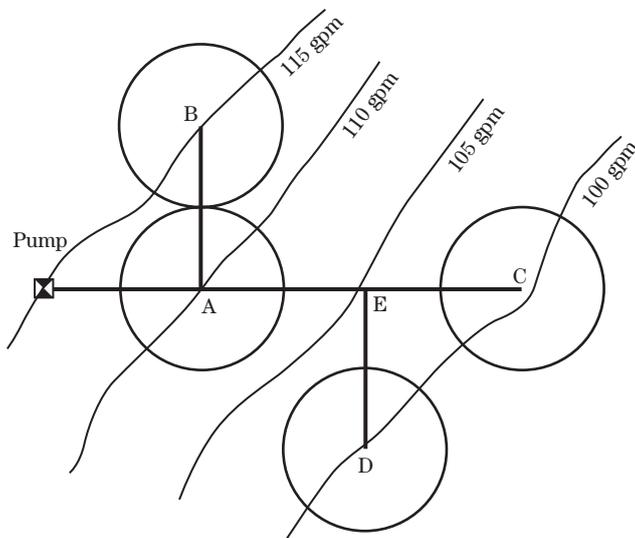


Table 11–37 Friction head loss calculations in each section for sample calculation 11–14

Pipe section	Flow (gpm)	D (in)	J (ft/100 ft)	L (ft)	$h_f = J \times L/100$ (ft)
Pipe sizes selected from economic chart					
P–A	800	10	0.45	1,000	4.5
A–B	200	6	0.42	1,000	4.2
A–E	400	8	0.37	1,000	3.7
E–C	200	6	0.42	1,000	4.2
E–D	200	6	0.42	1,000	4.2
Next smaller set of pipe sizes					
A–E	400	6	1.50	1,000	15.0
A–B	200	5	1.01	1,000	10.1
E–C	200	5	1.01	1,000	10.1
E–D	200	5	1.01	1,000	10.1

Replacing 478 feet of 8 inch pipe with 6 inch pipe in section A–E eliminates the excess head at inlets C and D as indicated in the bottom portion of table 11–38.

(d) Portable versus buried mainlines

The use of buried mainlines is restricted to areas that are to be irrigated permanently, whereas portable mainlines may be used on all areas. Aside from this restriction on the use of mainlines, the choice between portable and buried mains and between different pipe materials is largely a matter of economics. No installation costs are involved in portable mainlines, which can be moved about, and in most cases, a greater area can be covered with the same length of pipe. For example, if the water source were located in the center of a rectangular design area, the length of portable mainline pipe required would be only half of that

required for buried pipe. However, if the water source were located at one end of the area, the lengths of pipe required would be the same for both types of mains.

Buried mainlines have some distinct advantages over portable mainlines and because materials used in buried mainline pipe are not handled after initial installation, this type of line has a much longer life. For the same length and size of mainline, the annual fixed cost for buried mainlines is usually lower than that for portable lines. With buried mainlines, there are considerable savings in the labor that is required to move portable lines within the design area and to and from the place of storage at the start and end of the irrigation season. Furthermore, buried lines do not interfere with planting, cultural, or harvesting operations, and are protected from vandalism.

When making an economic comparison between two mainline pipe materials, develop a layout and select sets of pipe diameters using the economic methods described earlier for each pipe material. Then determine the total annual cost (fixed, energy, maintenance, and labor) of the mainline portion of each system.

Table 11–38 Location of critical pivot lateral inlet and trimming sequence for sample calculation 11–14

Pipe selection	h_r (ft)	ΔE_1 (ft)	$h_r + \Delta E_1$ (ft)	Excess (ft)
Using pipe sizes selected from the economic chart				
P–A	4.5	–5	–0.5	1
P–A–B	$4.5 + 4.2 = 8.7$	0	8.7	2
P–A–E–C	$4.5 + 3.7 + 4.2 = 12.4$	–15	–2.6	11.3
P–A–E–D	$4.6 + 3.7 + 4.2 = 12.4$	–15	–2.6	11.3
Replacing 6 in with 5 in pipe between E–C and E–D				
P–A–E–C	$4.5 + 3.7 + 10.1 = 18.3$	–15	3.3	5.4
P–A–E–D	$4.5 + 3.7 + 10.1 = 18.3$	–15	3.3	5.4
Replacing 478 ft of 8 in pipe with 6 in pipe between A–E				
P–A–E–C	$4.5 + 9.1 + 10.1 = 23.7$	–16	8.7	0
P–A–E–D	$4.5 + 9.1 + 10.1 = 23.7$	–16	8.7	0

1 Excess pressure at lateral inlets along critical path cannot be reduced by pipe size reductions.

2 The critical lateral inlet is at B.

(e) Design for continuous operation

Most irrigators prefer a sprinkler system that may be operated continuously without having to stop the pump each time a lateral line is uncoupled and moved to the next position. With portable mainlines, valve-tee couplers are placed at each lateral position, and each lateral line is equipped with a quick-coupling valve opening elbow. The elbows on the laterals open and close the valves in the couplers, thereby permitting the flow of water from the main to be turned on or off at will. If buried mainlines are used, takeoff or hydrant valves are placed on top of the riser and serve the same purpose as the valve-tee couplers in portable lines.

One or more extra lateral lines are often used so that the lines may be moved from one position to another while others are in use, thereby permitting uninterrupted operation. This type of operation offers several advantages. It eliminates long walks to the pump and back each time a lateral line is uncoupled and moved, and it takes fewer people (one or two) to move one lateral line while the other lines are running, so a relatively large system can operate continuously.

623.119 Pressure Requirements

To select a pump and power unit that will operate the system efficiently, determine the total of all pressure losses in the system. This yields the total dynamic head against which water must be pumped. Sketches showing the various losses that contribute to the total dynamic head are shown for both centrifugal and turbine pumps in NRCS 210–NEH, Part 623, chapter 8. If operating conditions vary considerably with the movement of laterals and mainline, or with a change in the number of sprinklers operated, both the maximum and minimum total dynamic head (TDH) must be computed.

Static head—Static head is the vertical distance (ΔE_s) the water must be raised or lowered between the water source and the point of discharge. Static head may be positive or negative. Static head in laterals has been considered in the design procedure for determining the lateral inlet pressure (P_m) required for proper operation and, therefore, need not be considered here.

The differences in elevation between the pump and the highest and lowest points on the mainline or submain give the maximum and minimum static heads. These must be included in computing the total dynamic head for maximum and minimum operating conditions. Suction lift, or the difference between the elevation of the water source and the elevation of the pump, is a form of static head that must be included in total head computations. For wells, the drawdown while pumping at the maximum required discharge should also be included in the figure for suction lift.

Velocity head—Since the velocity of flow in a sprinkler system seldom exceeds 8 feet per second (2.4 m/s), the velocity head seldom exceeds 1 foot (0.3 m), and may usually be disregarded in calculations for pressure requirement.

Total dynamic head—The total dynamic head (TDH) is the sum of:

- pressure head required to operate lateral (P_m) (ft or m)

- friction head losses in mainline and submains (h_f) (ft or m)
- friction head losses in fittings and valves (Δh_f) (ft or m)
- total static head including suction lift (ΔE_s) (ft or m)
- miscellaneous losses (for safety) usually taken as $0.2 h_f$ (ft or m)

Sample calculation 11–14 demonstrates the computation of the TDH for a simple sprinkler system.

Sample calculation 11–14—Determining the TDH for a sprinkler system.

Given:

- system layout shown in figure 11–57
- lateral: flow rate 300 gallons per minute, $P = 50$ pounds per square inch
- mainline: PVC plastic pipe, IPS, SDR, 41
- system capacity: $Q = 900$ gallons per minute

Find:

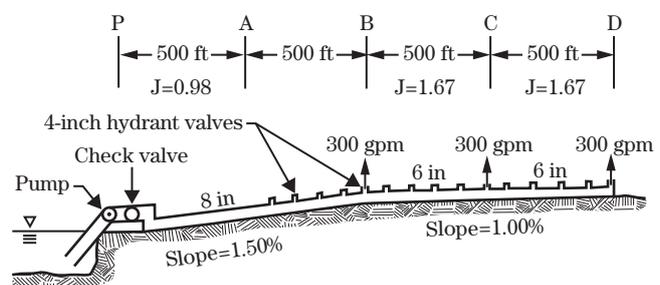
- the total dynamic head (TDH) required at the pump discharge

Calculations:

In figure 11–57 the critical lateral is at D and the pressure head required at the inlet is:

$$\begin{aligned} P_{\text{head}} &= P_m \quad (2.31) \\ &= 50 \quad (2.31) \\ &= 115.5 \text{ ft} \quad (\text{eq. 11-111}) \end{aligned}$$

Figure 11–57 Sample sprinkler system mainline layout



The friction loss in the mainline between P and D using J values from table 11-29 is:

$$\begin{aligned} \text{Section P-B: } 0.98(1000/100) &= 9.8 \text{ ft} \\ \text{Section B-C: } 1.67(500/100) &= 8.4 \text{ ft} \\ \text{Section C-D: } 0.47(500/100) &= 2.4 \text{ ft} \\ \text{Total } h_f &= \underline{20.6 \text{ ft}} \end{aligned}$$

The friction head loss in the fittings based on K_f values from table 11-22 and velocity head values from table 11-24 are:

Velocity heads are:

- Section P-B: 0.52 ft
- Section B-C: 0.71 ft
- Section C-D: 0.18 ft
- 4 inch hydrant: 0.91 ft

The fitting losses in section P-B are:

$$\begin{aligned} \text{One check valve } 1.3 \times 0.52 &= 0.7 \text{ ft} \\ \text{Two mitered elbows } 2(0.6 \times 0.52) &= 0.6 \text{ ft} \\ \text{Four hydrants (off) } 4(0.3 \times 0.52) &= 0.6 \text{ ft} \\ \text{One line-flow tee } 0.5 \times 0.52 &= 0.3 \text{ ft} \end{aligned}$$

The fitting losses in section B-C are:

$$\begin{aligned} \text{Four hydrants (off) } 4(0.3 \times 0.71) &= 0.9 \text{ ft} \\ \text{One line-flow tee } 0.5 \times 0.71 &= 0.4 \text{ ft} \end{aligned}$$

The fitting losses in section C-D are:

$$\text{Four hydrants (off) } 4(0.3 \times 0.18) = 0.2 \text{ ft}$$

The fitting loss of D are:

$$\begin{aligned} \text{One hydrant with opener } 7.5 \times 0.91 &= 6.8 \text{ ft} \\ \text{Total fitting losses, } h_f &= 10.5 \text{ ft} \end{aligned}$$

The static head between P and D is:

$$\begin{aligned} \text{Section P-B: } 1.5 \text{ percent} \times 1,000/100 &= 15.0 \text{ ft} \\ \text{Section B-D: } 1.0 \text{ percent} \times 1,000/100 &= 10.0 \text{ ft} \\ \text{Total: } \Delta E1 &= 25.0 \text{ ft} \end{aligned}$$

The miscellaneous losses are estimated to be:

$$0.2 h_f = 0.2(20.6) = 4.1 \text{ ft}$$

Finally,

$$\text{TDH} = 175.7 \text{ ft}$$

(a) Gravity pressure considerations

For the most convenient management of sprinkler irrigation systems, it is desirable to hold the application rate constant. In the areas adjacent to the water source for gravity systems, however, the elevation differential may not be sufficient for the desired full operating pressure. The sprinkler discharge will be below normal, and to obtain a constant average application rate, the sprinkler spacing must be decreased in the higher areas.

As pressure decreases, the diameter of the sprinkler coverage decreases slower than does the discharge; therefore, fairly good coverage and uniformity of application may be maintained at lower pressure by reducing the sprinkler spacing. Lateral spacing may be reduced in proportion to the drop in pressure; however, neither spacing nor pressure should be decreased below the manufacturer-recommended values. The alternative to operating at low pressures may be either adding a pump to the system or not watering certain high-elevation portions of the fields.

Since the sprinkler spacing on the lateral line is profiled, the lateral spacing on the mainline must be adjusted to compensate for the lower sprinkler discharge. An analysis of the integrated lateral spacing on the mainline may be derived in the following manner. The nozzle discharge can be expressed by equation 11-82, and the average application rate for a given sprinkler discharge at a given sprinkler spacing as given by equation 11-16. Combining equations 11-52 and 11-16, and rearranging the terms, yields (for English units):

$$S_1 = \frac{96.3K_d\sqrt{P}}{S_e I} \quad (\text{eq. 11-112})$$

where:

- S_1 = lateral spacing on the mainline, ft
- K_d = discharge coefficient for the sprinkler and nozzle combined
- P = sprinkler operating pressure, lb/in², ft
- I = average application rate, in/h
- S_e = sprinkler spacing on the lateral, ft

By holding I and S_e constant, equation 11-112 may be reduced to:

$$S_l = K_s \sqrt{P} \quad (\text{eq. 11-113})$$

where:

K_s = constant, and a function of I, S_e , and K_d

The constant, K_s , may be theoretically derived; however, a simpler method for evaluating it is to select the desired operating conditions for that portion of the field where sufficient lateral inlet pressure is available. In selecting the desired operating conditions, S_l and P are automatically set and K_s can be solved simply from equation 11-113. The pressure head, P , may be in either pounds per square inch or feet, as K_s will assume the necessary conversion factors.

The spacing between lateral moves that will give a constant average application rate can be determined easily for various pressure heads by solving equation 11-113, using K_s as determined, and the pressure head available at the lateral inlet. For example, a standard lateral inlet pressure of 50 pounds per square inch and a lateral move of 60 feet are selected for a given gravity sprinkler irrigation system. K_s equals 60 divided by the square root of 50 which equals 8.48. When the pressure at the head of the lateral is only 45 pounds per square inch because of insufficient elevation differentials, the lateral spacing should be S_l equals 8.48 times the square root of 48, which equals 57 feet to give the same average application rate. For 40 pounds per square inch, the spacing should be 54 feet; for 30 pounds per square inch, 47 feet; and for 20 pounds per square inch, 38 feet.

These procedures are useful for designing the lateral line spacing of gravity-fed sprinkler systems. The designer is provided with a quick method for determining the lateral spacing, which will yield a constant application rate in areas where below-normal operating pressures are encountered. Care must be taken, however, that the selected pressures provide sufficient jet breakup and sprinkler rotation.

(b) Selection of pump and power unit

Having determined the range of operating conditions (maximum and minimum capacities and total dynamic heads), the pump and power unit may be selected according to the procedures in NEH623.08, Irrigation Pumping Plants.

The pump efficiency is defined as:

$$\begin{aligned} E_p &= 100 \left(\frac{\text{water horsepower}}{\text{brake horsepower}} \right) \\ &= 100 \left(\frac{\text{WHP}}{\text{BHP}} \right) \end{aligned} \quad (\text{eq. 11-114})$$

E_p is in percent, and brake horsepower refers to the input power needed at the pump shaft. Pump efficiency is usually given by the pump manufacturer. Typically, use equation 11-114 to calculate required BHP, knowing E_p .

Water horsepower is defined as:

$$\text{WHP} = \frac{QH}{3,960} \quad (\text{eq. 11-115})$$

where:

WHP is in horsepower

Q in gpm

H in feet of head

Then, in the same units, brake horsepower is expressed as:

$$\text{BHP} = \frac{QH}{3,960 \left(\frac{E_p}{100} \right)} \quad (\text{eq. 11-116})$$

In metric units, water horsepower is defined as:

$$\begin{aligned} \text{WHP} &= \rho g Q H \\ &= \frac{(1,000 \text{ kg/m}^3)(9.81 \text{ m/s}^2)(\text{l/s})(\text{m})}{(1,000 \text{ l/m}^3)(1,000 \text{ W/kW})} \\ &= \frac{QH}{102} \end{aligned} \quad (\text{eq. 11-117})$$

Where WHP is in kW, Q in l/sec, and H in meters of head. Note that 1 horsepower (in the USA) is equal to 0.746 kW).

The total dynamic head, TDH, is defined as:

$$\text{TDH} = \Delta \text{Elev} + h_f + \frac{P}{\gamma} + \frac{V^2}{2g} \quad (\text{eq. 11-118})$$

Where the pressure, P , and velocity, V , are measured at the pump outlet, and h_f is the total friction loss from the entrance to the exit, including minor losses. At zero flow, with the pump running,

$$\text{TDH} = \Delta \text{Elev} + \frac{P}{\gamma} \quad (\text{eq. 11-119})$$

However, in some cases P/γ is zero for a zero flow rate. The elevation change, ΔElev , is positive for an increase in elevation (i.e., lifting the water, which is the usual case).

Sample calculation 11-15—Determine TDH and WHP for a centrifugal pump discharging into the air.

Given:

- figure 11-58
- data given

Calculations:

The head loss due to friction is:

$$h_f = h_{\text{screen}} + 3h_{\text{elbow}} + h_{\text{pipe}} \quad (\text{eq. 11-120})$$

for mid-aged PVC, $\varepsilon \approx 1.5(10) - 5$ m, relative roughness is:

$$\begin{aligned} \frac{\varepsilon}{D} &= \frac{1.5(10)^{-5}}{0.295} \\ &= 0.000051 \end{aligned} \quad (\text{eq. 11-121})$$

Average velocity,

$$\begin{aligned} V &= \frac{Q}{A} \\ &= \frac{4(0.102)}{\pi(0.295)^2} \\ &= 1.49 \text{ m/s} \end{aligned} \quad (\text{eq. 11-122})$$

Reynolds number, for 10 °C water:

$$\begin{aligned} N_R &= \frac{VD}{\nu} \\ &= \frac{(1.49 \text{ m/s})(0.295 \text{ m})}{1.306(10)^{-6} \text{ m}^2/\text{s}} \\ &= 336,600 \end{aligned} \quad (\text{eq. 11-123})$$

Values for the kinematic viscosity are obtained from table 11-39. From the Moody diagram, $f = 0.0147$. From the Blasius equation, $f = 0.0133$. Also, from the Swamee-Jain equation, $f = 0.0147$ (same as Moody). Using the value from Swamee-Jain:

$$\begin{aligned} h_{\text{pipe}} &= f \frac{L}{D} \frac{V^2}{2g} \\ &= 0.0141 \left(\frac{1,530}{0.295} \right) \frac{(1.49)^2}{2(9.81)} \\ &= 8.27 \text{ m} \end{aligned} \quad (\text{eq. 11-124})$$

Figure 11-58 Layout for example TDH and WHP calculations

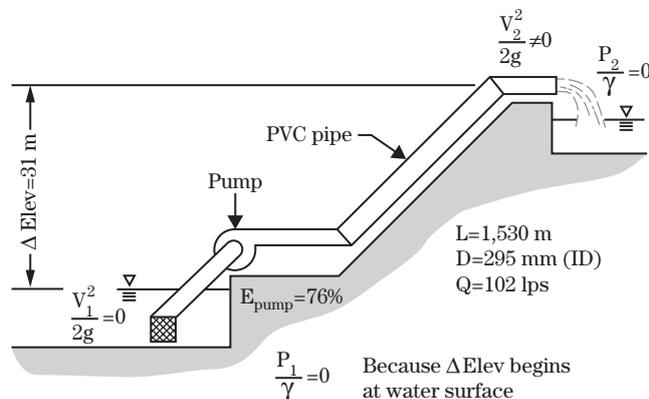


Table 11-39 Kinematic viscosity as a function of water temperature

Water temperature		Kinematic viscosity	
(°F)	(°C)	(ft ² /s)	(m ² /s)
32	0	1.92 e-05	1.79 e-06
41	5	1.64 e-05	1.52 e-06
50	10	1.41 e-05	1.31 e-06
59	15	1.23 e-05	1.14 e-06
68	20	1.08 e-05	1.00 e-06
77	25	9.61 e-06	8.93 e-07
86	30	8.61 e-06	8.00 e-07
104	40	7.08 e-06	6.58 e-07
122	50	5.95 e-06	5.53 e-07
140	60	5.10 e-06	4.74 e-07

From table 11–22 for a 12 inch (295 mm) pipe and long radius flanged elbow, the K_r value is 0.2. Then,

$$\begin{aligned} h_{\text{elbow}} &= K_r \frac{V^2}{2g} \\ &= (0.2) \frac{(1.49)^2}{2(9.81)} \\ &= (0.2)(0.11) \\ &= 0.022 \text{ m} \end{aligned} \quad (\text{eq. 11-125})$$

For the screen, assume a 0.2 meter loss. Then, the total head loss is:

$$\begin{aligned} h_r &= 0.2 + 3(0.022) + 8.62 \\ &= 8.9 \text{ m} \end{aligned} \quad (\text{eq. 11-126})$$

With the velocity head of 0.11 m, the total dynamic head is:

$$\begin{aligned} \text{TDH} &= 31 + 8.9 + 0.11 \\ &= 40 \text{ m} \end{aligned} \quad (\text{eq. 11-127})$$

The water horsepower is:

$$\begin{aligned} \text{WHP} &= \frac{QH}{102} \\ &= \frac{(102 \text{ lps})(40 \text{ m})}{102} \\ &= 40 \text{ kW (54 HP)} \end{aligned} \quad (\text{eq. 11-128})$$

The required brake horsepower is:

$$\begin{aligned} \text{BHP} &= 100 \left(\frac{\text{WHP}}{E_p} \right) \\ &= 100 \left(\frac{40 \text{ kW}}{76} \right) \approx 53 \text{ kW (71 HP)} \end{aligned} \quad (\text{eq. 11-129})$$

This BHP value would be used to select a motor for this application. These calculations provide one point on the system curve (Q and TDH). In this simple case, there would be only one system curve, as shown in figure 11–59.

Seasonal power cost—The annual cost of power to operate the pumping unit can be computed by:

$$\text{CE} = \frac{UQ_s \text{TDH}}{3,960} \quad (\text{eq. 11-130})$$

where:

- CE = present annual energy cost to operate system, \$
- U = present annual cost of energy from equation 11–104, \$/WHP-year

To determine the average annual energy cost over the economic life of the system, taking into account the time value of money and anticipated energy inflation rate, multiply CE by EAE.

System curves—The system curve is a graphical representation of the relationship between discharge and head loss in a system of pipes. It is completely independent of the pump characteristics. The basic shape of the system curve is parabolic because the exponent on the head loss equation (and on the velocity head term) is 2.0 or nearly 2.0. The system curve will start at zero flow and zero head if there is no static lift, otherwise the curve will be vertically offset from the zero head value.

Most sprinkle irrigation systems have more than one system curve because either the sprinklers move between sets (periodic-move systems), move continuously, or “stations” (blocks) of laterals are cycled on

Figure 11–59 Sample system curve

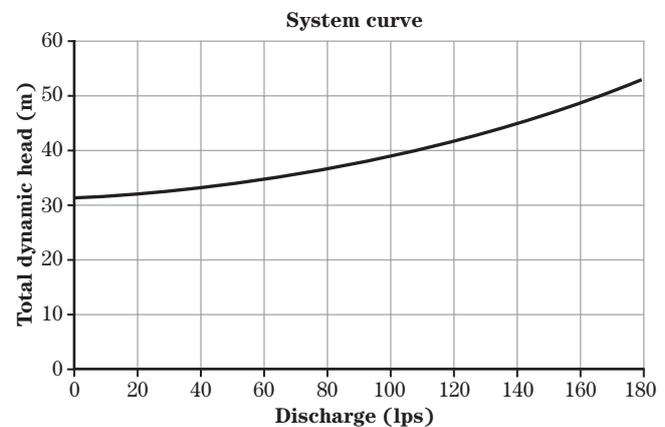


Figure 11-61 Sample system curve with mostly static lift, little friction loss

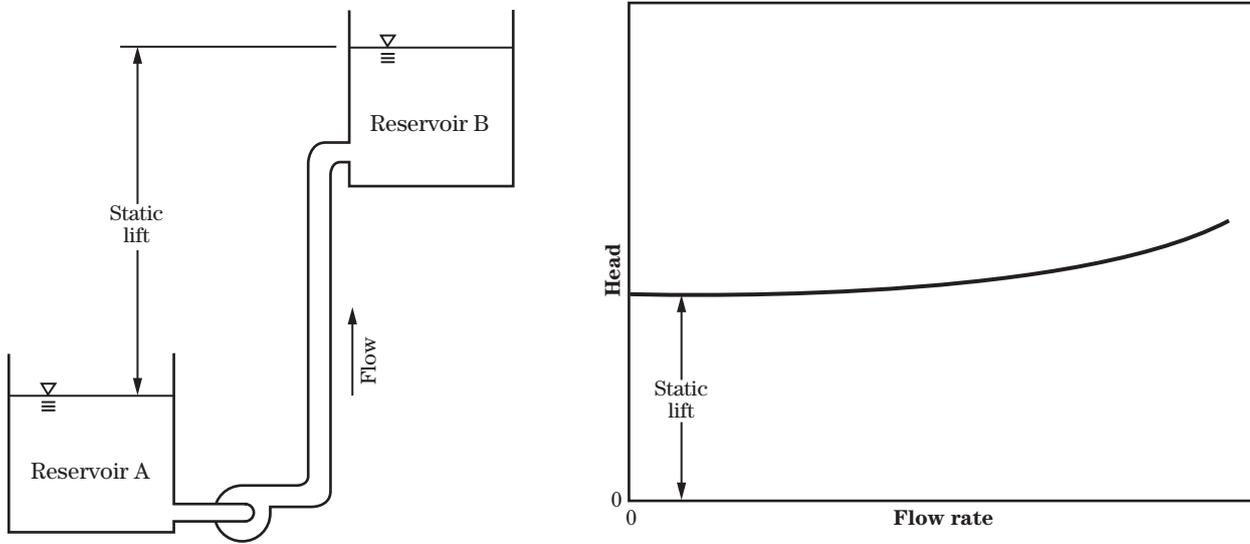


Figure 11-62 Sample system curve with negative static lift

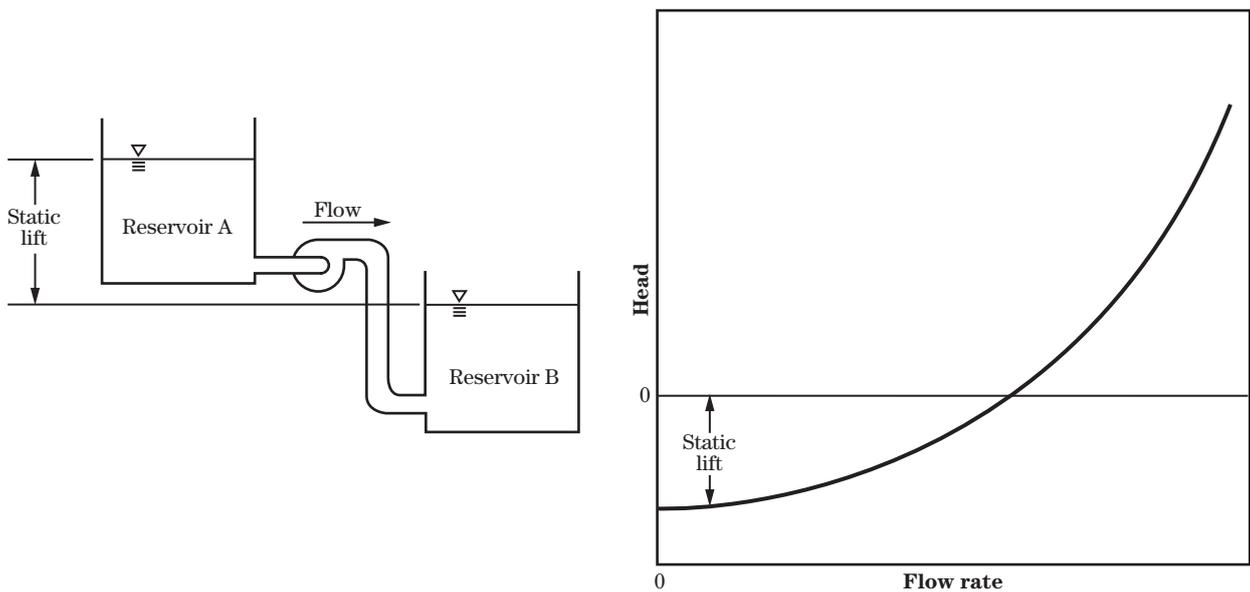


Figure 11-63 Sample system curve with two different static lifts

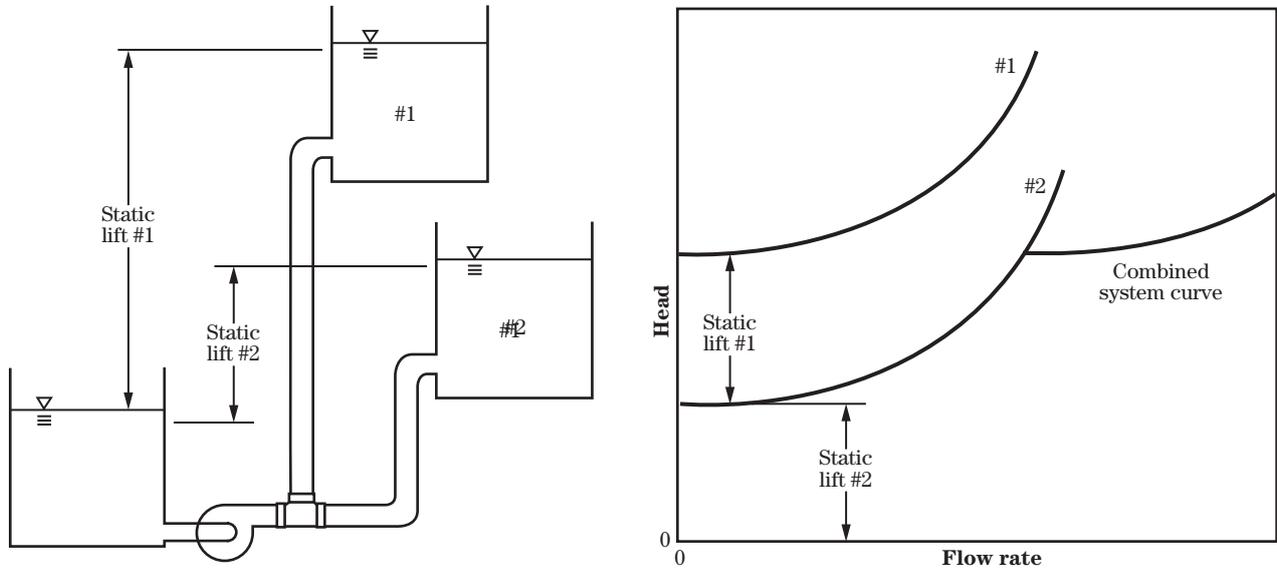


Figure 11-64 Sample composite system curve

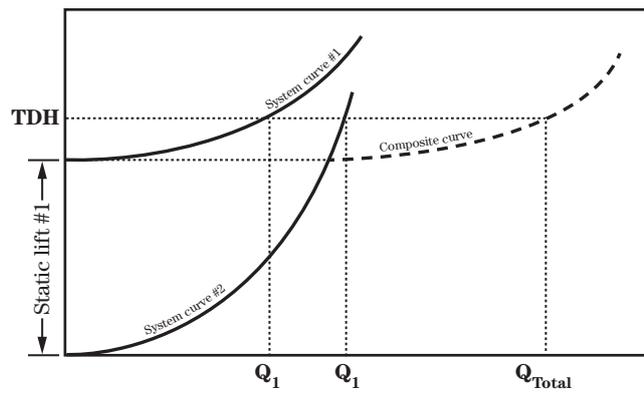
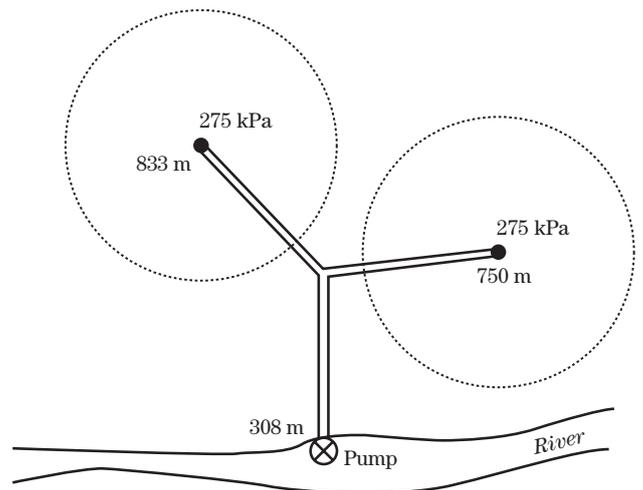


Figure 11-65 Two center pivots in a branching pipe layout



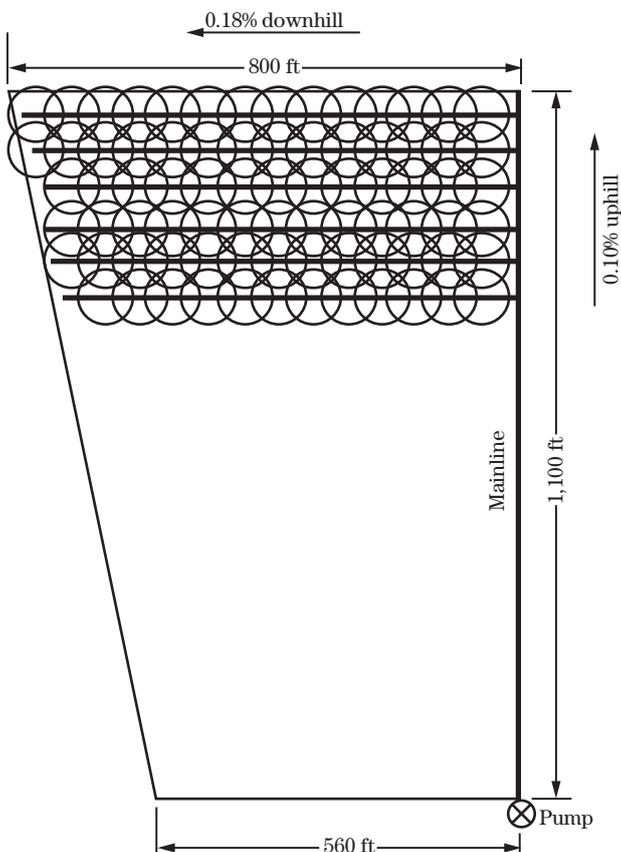
sure at the bifurcation point is obtained, the solution has converged – then, add the two flow rates and go upstream along the common branch to obtain the head at the pump. It is not correct to add the TDH from each of the branches.

Note that the system curve will change with center pivot lateral position when the topography is sloping and or uneven within one or both circles. Of course, the system curve will also be different if only one (not both) of the center pivots is operating.

(ii) A fixed sprinkler system with multiple laterals operating

Figure 11–66 shows a group of five laterals in parallel, attached to a common mainline in a fixed sprinkler system. All of the sprinklers operate at the same time (perhaps for frost control or crop cooling purposes,

Figure 11–66 Example layout for the calculation of pump operating point.



among other possibilities). This is another example of a branching pipe system in which there is a common mainline from which each lateral bifurcates. Hydraulic calculations would be iterative because you must determine the flow rate to each of the laterals for a given TDH, since the flow rate is changing with distance along the mainline. As in the example with two center pivots, once the flow rates are in each branch, any flow path can be followed from the pump to the end of the branch (lateral, in this case) to determine TDH. All such paths in the system must give exactly the same TDH.

(iii) Two flow rates for same head on pump curve

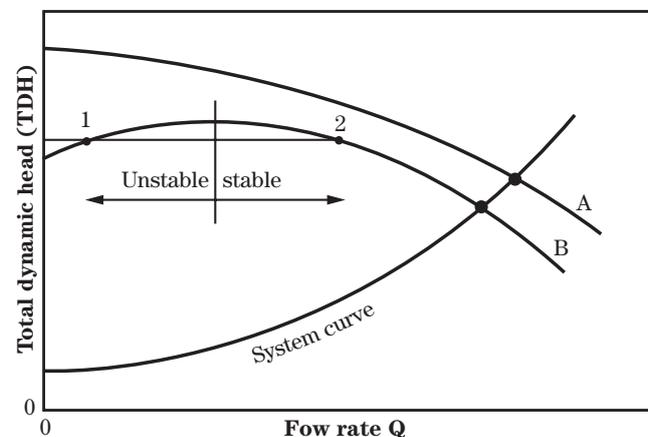
Consider the graph in figure 11–67. Characteristic curve A has a unique Q for each TDH value. Curve B has two flow rates for a given head, over a certain range of TDH values. Pumps with a characteristic curve like B should usually be avoided in irrigation applications, unless the operating point is far from the region of dual flow rates for a give TDH.

Sample calculation 11–16—Determine the system operating point for a fixed sprinkler system.

Given:

- a fixed sprinkler system (all sprinklers operate simultaneously) in an orchard
- buried IPS-PVC one and one-half inch lateral pipes

Figure 11–67 Example of a potentially unstable pump operating point



- Rainbird® under-tree M20VH impact sprinklers with five and sixty-fourth inch SBN-1 nozzle (see www.rainbird.com for technical specifications)
- lateral spacing: $S_l = 40.00$ feet
- sprinkler spacing: $S_e = 40.00$ feet
- field is trapezoidal in shape

In figure 11–67, only some of the laterals and sprinklers are shown, but the field area is covered with sprinklers in a fixed, permanent system with 27 laterals along the mainline. The suction (upstream) side of the pump has a 4-foot static lift from a pond and 10 feet of 8-inch PVC pipe (ID = 8.205 in) with one 90 degree elbow and a strainer screen at the inlet. The mainline is 8-inch PVC pipe (ID = 8.205 in), and is 1,100 feet long. The sprinkler riser height is: h_r is 3.0 feet. A Berkeley model 4GQH pump curve for 1,600 RPM is shown. Ignore minor losses along the mainline and laterals.

Required:

- Determine the irrigated area (acres).
- Develop an equation for sprinkler flow rate (q) as a function of pressure (P), whereby $q = KdPx$ (determine Kd and x based on manufacturer's data).
- Determine the number of sprinklers along each lateral, where lateral number 1 is the closest to the pump, and lateral number 27 is the furthest from the pump.
- Develop at least five points on the system curve and present those points numerically in a table.
- Plot the system curve points on the attached pump curve graph, and draw a smooth curve through the points.
- Determine the operating point (Q in gpm and TDH in ft) for this system.
- Determine the average application rate for the whole field area.

Calculations:

The irrigated area is approximately:

$$A = \frac{0.5(800 + 560)(1,100)}{43,560} = 17.2 \text{ ac} \quad (\text{eq. 11-131})$$

Due to the trapezoidal field shape and the fact that there are 27 laterals at S_l equals 40 feet, the effective irrigated area is slightly less than 17.2 acres.

A linear regression is performed on logarithms of the manufacturer's data for P and q (Rainbird® M20VH with 5/64-inch SBN–1 nozzle):

Pressure (lb/in ²)	Flow (gpm)	In (P)	In (q)
25	0.88	3.2189	–0.1278
30	0.97	3.4012	–0.0305
35	1.05	3.5553	1.1488
40	1.12	3.6889	0.1133
45	1.19	3.8067	0.1740
50	1.25	3.9120	0.2231

given an R^2 of 0.9996, and the equation 11–132:

$$q = 0.173P^{0.506} \quad (\text{eq. 11-132})$$

for q in gallons per minute and P in pounds per square inch. Note that the exponent is close to 0.500, which is expected for a straight-bore nozzle. But notice also that allowing for the flexibility in the exponent, x , gives a better mathematical fit to the manufacturer's data.

Let the first lateral be located at one-half S_l from the lower edge of the field (where the pump is located). Calculate the number of sprinklers per lateral by rounding the potential lateral length by S_e . The potential lateral length is calculated by linear interpolation along the left side of the field area (fig. 11–67). The equation is given, and the calculation results are shown in the table.

$$L = 800 - (1,100 - y) \left(\frac{800 - 560}{1,100} \right) \quad (\text{eq. 11-133})$$

where:

y = distance along the mainline, ft

L = potential lateral length, ft

Lateral	Distance (ft)	Length (ft)	Number of sprinklers
1	20	564.4	14
2	60	573.1	14
3	100	581.8	15
4	140	590.5	15
5	180	599.3	15
6	220	608.0	15
7	260	616.7	15
8	300	625.5	16
9	340	634.2	16
10	380	642.9	16
11	420	651.6	16
12	460	660.4	17
13	500	669.1	17
14	540	677.8	17
15	580	686.5	17
16	620	695.3	17
17	660	704.0	18
18	700	712.7	18
19	740	721.5	18
20	780	730.2	18
21	820	738.9	18
22	860	747.6	19
23	900	756.4	19
24	940	765.1	19
25	980	773.8	19
26	1,020	782.5	20
27	1,060	791.3	20

There is a total of 458 sprinklers (sum of the right-hand column)

Develop a computer program to start with a given pressure at the furthest downstream sprinkler on lateral number 27, calculate the flow rate at that sprinkler, calculate the pressure at the next upstream sprinkler, then the flow rate at that sprinkler, and so on, until reaching the mainline. Calculate the pressure in the mainline at the location of lateral number 26,

then iterate along lateral number 26 to get the same pressure in the mainline at that location. Repeat for all other laterals, moving in the upstream direction, until a pressure is obtained for the upstream end of the mainline. The system flow rate is known from these calculations (sum of all individual sprinklers). Assume pipe leakage is zero.

Knowing the system flow rate, determine the losses in the suction side of the pipe and determine TDH by adding the velocity head at the beginning of the mainline, the pressure head at the beginning of the mainline, the static lift on the suction side, and the hydraulic losses on the suction side of the pump.

Preliminary calculations and assumptions

Assume a water temperature of 10 degrees Centigrade, giving a kinematic viscosity of: $1.306(10)^{-6}$ square miles per second, or $1.406(10)^{-5}$ square foot per second. Use the Swamee-Jain equation with ϵ equals $4.92(10)^{-6}$ feet ($1.5(10)^{-6}$ m), for PVC to obtain the Darcy-Weisbach friction factor, f . The ID of the lateral pipe is 1.75 inches (0.146 ft). The ID of the mainline pipe is 8.21 inches (0.684 ft).

Once the pressure at the upstream end of the mainline is calculated, the additional TDH values include static lift, velocity head, and losses in the suction side of the pump, plus the riser height. Assume the pump outlet is at the same elevation as the upstream end of the mainline.

$$\text{TDH} = 2.308 P_{\text{main}} + h_{\text{lift}} + h_r + (h_f)_{\text{suction}} + \frac{V^2}{2g}$$

(eq. 11-134)

where:

P_{main} = pressure at the upstream end of the mainline (psi)

h_{lift} = 4.0 ft

h_r = 3.0 ft

$(h_f)_{\text{suction}}$ = hydraulic losses in the suction pipe, ft

The iterative part is to determine P_{main} ; the rest of the TDH terms are easy to calculate directly.

From table 11-2 (minor loss coefficients):

8-inch basket strainer— $K_r = 0.75$

8-inch regular 90-degree elbow— $K_r = 0.26$

Velocity head in the suction pipe:

$$\frac{V^2}{2g} = \frac{8Q^2}{g\pi^2 D^4} = 0.1151Q^2 \quad (\text{eq. 11-135})$$

Friction loss in the suction pipe:

$$h_f = f \frac{L}{D} \frac{V^2}{2g} = 1.684fQ^2 \quad (\text{eq. 11-136})$$

Putting it all together:

$$\text{TDH} = 2.308P_{\text{main}} + 4.0 + 3.0 + 1.684fQ^2 + 0.1151Q^2(1 + 0.75 + 0.26) \quad (\text{eq. 11-137})$$

or

$$\text{TDH} = 2.308P_{\text{main}} + 7.0 + Q^2[1.684f + 0.2314] \quad (\text{eq. 11-138})$$

The results are given in the table:

P (lb/in ²)	Q _s (gpm)	P _{main} (lb/in ²)	R _e	f	TDH (ft)
20	367.2	21.8	108,347	0.001761	57.50
25	411.2	27.2	121,318	0.01721	70.09
30	421.0	32.7	133,061	0.01689	82.66
35	487.6	38.1	143,853	0.01663	9521
40	521.6	43.5	153,902	0.01641	107.74
45	553.6	48.9	163,344	0.01622	120.26
50	583.9	54.3	172,277	0.01605	132.77
55	612.70	59.7	180,777	0.01577	145.28
60	640.2	65.1	188,901	0.01577	157.77

where:

- P = pressure at the furthest downstream sprinkler on lateral number 27
- Q_s = total system flow rate
- P_{main} = pressure at the upstream end of the mainline (just downstream of the pump)
- R_e = Reynold's number in the suction pipe
- f = value from Swamee-Jain
- TDH = total dynamic head

The system curve (Q_s versus TDH) is superimposed upon the pump manufacturer's curves, as shown in figure 11-68.

The operating point (intersection of the system curve and the 1,600 RPM pump curve) is seen to be approximately:

$$Q_s = 568 \text{ gpm}$$

$$\text{TDH} = 126 \text{ ft}$$

The average application rate at this operating point is approximately:

$$\text{AR}_{\text{avg}} = \frac{(568)(12)(3,600)}{\underbrace{(458)}_{\text{number of sprinklers}} \underbrace{(40)(40)}_{\text{sprinkler spacing}} (448.86)} = 0.075 \text{ in/h} \quad (\text{eq. 11-139})$$

or

$$\text{AR}_{\text{avg}} = 1.9 \text{ mm/h}$$

The MS™ Excel® VBA listing is:

```

Const Pi = 3.141593
Const Se = 40# 'ft
Const Sl = 40# 'ft
Const LatCount = 27 'number of laterals
Const Dlat = 0.1462 'ft
Const Dmain = 0.6888 'ft
Const SoLat = -0.0018 'ft/ft
Const SoMain = 0.001 'ft/ft

Function hf(ByVal Q As Double, ByVal D As Double, ByVal L As Double) As Double
'-----
' Returns friction loss in feet of water head (Darcy-Weisbach).
' If turbulent, uses the Swamee-Jain equation for the friction factor, f.
'-----

Dim Re As Double, RelRough As Double, f As Double

viscosity = 0.0000141 'ft2/s for water at 50 deg F

RelRough = 0.00000492 / D
Re = 4 * Q / (viscosity * Pi * D)

If Re > 4000 Then
    f = RelRough / (3.75 + 5.74 / Re ^ 0.9) 'Turbulent
    f = WorksheetFunction.Log10(f)
    f = 0.25 / f ^ 2
Else
    f = 64 / Re 'Laminar
End If

hf = 8# * f * L * (Q / Pi) ^ 2 / (32.2 * D ^ 5)

End Function

Function Lateral(ByVal P As Double, n As Integer, Qlat As Double) As Double
'-----
' Calculates lateral inlet pressure head for "n" sprinklers.
' Pressure, P, is in psi. Calculates DS to US along the lateral pipe.
'-----

Dim Qs As Double, h As Double

Qlat = 0# 'cfs

For i = 1 To n
    Qs = 0.173 * P ^ 0.506 'gpm
    Qlat = Qlat + Qs / 448.86 'cfs
    h = P * 2.308 + hf(Qlat, Dlat, Se) + SoLat * Se 'ft
    P = h / 2.308 'psi
Next

Lateral = h

End Function

Function ParabolaFit(x, y, target As Double) As Double
'-----
' Determines constants a, b, and c for a parabola through three points.
' Equation is: y = ax^2 + bx + c. If parabola impossible, uses bisection.
' Returns the x-value (P) which matches the specified target y-value (hmain).
' P is the pressure at the furthest DS sprinkler in the lateral.
'-----

Dim Bisection As Boolean
Dim foo As Double, boo As Double
Dim a As Double, b As Double, c As Double

ParabolaFit = 0

```

```

foo = x(2) - x(1)
Bisection = Abs(foo) < 0.0000000001

If Not Bisection Then

    C0 = x(1) ^ 2
    c1 = (x(3) - x(1)) / foo
    c2 = x(2) ^ 2 - C0

    boo = x(3) ^ 2 - C0 - c1 * c2
    Bisection = Abs(boo) < 0.0000000001

    If Not Bisection Then

        '-----
        ' Parabolic interpolation
        '-----

        a = ((y(1) - y(2)) * c1 - y(1) + y(3)) / boo
        b = (y(2) - y(1) - a * c2) / foo
        c = y(2) - x(2) * (a * x(2) + b)

        c = c - target
        ParabolaFit = (-b + Sqr(b * b - 4 * a * c)) / (2 * a)
        Exit Function
    End If
End If

If Bisection Then

    '-----
    ' Use bisection
    '-----

    If y(2) < target Then
        ParabolaFit = (y(2) + y(3)) / 2
    Else
        ParabolaFit = (y(2) + y(1)) / 2
    End If
End If

End Function

Function QsPmain(ByVal P As Double, Flow As Boolean) As Double
'-----
' Iterates to determine the system flow rate for a given starting pressure.
' Returns either flow rate (Q) or pressure (P...) at US end of the mainline.
' Call this function several times with different P to develop system curve,
' then plot the system curve on the pump graph to determine operating point.
'-----

Dim n As Integer
Dim lat As Integer
Dim LatHead(1 To 3) As Double
Dim Pressure(1 To 3) As Double
Dim Qlat As Double, x As Double
Dim Qmain As Double, L As Double, NewP As Double, hmain As Double

hmain = 0
Qmain = 0

'-----
' Start with furthest lateral
'-----

For lat = LatCount To 1 Step -1

    '-----
    ' Determine number of sprinklers this lateral
    '-----

```

```

x = 20 + (lat - 1) * S1
L = 800# - (1100# - x) * 0.2181818
n = Round(L / Se, 0)

'-----
' Calculate lateral inlet pressure head
'-----

If lat = LatCount Then

'-----
' No need to iterate for last lateral
' because P is specified at end of furthest lateral
'-----

  LatHead(2) = Lateral(P, n, Qlat)
Else

'-----
' Iterate to match lateral inlet & mainline heads
'-----

  Pressure(1) = P / 4
  Pressure(3) = 3 * P
  Pressure(2) = (Pressure(1) + Pressure(3)) / 2
  LatHead(1) = Lateral(Pressure(1), n, Qlat)
  LatHead(3) = Lateral(Pressure(3), n, Qlat)
  LatHead(2) = Lateral(Pressure(2), n, Qlat)

  If (LatHead(1) > hmain) Or (LatHead(3) < hmain) Then

    '-----
    ' Failed to bracket the solution
    '-----

    QsPmain = -100
    Exit Function
  End If

  For i = 1 To 50

    '-----
    ' Search by parabolic interpolation
    '-----

    NewP = ParabolaFit(Pressure, LatHead, hmain)

    If NewP < Pressure(2) Then
      Pressure(3) = Pressure(2)
      LatHead(3) = LatHead(2)
    Else
      Pressure(1) = Pressure(2)
      LatHead(1) = LatHead(2)
    End If

    Pressure(2) = NewP
    LatHead(2) = Lateral(NewP, n, Qlat)

    If Abs(LatHead(2) - hmain) < 0.001 Then

      '-----
      ' Solution converged
      '-----

      Exit For
    End If
  Next

End If

'-----

```

```

' Move upstream one hydrant along mainline
'-----

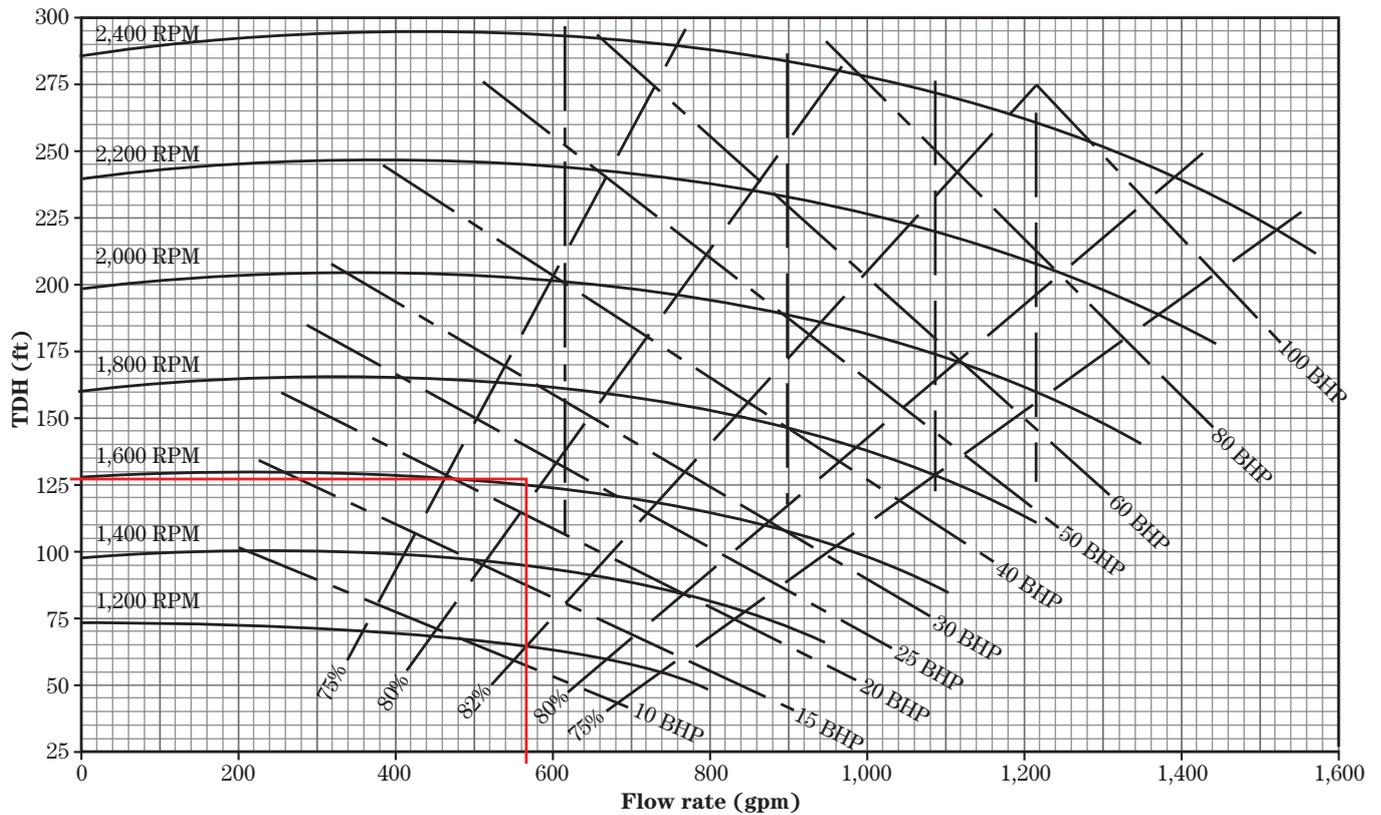
Qmain = Qmain + Qlat
hmain = LatHead(2) + hf(Qmain, Dmain, S1) + SoMain * S1
Next

'-----
' Return the system flow rate
' or the mainline pressure
'-----

If Flow Then
  QsPmain = Qmain * 448.86 'gpm
Else
  QsPmain = hmain / 2.308 'psi
End If

End Function
    
```

Figure 11-68 Sample layouts of periodic-move sprinkler systems that account for topography



(c) Traveling sprinkler system

A typical traveling sprinkler system consists of the following major components: pumping plant, mainline, flexible hose, traveler unit, and gun sprinkler. The general design procedure, system capacity requirements, depth of application, optimum application rates, and irrigation efficiency criteria are developed in the section on planning concepts. The selection of pumping plants and mainline designs is presented in the section on periodic-move and fixed systems.

(i) Sprinkler

Characteristics that need to be considered are nozzle size and type, operating pressure, jet trajectory, and sprinkler body design. The operating conditions that enter into the selection process are soil infiltration characteristics; desired depth and frequency of irrigation; tow-path length, potential tow-path spacings, and number of paths for each potential spacing; wind conditions; crop characteristics; and the mechanical properties of the soil.

(ii) Sprinkler variables

Gun sprinklers used in most travelers have trajectory angles ranging between 18 and 32 degrees. When operating at relatively low pressures, higher trajectory angles increase the altitude of the jet, which allows the stream to exhaust its horizontal velocity before the water droplets reach the soil surface. Therefore, the higher angles give maximum coverage in low winds, and droplet impact is minimized. The low angles give more uniform coverage in winds above 10 miles per hour (16.1 kph), but drop impact is quite severe and may be detrimental to all but the sturdiest crops and coarsest soil textures. For average conditions, trajectories between 23 and 25 degrees are satisfactory. These midrange trajectories give reasonable uniformity in moderate winds, have gentle enough drop impact for most crops and soils, and are suitable for operation on varying slope conditions where there will be some riser tilting.

Most gun sprinklers used on travelers can be fitted with either tapered or orifice-ring nozzles. The tapered nozzles normally produce a compact water jet that is less susceptible to wind distortion than the more diffuse stream from a ring nozzle. Therefore, for a given discharge, the tapered nozzles will also provide a greater distance of throw, which may permit wider tow-path spacing and lower application rates. Ring

nozzles, however, produce better stream breakup at lower operating pressures, which is an important factor on delicate crops. Furthermore, ring nozzles offer considerably greater flexibility in nozzle size selection at low cost.

Some irrigators may prefer to begin the irrigation season with small nozzles at high pressure that generate ideal droplet conditions during the critical germination or blossom stages. As the season progresses, the orifice size can be increased to meet greater crop demands during the peak moisture consumption period. At that time, the ground is normally covered with foliage, and the larger water droplets will not adversely affect production or soil tilth.

Typical nozzle discharges and diameters of coverage are presented in table 11-39 for gun sprinklers with 24 degree angles of trajectory and tapered nozzles. The wetted diameter would increase, or decrease, about 1 percent for each 1 degree change in trajectory angle. Ring nozzles sized to give similar discharges at the same pressures would produce diameters that are about 5 percent smaller than those presented in table 11-40.

Both full-circle and part-circle gun sprinklers are available in all nozzle types and size ranges. Some sprinklers need to be operated with part circle coverage to give even water distribution, a dry path for vehicle travel, or both. The use of part-circle sprinklers increases the application rate because the same discharge is applied over a smaller area. A half-circle coverage will double the full-circle application rate of the same sprinkler operating under similar conditions.

Gun sprinklers tend to produce Christiansen's E type profiles (fig. 11-23). Since the traveling sprinklers operate independently, the actual application rate at which water must infiltrate into the soil to eliminate runoff is approximately:

$$I_t = \frac{96.3 q}{\pi(0.9_t)^2} \left(\frac{360}{\omega} \right) \quad (\text{eq. 11-140})$$

where:

- I_t = approximate actual application rate from a traveling sprinkler, in/h
- q = sprinkler discharge, gpm
- t = wetted radius, ft
- ω = portion of circle receiving water, degrees

This is similar to equation 11–22. The wetted area is based on only 90 percent of the radius of throw to give the approximate application rate over the major portion of the pattern rather than the average rate over the whole wetted area. Using data from table 11–37, in equation 11–140, the actual application rates from 0.8 and 1.6 inch nozzles operating full circle at 80 pounds per square inch are 0.26 inch per hour and 0.44 inch per hour, respectively. Using ring nozzles that would reduce the wetted diameters by about 5 percent would increase the application rate to approximately 0.29 inch per hour and 0.49 inch per hour, respectively. For a tapered nozzle operating with a 25-inch dry wedge, as in figure 11–9, the application rates would be increased to 0.33 and 0.56 inch per hour, respectively.

(iii) Traveler

The traveler selected should provide the required flow rate and power to drag the hose at the travel speeds necessary to meet the design criteria. Controls to provide a uniform speed of travel that will not vary more than plus or minus 10 percent as the traveler moves from one end of the field to the other and positive shutoff at the end of travel are essential.

Constant travel speed is required for uniform water distribution over the irrigated area. Some of the factors that affect the ability of a traveler to maintain constant speed are:

- hose pull, which varies with hose size, soil type, terrain, and condition of the tow path
- water pressure and flow rate
- amount of cable buildup on the cable reel varies with the design of the cable drum and must be compensated for in the design of the traveler, or the machine will speed up through the travel run
- characteristics of the power unit on the traveler must be matched to the requirements of hose pull and other factors enumerated for operation at a constant speed

Many of the factors vary by as much as 200 to 300 percent, depending upon location, and the design and operation of the traveler must include the capability to handle such variations. The end pull required to drag a hose depends on the soil texture, soil moisture conditions, and crop cover. Pull is greatest on wet, bare, sticky soils and less on wet vegetation or bare, sandy soils. On sticky soils, the tow paths should be planted in grass or other vegetation.

Sprinkler performance will be affected by turbulence in the stream before it enters the sprinklers. Such turbulence can be caused by a variety of internal plumbing problems including protrusions in the pipe, poorly designed plumbing, changes in pipe size, elbows, and other obstacles near the base of the gun. When moving the hose from one location to the next, a hose reel

Table 11–40 Typical discharges and wetted diameters for gun sprinklers with 24° angles of trajectory and tapered nozzles operating when there is no wind

Sprinkler pressure lb/in ²	Tapered nozzle size (in)									
	0.80		1.00		1.20		1.40		1.60	
	Sprinkler discharge and wetted diameter		Sprinkler discharge and wetted diameter		Sprinkler discharge and wetted diameter		Sprinkler discharge and wetted diameter		Sprinkler discharge and wetted diameter	
	gal/min	ft								
60	143	285	225	325	330	365	—	—	—	—
70	156	300	245	340	355	380	480	435	—	—
80	166	310	260	355	380	395	515	456	675	480
90	175	320	276	365	405	410	545	470	715	495
100	185	330	290	375	425	420	575	480	755	510
110	195	340	305	385	445	430	605	490	790	620
120	205	350	320	395	465	440	630	500	825	535

should be used. The reel should be designed so that the hose may be placed on it without first removing the pull coupler. The reel also provides a good means of storing the hose in the off-season.

(iv) Tow-path spacing

Tests run by various researchers show that application uniformity is considerably affected by wind velocity and direction, quantity of water output, jet trajectory, type of nozzle, and operating pressure. With average wind speeds about 10 miles per hour, CUs were 70 to 75 percent in the central portion of the fields for tow-path spacings equal to 70 to 60 percent of the wetted diameters of the sprinklers.

Only the center section of a field irrigated by traveling sprinklers gets a full pass of the complete sprinkler pattern. About 400 feet (122 m) on each end of most fields are not irrigated as well as the center of the field. This under irrigation can be essentially eliminated, as described, by allowing the sprinkler to stand for a period of time at the end of the tow paths. The CU values were based on a constant travel speed. Obviously, these values would decrease if the travel speed varied from one part of the field to another.

The continuous movement of the traveler is equivalent to having periodic-move sprinklers very closely spaced along the lateral. The effect is to improve the uniformity as compared with periodic-move gun sprinkler installations. Figure 11–69 shows a comparison between a traveling and a set gun sprinkler application pattern measured across the tow path. The traveling sprinkler produces a uniform pattern in low winds. From figure 11–69, it is evident that a tow-path spacing of 80 percent of the wetted diameter would produce excellent uniformity under very calm wind conditions, whereas closer spacings would produce excessive application midway between adjacent tow paths.

Table 11–41 gives recommended tow-path spacings for 23- to 25-degree trajectory sprinklers as a function of wetted diameter and anticipated average wind velocities. These tow-path spacings will ensure full coverage midway between tow paths. The higher percentage values should be used for tapered nozzles and the lower values for ring nozzles. Where average winds are expected to exceed 10 miles per hour, 20- to 21-degree trajectory angles should be used. Where winds are negligible, 26- to 28-degree trajectories will give the best results.

(v) Travel speed

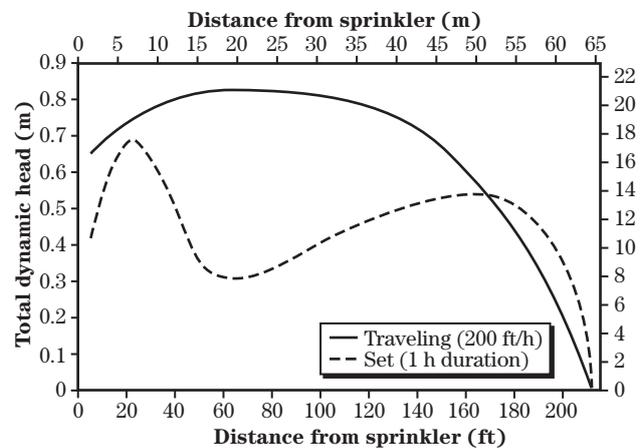
The travel speed should be set to traverse the length of the tow path so that there will be little down time with either one or two setups per day. Some typical travel speeds are:

- For a 1,320 foot run such as in figure 11–9, where the traveler starts and stops at the field boundaries, the travel speed for two setups per day should be approximately 1,320 divided by (11×60) equals 2 foot per minute. For one setup per day it should be between 0.9 and 1.0 foot per minute.
- For a 1,320 foot run where it is not permissible, or practical, to irrigate over the field boundaries, the sprinkler should be operated in a set position on each end of the tow path. In each case with average sized gun sprinklers having an effective wetted diameter of 400 feet, the travel speed for one setup per day should be approximately:

$$\frac{1,320 \text{ ft} - 400 \text{ ft}}{60 \text{ min/h} [23 \text{ h} - 2(1) \text{ h}]} \cong 0.75 \text{ ft/min} \quad (\text{eq. 11-141})$$

This allows for a 1-hour set time, 200 feet from the field boundary at each end of the tow path. With half-hour set times and two setups per day the travel speed should be approximately 1.5 feet per minute.

Figure 11–69 Typical application patterns of a traveling and a set gun sprinkler operating with low wind



(vi) Application depth

The rate of application is unaffected by travel speed, but the depth of application is a function of speed.

The average depth of water applied per irrigation by a traveling sprinkler can be computed by:

$$d = K \left(\frac{q}{W S} \right) \quad (\text{eq. 11-142})$$

where:

- d = gross water application depth, in or mm
- q = sprinkler discharge, gpm or l/min
- W = tow-path spacing, ft or m
- S = travel speed, ft/min or m/min
- K = 1.60 for English units or 1.0 for metric units

To obtain the net depth, assume an E_q between 55 and 67 percent, or an E_h between 65 and 77 percent.

(vii) Rate of irrigation coverage

The rate of irrigation coverage is a function of travel speed and tow-path spacing. Some useful rate of coverage formulas are:

$$\text{acres covered per hour} = \frac{W S}{726} \quad (\text{eq. 11-143})$$

$$\text{acres irrigated per 1/4-mile long run} = \frac{W}{33} \quad (\text{eq. 11-144})$$

(viii) Friction losses in hose and traveler

Hose-fed traveling sprinklers must have hoses that are long (typically 660 ft or 200 m), flexible, tough skinned, and capable of withstanding relatively high pressures. High-pressure traveler hoses are made in 2.5- to 5-inch diameters. They are several times more expensive than pipe and often have a relatively short life due to physical damage and difficulty of repair. Furthermore, the end pull required to drag a hose is approximately proportional to the square of the diameter. Therefore, as a rule of thumb, the relatively small diameter hoses are used for the discharge ranges in table 11-42.

The diameter of lay-flat hose increases by almost 10 percent under normal operating pressures. This gives the lay-flat hose about 20 percent more carrying capacity than the same diameter rigid plastic hose at the same friction loss gradient.

Table 11-43 gives estimated pressure losses for lay-flat hose operating at approximately 100 pounds per square inch (689 kPa). Friction loss can be estimated by equations 11-162 and 11-163 when the actual inside

Table 11-41 Recommended tow-path spacings for traveling sprinklers with ring (lower) and tapered (higher percentages) nozzles

Sprinkler wetted diameter	Percent of wetted diameter						
	50	55	60	65	70	75	80
	Wind over 10 mph		Wind up to 10 mph		Wind up to 5 mph		No wind
ft	ft	ft	ft	ft	ft	ft	ft
200	100	110	120	130	140	150	160
250	125	137	150	162	175	187	200
300	150	165	180	195	210	225	240
350	175	192	210	227	245	262	280
400	200	220	240	260	280	300	320
450	225	248	270	292	315	338	360
500	250	275	300	325	350	375	400
550	275	302	330	358	385	412	440
600	300	330	360	390	420	—	—

hose diameter during operation is known. The more rigid thick-walled plastic hoses do not lay flat and have calibrated inside diameters that are not changed appreciably by pressure. Equations 11-162 and 11-163 can be used directly to estimate friction head losses for plastic hoses.

The traveler vehicle can be powered by water turbines, water pistons, or engines. In determining system pressure requirements, the pressure head loss and

riser height of the traveler must be considered. This is especially true for turbine drive travelers when the pressure difference between the traveler inlet and sprinkler base typically exceeds 10 pounds per square inch (69 kPa). Manufacturers should provide friction-loss data for their travelers operation at various flow rates and travel speeds.

Sample calculation 11-17—System design for traveling sprinkler irrigation

Given:

- The 1/2-mile-long by 1/4-mile-wide 80 acre field with a well in the center shown in figure 11-13.
- Assumed irrigation efficiency of the low half: $E_n = 70$ percent
- Low winds ranging between 0 and 5 miles per hour
- Peak moisture-use rate 0.22 inch per day
- A corn crop to be grown on sandy soil on which the allowable application rate is 1 inch per hour and allowable moisture depletion is 3 inches

Table 11-42 Recommended hoses sizes for traveler sprinklers

Hose flow-rate range		Nominal inside diameter of lay-flat hose	
(gal/min)	(l/sec)	(in)	(mm)
Up to 150	Up to 10	2.5	64
100 to 300	6 to 19	3.0	76
260 to 600	16 to 38	4.0	102
400 to 750	25 to 47	4.5	114
500 to 1,000	32 to 63	5.0	127

Table 11-43 Estimated pressure head loss gradients for lay-flat irrigation hose operating at approximately 100 lb/in²

Flow rate gal/min	Nominal inside diameter (in)									
	2.5		3		4		4.5		5	
	Pressure head loss gradient per 100 ft of hose									
	lb/in ²	ft	lb/in ²	ft	lb/in ²	ft	lb/in ²	ft	lb/in ²	ft
100	1.6	3.7								
150	3.4	7.9	1.4	3.2						
200	5.6	12.9	2.4	5.5						
250			3.6	8.3	0.9	2.2				
300			5.1	11.8	1.3	3.1	0.6	1.4		
400					2.3	5.3	1.3	2.9		
500					3.5	8.1	2.1	4.8	1.1	2.5
600					4.9	11.3	2.7	6.1	1.6	3.7
700							3.6	8.2	2.1	4.9
800							4.6	10.5	2.7	6.2
900									3.4	7.9
1,000									4.2	9.7

- Irrigation over the field boundaries is both permissible and practical

Find:

- required sprinkler, nozzle, and operating pressures
- system layout
- pressure required at the hose inlet

Calculations:

The potential tow-path spacings for the 2,640-foot width of the field are:

Number of tow paths	Spacing (ft)
7	380
8	330
9	290
10	260
11	240

If two travelers are used, there should be an even number of tow paths. For the crop and soil conditions, no special consideration need be given to application rate or droplet impact. With an E_h equal to 70 percent and a peak moisture use rate of 0.22 inch per day the average gross depth of application per day during peak use periods must be d equals $0.221(70/100)$ equals 0.32 inch per day, and by equation 11-1, the system capacity must be at least:

$$\begin{aligned}
 Q &= 453 \frac{Ad}{fT} \\
 &= 453 \frac{(80)(0.32)}{(1)(23)} \\
 &= 504 \text{ gal/min} \quad (\text{eq. 11-145})
 \end{aligned}$$

From table 11-40, a 24-degree gun sprinkler with a 1.4-inch tapered bore nozzle will discharge 515 gallons per minute at 40 pounds per square inch and produce a 455-foot wetted diameter. From table 11-41, the tow-path spacing can be 76 percent of the wetted diameter in winds up to 5 miles per hour. For a 455-foot wetted diameter, this would be 340 feet. The nearest acceptable potential tow-path spacing for the design at hand is 330 feet. Thus, eight tow paths will be required as shown in figure 11-13.

It is desirable to have only one setup per day. Assuming an 8-day irrigation interval, the gross depth of water required per irrigation is 8 times 0.32 equals 2.56 in. From equation 11-142, the required travel speed is:

$$\begin{aligned}
 S &= \frac{1.605 q}{W d} \\
 &= \frac{(1.605)(515)}{(330)(2.56)} \\
 &= 0.98 \text{ ft/min} \quad (\text{eq. 11-146})
 \end{aligned}$$

The time required to travel the 1,320 foot length of each tow path is:

$$\frac{1,320}{(0.98)(60)} = 22.5 \text{ h} \quad (\text{eq. 11-147})$$

This is a reasonable design. In practice, the travel speed would probably be adjusted to as close to 1 foot per minute (0.305 m/min) as possible. This would decrease the depth of application slightly and reduce the travel time to 22 hours. A possible alternative is to limit the time to travel the 1,320 feet (402 m) to 23 hours by letting S equal 0.96 foot per minute. The required sprinkler discharge would then be:

$$\begin{aligned}
 q &= \frac{2.56(330)(0.96)}{1.605} \\
 &= 505 \text{ gal/min} \quad (\text{eq. 11-148})
 \end{aligned}$$

This agrees with the minimum system capacity (eq. 11-12).

An economic analysis using life-cycle costs was made assuming a hose life of 7 years and using the required sizes of travelers to drag the different sizes of hoses. The 4.5-inch-diameter hose proved to be the most economical size for the 515 gallons per minute (32.5 l/sec) design flow rate.

From table 11-33, the estimated pressure head loss gradient for the lay-flat irrigation hose is 2.1 pounds per square inch per 100 feet. Using equations 11-162 and 11-163 as a basis for interpolation, the expected pressure loss in a 660 foot hose at a flow rate of 515 gallons per minute (32.5 l/sec) is:

$$2.1 \left(\frac{515}{500} \right)^{1.75} \left(\frac{660}{110} \right) = 14.6 \text{ lb/in}^2 \quad (\text{eq. 11-149})$$

A turbine drive traveler was selected. According to the manufacturer's charts the friction plus drive turbine loss in the unit when traveling at 1 foot per minute will be 7.5 pounds per square inch (52 kPa). In addition the automatic shutoff valve has 3.5 pounds per square inch loss. The hose inlet pressure required for the traveling sprinkler is:

Sprinkler pressure	80.0 lb/in ²
Friction loss in hose	14.6 lb/in ²
Pressure loss in traveler	7.5 lb/in ²
Automatic shutoff valve	3.5 lb/in ²
Riser height (10 ft)	4.3 lb/in ²
Required hose inlet pressure	109.9 lb/in ²

System layout

Figure 11-13 shows a typical traveling sprinkler system layout. In the design and layout of traveling sprinkler systems, the general criteria that should be considered is:

- With unrestricted water supplies, it is usually desirable to design the system to operate at least 20 hours per day during peak-use periods.
- Traveling systems should normally be designed to require only one and at most two setups per day (travelers operate unattended until the end of a tow path is reached at which time the traveler and hose must be moved and setup for a new run in the next tow path).
- The maximum operating time should be 23 hours per day for systems requiring only one setup per day and 22 hours per day for two setups per day.
- Whenever possible, systems should be designed for the traveler to begin and end at the field boundary as shown in figure 11-13. Sometimes it is not advisable or practical to irrigate over the field boundaries at the ends of the tow paths, and the sprinklers must be started 160 to 200 feet inside of the field boundaries. In such cases, a better irrigation can be applied by allowing the traveling sprinkler to stand 1 hour at each end for once-a-day setups on quarter-mile tow paths,

and 30 minutes at each end for twice a day setups. For longer tow paths, this time should be increased and for shorter tow paths it should be increased in inverse proportion to the tow-path length.

- If practical, where prevailing winds exceed 5 miles per hour (8 kph), tow paths should be laid out so they do not line up with the prevailing wind direction.
- Tow paths should be laid out in the same direction as the rows, usually following the contours of steeply sloping fields.
- The actual application rate from full circle traveling gun sprinklers ranges from about 0.3 inch per hour for sprinklers discharging 300 gallons per minute (19 l/sec) to 0.6 inch per hour (15 mm/h) for 1,000 gallons per minute (63 l/sec) units. Therefore, where infiltration is apt to be a problem, a large number of low discharge sprinklers is preferable to a few large units.
- The width of the field should be divided by a series of integers to obtain a potential set of tow-path spacings provided that irrigation outside of the field boundaries is permitted (fig. 11-9). If it is not permissible to irrigate past the edges of the field, subtract the wetted diameter of one sprinkler from the width before dividing by the series of integers.
- The final design layout will be a compromise among these factors so that the number of tow paths is a multiple of the number of sprinklers; the spacing between tow paths gives reasonable uniformity under the expected wind conditions with the sprinkler nozzle size, angle of trajectory, and pressure selected; and the depth and frequency of irrigation fall within acceptable limits using one or two setups per day.

623.1110 Center pivot design

Center pivot irrigation machines are among the most popular systems for irrigating general field crops and are used on over half of the sprinkle-irrigated land in the United States, covering over 8 million acres. It is easy to efficiently irrigate many areas where surface or conventional sprinkle irrigation methods are not adaptable. Center pivot systems can apply light and frequent irrigations as needed to best fit crop water requirements and maximize production. This is practical because there is little labor associated with each irrigation. The applications can be scheduled without considering labor regimes or being tied to soil-moisture-holding capacity or content.

As with all irrigation machines, to reduce the cost per unit of area irrigated, it is advantageous to irrigate as large an area as possible with a minimum amount of equipment. In the case of center pivots, this is accomplished by irrigating as large a circle as possible because the cost of equipment is proportional to the radius, but the area irrigated is proportional to the square of the radius. The most common radius of center pivot machines is approximately 1,320 feet (400 m), which fits on a square 160 acre (65 ha) field commonly called a quarter-section in the United States.

The main factors to be considered in the design of center pivot irrigation systems are peak water use rate of the design area, system capacity, soil infiltration characteristics, sprinkler nozzle configuration, and system hydraulics. In ordinary practice, the system designer specifies the maximum required travel speed, hardware length, system discharge, nozzling configuration type, pipe diameter, and perhaps the available inlet pressure. The supplier provides the center pivot that meets the specifications. Ordinarily, the field engineer is not required to design the specific nozzle sizes or any mechanical aspects of the machine.

A step-by-step general design procedure is presented in this chapter in which special consideration is given to continuous-move systems. An outline of the first six steps of the procedure, which are known as the preliminary design factors, is illustrated in figure 11-13.

The main advantages of center pivot sprinkler irrigation machines are:

- Water delivery is simplified through the use of a stationary pivot point.
- Guidance and alignment are controlled relative to the fixed pivot point.
- Speed is set by the outside tower of the base circle.
- Relatively high water application uniformities are easily achieved with moving sprinklers.
- After completing one irrigation, the system is at the starting point for the next irrigation.
- Irrigation management is improved by accurate and timely application of water.
- Accurate and timely applications of fertilizers and other chemicals can be made in the irrigation water.
- Flexibility of operation aids in development of electric load management schemes.

These advantages eliminate the most difficult mechanical and operational problems associated with other types of self-propelled irrigation machines. Center pivots, however, have some definite disadvantages. As with all irrigation machines, to reduce the cost per unit area irrigated, it is advantageous to irrigate as large an area as possible with a minimum amount of equipment. With center pivot machines, irrigate as large a circle as possible since the cost of equipment is proportional to the radius, but the area irrigated is proportional to the square of the radius.

The most common radius of center pivot machines is 1,320 feet, which irrigates a 125- to 140-acre circular field, depending on how far water is thrown from the end sprinklers. From an irrigation standpoint, center pivots have disadvantages, such as:

- When the pivot point is in the center of a square field, only 125 to 132 acres of the 160 acre (65 ha) field will be irrigated. This leaves 20 percent of the area unirrigated unless special equipment is provided for the corners, which adds considerably to the system's cost (initial and maintenance) and complexity.

- The application rate at the outer edge of the irrigated circle will range between 1 and 8 inches per hour depending on the nozzle configuration.
- To reduce or eliminate runoff problems associated with these high application rates, light may need to be used, frequent applications on all but the most sandy soils or cracked clays. It may be necessary to operate faster than one revolution per day, which may not always be ideal for the crop or for the water use due to increased evaporation losses from frequently wet soil or crop canopy. Also, fast operation of the center pivot will lead to greater mechanical wear, usually requiring more frequent maintenance.
- Since the concentric band irrigated increases with each increment of radius, most of the water must be carried toward the end of the lateral, which results in high pipe friction losses.
- Elevation differences can be large between uphill and downhill lateral positions, resulting in wide variations in discharge unless pressure regulation and or flow control nozzles are used.

(a) System capacity

The required system capacity can be computed by equation 11–12. It is often desirable to compute the unit system capacity required for different water use rates. If a 7-day-per-week operation is assumed, equation 11–12 can be reduced to:

$$Q = \frac{453 Ad'}{T} \quad (\text{eq. 11-150})$$

or,

$$Q = \frac{R^2 d'}{30.6T} \quad (\text{eq. 11-151})$$

where:

- Q = required system capacity, gpm
- A = design area, ac
- d' = daily gross depth of application required during peak moisture use rate period, in
- R = maximum radius irrigated when a corner system, end sprinkler, or both is in operation ft
- T = average actual operating time, h/day

If a part circle machine is operated dry on the reverse leg, then the fraction of operating time, T, should be adjusted as:

$$T = \frac{0.9}{1 + \frac{\text{Speed}_{\text{wet}}}{\text{Speed}_{\text{dry}}}} \quad (\text{eq. 11-152})$$

where:

- Speed_{wet} = the speed of the end of the lateral during application of water, ft/min
- Speed_{dry} = the speed of the end of the lateral during the dry return, ft/min

The unit system capacity, in gallons per minute per acre, can be obtained by letting A equal 1. In metric units, equations 11–150 and 11–151 are:

$$Q = \frac{2.78Ad'}{T} \quad (\text{eq. 11-153})$$

or,

$$Q = \frac{R^2 d'}{1,146T} \quad (\text{eq. 11-154})$$

where:

- Q = l/sec
- A = ha
- d' = mm
- R = m
- T = h/day

Equation 11–151 is the better equation to use when an end gun or corner system is not operated full-time. In these situations, the system discharge must be sized for when the corner is fully extended, the end gun is on, or both. The use of equation 11–150 will underestimate the design system Q due to the design area being smaller than πR^2 .

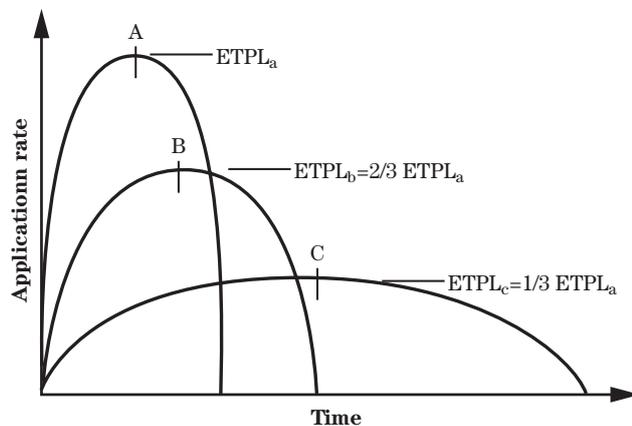
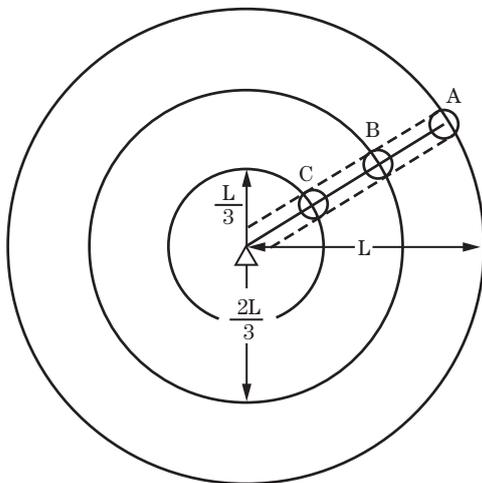
(b) Application intensity

The geometrical characteristics of the center pivot system are such that the application rate must increase with the distance from the stationary pivot point to obtain a uniform depth of application (fig. 11–70). As a result, the application rates, especially near the

moving end of the lateral, often exceed the infiltration capacity of moderate- to heavy-textured soils. The resulting runoff may severely reduce the uniformity of irrigation and cause considerable loss of water, energy, and crop production.

An elliptical water application rate pattern at right angles to the moving lateral is usually assumed as in figure 11-71. A stationary water application pattern can be transformed into a moving one by dividing the pattern base width by the speed of the pivot.

Figure 11-70 Water application rates at different points along a center pivot with uniform width of wetted strip

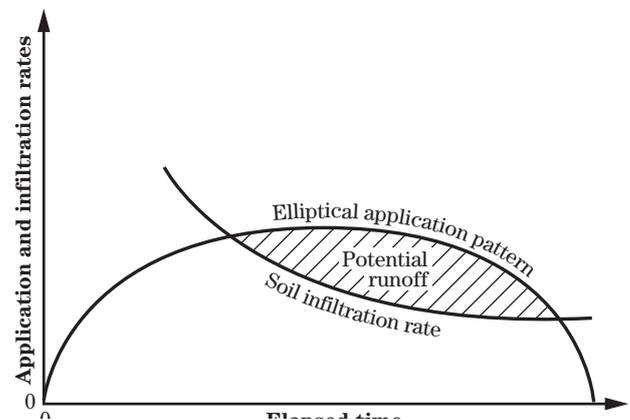


same stationary pattern and pivot speed, different moving patterns are obtained at different points along the lateral. The peak water application rate of the pattern is obtained by equating the area of the ellipse to the depth of water applied to the soil. Theoretically, the depth of water applied does not include the drift and evaporation losses; however, this is very difficult to control in practice.

(i) *Definition of ETPL*

A system parameter called ETPL can be used to simplify the analysis of field performance for transferring infiltration capacity evaluations. ETPL is the product of the gross peak daily water use rate (ETP) and the length of the pivot (L). A range of ETPL values from 11 to 66 square feet per day covers most of the practical combinations of ETP and L . As an example, for ETP equals 0.30 inch per day and L is a quarter mile, the value of ETPL is 33 square feet per day. The advantage of using the parameter ETPL can be demonstrated by referring to figure 11-50. The ETPL equals 33 square feet per day at the outer edge of the pivot, then ETPL equals 22 square feet per day along the circular path at two-thirds L and 11 square feet per day at one-third L . If the pivot were lengthened to 1,866 feet to irrigate twice as much area, the ETPL along the outer edge would be increased to 47 square feet per day. Analyses can be made of a few ETPL values to cover the entire range of application infiltration possibilities for different positions along system laterals designed for any conceivable climate, crop, and site.

Figure 11-71 Intersection between a typical elliptical pattern of water application rate under a center pivot and a potential infiltration curve



(ii) Application rate

Assuming that the application pattern under the sprinklers is elliptical, the average and maximum application rates at any location under the center pivot lateral are:

$$I = 2(K_u) \left(\frac{Q}{R^2} \right) \left(\frac{r}{w} \right) \quad (\text{eq. 11-155})$$

and,

$$I_x = \frac{8}{\pi} (K_u) \left(\frac{Q}{R^2} \right) \left(\frac{r}{w} \right) \quad (\text{eq. 11-156})$$

where:

- I = average application rate at any point r, in/h or mm/h
- r = radius from pivot to the point under study, ft or m
- I_x = maximum application rate at any point r, in/h or mm/h
- Q = system capacity, gpm or l/sec
- R = maximum radius irrigated by the center pivot, ft or m
- w = wetted width of the water pattern, ft or m
- K_u = 96.3 for English units, and 3,600 for metric units

The application rate is a function of geometric and irrigation demand factors and independent of the travel speed.

(iii) Infiltration rate

General soil infiltration characteristics for sprinkler systems are presented in table 11-5. The table values can often be increased by over 100 percent when applying light, daily irrigations with a center pivot sprinkler system.

Surface storage is important in minimizing runoff from center pivot systems. Pitting or diking implements can be used to increase surface storage. For example, assume daily irrigations of d' equals 0.30 inch are applied and 0.1 inch can be stored on the surface. Then, only 0.2 inch must be infiltrated while the system is overhead to prevent runoff. Potential values of surface storage are given in table 11-44.

Pitting or diking implements can be used to increase surface storage. More detail on surface storage is given in Keller-Bliesner (1990). Up to 0.1 inch (2 mm) of water can sometimes be intercepted and stored, temporarily, on plant foliage.

Many times, the greatest challenge in center pivot design and operations is to apply sufficient water to supply ET requirements, but with little or no surface runoff. Many soils have low infiltration capacities. These, coupled with the relatively quick application times near the outer spans of center pivot laterals present opportunities for runoff.

Soil infiltration capacity decreases with time, which allows center pivots to apply higher applications rates without runoff. Light, frequent applications take maximum advantage of this phenomenon. For example, in figure 11-72 the shaded portion suggests some surface ponding and depicts the potential runoff amount. This figure is for a given physical location under the pivot, and as the pivot moves past the location the (approximately) elliptical application pattern is traced out. If the system were speeded up, the peak of the application pattern would remain the same but the breadth (time) would decrease. This would decrease or even eliminate the potential runoff.

In many areas of the country, there are center pivot systems in place. Those systems that happen to be operating on similar types of soils and slopes should be observed by the designer to help gain an understanding of how the various soils in the area respond to the high intensity water application from center pivot systems. There is really no good substitute for field observations. Small exploratory field tests using single nozzles have difficulty in reproducing all of the conditions that will occur in the field, in particular the nature of vegetative cover, tillage history, soil crusting

Table 11-44 Potential values of surface storage

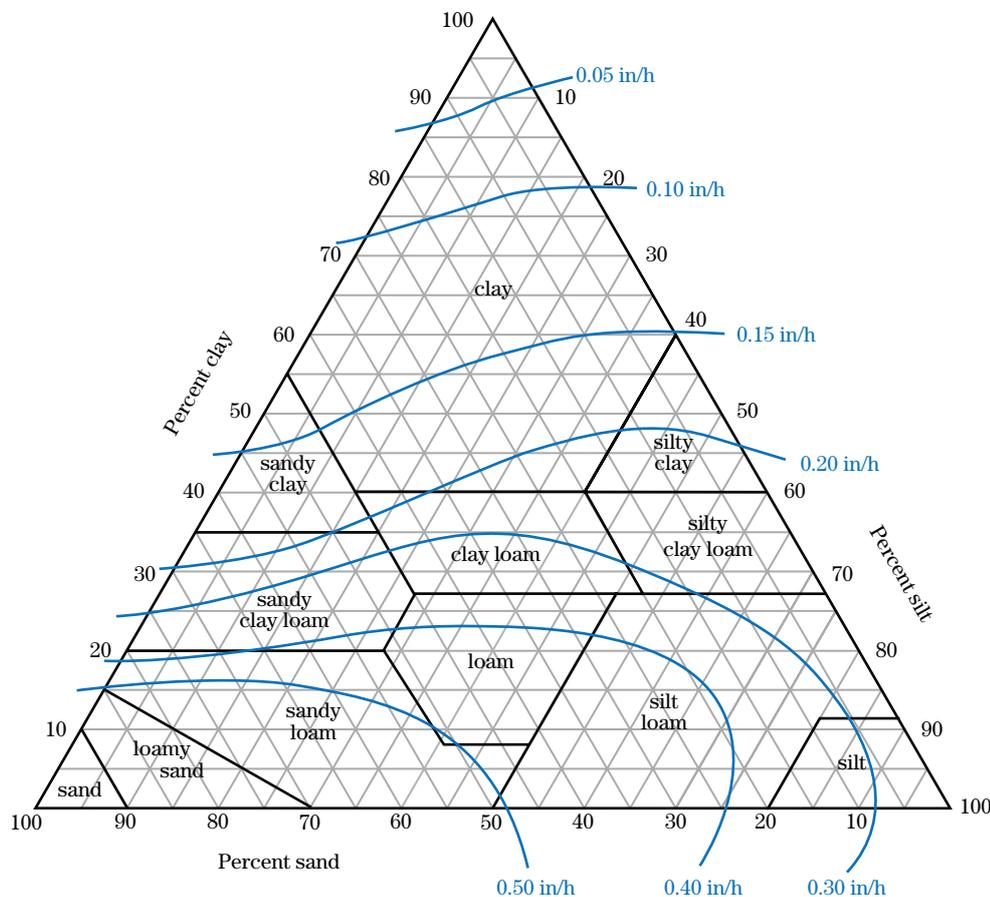
Slope (%)	Potential surface storage	
	(in)	(mm)
0-1	0.2	5
1-3	0.1	3
3-5	0.05	1.5

and sealing, and sprinkler intensity. However, these tests can be useful and are sometimes all the specific field information that a person has.

The peak application rate I of 4.8 inches per hour (120 mm/h) calculated in the previous practice example for the outer span of a center pivot lateral is much higher than that experienced for other types of sprinkler systems. However, this rate is typical under the moving end of center pivot laterals even in relatively mild climates. Such high application rates often cause runoff on all but the most permeable soils. To reduce the potential for runoff, surface storage SS , can be increased and/or light, frequent irrigation can be used. But the practical applications of these remedies are limited.

When field experience is not available for center pivot systems of various nozzling configurations, a guide can be used to identify potential runoff problems (fig. 11-72). In general, soils above the 0.3 inch per hour contour are questionable for center pivot irrigation; soils lying between the 0.3 and 0.6 inch per hour contour require careful design and management, and soils below the 0.5 inch per hour contour are ideal for center pivot irrigation. Additional and somewhat contradictory criteria are shown by the dotted lines. Figure 11-72 should only be used as a first approximation since factors other than soil texture affect the infiltration capacity of soils. Field measurements are always preferred to determine representative site-specific intake rates for center pivot design.

Figure 11-72 Soil triangle showing proportions of sand, silt, and clay for different soil textures, and approximate infiltration rate contours in in/h



(iv) Surface sealing

Field observations show that the surface seal or crust is important in the performance of the system. The soil seal is a thin, compacted layer between 5 and 30 millimeters thick, which is less permeable to water than the underlying layers. The two major factors involved in rearrangement of particles near the soil surface and development of the seal are surface puddling coupled with raindrop impact. These two factors rearrange the surface particles. Numerous studies have been conducted to investigate the problem of raindrop impact energy and soil surface sealing in relation to infiltration and runoff; however, no satisfactory quantitative relation has been established.

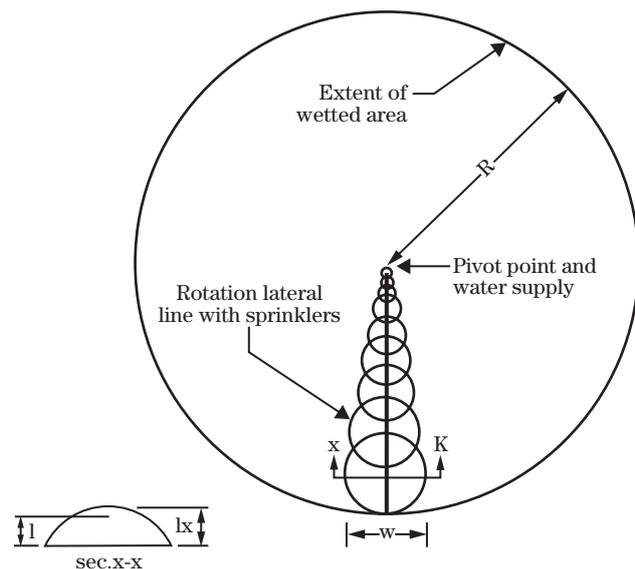
The hydraulic permeability of the soil surface seal is a function of drop diameter (fig. 11-22). Larger water drops travel farther because of their greater mass and velocity. As a result, drop size increases with the distance from the sprinkler. With impact sprinklers, a wider pattern is usually obtained by using sprinklers with relatively larger nozzle sizes operating at relatively higher pressures. Therefore, the water spectrum of such a pattern is usually made up of larger drops than are found in narrow patterns (fig. 11-21). For a given nozzle size, a change in pressure would affect the drop size distribution and the wetted diameter. Generally, as pressure increases, drop size decreases. Beyond a certain recommended operating pressure, however, the wetted radius or distance of throw also decreases as a result of the excessive reduction in drop sizes. Narrow patterns produced by a spray nozzle arrangement are usually made up of small drops. Many spray nozzle designs have been developed that increase drop size and distance of throw. This is especially important for low pressure nozzles where exit velocities from the nozzle orifices are low.

The ultimate consequence of raindrop impact is that the wetted radius produced by a sprinkler or nozzle can be used as an index to the average size of the drops produced by it. Therefore, the detrimental effect of the falling raindrops on the hydraulic permeability of the soil surface and the formation of a soil surface seal can be related to the wetted radius of the sprinkler pattern. High instantaneous application rates also contribute to sealing. As a rule, instantaneous rates increase proportionately with wetted radius unless pressures are abnormally high or low.

Various soils show different degrees of aggregate breakdown and surface sealing under falling raindrops. With coarse-textured soils, such as sands, surface sealing is usually not a problem because of good structural stability and the absence of very fine particles. However, surface sealing is often a problem on medium- and fine-textured soils with weak structures. Such soils are apt to collapse, settle, and have vertical movement of fine particles, thereby reducing permeability.

The wetted width, W , of the spray pattern influences the intensity of application for a given design discharge. The wetted width can be increased using spinners, wobbling, rotating types of spray nozzles or by using boom drops. Another way to reduce or prevent runoff is by reducing the rotation time by increasing the speed of the center pivot system. Lateral speed does not change the application intensity, but it does truncate the total time length of the application curve.

Figure 11-73 Watering characteristics of center pivots



(c) Sprinkler-nozzle configuration

The sprinkler-nozzle configuration used for most center pivot laterals is one of these:

- Uniform spacing of 30 to 40 feet between nozzles, with the discharge increasing in proportion to the distance from the pivot (fig. 11-73)
- Uniform sprinkler discharge, with the distance between nozzles decreasing from maximum allowable spacings near the pivot to 5 feet toward the end of the lateral in inverse proportion to the distance from the pivot
- A combination of both

Uniform spacing between outlets is most commonly used for simplicity of manufacture and ease of field assembly; however, when uniform sprinkler spacings are used, relatively large nozzles and high pressures are required. The high pressures result in high energy costs, and on delicate soils without cover, the droplets from the large nozzles may cause crusting land surface sealing.

To avoid the problems associated with the use of large nozzles, combination spacings are often used. A typical combination spacing strategy is to use a 40 foot sprinkler spacing along the first third of the lateral, a 20 foot spacing along the middle third and a 10 foot spacing along the last third of the lateral. Thus, the outlets can be uniformly spaced at 10 foot intervals along the lateral. To vary the sprinkler spacing merely close off some of the outlets with pipe plugs. Sprinklers are installed in every fourth outlet along the first third of the lateral, every other outlet along the middle third, and every outlet along the last third of the lateral.

The general strategy for selecting the nozzle sizes along a center pivot lateral is:

- Determine the discharge required from each sprinkler to apply a uniform application of water throughout the irrigated area.
- Determine the pressure available at each sprinkler outlet starting with a design pressure at the end.

- Select the appropriate nozzle size in accordance with equation 11-155 from the required discharge and available pressure.

(i) Sprinkler discharge

The sprinkler or nozzle discharge required at any outlet along a center pivot lateral can be computed by:

$$q_r = r S_r \left(\frac{2Q}{R^2} \right) \quad (\text{eq. 11-157})$$

where:

- q_r = sprinkler discharge required at r , gal/m or l/sec
- r = radius from pivot to outlet under study, ft or m
- S_r = sprinkler spacing at r , which is equal to half the distance to the next upstream sprinkler plus half the distance to the next downstream sprinkler, ft or m
- Q = system capacity, gpm or l/sec
- R = maximum radius effectively irrigated by the center pivot, ft or m

(ii) Sprinkler configurations

For the first 30 years of their existence, nearly all center pivots were equipped with overhead impact sprinklers discharging at pressures of 50 to 90 pounds per square inch. Beginning in the late 1980s, low pressure hanging nozzle systems came into usage. Today, nearly all center pivot systems are equipped with low pressure nozzles. Low pressure hanging nozzles are desirable for several important reasons:

- low pressure and energy requirement
- ability to suspend the nozzles close to the crop canopy
- reducing wind drift and evaporation losses

Manufacturers have developed nozzle systems having rotating streams that create large drops, increasing the throw distance, even under pressures as low as 10 pounds per square inch. Improvement in accuracy and consistency of pressure regulators on drops has allowed the use of low pressure nozzle systems with high uniformity.

The principle reason for using low pressure spray nozzles on a center pivot lateral is to conserve energy. However, if not designed properly, the desired energy (and water) savings may be more than offset by poor application efficiency because of excessive runoff, wind drift, and pressure variations due to elevation differences across sloping fields. The jets of many spray heads used on center pivots impinge on plates to divert the water and to produce a 360 degree wetting pattern. These nozzles may produce narrow pattern widths and consequently high application rates.

One of the challenges in using low pressure spray devices is to spread the application of water across a wider area and thereby reduce the intensity of the application rate. In the past, nozzles were sometimes mounted on horizontal spray booms. Usually, three or more spray nozzles were mounted on each boom. Horizontal booms are no longer used much in current center pivot design due to problems with wind, difficulty in maintaining angles between boom and lateral, and cost, in addition to the evolution of rotating spray devices that have larger wetted coverage. These spray devices have wetted diameters that can be in excess of 60 feet (18 m). Today, boom drops (also re-

ferred to as offset booms or boom backs) are typically used to broaden the width of coverage. Boom drops are created by angling a normal drop tube away from the lateral pipe at approximately 45-degree angles both fore and aft of the lateral (fig. 11-74). Only one nozzle is placed at the end of a boom drop. The placement of boom drops fore and aft of the center pivot lateral is generally done in an alternating manner. The drop conduit may be reinforced and held in place by a small truss system that extends down from the lateral pipe. In other applications, drop tubing may be suspended over lateral truss rods, except near drive towers, and held in place by clips.

Boom drops are relatively inexpensive and can be effective in reducing the intensity of water application. Boom drops are generally only used if there is a need to spread water further from the center pivot. Sometimes boom drops are only used on the outlets closest to towers so that the majority of soil wetting is done behind the wheels (fig. 11-75). However, in many cases, a part circle spinner type of nozzle suspended below the center pivot can provide better control of wheel slippage than an aft-oriented boom back having a full-circle nozzle.

Figure 11-74 Boom drops used along the outer spans of a center pivot to increase the wetted width



The decision to use boom drops depends on whether the cost for the booms with low cost spray heads is less than the higher cost for rotating spray heads having larger wetting width or if runoff occurs without the added width afforded by the boom drops. Generally, boom drops are used only on the outer portion of the center pivot lateral where the application rates are more intense.

Manufacturers are continually evolving the design of spray nozzles to increase the wetting width or to change the shape of the application profile. Table 11-44 gives approximate ranges of required operating pressures and associated widths of W by various classes of sprinkler and spray devices. Higher pressures are generally required by spray or sprinkler devices that obtain larger wetted widths.

Given the same discharge per nozzle, a nozzle that has the smaller diameter of W will have the largest application rate and intensity (fig. 11-76). The smaller diameters of coverage will be more prone to runoff. This should be a major consideration in the selection of the type and pressure of the spray or impact device.

Figure 11-77 illustrates a way of looking at the relationship between time of wetting and required application rate (intensity) for a given application depth. As the time of application is shortened, perhaps by using nozzles having smaller wetted diameter, that the application intensity must increase for the same depth of application.

The discharge capacity of a center pivot, Q_s , does not substantially change with the type of spray or sprinkler device, because it is tied to the daily water use requirement, as given by equations 11-150 and 11-151. Therefore, when selecting the spray or sprinkler device, the application intensity must increase in proportion to any reduction in W (figs. 11-76 and 11-77). One important realization to make with center pivots is that once a particular nozzle package, pressure, and nozzle size have been selected, the application intensity and peak application rate for the system is fixed and will not change with change in speed of the center pivot lateral. The fixed spacing of nozzles along a center pivot later can produce narrow pattern widths near the pivot, due to small stream diameters and can produce high application rates near the end of the lateral, depending on the spacing, as seen in equations 11-155 and 11-156. Their use is limited to high infiltration

Figure 11-75 Boom backs behind center pivot towers

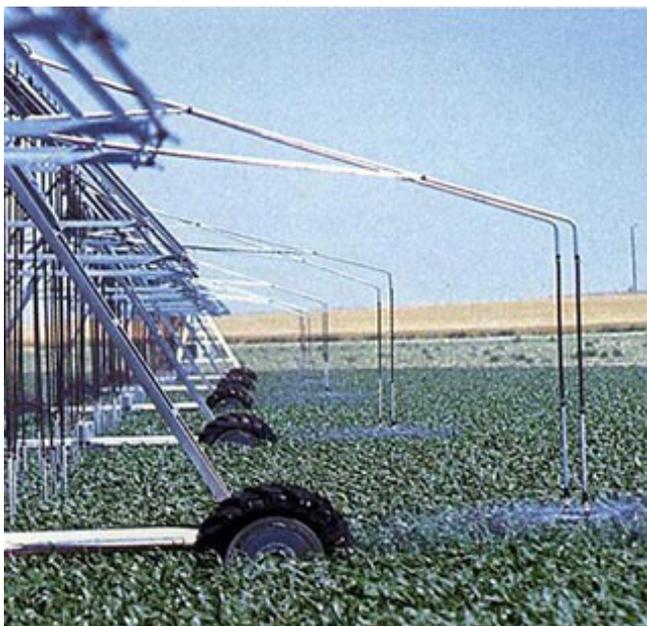


Figure 11-76 Relationship between width of wetted coverage (W) and application intensity for the same discharge rate

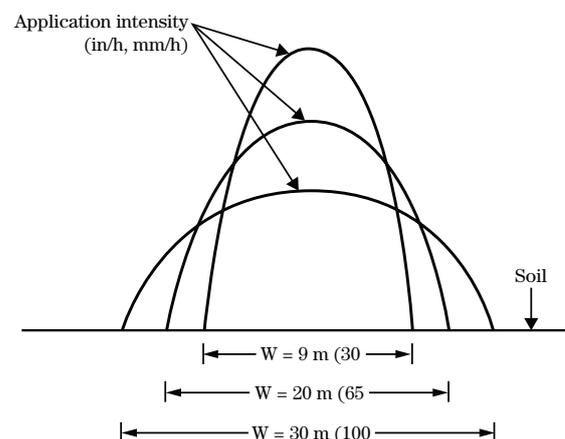


Table 11-45 Ranges of normal operating pressures and associated pattern widths for different sprinkler type and spacing configurations most commonly used on center pivot laterals.

Sprinkler type and spacing configuration	Pressure range ^{1/}		Pattern width range ^{2/}	
	(lb/in ²)	(kPa)	(ft)	(m)
Low-pressure spray: ^{3/}				
1. Single-row drop ^{4/}	6–40	40–280	10–35	3–11
2. Single-row top	10–40	70–280	20–40	6–12
3. On-boom drops	6–40	40–280	20–55	6–17
Low-pressure spinners: ^{3/}				
4. Single-row drop	10–30	70–210	25–50	7–16
5. On-boom drops	10–30	70–240	30–65	10–20
Low-pressure rotating or wobbling sprays: ^{3/}				
6. Single-row drop ^{4/}	15–40	100–300	50–70	15–21
Low-pressure impact: ^{5/}				
7. Variable spacing	20–35	140–240	60–75	18–23
8. Semiuniform spacing	30–40	205–275	70–80	21–24
Medium-pressure impact:				
9. Variable spacing	40–50	275–345	90–110	27–34
10. Semiuniform spacing	40–55	275–380	100–120	30–37
High-pressure impact:				
11. Uniform spacing	55–65	380–450	130–160	40–50
LEPA (Low Energy Precision Application):				
12. Uniform spacing	6–10	40–70	point	point

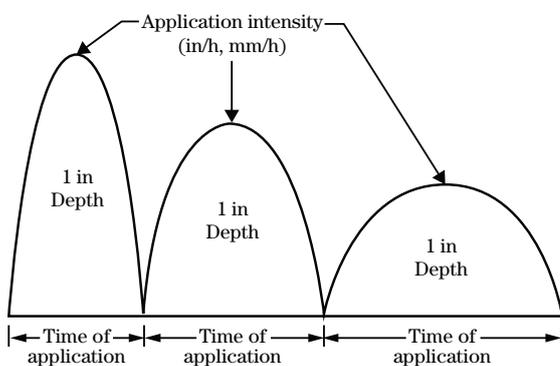
1 Values are sprinkler or boom inlet pressures that include typical pressure regulator losses at the high end of the range.

2 Pattern width (diameter) with full-circle devices at the moving end of lateral with L = 1,300 ft (400 m).

3 For all sprayers the range depends on height of sprayers above crop, configuration of spray plate, and pressure.

4 Sprayers on drops should be at least 3.3 ft (1 m) above the crop.

5 These sprinklers have nozzles that diffuse the jets for better breakup and distribution.

Figure 11-77 Relationship between required application intensity and time of application for the same depth of application

soils or to nearly level fields with good potential for surface water storage. Spray nozzles tend to produce small drops that cause less surface sealing than impact sprinklers, but can be more subject to high wind drift losses if high above the crop. Some spray nozzles are available that produce coarser sprays to reduce wind drift problems. While low pressure is an advantage of spray nozzles in terms of energy use, care must be exercised to avoid water distribution problems caused by sensitivity to pressure changes resulting from lateral rotation over uneven topography unless precision, individual pressure regulation is used.

With impact sprinklers, the large nozzles used for uniform spacing produce a wide pattern and coarse drops toward the end of the lateral. The wide pattern gives a relatively low application rate, but due to drop impact surface sealing reduces the soil infiltration capacity and runoff becomes a problem on many soil types.

The combination spacing with rotating sprinklers is perhaps the best compromise for most soils. Where soil sealing and infiltration rate are likely to be problems, relatively low pressures can be used to save energy. For soils that are more difficult to manage, higher pressures should be used. On undulating topography, where pressures vary because of elevation changes, flexible orifice nozzles on impact sprinklers and pressure regulators on drops can be used to maintain the desired discharge.

(iii) Height above the ground

The height of the nozzle above the ground affects the diameter of wetted coverage. The higher the nozzle, the longer the travel time for the drops and the larger

the diameter. However, the higher the nozzle, the more opportunity for distortion of the spray or sprinkler pattern by wind. Higher heights provide larger w for the same nozzle type and size, and therefore, the overlap percentage is increased and the uniformity of water application along the lateral is improved. A variety of figures and guidelines are available from manufacturers. Table 11–46 shows recommended maximum nozzle spacings for low-pressure spray devices for a 6 foot height. This table provides an indication of the impact of nozzle pressure on spacing distance.

An important reason to reduce the elevation of spray nozzles above the canopy is to reduce wind-caused drifting of water droplets and localized evaporation losses. Water losses from droplet evaporation from spray heads near the top of the canopy typically range from only 0 to 2 percent, wind drift is usually less than 5 percent, evaporation from crop canopy may range from 4 to 8 percent, and soil evaporation following the wetting event will often less than 5 percent when under full canopy cover. Spray heads and impacts mounted on top of the center pivot lateral may have droplet evaporation and wind drift losses as high as 15 percent. It should be recognized that local evaporation of water droplets will cool and humidify the air boundary layer so that total ET demands of the boundary layer are reduced for some distance downwind of the center pivot lateral, for example, up to several hundred meters. If the downwind area is within the same field or farm, then the ET reduction should be counted as a benefit against the evaporation loss near the center pivot lateral, although the compensation is less than a 1 to 1 ratio due to mixing of some vapor upward into the atmosphere. The evaporation of free water from a wet canopy also reduces the transpiration demand from the crop, due to the limitation of total energy for evaporation. However, the evaporation will tend to be greater than the reduction in transpiration by as much as 10 to 20 percent, especially in arid climates. For spray irrigation on drops over a crop with a full canopy, application efficiencies of about 90 to 92 percent are attainable if there is no surface runoff, whereas sprinklers on the top of the pipe may attain efficiencies from 80 to 85 percent.

(iv) Within-canopy sprays

Often, application uniformity suffers under specific crop or tillage conditions, such as for within canopy spraying, where nozzles are at heights less than the height of the crop. This is common for tall crops such

Table 11–46 Recommended maximum nozzle spacings (feet) for spray devices at 6 foot height (Kincaid 1996)

Type of spray device	Pressure (lb/in ²)			
	10	15	20	30
Fixed-plate sprays	6	8	8	10
Rotator—four-groove	8	10	12	14
Rotator—six-groove	8	10	12	14
Wobbler—low angle	12	14	14	16
Wobbler—high angle	14	16	16	18

as corn. Under these conditions, spray trajectories are intercepted and shortened by plant leaves. Therefore, the effective overlap and wetted coverage are reduced. In these circumstances, the lateral extent of plant roots defines the scale on which the impact to uniformity should be defined. The NRCS Conservation Practice Standard 442 (CPS 442) recommends, for low pressure in canopy (LPIC) and mid-elevation-spray-application (MESA) systems, that nozzle spacing not exceed every other crop row and that in-canopy heights avoid areas of high leaf concentration, for example near corn ear height.

Under some systems, such as LEPA systems, the start-stop motion of individual towers can cause variation in inflow time to individual dikes or reservoirs. Under these types of situations, the uniformity tends to improve over the course of several irrigations due to randomness of start-stop, unless there is some deep percolation. CPS 442 recommends that nozzle spacing of LEPA systems not be greater than two times the row spacing of the crop, not to exceed 80 inches.

For above-canopy sprinklers and nozzles, CPS 442 recommends that from a point midway between the first and second tower to the distal end of a center pivot, spray nozzle spacing along lateral lines must not exceed 25 percent of the effective wetted diameter and impact sprinkler spacing must not exceed 50 percent of the effective wetted diameter.

(v) Selecting the nozzle type to avoid runoff

The distance traveled by each sprinkler along a center pivot lateral is equal to $2\pi r$, where r is the radial distance of the sprinkler (or spray nozzle) from the pivot point. The application rate must increase with increasing r to obtain a uniform application depth. Even given identical widths of w along a center pivot lateral, because the lateral is traveling faster toward the end, the opportunity time for application is reduced. The reduction is proportional to the speed of the lateral, which is proportional to the distance, r , from the pivot. Because the same depth of water is applied all along the center pivot, and because application depth equals the application rate multiplied by opportunity time (i.e., mm/min multiplied by minutes = mm), then as the speed increases toward the outer spans of the lateral, the application rate must necessarily increase. This is demonstrated in figure 11–70 for a center pivot lateral using variably spaced sprinklers that produce a uni-

form wetted width. The areas under the three curves are all the same, and represent the depth of water applied each pass.

(vi) Time of wetting

Often it is useful to calculate the minutes of wetting time at various locations along the lateral. Wetting time, coupled with application rate intensity can be useful in predicting whether runoff may occur on specific soils. The wetting time at any radius r from the pivot point can be calculated as:

$$t_{\text{wet}} = \frac{w}{\text{Speed}_r} \quad (\text{eq. 11-158})$$

where:

- t_{wet} = time that any point on the soil surface at radius r gets wet, min
- w = wetted width (diameter) of nozzle pattern at r , ft or m
- Speed_r = speed of the lateral at radius r , ft/min or m/min

Speed can be calculated knowing the rotation time of the center pivot and the distance r :

$$\text{Speed}_r = \frac{2\pi r}{60 t_{\text{rotation}}} \quad (\text{eq. 11-159})$$

where:

- t_{rotation} = time required for one rotation of the center pivot system, h
- r = radius from the center pivot to point r , ft or m

Sample calculation 11–18—System capacity, application rate, and wetting time for a center pivot system.

Given:

- A center pivot is to apply an application depth of 0.31 inches per day (8 mm/day).
- A spray nozzle having a diameter of w of 30 feet is used.
- The center pivot rotates once each 22 hours at the typical maximum wet speed.
- Two hours per day are reserved for downtime during the peak water use period.

- The total irrigated area has a radius of 1,270 feet.

Find:

- system discharge
- wetting time of the application at some point at a radius of 1,000 feet and at the end
- peak application intensity at 1,000 feet and at the end

The discharge for the center pivot can be calculated using equation 11-150 using the gross application depth per day and the total irrigated area. For an irrigated radius of R equals 1,270 feet, the basic circular irrigated area is:

$$\begin{aligned} A &= \pi \frac{R^2}{43,560} \\ &= \frac{(1,270^2)}{43,560} \\ &= 116.3 \text{ acres} \end{aligned}$$

for T = 22 h/d:

$$\begin{aligned} Q &= 453 \frac{Ad'}{T} \\ &= 453 \frac{116.3(0.31)}{22} \\ &= 742 \text{ gal/min} \end{aligned} \quad (\text{eq. 11-160})$$

Using equation 11-151:

$$\begin{aligned} Q &= \frac{R^2 d'}{30.6 T} \\ &= \frac{1,270^2 (0.31)}{30.6 (22)} \\ &= 742 \text{ gal/min} \end{aligned} \quad (\text{eq. 11-161})$$

The peak application rate at r = 1,000 feet is then, from equation 11-156:

$$\begin{aligned} I_x &= \frac{8K_u}{\pi} \left(\frac{Q}{R^2} \right) \left(\frac{r}{w} \right) \\ &= \frac{8(96.3)}{\pi} \left(\frac{742}{1,270^2} \right) \left(\frac{1,000}{30} \right) \\ &= 3.76 \text{ in/hr} \end{aligned} \quad (\text{eq. 11-162})$$

The speed of the center pivot lateral at 1,000 feet from the pivot is:

$$\begin{aligned} \text{Speed}_{1000} &= \frac{2\pi r}{60 t_{\text{rotation}}} \\ &= \frac{2\pi(1,000 \text{ ft})}{(60 \text{ min/h})(22 \text{ h})} \\ &= 4.8 \text{ ft/min} \end{aligned} \quad (\text{eq. 11-163})$$

The wetting time (this is also the infiltration opportunity time) for a nozzle at 1,000 feet is:

$$\begin{aligned} t_{\text{wet}} &= \frac{w}{\text{Speed}_r} \\ &= \frac{30 \text{ ft}}{4.8 \text{ ft/min}} \\ &= 6.3 \text{ min} \end{aligned} \quad (\text{eq. 11-164})$$

At the far (downstream) end of the lateral, r is 1,270 feet, and,

$$\begin{aligned} I_x &= \frac{8K_u}{\pi} \left(\frac{Q}{R^2} \right) \left(\frac{r}{w} \right) \\ &= \frac{8(96.3)}{\pi} \left(\frac{742}{1,270^2} \right) \left(\frac{1,270}{30} \right) \\ &= 4.8 \text{ in/hr} \end{aligned} \quad (\text{eq. 11-165})$$

The speed at the far end of the lateral (r = 1,270 ft) is:

$$\begin{aligned} \text{Speed}_{1270} &= \frac{2\pi(1,270 \text{ ft})}{(60 \text{ min/h})(22 \text{ h})} \\ &= 6.05 \text{ ft/min} \end{aligned} \quad (\text{eq. 11-166})$$

The time of wetting at the end is:

$$\begin{aligned} t_{\text{wet end}} &= \frac{30 \text{ ft}}{6.05 \text{ ft/min}} \\ &= 5.0 \text{ min} \end{aligned} \quad (\text{eq. 11-167})$$

The depth of water reaching the soil does not include the drift and evaporation losses (from the droplets); however, this is difficult to measure or calculate in practice. Figure 11-78 shows the solution to equation 11-155 for r equals 1,300 feet (i.e., at the end of a quarter-mile-long lateral) and as a function of the system

capacity expressed as gallons per minute per acre (as Q/A) and for a range of wetted diameters, w .

(d) End gun and corner system operation

In the 1970s, when energy costs were less, end guns were commonly used to extend the length of the center pivot coverage. The annual cost for energy was less than the annual cost of ownership of the additional lateral pipe that the end gun replaced. Since the 1990s, however, energy costs have grown proportionately greater, and often, the annual cost of ownership for an additional span of lateral pipe is less than the costs for energy to pressurize and operate the end gun. Therefore, end guns became less common for extending the base circular area. They are, however, still commonly used to increase the irrigated areas of corners of fields.

In areas where land prices are high, corners of fields are generally irrigated. In areas where land is plentiful, but water supplies are limited, often corners of fields are left unirrigated and more fields are placed under production. When corners are to be irrigated, the question is whether the cost for the corner system or end gun, and pump, electricity, and perhaps pressure regulators is offset by the increase in crop production from the extra land irrigated.

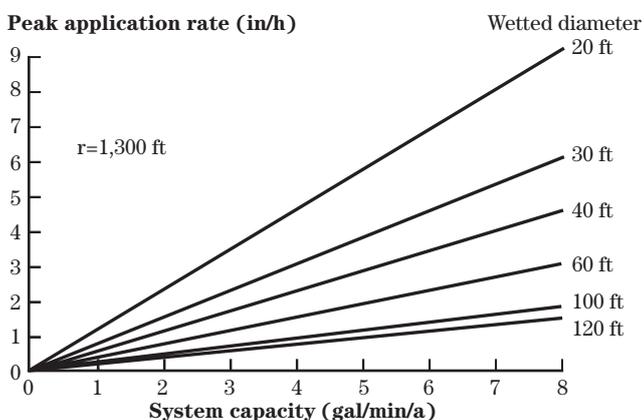
Examples of typical end gun installations are shown in figure 11–79. The way that connections are plumbed varies with manufacturer. Often, low-pressure systems that use spray, spinner, or rotator nozzles require booster pumps to create sufficient pressure to operate the end gun.

End gun pressures should be at least 50 pounds per square inch (345 kPa) and preferably above 65 pounds per square inch (450 kPa). The recommended pressure depends on nozzle size and type, as well as on soil, crop, and wind characteristics. To achieve the necessary pressure, a booster pump mounted on or next to the last drive unit is often used. The pump increases the pressure to the end gun. With medium- and high-pressure sprinkler configurations, a booster pump may not be required. The calculations for pressure at the pivot point and the specific nozzling package should be based on when the end gun is operating.

Intermittently operated end guns and corner systems on center pivot laterals generally require the use of pressure regulators on all nozzles, because turning on the end gun or corner system will reduce pressure along the lateral due to increased friction and the pump operating point for the system will change. Both effects will reduce lateral pressure. The friction loss and pump operating point should be evaluated with and without the end gun or corner system operating. This will then provide an indication of the change in pressure at the lateral pivot point. The need to consider the impact of intermittent end gun operation on nozzle discharge is even more important when the system is being used for chemical application (fertilizers, herbicides, and pesticides).

A challenge with end gun and corner system operation occurs when the water supply is by canal delivery where the delivery is fixed over periods of 24 to 48 hours. In these situations, the water delivery rate must be sufficient to meet the maximum discharge of the system, which occurs when the corner or end gun are fully on. This means that water must be spilled when the corner and end gun are turned off. Otherwise, temporary storage must be supplied upstream of the pressurization point. The storage volume must be at least the product of the discharge of the end gun times t_{rotation} divided by 8 where t_{rotation} is the rotation time of the system. The one-eighth factor assumes that the corner or end gun system are turned off about half of the time. With the temporary storage, the water

Figure 11–78 Peak application rate for a center pivot for $r = 1,300$ ft as a function of the system capacity expressed as gal/min per acre (as Q/A) and for a range of w



delivery rate should be sized to supply the average discharge of the system during the t_{rotation} . That average discharge will be between the base circle discharge rate and the maximum discharge rate, depending on the on and off percentages.

The high application intensity of big gun systems can be of concern. Large drop size and velocities can cause erosion and crusting of the soil surface, causing reduction in infiltration capacity and soil structure, and increasing the potential for runoff. An additional consideration in the determination of installing a corner or end gun systems is whether the water supply is sufficient to support the additional discharge requirement.

The use of end guns in the four corners of fields can increase the irrigated area by about 9 acres for an effective radius of throw by the end gun of 75 feet and by about 11 acres for an effective radius of throw of 120 feet. These additions are equivalent to about 7 and 9 percent of the base circle for a quarter-mile-base lateral. Single swing arm corner systems can typically add 20 acres to a quarter-mile lateral base circle, or

16 percent increase in irrigated area, increasing the irrigated area of a 160 acre field from the 125 acre base circle (79% of a square field) to about 145 acres (91% of a square field). Articulated corner systems can irrigate even more of the corner areas, up to about 95 percent of a square field.

The advantage of increased irrigated area by corner systems must be balanced with the additional cost and operating complexity of these systems. Nozzles on corner systems require individual solenoids and valves for sequencing according to the angle of the corner arm. Either buried cable systems or GPS systems are needed for guidance. Often, corner systems are as long as 270 feet, including an overhang past the drive wheels, to maximize the additional irrigated area. However, these relatively long span lengths are heavy when filled with water, placing a large load on the drive wheels. Dual wheels or other flotation means may be required to avoid the creation of deep wheel tracks and traction problems. Because the outer end of a center pivot lateral is the area of highest application, it will typically be the area having highest runoff potential. Runoff is

Figure 11-79 Example center pivot end gun installations where the pump, valve, and end gun are short-coupled at the end of the lateral (left side), and an end gun on a corner system (right side)



often intercepted by wheel tracks, which softens the tracks, increasing the potential for deep rutting and loss of traction.

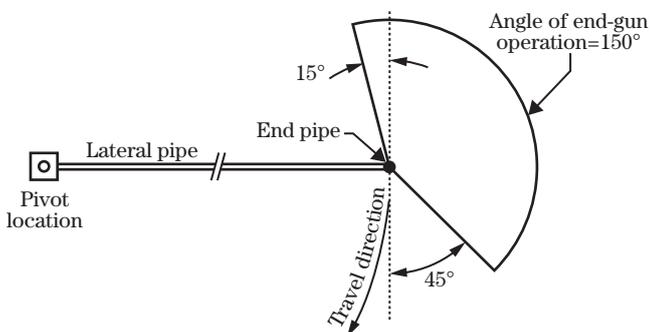
In some situations, the irrigated area can be extended sufficiently by using large impact sprinklers, for example, twin impact sprinklers with shaped five-eighths inch nozzles, as shown in figure 11–8, rather than end guns. Using impact sprinklers results in a smaller irrigated area as compared to with end guns, but the need for a booster pump is often eliminated and the impact on system discharge and pressure variation during intermittent operation is greatly reduced.

End gun systems are operated as a part circle, as shown in figure 11–80. An arc of about 15 degrees is made into the base circle area to augment the distribution pattern of the last nozzle span and an arc of about 135 degrees is made outside of the base circle to provide the most uniform distribution of water to that area. Many, but not all, end guns are set up this way.

Sizing of the end gun is normally determined by the manufacturer as a part of the specification of the nozzling package. However, these equations should be applied as a check on manufacturer calculations. The radius, R , of the irrigated area created by a center pivot system with an end gun operating can be estimated as:

$$R = L + 0.75 R_g \quad (\text{eq. 11-168})$$

Figure 11–80 Top view of end gun sprinkler wetting pattern showing recommended angle of operation



where:

R_g = radius of throw for the end gun

Because R_g may be reported by the manufacturer as the maximum throw under low wind conditions, the outer 25 percent of this radius may not have sufficient water application to produce a crop, so it may not even be planted. Therefore, the 0.75 reducing coefficient is applied. Values for R_g change with pressure and nozzle size and are available from sprinkler manufacturers.

For corner systems, the maximum radius R of the irrigated area is:

$$R = L + R_c \quad (\text{eq. 11-169})$$

where:

R_c = length of the corner system when fully extended

There is usually still some angle (less than 180°) of the corner system relative to the base lateral, even when the corner system is fully extended. For corner systems having end guns, the maximum radius, R , of the irrigated area is:

$$R = L + R_c + 0.75 R_g \quad (\text{eq. 11-170})$$

The discharge of an end gun, or corner system and end gun, on a base circle can be estimated as:

$$Q_g = 1.1 \left(\frac{R^2}{L^2} \right) Q_b \quad (\text{eq. 11-171})$$

where:

Q_g = required discharge from the end gun or fully extended corner system, gpm or l/sec

R = radius of area sufficiently irrigated when end gun (and/or corner system) is in operation, ft or m

L = length of lateral or radius irrigated in the basic circle when the end gun (and corner system) is not operating, ft or m

Q_b = design discharge for the base circle having radius L , gal/m or l/sec

Q_b is calculated from equation 11–150, when area, A , is computed using radius equals L , where L is the length

of the lateral or from equation 11–150 with R set equal to L. The 1.1 coefficient in equation 11–171 compensates for the amount of end gun discharge that will extend beyond R as computed in equation 11–168, and for generally poorer distribution uniformity of the end gun area. This coefficient can be reduced to 1.0 if only a corner system is used and is designed and operated to have high distribution uniformity. The end gun flow rate can also be computed as:

$$Q_g = 1.1 \left(1 - \frac{L^2}{R^2} \right) Q \quad (\text{eq. 11-172})$$

where:

Q = maximum system capacity, gpm or l/sec when the end gun, corner system, or both are fully on

Q is calculated from equations 11–150 or 11–151 using radius R representing the radius of the area sufficiently irrigated when end gun (and/or corner system) is in operation.

The question often arises on whether the application efficiency (AE) of the end gun should be adjusted from the value used to design the base pivot. Several factors come into play.

If there is any runoff from the end gun, then AE would definitely suffer and could be adjusted as:

$$AE_{\text{gun}} = AE_{\text{base}} - \text{fraction of runoff}$$

Less evaporation of water droplets due to the larger droplet size of the gun might occur, in which case AE might improve by one to two percent.

Conversely, more evaporation of water droplets from the gun might occur because the droplets remain suspended much longer in the air, due to the large flow and upward trajectory; in this case, AE might degrade by one to five percent.

The application uniformity of the end gun may be poorer than the base circle. In this case, the AE_{gun} should be reduced from that of the base.

When an effective radius is used to define the added acreage under the gun. The effective radius impacts AE in two ways:

- Any sprinkling outside the effective radius, assuming that it is not farmed, should probably be considered as a loss to the system and subtracted from AE.
- The uniformity of the gun coverage should be computed using the effective radius area. Therefore, the larger the effective radius estimate, the poorer the uniformity, due to incorporation of areas receiving less application, but the smaller the lost part of the stream beyond the radius.

All of these factors are important. When the aggregate effect is considered, the application efficiency for the gun could probably be set at about 10 percent less than the application efficiency used for the base pivot. One caveat, however, is that manufacture may have already increased the discharge of the gun, during design or sizing, relative to the base gallons per acre to incorporate an implied lower application efficiency value.

Using a different value for the end gun places more burdens on the user to develop the application efficiency and more importantly, the acreage or discharge proportions during the preliminary and final design phases.

The added acreage of the gun might be small enough that, when multiplied by the difference in AE, it is smaller than the uncertainty in the base (or system wide) AE. If this is the case, then there is probably no reason to attempt to incorporate it.

(e) Lateral friction loss

The pipe friction loss for a center pivot lateral can be computed as:

$$(h_f)_{\text{cp}} = 10.50FR \left(\frac{Q}{C} \right)^{1.852} D^{-4.87} \quad (\text{eq. 11-173})$$

where:

$(h_f)_{\text{cp}}$ = total friction loss along the center pivot lateral at maximum discharge, ft (m) F
= reduction coefficient for multioutlet center pivot laterals (F = 0.555 for center pivot laterals that have a large number of uniformly increasing discharges)

- R = maximum radius, ft (m), of the irrigated area, when the end gun, corner system, or both are fully on
- Q = system design discharge for when end gun, corner system, or both are fully on, gpm (lps)
- C = Hazen-Williams friction coefficient (table 11-21)
- D = inside diameter of the lateral pipe, in (mm)

This procedure can be expressed in a single formula for systems with end guns as:

$$(h_f)_{\text{cpg}} = 5.8R' \left(\frac{Q}{C} \right)^{1.852} D^{-4.87} \quad (\text{eq. 11-176})$$

where:

$$R' = R - (R - L) \left(1 - \frac{L^2}{R^2} \right)^{1.852} \quad (\text{eq. 11-177})$$

The 10.50 factor becomes $1.21 \times (10)^{10}$ for metric units where $(h_f)_{\text{cp}}$ and R are in meters, Q is in liters per second, and D is in millimeters. Combining the units factor and F results in a version of the friction loss equation which is unique to center pivots:

$$(h_f)_{\text{cp}} = 5.8R \left(\frac{Q}{C} \right)^{1.852} D^{-4.87} \quad (\text{eq. 11-174})$$

The Hazen-Williams friction coefficient, C, usually is taken as 135 to 145 for galvanized steel used in center pivot lateral pipes, and 145 to 150 for epoxy-coated steel. Typical values for C for other materials are listed in table 11-47. Standard inside diameters of center pivot lateral pipe are listed in table 11-48.

Equation 11-248 assumes that there is uniformly increasing discharge per unit length along the pipe that is in proportion to the radius of the irrigated area. For ordinary end guns, the maximum irrigated radius (R) is used in the equation to compute $(h_f)_{\text{cp}}$. When a large end gun discharge, in proportion to the discharge of the base circle (plus any corner system), is used, then the artificial friction loss along the r_g length (from L to R) can be subtracted from $(h_f)_{\text{cp}}$ as:

- Determine $(h_f)_R$ with R representing the maximum radius of the system, with corner system and/or end gun fully on.
- Determine $(h_f)_{LR}$ by letting Q be the discharge of the end gun (q_g) and R is equal to $0.75 r_g$ where r_g is the radius from the end of the pivot, including the extended corner system, to the end of the throw of the end gun. Finally,

$$(h_f)_{\text{cp}} = (h_f)_R - (h_f)_{LR} \quad (\text{eq. 11-175})$$

Table 11-47 Typical values for the Hazen-Williams friction coefficient, C

Pipe material	C
Plastic, PVC, PE	150
Epoxy-coated steel	145-150
Polyethylene-lined steel	135-145 ^{1/}
Cement asbestos	140
Galvanized steel	135-145
Aluminum (with couplers every 30 ft)	120-130
Steel (new)	130
Steel (15 years old) or concrete	100
Butyl rubber drop tubes	150
Rigid drop tubes	145

1 With polyethylene-lined steel pipe having bulk head fittings at each outlet and with outlets spaced each 30 inches, the C value may decrease to 135 due to the added roughness elements.

Table 11-48 Typical values for inside diameters, D, of center pivot lateral pipe

Nominal diameter (in)	Approx. inside diameter	
	(in)	(mm)
5-9/16	5.318	135
6	5.755	146
6-5/8	6.375	162
8	7.755	197
8-5/8	8.375	213
10	9.755	248

where:

- R = radius of area sufficiently irrigated when end gun (and corner system) is in operation, ft or m
- L = length of lateral or radius irrigated in basic circle when the end gun (and corner system) is not operating, ft or m

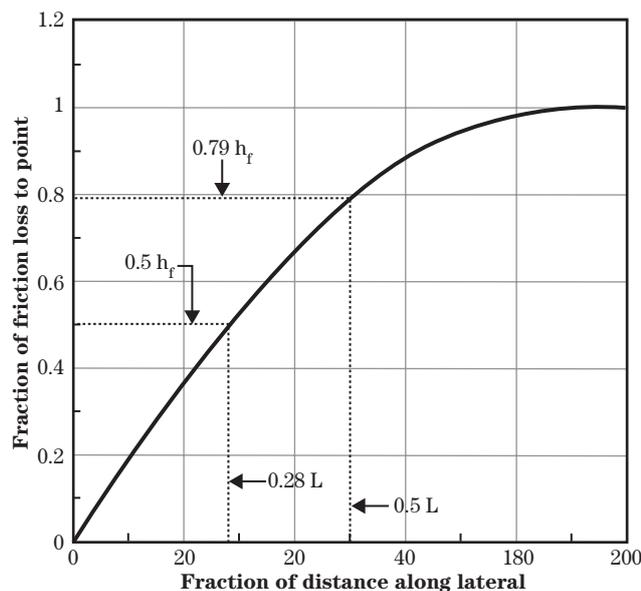
(i) *Friction loss for two pipe sizes in center pivot laterals*

When more than one diameter of lateral pipe is used along a center pivot lateral, the calculation of total friction becomes more complicated. Because the flow rate decreases along the lateral, it may often be profitable to use two sizes of lateral pipe along a center pivot to reduce total friction loss. For example, an eight inch pipe may be used for the first two or three spans from the pivot point. Then six and five-eighths inch pipe may be used for the balance of the lateral. Smaller diameter pipes not only save on pipe material costs, but also on supporting drive-unit costs, because smaller pipes are considerably lighter, especially when full of water. With more than one pipe size, total friction loss along the lateral must be calculated by

breaking it up into friction losses within each different pipe size. This friction loss can be determined using a stepwise (nozzle-by-nozzle section) procedure.

When designing center pivot laterals that have more than one size of pipe, it is important to recognize that most friction occurs along the first third to half of the lateral. Figure 11–81 and table 11–49 demonstrate this. Figure 11–81 shows the fraction of total friction loss that is lost along the first r distance of a center pivot lateral (beginning at the lateral inlet). This figure shows that the majority of friction loss occurs in the first half of the lateral pipe. In fact, as shown in the figure, when r equals $0.5L$, 79 percent of the total friction loss has already occurred within the center pivot lateral. When r equals $0.28L$, half of the friction loss as occurred. In other words, more than half of the friction along a single-sized center pivot lateral occurs in the first third of the lateral. When r equals $0.8L$, 98 percent of the friction loss has occurred. It is therefore easy to see why smaller pipe, for example six or six and five-eighths inch, may be used for the outer half or more of a center pivot lateral, with larger, for example eight inch pipe, used for the inner most spans.

Figure 11–81 General dimensionless friction curve for a center pivot lateral, where the Y-axis shows the fraction of total lateral friction loss that occurs from the pivot point to some point along the lateral



The fractions of friction that are shown in figure 11–81 are also listed in columns 1 and 5 of table 11–49. In addition, table 11–49 includes ratios of irrigated area, pipe discharge and friction loss for various fractions of distance from the inlet to the end of a center pivot lateral. These ratios are useful in appreciating the distribution of area, discharge and friction loss in the center pivot lateral. The friction loss fraction in column 5 of table 11–49 is the same as the Y-axis of figure 11–75, and column 1 of table 11–49 is the same as the X-axis of figure 11–81. Figure 11–81 and table 11–49 represent laterals having only a single size of pipe.

(ii) *Procedure for friction loss in a dual-sized lateral*

Table 11–50 lists adjustment coefficients, K_{dual} , that can be used to calculate h_f in a center pivot having two different pipe sizes. The table can be applied to standard sizes of pipe that are used on U.S. center pivot systems. The total friction loss in a center pivot lateral having two sizes of pipe is estimated as:

$$(h_f)_{\text{cp}} = K_{\text{dual}} (h_f)_{\text{cp smaller}} \quad (\text{eq. 11-178})$$

Table 11-49 Length, area, discharge, flow ratio, and friction loss for a center pivot lateral irrigating a circular area

Fraction of distance from inlet to end (r/L)	Fraction of total circular area irrigated	Nozzle discharge as a fraction of total discharge for spacing $S_r = 0.01 L$	Flow rate in lateral as a fraction of total system discharge, Q	Friction loss from inlet to this point as a fraction of total h_f	Friction loss from this point to end as a fraction of total h_f
(1)	(2)	(3)	(4)	(5)	(6)
0.00	0.0000	0.0000	1.000	0.000	1.000
0.05	0.0025	0.0010	0.998	0.094	0.906
0.10	0.0100	0.0020	0.990	0.186	0.814
0.15	0.0225	0.0030	0.978	0.277	0.723
0.20	0.0400	0.0040	0.960	0.365	0.635
0.25	0.0625	0.0050	0.938	0.450	0.550
0.30	0.0900	0.0060	0.910	0.530	0.470
0.35	0.1225	0.0070	0.878	0.605	0.395
0.40	0.1600	0.0080	0.840	0.674	0.326
0.45	0.2025	0.0090	0.798	0.737	0.263
0.50	0.2500	0.0100	0.750	0.793	0.207
0.55	0.3025	0.0110	0.698	0.842	0.158
0.60	0.3600	0.0120	0.640	0.884	0.116
0.65	0.4225	0.0130	0.578	0.919	0.081
0.70	0.4900	0.0140	0.510	0.947	0.053
0.75	0.5625	0.0150	0.437	0.968	0.032
0.80	0.6400	0.0160	0.360	0.983	0.017
0.85	0.7225	0.0170	0.277	0.992	0.008
0.90	0.8100	0.0180	0.190	0.998	0.002
0.95	0.9025	0.0190	0.097	1.000	0.000
1.00	1.0000	0.0200	0.000	1.000	0.000

Column 3 is based on total discharge and L for an equivalent circular irrigated area for the center pivot system. To determine nozzle discharge per foot (or m) at a point r along the lateral, multiply the value in column 3 by $Q / (0.1 L)$, where L is the equivalent hydraulic length of the lateral that is associated with Q.

Table 11–50 Values for K_{dual}

r/L	6-5/8 to 6	8 to 6	8-5/8 to 6	8 to 6-5/8	8-5/8 to 6-5/8	10 to 8	10 to 8-5/8
	K_{dual}						
0.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.06	0.956	0.914	0.906	0.931	0.917	0.924	0.941
0.08	0.941	0.886	0.875	0.908	0.890	0.900	0.922
0.10	0.927	0.857	0.844	0.885	0.863	0.875	0.902
0.12	0.913	0.829	0.813	0.863	0.836	0.850	0.883
0.14	0.898	0.802	0.783	0.841	0.810	0.826	0.864
0.16	0.884	0.774	0.753	0.819	0.783	0.802	0.845
0.18	0.870	0.747	0.723	0.797	0.757	0.778	0.827
0.20	0.857	0.720	0.694	0.775	0.732	0.754	0.809
0.22	0.843	0.694	0.665	0.754	0.706	0.731	0.791
0.24	0.830	0.668	0.637	0.734	0.682	0.709	0.773
0.26	0.817	0.643	0.609	0.713	0.657	0.686	0.756
0.28	0.804	0.618	0.582	0.694	0.634	0.665	0.739
0.30	0.792	0.594	0.556	0.674	0.611	0.644	0.722
0.32	0.780	0.571	0.530	0.655	0.588	0.623	0.706
0.34	0.768	0.548	0.505	0.637	0.566	0.603	0.691
0.36	0.757	0.526	0.481	0.619	0.545	0.584	0.676
0.38	0.746	0.504	0.457	0.602	0.524	0.565	0.661
0.40	0.736	0.484	0.435	0.586	0.505	0.547	0.647
0.42	0.725	0.464	0.413	0.570	0.485	0.529	0.633
0.44	0.716	0.445	0.392	0.554	0.467	0.512	0.620
0.46	0.706	0.427	0.372	0.540	0.450	0.496	0.608
0.48	0.697	0.409	0.353	0.526	0.433	0.481	0.596
0.50	0.689	0.393	0.335	0.512	0.417	0.466	0.584
0.52	0.681	0.377	0.317	0.500	0.402	0.453	0.574
0.54	0.673	0.362	0.301	0.488	0.388	0.440	0.563
0.56	0.666	0.348	0.286	0.477	0.374	0.427	0.554
0.58	0.659	0.335	0.271	0.466	0.362	0.416	0.545
0.60	0.653	0.323	0.258	0.456	0.350	0.405	0.536
0.62	0.647	0.311	0.246	0.447	0.339	0.395	0.529
0.64	0.642	0.301	0.234	0.439	0.329	0.386	0.522
0.66	0.637	0.291	0.224	0.431	0.320	0.378	0.515
0.68	0.633	0.283	0.214	0.424	0.311	0.370	0.509

where:

$(h_r)_{cp \text{ smaller}}$ = total pipe-friction loss along the lateral when comprised only of the smaller pipe (eqs. 11–249 or 11–250) using D of the smaller pipe, ft or m

K_{dual} = friction reduction factor from table 11–50, based on the fraction of center pivot lateral that is comprised of the larger pipe

is the fraction of larger pipe is used in the lateral. Pipe sizes in the header are the nominal large and small sizes in inches.

The development of K_{dual} and equations for creating table 11–50 are described by Allen et al., (1998) and are based on equations by Chu and Moe (1972). Allen et al. also includes the calculation of $(h_r)_{cp}$ for pivots having three pipe sizes.

To use table 11–50, enter the first column with r/L , where r/L is the fraction of the center pivot that will be comprised of the larger pipe. Read across the row and select the value of K_{dual} that is in the column that contains the sizes for the two lateral diameters that are to be combined. For example, for a center pivot lateral that is to be 0.3 of an 8 inch pipe and with the outer 0.7 of the lateral of 6-5/8 inch pipe, the value for K_{dual} from table 11–50, for r/L equals 0.3, would be 0.674. The fraction r/L must be between 0 and 1. Note that if the entire lateral is comprised of small pipe (so that $r/L = 0$), that the value for K_{dual} will be 1.0. In table 11–50 the values for K_{dual} for calculating total friction loss for a multiple-sized center pivot lateral where r/L

(f) Economic pipe sizes

Center pivot lateral pipe should be sized according to the economic selection procedures described under life-cycle costs. The sum of annual fixed costs plus fuel costs should be minimized. Since the flow rate (Q_r) in the pipe decreases as the radius from the pivot (r) increases it is often profitable to use multiple pipe size laterals. Smaller pipes not only save on material costs, but the span length for smaller pipes can often be increased, resulting in further savings on the supporting towers and drive units. Smaller pipe with the same span length, when filled with water, weighs less than larger pipe, resulting in less wear on tower drives and with fewer rutting problems along wheel tracks.

Table 11–50 Values for K_{dual} —continued

r/L	6-5/8 to 6	8 to 6	8-5/8 to 6	8 to 6-5/8	8-5/8 to 6-5/8	10 to 8	10 to 8-5/8
	K_{dual}						
0.70	0.628	0.275	0.206	0.418	0.304	0.363	0.504
0.72	0.625	0.268	0.198	0.412	0.297	0.357	0.499
0.74	0.622	0.261	0.191	0.407	0.291	0.351	0.495
0.76	0.619	0.256	0.185	0.403	0.286	0.346	0.491
0.78	0.616	0.251	0.180	0.399	0.281	0.342	0.488
0.80	0.614	0.247	0.175	0.396	0.277	0.339	0.485
0.82	0.613	0.244	0.172	0.393	0.274	0.336	0.482
0.84	0.611	0.241	0.168	0.391	0.271	0.333	0.481
0.86	0.610	0.239	0.166	0.389	0.269	0.331	0.479
0.88	0.609	0.237	0.164	0.388	0.268	0.330	0.478
0.90	0.608	0.236	0.163	0.387	0.266	0.329	0.477
0.92	0.608	0.235	0.162	0.386	0.266	0.328	0.476
0.94	0.608	0.234	0.161	0.385	0.265	0.327	0.476
1.00	0.608	0.234	0.161	0.385	0.265	0.327	0.476

The best trade-off between fixed and operating costs can be based on a unit-length analysis as described in sample calculation 11–18. If several center pivot systems are designed using the same economic and hydraulic parameters, a chart such as figure 11–53 can be developed for the selection of center pivot pipe using economic parameters.

(g) Application uniformity and depth

High DU and CU values should be obtained from center pivots that are properly nozzled and where pressure variations due to topographic effects are not significant. Under high winds, an individual pass of the lateral may not produce a good uniformity, but the sum of multiple passes should. To ensure better seasonal uniformity, the pivot speed should be set to require approximately 6 hours more or less than a full number of days per revolution (18, 30, 42, 64 hr). This will ensure that the pivot experiences different wind conditions as the lateral passes over a given site from one irrigation to the next. Travel speed of the center pivot lateral at distance r is calculated using equation 11–233.

Pressure changes due to elevation differences in the field adversely affect uniformity and system flow rate especially where low-pressure nozzling is used. To compensate for topographic effects, flow control devices, such as flexible orifice nozzles, can be used at each sprinkler; the system can be sped up when pointing downhill, slowed down when pointing uphill; or the inlet pressure can be decreased when the lateral is pointing downhill and increased when it is pointing uphill.

(h) Pressure regulators

Spring-loaded pressure regulators are commonly used on center pivot laterals to maintain nearly constant pressure at nozzles regardless of elevation changes or corner or end gun systems turning on and off. Modern pressure regulators are economic, operate efficiently between 1.6 to 16 gallons per minute (0.1 and 1.0 L/sec), and withstand surges quite well. Such suitable regulators are provided with preset pressure ratings of 6, 10, 15, 20, 25, 30, 40, and 50 pounds per square inch (40, 70, 105, 140, 170, 205, 275, and 345 kPa).

When using pressure regulators, the pressure at the sprinkler inlet is equal to the pressure at the lateral outlet minus the pressure loss through the regulator itself. The purpose of the regulator is to hold the downstream pressure constant, but the downstream pressure is a function of the flow rate through the regulator. In other words, the discharge pressure of a pressure regulator is flow rate dependent. The flow rate dependence is predictable; therefore, it can be included when designing the sprinkler, nozzle, and regulator package.

Pressure regulators are not perfect. The regulated pressure can vary up to five percent as the discharge through the pressure regulator varies. The outlet pressure downstream of a pressure regulator changes somewhat with the size of nozzle attached. Some manufacturer nozzle sizing software may account for this. Another disadvantage is that pressure regulators can display hysteresis or memory. Hysteresis is where the outlet pressure from the regulator varies according to whether the pressure is decreasing (lateral is moving uphill) or the pressure is increasing (lateral is moving downhill). The amount of hysteresis often increases as the regulators age. The hysteresis factor is more significant on regulators rated at 15 pounds per square inch or below. The magnitude of hysteresis averages to about 0.75 pound per square inch on new pressure regulators. After about 3 years, hysteresis may double that of new regulators for some types of regulators. The total manufacturing variation for many pressure regulators, including the hysteresis, is about 5 percent.

The hysteresis and natural variability problems with pressure regulators makes the use of regulators questionable unless there are substantial changes in terrain or hydraulics due to intermittent operation of end gun or corner systems. Even when the pressure upstream of the pressure regulator is at the regulated value, there is still some pressure loss through the regulator. Generally, this minimum pressure loss is about five pounds per square inch. This minimum pressure loss must be factored into the total system pressure requirement.

(i) When to use pressure regulators

Variation in pressure can result with changes in lateral elevation, friction losses in pipes and drop tubes, changes in pumping head, caused by changes in draw-down or aging, and end gun or corner system operation. All effects should be added when considering the

need for pressure regulators. Generally, friction losses in pipes and drop tubes can be compensated for during nozzle selection. Therefore, pressure variation on a center pivot, when considering the use of pressure regulators, should include primarily only elevation changes, changes in pumping lift, and end gun operation. Because of the manufacturer variation among regulators of the same type and rating and the hysteresis, one should only use pressure regulators if the variation in pressure exceeds the inherent regulator variation by some amount. The pressure variation includes elevation change from lateral movement, pumping lift variation, and increased friction loss by end gun or corner system turn-on. A good rule of thumb is to utilize pressure regulators when the pressure variation is greater than 20 percent of the design pressure.

For example, if a system is on a field where elevation changes by 10 feet as the lateral travels around the pivot, the water surface in the ground water well changes by 10 feet over the course of the irrigation season, and an end gun, when turned on, causes an increase in friction along the lateral of 2 feet. The total potential pressure head change along the lateral is 10 plus 10 plus 2 equals 22 feet during rotation and time of year. This pressure head change is equivalent to 22 feet times 0.433 pounds per square inch per foot equals 9.5 pounds per square inch. If the design pressure of the system is 20 pounds per square inch, then the ratio of pressure variation to design pressure is 9.5/20 equals 0.48 and, clearly, pressure regulators are recommended. If the design pressure of the system were 50 pounds per square inch, then the ratio of pressure variation to design pressure is 9.5/50 equals 0.19 and pressure regulators would not be recommended. When the design pressure is low, less elevation change can be tolerated before pressure regulators are recommended.

(ii) Discharge-pressure relationship for unregulated systems

An unregulated center pivot lateral behaves, hydraulically, as one giant sprinkler, and the general relationship between discharge and inlet pressure can be approximated by:

$$Q = K_{cp} \sqrt{P_{cp}} \quad (\text{eq. 11-179})$$

where:

Q = system discharge, gpm or l/sec

K_{cp} = discharge coefficient of the system

P_{cp} = lateral pipe inlet pressure measured at the top of the pivot point, lb/in² or kPa

The value of K_{cp} can be computed letting Q and P_{cp} be the design values. Discharge at some other inlet pressure can be estimated as:

$$Q_2 = Q \left(\frac{P_{cp2}}{P_{cp}} \right)^{1/2} \quad (\text{eq. 11-180})$$

Equations 11-179 and 11-180 are only valid if no pressure regulators or flow control nozzles are used on the center pivot.

Sample calculation 11-19—Center pivot lateral design

Given:

A center pivot lateral with the following specifications:

- Length: L = 1,300 ft, L' = 1,260 ft to end drive unit
- Pipe: galvanized 6-5/8-in 10-gauge steel with C = 135 and D = 6.36 in
- Wetted area: The desired maximum irrigated radius when the end gun is in operation, R = 1,400 ft
- Capacity: Sufficient to apply a gross of d' = 0.30 in/d when operating an average of 22 h/d
- Nozzling: Combination spacing of rotating sprinklers with a minimum pressure of 45 pounds per square inch at the end of the lateral for impacts and 15 pounds per square inch at the end nozzle for rotating nozzles

Find:

- system capacity, Q
- discharge of a sprinkler at r = 1,300 ft from the pivot where the sprinkler spacing, S = 10 ft
- average application rate 1,300 feet from the pivot
- required discharge rate of the end gun, q_g
- pipe friction loss, $(h_f)_{cp}$
- end drive unit travel speed for making a lateral rotation every 66 hours of continuous operation
- depth of application with a 66-hour cycle time

Calculations:

The area irrigated, if the end gun sprinkler is always on, is:

$$\begin{aligned} A &= \frac{\pi 1,400^2}{43,560} \\ &= 141.4 \text{ ac} \end{aligned} \quad (\text{eq. 11-181})$$

By equation 11-151, the system capacity should be:

$$\begin{aligned} Q &= 453 \left(\frac{Ad'}{T} \right) \\ &= 453 \left(\frac{141.4(0.30)}{22} \right) \\ &= 873 \text{ gal/min} \end{aligned} \quad (\text{eq. 11-182})$$

Alternatively, using equation 11-157:

$$\begin{aligned} Q &= \frac{R^2 d'}{30.6 T} \\ &= \frac{1,400^2 (0.30)}{30.6 (22)} \\ &= 873 \text{ gal/min} \end{aligned} \quad (\text{eq. 11-183})$$

The discharge of a sprinkler at $r = 1,300$ feet can be determined by equation 11-151 as:

$$\begin{aligned} q_r &= r S_r \frac{2Q}{R^2} \\ &= 1,300(10) \frac{2(873)}{1,400^2} \\ &= 11.6 \text{ gal/min} \end{aligned} \quad (\text{eq. 11-184})$$

From table 11-13, this discharge requires a nozzle about one size larger than the 7/32 inch nozzle listed as the largest nozzle in the table. Using equation 11-107, with $K_o = 36.8$ from table 11-19, the nozzle size for an impact sprinkler operating at 45 pounds per square inch needs to be:

$$\begin{aligned} d_{\text{noz}} &= \left(\frac{4q}{\pi K_o \sqrt{P}} \right)^{1/2} \\ &= \left(\frac{4(11.6)}{\pi(36.8)\sqrt{45}} \right)^{1/2} \\ &= 0.245 \text{ in} \end{aligned} \quad (\text{eq. 11-185})$$

which is about a quarter-inch nozzle. The estimated wetted width of the throw pattern, from table 11-13, is w equals 105 feet, for the impact sprinkler.

For rotator nozzles on drops, using the nozzle size at 15 pounds per square inch needs to be about:

$$\begin{aligned} d_{\text{noz}} &= \left(\frac{4q}{\pi K_o \sqrt{P}} \right)^{1/2} \\ &= \left(\frac{4(11.6)}{\pi(36.8)\sqrt{15}} \right)^{1/2} \\ &= 0.322 \text{ in} \end{aligned} \quad (\text{eq. 11-186})$$

which is just a little larger than 41/128 inches, resulting in selection of a number 41 nozzle size at 15 pounds per square inch, having an estimated w of about 55 feet.

The average application rate at r equals 1,300 feet by equation 11-155 is:

$$\begin{aligned} I &= 2K_u \left(\frac{Q}{R^2} \right) \left(\frac{r}{w} \right) \\ &= 2(96.3) \left(\frac{873}{1,400^2} \right) \left(\frac{1,300}{105} \right) \\ &= 1.06 \text{ in/h} \end{aligned} \quad (\text{eq. 11-187})$$

for the impact sprinkler, and

$$\begin{aligned} I &= 2K_u \left(\frac{Q}{R^2} \right) \left(\frac{r}{w} \right) \\ &= 2(96.3) \left(\frac{873}{1,400^2} \right) \left(\frac{1,300}{55} \right) \\ &= 2.03 \text{ in/h} \end{aligned} \quad (\text{eq. 11-188})$$

for the rotating nozzle on a drop tube.

The required end gun discharge is computed by equation 11-189 as:

$$\begin{aligned} Q_g &= 1.1 \left(1 - \frac{L^2}{R^2} \right) Q \\ &= 1.1 \left(1 - \frac{1,300^2}{1,400^2} \right) 873 \\ &= 132 \text{ gal/min} \end{aligned} \quad (\text{eq. 11-189})$$

The pipe friction loss can be computed directly by equation 11-174, or in a three-step process by equations 11-172 and 11-173. The three-step process starting with equation 11-172 gives:

$$\begin{aligned} (h_f)_{cp} &= 5.8R \left(\frac{Q}{C} \right)^{1.852} D^{-4.87} \\ &= 5.8(1,400) \left(\frac{873}{135} \right)^{1.852} (6.36)^{-4.87} \\ &= 31.5 \text{ ft} \end{aligned} \quad (\text{eq. 11-190})$$

and

$$\begin{aligned} (h_f)_{L-R} &= 5.8(100) \left(\frac{132}{135} \right)^{1.852} (6.36)^{-4.87} \\ &= 0.07 \text{ ft} \end{aligned} \quad (\text{eq. 11-191})$$

Note that the friction loss along the last 100 feet of center pivot lateral (if it existed) would only be 0.07 feet due to the relatively low discharge rate and relatively large pipe diameter for that section. Therefore, by equation 11-175:

$$\begin{aligned} (h_f)_{cp} &= (h_f)_R - (h_f)_{L-R} \\ &= 31.5 - 0.07 \\ &= 31.4 \text{ ft} \end{aligned} \quad (\text{eq. 11-192})$$

These computations point out that $(h_f)_{cp}$ for systems with end guns can be computed directly by using the full value of R in equation 11-174 when q_g is less than $1/4Q$. This is demonstrated by the insignificance of the computed $(h_f)_{R-L}$ equals 0.1 foot as compared to $(h_f)_{cp}$ equals 33.1 feet.

The speed at which the end drive unit, at 1,260 feet from the center, must travel to complete a cycle in 66 hours can be determined by equation 11-200 as:

$$\begin{aligned} \text{Speed}_{1,260} &= \frac{2\pi(1,260)}{(60 \text{ min/h})(66 \text{ h})} \\ &= 2.0 \text{ ft/min} \end{aligned} \quad (\text{eq. 11-193})$$

The gross depth of application with a 66-hour cycle time by equation 11-12 is:

$$\begin{aligned} d_g &= \frac{Q f T}{453 A} \\ &= \frac{873(66)}{453(141.44)} \\ &= 0.90 \text{ in} \end{aligned} \quad (\text{eq. 11-194})$$

The net depth of application assuming E_q equals 80 percent is:

$$\begin{aligned} \text{net depth/irrigation} &= \frac{E_q d_g}{100} \\ &= 80 \times 0.90 \end{aligned} \quad (\text{eq. 11-195})$$

Sample calculation 11-20—Calculating friction loss in a dual-sized lateral

Given:

- A center pivot system from sample calculation 11-19 is being designed to include two sizes of pipe: 8 inch and 6-5/8 inch.
- The total system has a flow rate of 873 gallons per minute.
- The lateral is the galvanized steel pipe having an estimated C-value of 135.
- The end gun and the length of the lateral pipe (L) are the same as in sample calculation 11-19 (1,300 ft).
- The length of 8 inch pipe is to be 555 feet, and the length of 6-5/8 inch pipe is to be 745 feet.

Find:

The total friction loss along the lateral.

Calculations:

From sample calculation 11-19, the following calculation is used, where the head loss for a center pivot

comprised of only the smaller (6-5/8 inch) pipe ($h_{f, \text{smaller}}$) was determined to be $h_{f, \text{smaller}}$ equals 31.5 feet:

$$\begin{aligned} (h_f)_{\text{cp-6-5/8}^*} &= 5.8R \left(\frac{Q}{C} \right)^{1.852} D^{-4.87} \\ &= 5.8(1,400) \left(\frac{873}{135} \right)^{1.852} (6.36)^{-4.87} \\ &= 31.5 \text{ ft} \end{aligned} \quad (\text{eq. 11-196})$$

The ratio of r/L , where r is the length of the larger pipe to be used is:

$$\begin{aligned} \frac{r}{L} &= \frac{555}{1,300} \\ &= 0.43 \end{aligned} \quad (\text{eq. 11-197})$$

From table 11-50, for the 8 to 6-5/8 column, a value for K_{dual} is 0.56 when the ratio of r/L is 0.43. Therefore, using equation 11-153, the friction loss for the total lateral that is comprised of both 8 and 6-5/8 inch pipe is:

$$\begin{aligned} (h_f)_{\text{cp}} &= K_{\text{dual}} (h_f)_{\text{cp, smaller}} \\ &= 0.56(31.5) \\ &= 17.6 \text{ ft} \end{aligned} \quad (\text{eq. 11-198})$$

This calculation indicates that if the 8 inch pipe were inserted into the first 555 feet of this center pivot in place of 6-5/8 inch pipe, that the friction loss would reduce from 31.5 to 17.6 feet, or by about 44 percent.

The economics of the savings in energy to be expected can be estimate by multiplying the 14 feet of saved head loss by the center pivot discharge, converting this into kilowatts and then multiplying by the hours of operation per year and by the price of energy per kilowatt hour. This would estimate the annual savings in energy. For example, for the 873 gallons per minute system in this example, the 14 feet represent $(14)(873)/(5,308(0.8)(0.9))$ is 3.2 kilowatts, where the 0.8 and 0.9 are the estimated efficiencies of the pump and electric motor and 5,308 converts gallons per minute per foot into kilowatts. If the center pivot were operated 1,400 hours per year, then the savings would be 3.2(1,400) is 4,480 kilowatts hour per year. If energy costs \$0.08 per kilowatt hour, then the savings in head loss would be \$360 per year, not including any reductions in demand charges. If the interest rate were about 9

percent and the center pivot would have an expected life of 15 years, then the total savings in present dollars would be about $\$360/\text{CRF} = 360/0.1014 = \$3,530$. The capital recovery factor (CRF) is calculated for the 9 percent interest over 15 years. The CRF represents the fraction of the amount borrowed that must be paid back each year to pay off a loan. Values for CRF are available in economics text books. The \$3,530 is the present value of the saved head loss. If the cost to upgrade the first 555 feet of the center pivot from 6-5/8 to 8 inch pipe, including the likelihood of requiring shorter spans, is less than \$3,530, then it should strongly be considered. If the cost difference for the 8 inch pipe exceeds \$3,530, then a shorter length of 8 inch pipe and longer length of the 6-5/8 inch pipe should be considered.

(i) Operating pressures

The minimum, inlet, and end gun pressures for center pivot systems should all be examined.

(i) Minimum pressure

The minimum pressure will normally occur at the end of the lateral when it is pointing uphill. The minimum pressure should be set according to the minimum pressure required for the sprinkler-nozzle configuration and, for impact sprinklers, should be one that avoids producing a watering pattern that will cause surface sealing or crop damage.

(ii) Inlet pressure

The inlet pressure required at the base of the pivot point is equal to the sum of the pressure heads, elevation differences, and friction losses:

- Minimum sprinkler pressure
- Minimum pressure loss through pressure regulators, if used
- Elevation difference between the pivot and the end of the lateral when it is pointing uphill. When the pivot is at the high point of the field the elevation difference will be positive. In rolling fields, use the elevation difference between the pivot and the highest point in the field.
- Height of the nozzles above the ground

- Friction loss in lateral pipe plus 10 percent to cover miscellaneous losses
- Friction loss in on/off and flow control valves

When several pivots are operated from the same pumping plant, an automatic valve should be provided to shut the water off at the pivot in case of a mechanical breakdown. For center pivots supplied directly from a well, the pump itself can be shut down; however, an on/off valve may still be necessary to abide by local or State regulations, especially if chemicals are to be injected into the pivot system. Check valve and pressure/vacuum relief devices should also be installed. End guns may also need to be shut on and off to water the corners without wetting roadways running along the field. The head losses through the end gun valves and plumbing are only included in the inlet pressure requirement if no booster pump is used; otherwise, these losses are only factored into the size of the booster pump.

Table 11–51 lists the losses and can be used to calculate total inlet pressure requirement.

Table 11–51 Calculation of the total inlet pressure requirement for center pivot systems

Item	(lb/in ²)	(ft)
1	Minimum sprinkler pressure	
2	Minimum pressure loss through pressure regulators, if used	
3	Friction loss through the last drop tube	
4	Elevation difference between the pivot and the end of the lateral when it is pointing uphill	
5	Height of the nozzles above the ground	
6	Friction loss in lateral pipe	
7	Miscellaneous losses (10 percent of friction loss)	
8	Friction loss in on-off and flow control valves, etc.	
9	Total inlet pressure at ground level	

(iii) End gun pressure

End gun pressures should be at least 50 pounds per square inch and preferably above 65 pounds per square inch for good irrigation. The recommended pressure depends on nozzle size and type as well as on soil, crop, and wind characteristics. Booster pumps can be mounted on the last drive unit or at the end gun to provide the necessary pressure.

(j) Elevation-discharge relationship

Typical nozzling configurations, without regulation, are designed to give uniform water application when the lateral is on a contour (i.e., level). However when the center pivot system is used on a sloping field, the pressures along the lateral will vary as the lateral rotates. Thus, when the lateral is pointing uphill, individual sprinkler discharges drop, without pressure regulators or flow control devices, causing the system discharge to decrease. When pointing downhill, the discharges will increase.

(i) Discharge variations

For unregulated center pivot systems, the variation in discharge caused by elevation differences is a function of the nozzle discharge coefficients and pipe friction loss characteristics. To simplify estimating the system discharge when the lateral is on a uniform slope, the elevation changes at each sprinkler can be represented by a weighted average elevation location for the entire lateral:

$$R_w = \frac{L}{3Q} (2Q + q_g) \quad (\text{eq. 11-199})$$

which can also be computed by:

$$R_w = \frac{2L}{3} + \frac{L}{3} \left(1 - \frac{L^2}{R^2} \right) \quad (\text{eq. 11-200})$$

where:

- R_w = radius from the pivot to the location of the weighted average elevation, ft or m
- L = length of the lateral pipe, ft or m
- Q = system capacity, gpm or l/sec
- q_g = end gun discharge, gpm or l/sec
- R = maximum radius effectively irrigated by the center pivot, ft or m

To estimate the overall effect of elevation changes on nonregulated systems, the sprinklers along the lateral can be thought of as all being at R_w . The pressure head changes as the lateral rotates will then be (\pm slope) multiplied by R_w . From this, the variations in Q can be computed as demonstrated in sample calculation 11–20.

Variations in discharge are not uniform and obviously become greater as one moves away from the pivot point. This reduces the application uniformity and even where Q may be sufficient in the uphill position, underirrigation may occur at the end of the lateral. One method for reducing the uneven watering resulting from elevation-induced flow rate changes is to slow the lateral rotation when it is in the uphill position and speed it up when in the downhill position. Another possibility, besides pressure or flow regulation for each sprinkler, is to increase and decrease the pivot inlet pressure when pointing uphill and downhill, respectively. However, these operating practices can be complicated.

When center pivots are fed directly from wells or individual pumping plants, the changes in Q will be further modified by the well and pump characteristics. Therefore, a plot should be made to determine where the uphill and downhill system curves intersect the pump curve to accurately determine the expected variations in Q .

Sample calculation 11–21—Pivot inlet pressure and end gun booster pump design

Given:

- The pivot information from sample calculation 11–19.
- The field has a uniform 2 percent slope.
- The nozzle outlets are 12 feet above the ground.
- No pressure regulation is used.

Find:

- The inlet pressure required at the base of the pivot.
- The booster pump horsepower required to provide a gun pressure of 65 pounds per square inch (448 kPa).

- The system discharges when the lateral is pointing uphill and downhill assuming the system is designed for Q is 873 gallons per minute (55 l/sec) when the lateral is on the contour.

Calculations:

Using table 11–51:

Item	(lb/in ²)	(ft)
1 Minimum sprinkler pressure	45	104
2 Minimum pressure loss through pressure regulators, if used		---
3 Friction loss through the last drop tube		---
4 Elevation difference between the pivot and the end of the lateral when it is pointing uphill		=1,300 ft × 2% = 26 ft
5 Height of the nozzles above the ground		10
6 Friction loss in lateral pipe		33.1
7 Miscellaneous losses (10% of friction loss)		3.3
8 Friction loss in on-off and flow control valves, etc.		8
9 Total inlet pressure at ground level	80	184 ft

To operate the end gun at 65 pounds per square inch and to take care of valve and plumbing friction losses (5 lb/in²), the pressure of the end of the lateral should be boosted by:

$$70 - 45 = 25 \text{ lb/in}^2, \text{ or } 58 \text{ ft} \quad (\text{eq. 11-201})$$

The horsepower required for a 65 percent efficient booster pump can be computed by equation 11–190 as:

$$\begin{aligned} \text{BHP} &= \frac{q_g H}{3,960 (E_p / 100)} \\ &= \frac{120 (58)}{3,960 (65 / 100)} \\ &= 2.7 \text{ HP} \end{aligned} \quad (\text{eq. 11-202})$$

The effect of elevation changes on the system discharge (Q), assuming the pivot inlet pressure is constant, is computed by equation 11-199. The average nozzle pressure variation can be approximated by the elevation changes at the weighted average elevation radius (R_w). The value of R_w can be determined by equation 11-273:

$$\begin{aligned} R_w &= \frac{L}{3Q} (2Q + q_g) \\ &= \frac{1,300}{3(873)} [2(873) + 120] \\ &= 926 \text{ ft} \end{aligned} \quad (\text{eq. 11-203})$$

The elevation 926 feet from the pivot will vary $\pm 0.02(926) = \pm 18.5$ feet.

If the lateral were designed for Q is 873 gallons per minute at an inlet pressure of 184 feet, the flow variation can be computed by equation 11-179.

Subtract the height of the nozzles above the ground since this does not vary with flow rate, then compute K , by inverting equation 11-179 as:

$$\begin{aligned} K_{cp} &= \frac{Q}{\sqrt{P_{cp}}} \\ &= \frac{873}{\sqrt{184 - 12}} \\ &= 66.6 \end{aligned} \quad (\text{eq. 11-204})$$

The calculated P_{cp} already includes the full elevation change for when the lateral pointed uphill. Therefore, Q_{up} equals Q equals 873 gallons per minute. When the lateral is downhill, the elevation change from the uphill position is 18.5 feet times 2, which is 37 feet. So the discharge in the downhill position is estimated, without pressure regulation, to be:

$$\begin{aligned} Q_{dn} &= K_{cp} \sqrt{P_{cp_dn}} \\ &= 66.6 \sqrt{184 - 12 + 37} \\ &= 963 \text{ gal/min} \end{aligned} \quad (\text{eq. 11-205})$$

The discharge variation without pressure regulation will be $(963-873)/((963+873)/2)$ equals 9.8 percent. If pressure regulators were used then the pressure requirement at the inlet will be about 5 pounds per square inch higher; however, discharge uniformity as the center pivot lateral rotates will be considerably higher.

(k) Machine selection

Ultimately the type, power, and speed of drive system, type of pipe and protective coating, span length, lateral height, type of end gun or corner system, wheel or tire size, and supplier must be selected by the user. Local field experience and availability of service should be considered as well as cost. Proper tire selection is critical to avoid problems with traction and deep ruts and enable easy crossing of the wheel tracks by farm equipment. Tires will vary with width and diameter ranging in size from about 24 to 38 inches (610 to 965 mm) in height and 11 to 17 inches (280 to 430 mm) in width. Generally, narrow, larger-diameter tires are used on heavy clay or loamy soils, while wider tires are used on lighter sandy soils for greater flotation. Farmers sometimes place a layer of rounded gravel along the wheel tracks under a center pivot on problematic soils.

Some considerations as to machine suitability:

- For the application of chemicals, a drive system capable of providing a fast rotation speed is needed.
- On undulating terrain, span length may need to be adjusted to keep the lateral from scraping the crop or ground.
- On unstable soils, high flotation tires or narrow, tall tire may be required.
- For steep and undulating terrain, heavy duty drive systems are needed.
- Some waters may cause corrosion in galvanized pipe. In such instances, epoxy-coated pipe and structures are recommended.

623.1111 Linear-move design

Self-propelled linear-move laterals have become fairly common in irrigated agriculture. A linear-move system must be fed by a hose, hydrant valves, or by water pumped from a channel that runs down the center or along the edge of the field. The lateral pipe hydraulics are the same as for periodic-move system laterals because discharge and outlet spacing is uniform. Linear-move systems are usually operated at slow speeds and depths of application per irrigation are similar for both systems. Because the laterals are continuously moving, and in a straight line, the potential uniformity of application is high under linear-move systems. Application rates can be high because it is economically attractive to irrigate as much area as possible with each lateral.

(a) Sprinkler-nozzle configuration

The sprinkler-nozzle configuration used on linear-move laterals is similar to that used along the middle portions of center pivot laterals. Therefore, many of the comments presented in the section on center pivots apply to sprinkler spacing, nozzle pressures, trajectory angles to surface sealing, application intensity and rate, and drift losses.

(i) Application rate

Assuming that the application pattern under the sprinklers is elliptical, the average and maximum application rates under a linear-move lateral are:

$$\begin{aligned} I &= \frac{93.3 q}{S_e w} \\ &= \frac{96.3 Q}{w L} \end{aligned} \quad (\text{eq. 11-206})$$

and

$$\begin{aligned} I_x &= \frac{4}{\pi} \left(\frac{93.3 q}{S_1 w} \right) \\ &= \frac{122.6 q}{S_1 w} \end{aligned} \quad (\text{eq. 11-207})$$

where:

- I = average application rate, in/h
- Q = sprinkler discharge, gpm
- S_e = spacing between sprinklers in the lateral, ft
- w = wetted width of water pattern, ft
- Q = system discharge, gpm
- L = length of lateral, ft
- I_x = maximum application rate, in/h

(ii) Application depth

The depth of water applied is a function of the application rate and lateral travel speed; however, lateral travel speed does not affect the application rate, which is controlled by sprinkler nozzle size and operating pressure. If the application decreases for any reason, the speed of lateral movement will likewise need to be reduced to apply the same total depth of water. This means a decrease in acreage that can be irrigated by the system in a given period.

(b) Maximizing linear-move field length

A linear-move sprinkler system is more cost effective when it irrigates the largest possible rectangular field area. Thus, a design strategy is to maximize the travel distance for a given lateral length. The next procedure for maximizing linear-move field length is from Allen (1983) and Allen (1990). The basic strategy is to examine different application depths and different w values to maximize the area covered by the sprinkler system, minimize labor requirements, or both.

Step 1: Calculate the maximum application depth per irrigation ($AD \leq MAD W_a Z$). Note that the actual application depth may be less than $MAD W_a Z$ with an automatic system to maintain optimal soil water conditions and to keep soil water content high in case of equipment failure (i.e., do not need to take full advantage of W_a).

$$f' = d_n / U_d \text{ (round down to an even part of a day)}$$

Step 2: Calculate net and gross application depths:

$$d_n = f(U_d) \quad (\text{eq. 11-208})$$

$$d = \frac{d_n}{E_{pa}} \quad (\text{eq. 11-209})$$

Step 3: Calculate the (presumed) average infiltrated depth of water per irrigation:

$$(D_f)_{\max} = d R_e O_e \quad (\text{eq. 11-210})$$

where:

$(D_f)_{\max}$ = maximum depth to be evaluated, and assuming no runoff

Step 4: For a series of 10 or so infiltration depths, d_f , beginning with d_f equal to some fraction (1/10) of $(D_f)_{\max}$:

$$d_f = \left(\frac{i}{10}\right)(D_f)_{\max} \quad (\text{eq. 11-211})$$

where:

$i = 1 - 10$

and

$$\begin{aligned} f' &= d_f \left(\frac{DE_{pa}}{100 U_d} \right) \\ &= \frac{d_n}{100 R_e O_e U_d} \end{aligned} \quad (\text{eq. 11-212})$$

f equals f' minus days off (days off may be zero because the system is automatic), where f' is irrigation frequency for depth, d_f . DE_{pa} is used here (in percent) because U_d is net, not gross.

Step 5: Determine the maximum AR_x for a particular df value using the next two equations (assuming an elliptical pattern):

$$AR_x = \frac{\left(1 - \frac{(SF)(AR_x)}{k}\right) \left(k^{\frac{1}{n+1}} (n+1)^{\frac{n}{n+1}} (D - SS - c)^{\frac{n}{n+1}}\right)}{\sqrt{1.05 - 1.6 \left(\frac{\pi}{2}\right)^2 \left(\frac{D}{d_f} - 0.5\right)^2}} \quad (\text{eq. 11-213})$$

where:

$$D = \left[\frac{\left(1.05 AR_x^2 - 1.6 AR_x^2 \left(\frac{\pi}{2}\right)^2 \left(\frac{D}{d_f} - 0.5\right)^2\right)^{-0.5} \left(-1.6 AR_x^2 \left(\frac{\pi}{2}\right)^2 \left(\frac{D}{d_f} - 0.5\right)\right)}{d_f n \left(1 - \frac{(SF)(AR_x)}{k}\right) \left((n+1)^{\frac{-1}{n+1}}\right) \left(\frac{1}{k^{n+1}}\right)} \right]^{-n-1} + SS + c \quad (\text{eq. 11-214})$$

where:

AR_x = peak application per pass, in/min or mm/min
 D = applied depth at time $t = \int (AR) dt$, in or mm
 SS = allowable surface storage (after ponding) before runoff occurs, usually less than about 0.2 in or 5 mm
 c = instantaneous soil infiltration depth from NRCS soil intake families, mm
 k = coefficient in the Kostiakov-Lewis equation
 d_f = total depth of water applied to the ground surface, in or mm

The parameter, n , is defined as n equals a minus 1, where a is the Kostiakov soil infiltration exponent (see the NRCS soil curves). Note that SS is a function of the field topography and microtopography, and is affected by foliar interception of applied water. These last two equations have π in them because there is an inherent assumption of an elliptical water application profile from the sprinklers or sprayers. Recall that AR_{av} equals $(\pi/4)AR_x$ for an assumed elliptical application pattern.

A relative sealing factor (SF) (in terms of soil water infiltration) may have values in the range of 0 to about 0.36. The higher values of SF tend to be for freshly tilled soils, which are generally most susceptible to surface sealing from the impact of water drops. Lower values of SF are for untilled soils and vegetative cover, such as alfalfa or straw, which tend to reduce the impact of water drops on the soil and help prevent runoff, too. If the linear move irrigates in both directions (no dead-heading), then d_f is half the value from these two equations.

Step 6: Compute the total wetting time, t_i , in minutes:

$$t_i = \frac{d_f}{\frac{\pi}{4} (AR_x)} \quad (\text{eq. 11-215})$$

where:

d_f = mm
 AR_x = in/min, mm/min

Step 7: Compute the speed of the system for the required t_i :

$S = w/t_i$ (m/min) (w is for a specific nozzle type)

If $S \geq S_{\max}$ (this may occur for a high intake soil or for a light application with surface storage), then reduce the application rate and increase time as

$$t_i = \frac{w}{S_{\max}} \quad (\text{eq. 11-216})$$

$$AR_x = \frac{4 d_f}{\pi t_i} \quad (\text{eq. 11-217})$$

Thus,

$$S = S_{\max} \quad (\text{eq. 11-218})$$

Step 8: Calculate maximum field length, X:

For irrigation in only one direction (dry return, or deadheading back):

$$X = \frac{60 f T - 2 t_{\text{reset}}}{\left(\frac{1}{S_{\text{wet}}} + \frac{1}{S_{\text{dry}}} + \frac{t_{\text{hose}}}{100} \right)} \quad (\text{eq. 11-219})$$

where:

coefficient 60 converts from hours to minutes

X = maximum length of field, ft or m

f = system operating time per irrigation, d

T = hours per day system is operated, usually 21 to 23

t_{reset} = time to reset lateral at each end of the field, min

t_{hose} = time to change the hose, min/ft or min/m

S_{wet} = maximum speed during irrigation, ft/min or m/min

S_{dry} = maximum dry (return) speed, ft/min or m/min

$$\text{labor} = \frac{2 t_{\text{reset}} + 0.01 X (t_{\text{hose}} + 2 t_{\text{super}})}{60 f} \quad (\text{eq. 11-220})$$

where:

labor = h/d

t_{super} = minutes of supervisory time per 100 ft (or 100 m) of movement

For irrigation in both directions (no deadheading):

$$X = \frac{60 f T - 2 t_{\text{reset}}}{2 \left(\frac{1}{S_{\text{wet}}} + \frac{t_{\text{hose}}}{100} \right)} \quad (\text{eq. 11-221})$$

and labor is calculated as in step 8.

Step 9: Calculate the irrigated area:

$$\text{Area}_{\max} = \frac{X L}{10,000} \quad (\text{eq. 11-222})$$

where:

Area_{\max} = acres or ha

L = total lateral length, ft or m

Step 10: Labor per hectare per irrigation, L_{ha} :

$$L_{\text{ha}} = \frac{\text{labor}}{\text{Area}_{\max}} \quad (\text{eq. 11-223})$$

Step 11: Repeat steps 5 through 10 for a different value of d_f .

Step 12: Repeat steps 4 through 11 for a new w (different application device or different operating pressure).

Step 13: Select the nozzle device and application depth which maximizes the field length (or fits available field length) and which minimizes labor requirements per acre or per ha.

Step 14: System capacity:

$$Q_s = \frac{\pi AR_x w L}{4 k_3 R_e} \quad (\text{eq. 11-224})$$

where:

k_3 = 96.3 for L and w in ft

Q_s = gpm

AR_x = in/h

k_3 = 60 for L

w = m

Q_s = l/sec

AR_x = mm/min

The system capacity can also be computed as:

$$Q_s = \frac{d_f w L}{t_i k_3 R_e} \quad (\text{eq. 11-225})$$

- In the procedure, when designing for a system that irrigates in both directions, the second pass is assumed to occur immediately after the first pass, so that the infiltration curve is decreased due to the first pass before the AR_x of the second pass is computed.
- This will occur near the ends of the field, where the design is most critical. The proposed procedure assumes that:
 - There is no surge effect of soil surface sealing due to a brief time period between irrigation passes (when irrigating in both directions).
 - The infiltration curve used represents soil moisture conditions immediately before the initiation of the first pass.
 - The infiltration curve used holds for all frequencies (f) or depths (d_p) evaluated, while in fact, as $f \uparrow$, $\theta \downarrow$, so that the Kostiakov coefficients will change. Therefore, the procedure (and field ring infiltration tests) should be repeated using coefficients which represent the Kostiakov equation for the soil moisture condition that is found to be most optimal in order to obtain the most representative results.

Sample calculation 11-22—Linear-move design example

Given:

Consider a hose-fed linear-move system, irrigating in only one direction in a 160 acre field that is a quarter-mile wide and 1 mile long (1,320 × 5,280 ft). The pressure is 20 pounds per square inch for spray booms with a preliminary w of 33 feet. The soil infiltration characteristics are defined for the Kostiakov-Lewis equation as:

$$Z = 0.214\tau^{0.49} \quad (\text{eq. 11-226})$$

where:

- Z = cumulative infiltrated depth, in
- τ = intake opportunity time, min

Thus,

- k = 0.214
- a = 0.49

Other design parameters are:

- U_d = 0.30 in/d
- MAD = 50%
- Z = 3.0 ft
- W_a = 1.5 in/ft
- Oe = 1.00
- R_e = 0.94
- E_{pa} = 84%

- Maximum dry (returning) speed = $S_{dry} = 11.0$ ft/min
- Maximum wet (irrigating) speed = $S_{wet} = 10.0$ ft/min
- Reset time = $t_{reset} = 30$ min at each end of the field
- Hose reset time = $t_{hose} = 3.0$ min/100 ft of travel distance
- Supervisory time = $t_{super} = 1.5$ min/100 ft of travel distance
- Operating hours per day: $T = 22$ h/d

Calculations:

This design example considers only spray booms with w equals 33 feet. Note that the full procedure would normally be performed with a computer program or spreadsheet, not by hand calculations.

Step 1: Calculate the maximum application depth per irrigation ($d_n = MAD W_a Z$, or less):

$$\begin{aligned} d_n &= (0.5)(3.0)(1.5) \\ &= 2.25 \text{ in} \end{aligned} \quad (\text{eq. 11-227})$$

$$\begin{aligned} f' &= \frac{d_n}{U_d} \\ &= \frac{2.25}{0.30} \\ &= 7.5 \Rightarrow f' \\ &= 7 \text{ days} \end{aligned} \quad (\text{eq. 11-228})$$

Step 2: Net and gross application depths:

$$\begin{aligned}d_n &= f U_d \\ &= (7)(0.30) \\ &= 2.10 \text{ in} \quad (\text{eq. 11-229})\end{aligned}$$

$$\begin{aligned}d &= \frac{d_n}{E_{pa}} \\ &= \frac{2.10}{0.84} \\ &= 2.5 \text{ in} \quad (\text{eq. 11-230})\end{aligned}$$

Step 3: Infiltrated depth at each irrigation:

$$\begin{aligned}D_f &= d R_e \\ &= (2.5)(0.94) \\ &= 2.35 \text{ in} \quad (\text{eq. 11-231})\end{aligned}$$

Step 4: For a series of 10 infiltration values, calculate d_f , beginning with $d_f = D_f/10$:

$$d_f = D_f \left(\frac{i}{10} \right) \quad (\text{eq. 11-232})$$

where:

$i = 1$ to 10

In this example, let $i = 4$ and $d_f = (0.4)(2.35 \text{ inch}) = 0.94 \text{ inch}$. Then,

$$\begin{aligned}f' &= \frac{d_f D E_{pa}}{U_d} \\ &= \frac{(0.94) \left(\frac{0.84}{0.94} \right)}{0.30} \\ &= 2.8 \text{ d} \quad (\text{eq. 11-233})\end{aligned}$$

Assume no days off (no down time during the peak use period)

$$\begin{aligned}f &= f' - \text{days off} \\ &= 2.8 - 0 \\ &= 2.8 \text{ days} \quad (\text{eq. 11-234})\end{aligned}$$

Step 5: Determine the maximum AR_x for the particular d_f depth:

Applying equations 11-287 and 11-288, $AR_x = 0.038 \text{ inch per minute}$. Then, AR_x reaching the soil surface equals $0.038R_e$ equals $0.036 \text{ inch per minute}$.

Step 6: Compute the total wetting time, t_i , in minutes:

$$\begin{aligned}t_i &= \frac{4 d_f}{\pi AR_x} \\ &= \frac{4(0.94)}{\pi(0.036)} \\ &= 33 \text{ min} \quad (\text{eq. 11-235})\end{aligned}$$

Step 7: Compute the speed of the system for the required t_i by rearranging equation 11-216:

$$\begin{aligned}S &= \frac{w}{t_i} \\ &= \frac{33}{33} \\ &= 1.0 \text{ ft/min} \quad (\text{eq. 11-236})\end{aligned}$$

Thus, $S < S_{\max}$ (10.0 ft/min), so this is acceptable.

Step 8: Calculate the maximum field length, X :

For irrigation in only one direction (deadhead back):

$$\begin{aligned}X &= \frac{60 f T - 2 t_{\text{reset}}}{\left(\frac{1}{S} + \frac{1}{S_{\text{dry}}} + \frac{t_{\text{hose}}}{100} \right)} \\ &= \frac{60(2.8)(22) - 2(30)}{\left(\frac{1}{1.0} + \frac{1}{11} + \frac{3}{100} \right)} \\ &= 3,240 \text{ ft} \quad (\text{eq. 11-237})\end{aligned}$$

and the labor requirements are:

$$\begin{aligned}\frac{2 t_{\text{reset}} + 0.01(t_{\text{hose}} + 2 t_{\text{super}}) X}{60 f} &= \\ \frac{2(30) + 0.01[3.0 + 2(1.5)][3,240]}{60(2.8)} &= 1.5 \text{ h/d} \quad (\text{eq. 11-238})\end{aligned}$$

where:

t_{reset} = reset time at the ends of the field, min
 t_{hose} = hose reconnection time, min/100 ft

t_{super} = supervisory time, min/100 ft

Step 9: Maximum irrigated area:

$$\begin{aligned} \text{Area} &= \frac{XL}{43,560} \\ &= \frac{(3,240 \text{ ft})(1,320 \text{ ft})}{43,560 \text{ ft}^2/\text{acre}} \\ &= 98 \text{ acres} \end{aligned} \quad (\text{eq. 11-239})$$

which is $100(3,240/5,280) = 61$ percent of the total field area.

Step 10: Estimated labor hours per acre per day during irrigation:

$$\frac{1.5 \text{ h/d}}{98 \text{ acres}} = 0.015 \text{ h/d/acre} \quad (\text{eq. 11-240})$$

Step 11: Repeat steps 5 through 10 for a new d_r (not shown in this example).

Step 12: Repeat steps 4 through 11 for a new w (different application device or operating pressure)(not shown in this example).

Step 13: Select the nozzle, device and application depth that maximizes the field length (or fits the available field length), and which minimizes the labor requirements per acre.

Note that 98 acres < 160 acres, which is the size of the field. Therefore, it is important to continue iterations (steps 11 and 12) to find an application depth and or new “ w ” (different sprinkler or spray device) to reach 5,280 feet and 160 acres, if possible.

(i) Additional observations

For a 6 meter spray boom, applying a 12 millimeter depth per each 1.4 days would almost irrigate the 64 hectares. However, the labor requirement is doubled, as the machine must be moved twice as often. This additional cost must be considered and weighed against the larger area irrigated with one linear move machine. If larger spray booms were used ($w = 16$ m rather than 10 m) (these would be more expensive) then 18 millimeters could be applied each 2.1 days, and all 64 hectares could be irrigated with one machine.

If low pressure impact sprinklers were used (these would be less expensive than spray booms, but energy costs would be higher), then w equals 22 meters, and 30 millimeters could be applied each 3.5 days (more water can be applied since the application rate is spread over a wider area from the lateral), and all 64 hectares could be irrigated. In addition, ET_c would be less since the soil would be wetted less often. Also, the soil intake rate would be higher each irrigation because of a drier antecedent moisture at the time of irrigation.

Notice that required wetting time for rotation times (f) greater than 2 days are identical between all types of spray devices. For the large depths applied, a minimum wetting time is required. The system speed is adjusted to fit the w value of the water application device.

If no acceptable solution for this problem were found, then alternatives to be evaluated would be to irrigate in both directions, or to consider a ditch-fed linear move. This requires a leveled ditch, but it does not require time for moving hoses and hose friction losses. A mechanically controlled machine that automatically connects alternating arms to hydrants on a buried mainline can also be considered, but this is an expensive alternative.

In some cases, an investment in a linear-move machine is unjustifiable when there is a significant labor requirement for reconnecting the supply hose, resetting at the end of the field, and supervising the operation. A center pivot or a side-roll system can be preferable under these conditions. If one linear-move system cannot cover the entire field length in the available period, “ f ” (days), consider two linear-move machines for the same field.

System capacity:

$$\begin{aligned} Q_s &= \frac{\pi AR_x w L}{4 k_3 R_e} \\ &= \frac{\pi (0.91)(10)(400)}{4 (60)(0.94)} \\ &= 809 \text{ gal/min (51 l/sec)} \end{aligned} \quad (\text{eq. 11-241})$$

alternatively,

$$\begin{aligned}
 Q_s &= \frac{d_f w L}{t_1 k_3 R_e} \\
 &= \frac{(24)(10)(400)}{(33.6)(60)(0.94)} \\
 &= 809 \text{ gal/min (51 l/sec)} \quad (\text{eq. 11-242})
 \end{aligned}$$

Note that the computed Q_s is larger than one based strictly on U_d and T , because the machine is shut off during reset and hose moving.

623.1112 Field evaluation

(a) Field test data

Successful operation of sprinkle irrigation systems requires that the frequency and quantity of water application be accurately scheduled. Field application efficiency must be known to manage the quantity of application. Since system performance changes with time, periodic field checks are recommended. Various software applications are available to assist in the analysis of field evaluation data for sprinkler systems (e.g., Space, SpacePro, Catch3D, CPED, and others). Also, there are various databases of test data for many commercially available sprinklers, including those from Fresno State University (Center for Irrigation Technology) and Rainbird®, among others. However, it should be understood that sprinkler test data from indoor facilities may not be representative of actual field conditions and should be used with due caution.

The procedure for collecting the data is:

(i) Required information

These steps should be included in a sprinkler-lateral evaluation:

Step 1: Duration of normal irrigations

Step 2: Spacing of sprinklers along lateral lines

Step 3: Spacing of lateral lines along mainlines

Step 4: Measured depths of water caught in catch containers at a test location

Step 5: Duration of the test

Step 6: Water pressures at the sprinkler nozzles at the test location and along laterals throughout the system

Step 7: Rate of flow from the tested sprinklers

Step 8: Additional data specified on figure 11-82

Know what wetting patterns the operation produces at different pressures and also the operating pressures at the pump and along the mainline and laterals. General study of data obtained in the field enables determi-

nation of system uniformity. Further study enables determination of the uniformity and economics of the spacings, the economics of sizes of pipes used for mains and laterals, the desirability of using other operating pressures and other durations of application, and the effect of wind.

The evaluation form in figure 11–82 can be modified to accommodate specific situations or needs. No units are included in the form as given here, but it is essential to write the units for all numerical values recorded on it.

(ii) Equipment needed

The equipment the evaluator needs includes:

- pressure gage (0–100 lb/in²) with pivot tube attached (fig. 11–83)
- stopwatch or watch with an easily visible second hand
- large, clearly marked container (1 gal or larger for large sprinklers fig. 11–84)
- 4-foot length of flexible hose of inside diameter appreciably larger than the outside diameter of nozzles
- from 50 to 100 (or more depending on sprinkler size) catch containers such as 1-quart oil cans or plastic freezer cartons
- measuring stick (or ruler) to measure depth, or a 500 milliliter graduated cylinder to measure water caught in containers
- soil probe or auger
- 50 or 100 foot tape for measuring distances in laying out catch container grid
- shovel for smoothing spots to set containers and for checking soil, root, and water penetration profiles
- form (fig. 11–82) for recording data
- manufacturers' sprinkler performance charts showing the relationship between discharge, pressure, and wetted diameter plus recommended operating pressure ranges
- set of drill bits ranging from 31/64 to 1/14 inch in diameter in increments of 11/64 inch to check nozzle wear

(b) Field evaluation procedure

The information obtained from the field procedure should be entered in a data sheet similar to that shown in figure 11–82.

1. Choose a location along a lateral for the test. It may be either a single location at which the pressure is representative of the entire system, or two locations near the ends of a lateral to permit study of effects of differences in pressure. Loss of pressure due to friction in a lateral that has only one size of pipe is such that about half of the pressure loss occurs in the first 20 percent of the length and over 80 percent occurs in the first 50 percent of the lateral's length (fig. 11–85). On a flat field, the most representative pressure is at about 40 percent of the distance from the inlet to the terminal end.
2. Set out at least 24 catch containers (see the pattern in fig. 11–85) on a grid having a spacing not to exceed 10 by 10 foot for testing along a single lateral line. The catch container pattern should be laid out to cover two adjacent areas between three sprinklers, since sprinklers may not apply water at precisely uniform rates. Each catch container is assumed to give the representative depth of catch over the square having the same dimensions as the can spacing in which it is centered (see the dotted grid lines in fig. 11–86).

For solid-set or block-move systems where several adjacent laterals operate simultaneously, the catch containers should be placed in the area between two adjacent laterals (fig. 11–87). Caution should be exercised to allow for any water that could enter the test container area from adjacent blocks. These tests cannot be used to study any other lateral spacings.

Each container (or catch can) should be located within a foot of its correct grid position and carefully set in an upright position with its top parallel to the ground; any surrounding vegetation that would interfere with a container should be removed. When it is windy, it may be necessary to fasten containers to short stakes with rubber bands and weight them

with a known depth of water (which is later subtracted from the total depth shown after the catch) or with a stone, or they may be set in shallow holes. The most accurate means for measuring the catch can be achieved volumetrically by using a graduated cylinder. These measurements can be converted to depths if the area of the container opening is known. For 1-quart oil cans, 200 milliliters corresponds to a 1-inch depth. Other suitable catch containers may be square or cylindrical

plastic freezer containers with sides tapered slightly for nesting, or any similar container. Some specifications for catch cans/containers are provided in ASABE Standard S436 and in other technical publications. Winward and Hill (2007) give detailed recommendations about the use of catch cans for sprinkler system evaluations. Merriam and Keller (1978) also provide practical information about sprinkler irrigation field evaluations in general.

Determine and record the container grid spacing and the ratio of volume to depth of catch. Also indicate the position of the lateral and record the location and position numbers of the sprinklers on the lateral (fig. 11–82, part 10).

Alternatively, one or more radial legs of catch containers (fig. 11–88) can be used instead of a grid of containers. The use of radial legs is common in practice because it takes less time and effort to obtain application uniformity data. Also, one or more radial legs of containers are almost always used in center pivot evaluations. But when radial legs are used for single sprinklers used in rectangular or triangular spacings, the catch data are mathematically converted to a grid of values by simulating rotation of the legs and using interpolation algorithms, such as cubic splines. The calculated grid values are then used to determine

Figure 11–83 Measuring pressure at sprinkler nozzle with gage connected to a pitot tube



Figure 11–84 Loss of pressure due to friction along a lateral having only one pipe size

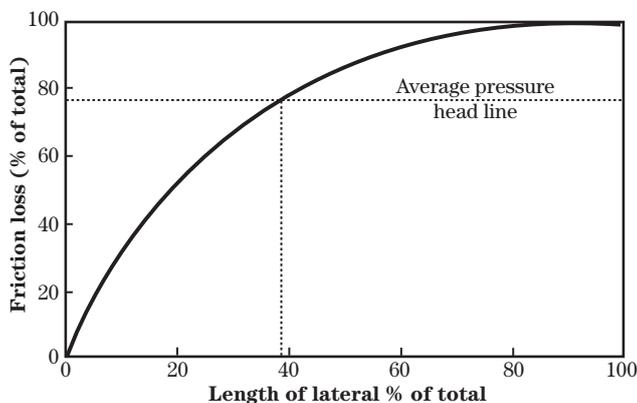


Figure 11–85 Measuring sprinkler discharge using a hose to direct the water into a container

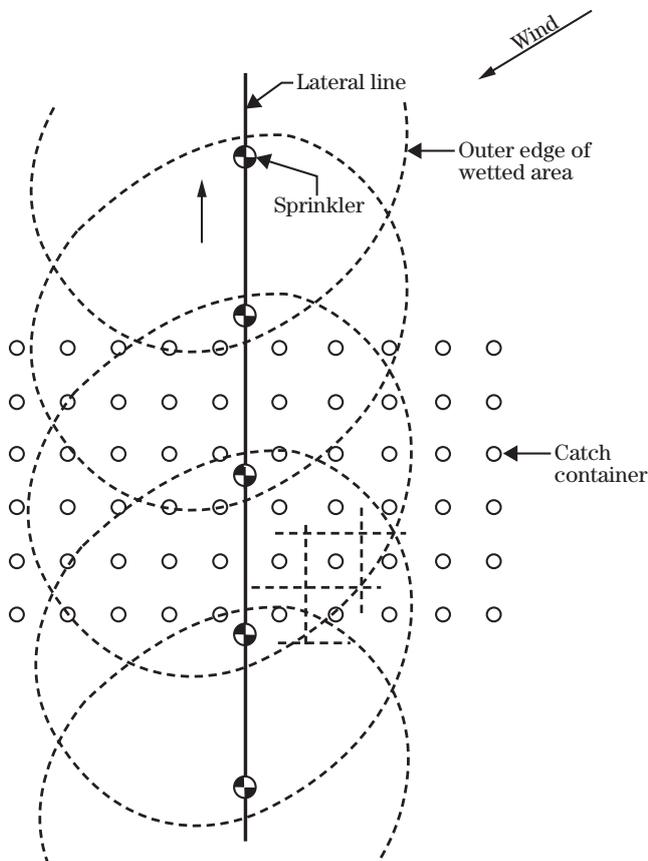


uniformity indices, just as if a full grid of catch containers had been used. This practice is most representative of actual field conditions in the absence of wind and with a perfectly vertical sprinkler riser pipe.

3. Determine the soil texture profile and management allowed deficit (MAD) then estimate the available soil moisture capacity in the root zone and check the soil moisture deficit (SMD) in the catch area on the side of the lateral that was not irrigated during the previous set. These values should be recorded in lines 2 and 3.
4. Check and record the make and model of the sprinkler and the diameter of the nozzles.

5. Obtain the normal sprinkler spacing, duration, and frequency of irrigation from the operator and record them. The standard way of expressing the sprinkler grid spacing is by feet; this indicates the sprinkler spacing on the lateral and the spacing between laterals in that order.
6. Read and record the rated sprinkler discharge, pressure, and the computed average design application rate from the system design data and manufacturer's sprinkler catalogs.
7. Check and record the size and slope of the lateral pipe and the height and erectness of the risers.
8. Before starting the test, stop the rotation of the sprinklers at the test site by wedging a short piece of wire or stick behind the swinging arm.

Figure 11-86 Layout of catch containers for testing the uniformity of distribution along a sprinkler lateral line



Turn on the water to fill the lateral lines. When the test lateral is full, turn the pressure up slowly to observe the trajectory, breakup of drops, and effect of wind at different pressures. Then set the pressure at the value desired for the test. Measure and record the pressure at sprinklers at several places along the line and at both ends of the line to observe the differences in pressure. Pressures should be checked at both the beginning and end of the test period and recorded. When measuring sprinkler pressures (fig. 11-83), the pitot tube must be centered in the jet, which must

Figure 11-87 A grid of catch containers between two adjacent sprinklers, straddling a single sprinkler lateral at a test facility



impinge directly onto its tip. The tip may be rocked slightly. Record the highest pressure reading shown while the pitot tube is being held about 1/8 inch from the sprinkler nozzle.

Also, record how long it takes each sprinkler in this test area to fill the large container of known volume. Do this by slipping a short length of hose over the sprinkler nozzle and collecting the flow in the container. To improve accuracy, measure the nozzle output several times and take the average. (If the sprinkler has two nozzles, each can be measured separately with one hose.) The measured sprinkler discharge rate is often greater than that specified by the manufacturer at the given pressure. This occurs because sprinkler nozzles often become enlarged during use, or because the hose fits too tightly and creates a siphoning action. Check nozzle erosion with a feeler gauge such as a drill bit that has the diameter specified for the nozzle.

9. Note the wind speed and direction and record the wind direction in part 9 by drawing an arrow in the direction of water flow in the lateral.
10. Empty all catch containers before starting the test; start the test by removing the wires or sticks and releasing all sprinklers surrounding

the test site so they are free to rotate. Note the starting time in part 10.

11. Set outside the catchment area a container holding the anticipated amount of catch to check the approximate volume of water lost by evaporation (fig. 11–82, part 10).
12. While the test is in progress, check sprinkler pressures at 20 to 40 judiciously selected locations throughout the system (for example, at the two ends and quarter points along each lateral) and record in part 12, the maximum, minimum, and average pressures.
13. Terminate the test by either stopping the sprinklers surrounding the test site in a position so that the jets do not fall into the containers, or by deflecting the jets to the ground. Note the time, check and record the pressure, and turn off the water. It is most desirable for the duration of the test to be equal to the duration of an irrigation to get the full effect of wind and evaporation. Ideally, minimum-duration tests should apply an average of about a half inch of water in the containers.

Measure the depth of water in all the containers (fig. 11–89) and observe whether they are still upright; note any abnormally low or high catches. As shown in part 10, depths or volumes caught are recorded above the line at the proper grid point, which is located relative to the sprinkler and direction of flow in the pipe line (figs. 11–90 and 11–91). For long runs, where maximum depths exceed two inches, a measuring stick provides suitable accuracy up to ± 0.1 inch.

Figure 11–88 A radial leg of catch cans for the uniformity evaluation of a single sprinkler (data from the test would be mathematically overlapped using software to simulate different sprinkler spacings)



(c) Application of the field data

Use of the data is described in connection with the test data presented in figure 11–92. The general procedure for analyzing the data is:

Step 1: Convert the depths or volumes of water caught in the containers to application rates and record them (in/h or mm/h) below the line on part 10 of the data sheet. Assuming that the test is representative and that the next set would give identical results, the right-hand side of the catch pattern may be overlapped (or superimposed) on the left-hand side (fig. 11–93), as if it were a subsequent set, to simulate different lateral spac-

Figure 11-89 Measuring the volume of water in catch containers as part of a sprinkler evaluation.



ings. For lateral spacings that are whole units of the container spacings, the sum of the catches of the two sets represents a complete irrigation. For close lateral spacings, water may overlap from as many as four lateral positions. The simulation of overlapping described is not recommended where winds are likely to change appreciably between subsequent lateral sets. It is most useful for 24-hour sets.

Step 2: To determine whether sprinklers are operating at acceptable efficiency, evaluate the system DU and CU using equations 11-29, 11-30, 11-43, and 11-44. The system DU is based on the average rate or depth recorded for the lowest fourth of the catch locations; hence, about one-eighth of the area may actually have received slightly less water. If an individual low value was due to a poor field measurement, perhaps no area actually received less. If the average low quarter depth infiltrated just matches the SMD, the percent of the infiltrated water going too deep would

Figure 11-90 Milliliters of water collected by catch cans placed with a 10 ft spacing on each side of a single lateral between sprinklers 4, 5, and 6

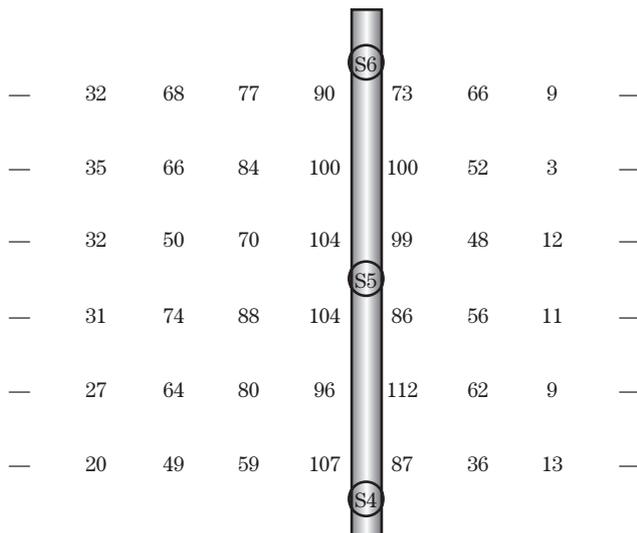


Figure 11-91 Water application rate, inch per hour, collected by catch cans placed at 10 ft. spacing on each side of a single lateral between sprinklers 4, 5, and 6

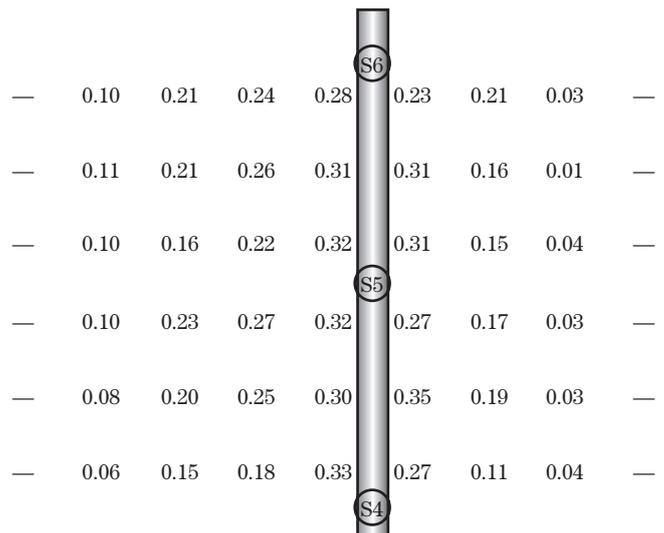


Figure 11-92 Sample sprinkler-lateral irrigation evaluation

1. Location Field C-22
2. Crop Tomatoes, root zone depth 4.0 ft, MAD 50 percent, MAD 4.4 in
3. Soil: texture clay loam; available moisture 2.2 in/ft, SMD 4.4 in
4. Sprinkler: Rain Bird, model 29B, nozzles 5/32 by in
5. Design sprinkler spacing 30 by 50 ft, design irrigation duration 23.5 hr
6. Rated sprinkler discharge 4.4 gpm at 40 psi giving 0.28 in/hr
7. Lateral: diameter 2 in, slope 1½ percent, riser height 18 in
8. Actual sprinkler pressure and discharge:

	Sprinkler location number on test lateral					
	1	4	5	6	10	15 end
Initial pressure (psi)	45	40	40	40	39	40
Final pressure (psi)	45		40		39	40
Catch volume (gal)	1.0	1.0	1.0	1.0		1.0
Catch time (min)	0.21	0.22	0.22	0.22		0.22
Discharge (gpm)	4.8	4.6	4.6	4.6		4.6

9. Wind: direction relative to lateral

Part 10: initial  during  final 

Speed (mph): initial 2+ during 5+ final 5+

10. Container grid test data in units: of ml, volume/depth 200 ml/in
11. Container opening diameter (cm): 10.09
12. Container grid spacing: 10 by 10 ft.
13. Test: start 2:55pm, stop 4:30pm, duration 1 hr 35min = 1.58 hr
14. Evaporation container: initial 2.15 final 2.10 loss 0.05 in.
15. Sprinkler pressures: max 45 psi; min 39 psi, avg 40 psi
16. Comments: Test duration of 1.58 hr was too short. Depths caught measured in 1000-ml graduated cylinder. Wind velocities are less than normal.

be approximately equal to 100 minus the system DU (a similar relationship exists for CU).

Step 3: The potential system application efficiency (E_q and E_h) should be determined to evaluate how effectively the system can use the water supply and what the total losses may be. The total amount of water required to fully irrigate the field can be estimated.

The E_q and E_h values are always a little lower than the DU and CU of a sprinkle irrigation system because the average water applied is greater than the average water caught. The difference between the water applied and the water caught approximates losses due to evaporation and drift, loss of water from ungauged areas, and evaporation from the gauge cans. The system E_q and E_h indicate how well the tested sprinklers can operate if they are run the correct length of time to satisfy the SMD or MAD. It is, therefore, a measure of the best management can do and should be thought of as the potential of the system, assuming that the test area truly represents the whole field.

The effective portion of applied water (R_e) (used in equations 11-39 and 11-40 for computing E_q and E_h) can be determined from the field data by:

$$R_e = \frac{\text{average catch rate (or depth)}}{\text{application rate (or depth)}} \quad (\text{eq. 11-243})$$

or,

$$R_e = \frac{\text{average catch rate}}{\left(\frac{96.3q}{S_1 S_e} \right)} \quad (\text{eq. 11-244})$$

where:

- q = average sprinkler discharge rate, gpm or l/min
- S_e = sprinkler spacing on the lateral, ft or m
- S_1 = lateral spacing along the mainline, ft or m

(d) Example calculation of application uniformity

Obviously, the spacing of sprinklers along the lateral (S_l) and spacing of laterals along the mainline (S_1) affects the amount of overlap and, consequently, the uniformity and depth of application. Figure 11-90 shows the data from a typical uniformity field test on a sprinkler lateral where two sections of the lateral were tested (the procedure for collecting the catch can data is presented at the end of this section). The basic catch data that were measured in milliliters and have been converted to the application rates in inches per hour received at each location. This was done by dividing the milliliters by the area of the catch can opening (79.9 cm^2) to get depth in centimeters and dividing by 2.54 centimeters per inch to get inches. This depth was divided by the time of the test, which was 1.58 hours to get inches per hour. The catch can opening was 10.09 centimeters diameter. These application rates can be used in place of depths when computing DU and CU values.

Figure 11-91 shows the data in inches per hour for the two lateral sections (area receiving contribution by three sprinklers). The sprinklers were spaced 30 feet apart on the lateral and the catch cans were spaced on a 10 foot grid, with the first column of cans placed 5 feet on each side of the lateral and the first row of cans placed 5 feet in from the first sprinkler.

Figure 11-93 Combined catch pattern in in/h between sprinklers 5 and 6 for a 50-ft lateral spacing and 30-ft sprinkler spacing along the laterals

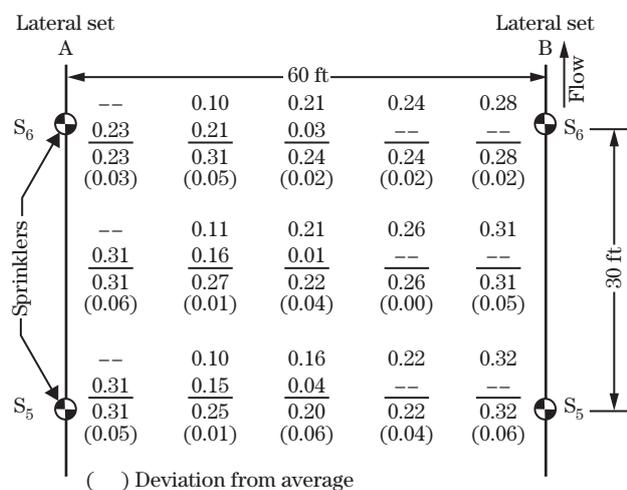


Figure 11-93 shows the application rate data gathered between sprinklers 5 and 6 from figure 11-90 overlapped to simulate a 50-foot lateral spacing. The sprinklers were spaced 30 feet apart on the lateral, and S_l equals 50 feet; thus, the sprinkler spacing is referred to as a 30- by 50-foot spacing. To create the overlap for an area that would be bounded by two sprinkler laterals, the catch depths to the right side of the tested lateral are added to the left side catch; the totals at each point represent a complete 11-hour irrigation for a 30- by 50-foot spacing. Only the first three rows of catch can data were used to simulate the area between four sprinklers for this particular analysis. For the simulated 50-foot lateral spacing, the total catch at all 15 grid points is 3.97 inches per hour (100 mm/h), which gives:

$$\begin{aligned} \text{mean catch rate} &= \frac{3.95}{15} \\ &= 0.263 \text{ in/h} \end{aligned} \quad (\text{eq. 11-245})$$

The calculation of the DU requires determining the lowest one-quarter of the catch rates. The fifteen rates are ordered as follows:

0.19	0.21	0.22	0.23	0.24	0.24	0.25
0.26	0.27	0.28	0.30	0.31	0.31	0.31
0.32						

The average of the lowest quarter of the catch rates (use 4 out of 15) is:

$$\begin{aligned} \text{Average low-quarter rate} &= \\ &= \frac{0.20 + 0.22 + 0.22 + 0.23}{4} = 0.218 \text{ in/h} \end{aligned} \quad (\text{eq. 11-246})$$

From equation 11-29:

$$\begin{aligned} \text{DU} &= 100 \left(\frac{0.218}{0.263} \right) \\ &= 83\% \end{aligned} \quad (\text{eq. 11-247})$$

To estimate the CU, from the mean determine the total deviations (X) by summing the deviations of the individual observations as shown by the numbers in parentheses on figure 11-86. The sum of these deviations is 0.513, when using unrounded values in a spreadsheet, and from equation 11-6:

$$\begin{aligned} \text{CU} &= 100 \left(1.0 - \frac{0.53}{0.263(15)} \right) \\ &= 87\% \end{aligned} \quad (\text{eq. 11-248})$$

As mentioned, the CU can be approximated from the average low-half and mean values of the observations by equation 11-31 (using unrounded values in a spreadsheet):

$$\begin{aligned} \text{CU} &\cong 100 \left[\frac{(0.19 + 0.21 + 0.22 + 0.23 + 0.24 + 0.24 + 0.25)/7}{0.263} \right] \\ &= 86\% \end{aligned} \quad (\text{eq. 11-249})$$

Or, the CU can be approximated from DU = 83 percent by equation 11-32:

$$\begin{aligned} \text{CU} &\cong 100 - 0.63(100 - 83) \\ &= 89\% \end{aligned} \quad (\text{eq. 11-250})$$

The deviations between the approximated values of CU and the value computed by equation 11-30 result from the small size of the sample and consequent deviation from a typical bell-shaped normal distribution. Although the system was designed for a 50-foot lateral move, the effect on uniformity of the other move distances can also be evaluated from the field test data. Table 11-52 is a summary of computations for DU and CU for four typical lateral spacings, for the area between sprinklers 5 and 6 and the area between the sprinklers 4 and 5, computed as above from the data in figure 11-92 parts 8 and 10. Comparison of percentage values illustrates the problem of choosing a representative and or minimum sample area.

Some other sites in the field undoubtedly were poorer and some were better than the tested site, as illustrated by comparing the DU, 81 percent, and CU, 87 percent, computed above using the top half of the catch-can data with the DU, 74 percent, and CU, 85 percent, computed using the bottom half of the catch-can data (different area between sprinklers); therefore, computed uniformities from single catch can tests are not universally applicable, but they are useful for evaluating providing an index of the system performance. Even with nearly identical sprinklers operating simultaneously, the uniformity test values may vary by a significant percentage. Usually, the accuracy of the catch data itself results in a deviation of 1 to 2 percent. In

addition, the normal variation of the uniformity values can be approximated by (Keller and Bliesner 1990):

$$[0.2(100 - CU)]\%; \text{ or } [0.2(100 - DU)]\% \quad (\text{eq. 11-251})$$

(e) Center pivot field evaluations

A good practice is to occasionally test the performance of a center-pivot system to check the uniformity of application and flow characteristics. Refer to ASABE Standard S436 for additional information about the field evaluation of center pivots.

(i) Information required

Modern center-pivot systems are propelled using electrical motor drives or oil-based hydraulic drives. Older systems sometimes used water or compressed air to move the lateral, but these are now rare. If water is used, it must be included as part of the total water applied; this somewhat lowers computed values of water use efficiency. The vast majority of modern center pivots use electric motors for the drive towers. Systems using electric drives can suffer some distribution uniformity degradation during individual passes due to the start-stop (full on and full off) action of the drives. Oil-driven systems are more continuous. This needs to be considered when laying out and conducting a

field test for distribution uniformity and in interpreting results.

The procedures are similar for evaluating all types of sprinkler systems. Effective use of procedures given in this section will depend on a good understanding of the procedures described in the section on testing periodic-move and fixed sprinkler systems. The following information is required for evaluating center-pivot irrigation systems:

- rate of flow for the total system
- rate of flow required to propel the system if it is water driven
- depth of water caught in a radial row (or two radial rows) of catch containers
- travel speed of end-drive unit, as a percentage of maximum speed and measured in feet per minute or meters per minute
- lateral length to end-drive unit and radius of the portion of the field irrigated by the center pivot
- width of the wetted strip at end-drive unit
- operating pressure and diameter of largest sprinkler nozzles at the end of the lateral
- approximate differences in elevation between the pivot and the high and low points in the field and along the lateral at the test position radius
- additional data indicated on figure 11-94

Table 11-52 DU and CU values of four standard sprinkler spacings for areas between sprinklers 5 and 6 and between sprinklers 4 and 5 (fig. 11-91)

Test area criteria	Sprinkler spacing (ft)			
	30 × 40	30 × 50	30 × 60	30 × 160 alt ¹
Area between sprinklers 5 and 6				
DU	810	841	641	9188 (78)
CU	875	87	754	93 (86)
Area between sprinklers 4 and 6				
DU	797	764	502	8082 (72)
CU	86	895	7069	9190 (83)

¹ The DU and CU for alternate set values are the same as for a 30 × 30 ft spacing. The values in parentheses are estimates from eq. 11-8a and 11-8b.

Accurate measurement of the flow rate into the system is needed for determining the E_q of the system; however, if no accurate flow metering device is at the inlet, the E_q can only be estimated.

(ii) Equipment needed

The equipment needed is essentially the same as for the full evaluation of rectangular sprinkler-lateral systems.

- pressure gauge (0–100 lb/in²) with a pitot attachment (fig. 11-83)
- stopwatch or watch with an easily visible second hand
- from 60 to 100 (depending on the lateral length) catch containers such as 1-quart oil cans or plastic freezer cartons

Figure 11-94 Center-pivot sprinkle irrigation evaluation (page 1)

Location _____ Observers _____ Date _____
 Owner _____ Coordinates _____ Start time _____
 Pivot ID _____ Elevation _____ End time _____

Pivot and site data

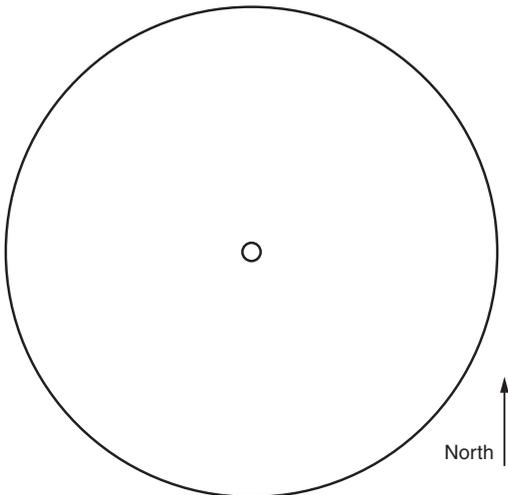
Pivot manufacturer _____
 Pivot length _____
 Number of towers _____
 Nozzle head type/brand _____
 Drop spacing _____
 Nozzle height _____
 Lateral dist. past last tower _____

End tower travel speed

Time marker set _____
 End time _____
 Distance traveled _____

Pivot position

Show position of pivot, catch cans, Evaporation cans, wind, and runoff



Agronomic and meteorological data

Wind direction _____
 Weather coditons _____
 Crop _____
 Crop height _____
 Soil type _____

Pivot settings and flow rate

Speed setting _____
 Pressure a inlet _____
 Hour meter reading _____
 Flow rate _____
 Time of flow measure _____

Application rate/intensity at last nozzle

Last nozzle pattern diameter _____
 Time water hit can _____
 Time stopped hitting can _____
 Last nozzle flow rate _____
 Pressure at last nozzle _____

Evaporation during study

Initial time _____ Final time _____

	Initial volume	Final volume
Evap can 1	_____	_____
Evap can 2	_____	_____
Evap can 3	_____	_____

Runoff

Surface runoff at 3/4 point _____
 Surface runoff at end _____

Additional observations _____

Figure 11-94 Center-pivot sprinkle irrigation evaluation (page 2)—continued

Location _____ Observers _____ Date _____
 Owner _____ Time started placing cans _____ Start time _____
 Pivot ID _____ Time last can placed _____ End time _____

Can catches					Can catches					Can catches				
Can #	Dist	Span #	Volume	Misc. *	Can #	Dist	Span #	Volume	Misc. *	Can #	Dist	Span #	Volume	Misc. *
1					41					81				
2					42					82				
3					43					83				
4					44					84				
5					45					85				
6					46					86				
7					47					87				
8					48					88				
9					49					89				
10					50					90				
11					51					91				
12					52					92				
13					53					93				
14					54					94				
15					55					95				
16					56					96				
17					57					97				
18					58					98				
19					59					99				
20					60					100				
21					61					101				
22					62					102				
23					63					103				
24					64					104				
25					65					105				
26					66					106				
27					67					107				
28					68					108				
29					69					109				
30					70					110				
31					71					111				
32					72					112				
33					73					113				
34					74					114				
35					75					115				
36					76					116				
37					77					117				
38					78					118				
39					79					119				
40					80					120				

- graduated cylinders (100, 250, and 500 ml will usually cover the range) to measure volume of water caught in the containers
- metal hooks to hold the catch containers in place and prevent them from tipping over
- tape for measuring distances in laying out the container row and estimating the machine's speed
- soil probe or auger
- hand level or a topographic level to check differences in elevation
- shovel for smoothing areas in which to set catch containers and for checking profiles of soil, root, and water penetration
- figure 11-94 for recording data
- manufacturer's nozzle specifications giving discharge and pressure and the instructions for setting machine's speed
- for water-driven machines which do not incorporate the drive water into the sprinkler patterns, a 2 to 5 gallon bucket and possibly a short section of flexible hose to facilitate measuring the drive water discharge

(iii) Field procedure

Fill in the data blanks of figure 11-94 while conducting the field procedure. In a field having a low-growing crop or no crop, test the system when the lateral is in the position at which the elevation differences are least, if possible. In tall-growing crops, such as corn, it is preferable to test the system where the lateral crosses the access road (if any) to the pivot point, thereby facilitating access to the catch containers. Use metal hooks if necessary to prevent the catch containers from tipping over due to wind and or rough ground surfaces, but do not place rocks in the containers because they are porous and will take up some of the water.

Step 1: Set out the catch containers along a radial path or two radial paths beginning at the pivot, with a convenient spacing no wider than 30 feet; a 15 or 20 foot spacing is preferable (fig. 11-95). The radial path does not need to be a straight line. Convenient spacings can be obtained by dividing the span length by a whole number such as 3, 4, 5, 6, and so forth. For example, if the span

length is 90 feet, use a 30 or 22.5 foot spacing. This simplifies the catchment layout since measurements can be made from each wheel track and the spacing related to the span (e.g., fourth span + 50 ft). Obviously, containers should not be placed in wheel tracks or where they would pick up exhaust water from water-driven systems in which the exhaust is not distributed. When exhaust water is incorporated into the wetting pattern, lay out containers so they will catch representative samples of the drive water. A second radial path is useful to reduce the impact of start-stop actions of electric drive motors. The values from the two paths are averaged for the same position.

As an example, a typical layout between wheel tracks for 90 foot (27 m) spans and any type of drive would be:

- Place the first container 5 feet downstream from the pivot.
- Set containers 2, 3, and 4 at 22.5 foot intervals. The fourth container is now 17.5 feet from the wheel track of the first span.
- Repeat the procedure to the end of the actual wetted circle.

To save time, it may be convenient to leave out the first few containers adjacent to the pivot since the watering cycle is so long in this area. The containers under the first one or two spans are

Figure 11-95 Center-pivot field evaluation with catch-cans spaced 10-ft apart in a radial leg



frequently omitted with little adverse effect on the evaluation. A number should be assigned to each container position with a sequential numbering system beginning with one at the container position nearest the pivot point. Even the locations not having containers under the first spans should be numbered.

Step 2: Fill in the blanks in parts 1 through 9 dealing with climatic and soil moisture conditions, crop performance, topography and general system, and machine and test specifications. Determine the irrigated area, part 4, in acres by first estimating the wetted radius of the irrigated circle.

Step 3: Determine the length of time required for the system to make a revolution by dividing the circumference of the outer wheel track by the speed of the end-drive unit (see parts 10 and 11 in which the conversion constant is $60/(2 \times 3.14) = 9.44$).

- Stake out a known length along the outer wheel track and determine the time required for a point on the drive unit to travel between the stakes. The speed of travel will be the distance divided by the number of minutes. An alternate method is to determine the distance traveled in a given time.
- Since many machines have uniform span lengths, excepting perhaps the first span, the radius between the pivot and the outer wheel track can normally be determined by multiplying the span length by the number of spans.

Step 4: Estimate the width of the wetted pattern perpendicular to the lateral and the length of time water is received by the containers near the end drive unit (see part 12). The watering time is approximately equal to the pattern width divided by the speed of the end-drive unit.

Step 5: On water-driven systems, number each drive unit beginning with the one next to the pivot. Time how long it takes to fill a container of known volume with the discharge from the water motor in the outer drive unit and record in part 13. The exact method for doing this depends on the water motor construction and may require using a short length of hose.

Step 6: If the system is equipped with a flow meter, measure and record the rate of flow into the system in part 14 of figure 11–96. Most standard flow meters indicate only the total volume of water that has passed. To determine the flow rate, read the meter at the beginning and end of a 10-minute period and calculate the rate per minute. To convert from cubic feet per second (or acre-in/h) to gallons per minute, multiply by 450.

Step 7: At the time the leading edge of the wetted patterns reaches the test area, set aside two containers with the anticipated catch to check evaporation losses. Measure and record in part 17 the depth of water in all the containers as soon as possible after the application has ended and observe whether they are still upright; note abnormally low or high catches. The highest accuracy can be achieved by using a graduated cylinder to obtain volumetric measurements. These can be converted to depths if the area of the container opening is known. For 1-quart oil cans, 200 milliliters corresponds to a depth of 1.0 inch. Measure the catch of one of the evaporation check containers about midway during the catch reading period and the other one at the end.

Sample calculation 11–23—Using center pivot field test data.

Given:

- Field data presented in figure 11–96.

Find:

- Evaluate the system using the field data.

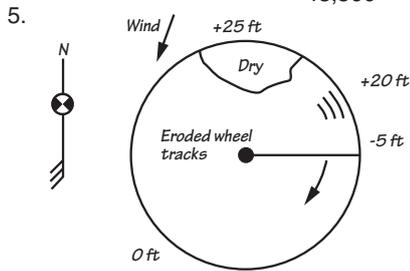
Calculations:

The volumes caught in the containers must be weighted, since the catch points represent progressively larger areas as the distance from the pivot increases. To weight the catches according to their distance from the pivot, each catch value must be multiplied by a factor related to the distance from the pivot. This weighting operation is simplified by using the container layout procedure in figure 11–96, part 17.

The average weighted system catch is found by dividing the sum of the weighted catches by the sum of the catch position's numbers where containers were placed. Space for this computation is provided in parts 15 and 17.

Figure 11-96 Center-pivot sprinkle irrigation evaluation (page 1)

1. Location Field F202 observer JK date and time 8-12-71 pm
2. Equipment make HG 100 length 1,375 ft pipe diameter 6 5/8 in
3. Drive type Water speed setting —% water distributed? Yes
4. Irrigated area= $\frac{3.14 (\text{wetted radius } 1,450 \text{ ft})^2}{43,560} = 152 \text{ acres}$



*Mark position of lateral, direction of travel, elevation differences, wet or dry spots and wind direction

Wind	<u>6 5/8 in</u>	temperature	<u>90°F</u>
Pressure at pivot	<u>86 psi</u>		
	at nozzle end	<u>60 psi</u>	
Diameter of largest nozzle	<u>1/2 in</u>		
Comments	<u>Sprinklers operating</u>		

OK but end part circle sprinklers out of adjustment

6. Crop condition Corn, good except north edge root depth 4 ft
7. Soil texture Sand loam tilth Poor available moisture 1.0 in/ft
8. SMD near pivot 0.5 in at 3/4 point 0.5 in at end 3.0 in
9. Surface runoff conditions at 3/4 point Slight and at end Moderate
10. Speed of outer drive unit 45 ft per 10 min = 4.5 ft/min

11. Irrigated area= $\frac{(\text{outer drive unit radius } 1,350 \text{ ft})}{49.55 (\text{speed } 4.5 \text{ ft/min})} = 152 \text{ acres}$

12. Outer end water pattern width 165 ft watering time 39 min
13. Discharge from end drive motor 5.0 gal per 0.37 min = 13.5 gpm
14. System flow meter 11,500 gal per 10 min = 1,150 gpm
15. Average weighted catches

System= $\frac{(\text{Sum of all weighted catches } 256,255)}{(\text{Sum all used position numbers } 2,044)} = 125 \text{ ml} = 0.05 \text{ in}$

Low 1/4= $\frac{(\text{Sum of 1/4 weighted catches } 53,416)}{(\text{Sum of 1/4 position numbers } 518)} = 104 \text{ ml} = 0.42 \text{ in}$

16. Minimum daily (average daily weighted low 1/4) catch

$\frac{(24 \text{ h operation/day}) \times (\text{Low } 1/4 \text{ catch } 0.42 \text{ in})}{(\text{31.4 h/revolution})} = 0.32 \text{ in/day}$

17. Container catch data in units of ml volume/depth 250 ml/in

Span length 90 container spacing 22.5 ft

Evaporation:	Initial	<u>150 ml</u>	<u>150 ml</u>
	Final	<u>-147 ml</u>	<u>-145 ml</u>
	Loss	<u>3 ml</u>	<u>5 ml</u> ave <u>4 ml</u> = <u>0.016 in</u>

Figure 11-96 Center-pivot sprinkle irrigation evaluation (page 2)—continued

Span no.	Position number	Container		Span no.	Position number	Container	
		×Catch=	Weighted catch			×Catch=	Weighted catch
1	1	Start numbering at pivot end of inner span. Do not wait for completion of irrigation at first few containers.		10	37	118	4,366
1	2			10	38	127	4,826
1	3			10	39	115	4,485
1	4			10	40	147	5,880
2	5			11	41	127	5,207
2	6			11	42	122	5,124
2	7			11	43	118	2,074
2	8			11	44	144	6,336
3	9	141	1,269	12	45	112	5,040
3	10	160	1,600	12	46	124	5,704
3	11	122	1,342	12	47	126	5,922
3	12	130	1,560	12	48	151	7,248
4	13	143	1,859	13	49	120	5,880
4	14	150	2,100	13	50	122	6,100
4	15	134	2,010	13	51	115	5,865
4	16	123	1,968	13	52	143	7,436
5	17	144	2,448	14	53	124	6,572
5	18	138	2,484	14	54	114	6,156
5	19	135	2,565	14	55	115	6,325
5	20	107	4,140	14	56	160	8,960
6	21	122	2,562	15	57	120	6,840
6	22	114	2,508	15	58	110	6,380
6	23	115	2,645	15	59	109	6,431
6	24	138	3,312	15	60	117	7,020
7	25	109	2,725	16	61	85	5,185
7	26	113	2,938	16	62	194	12,028
7	27	114	3,078	16	63	148	9,324
7	28	126	3,528	End	64	82	5,248
8	29	116	3,364		65	12	Omit
8	30	107	3,210		66		
8	31	122	3,782		67		
8	32	140	4,480		68		
9	33	117	3,861		69		
9	34	105	3,570		70		
9	35	111	3,885		71		
9	36	125	4,500		72		

Sum all: used position number 2044, weighted catches 256,255

Sum low 1/4: position numbers 514, weighted catches 53,416

For the average minimum weighted catch, an unknown number of containers that represents the low quarter of the irrigated area must be used. The low quarter is selected by picking progressively larger (unweighted) catches and keeping a running total of the associated position numbers until the subtotal approximates 1/4 of the sum of all the catch position numbers. The average weighted low quarter of the catch is then found by dividing the sum of the low quarter of the weighted catches by the sum of the associated catch position numbers. Space for this computation is also provided in parts 15 and 17.

To determine whether the system is operating at acceptable efficiency, evaluate the losses to deep percolation and DU by using equation 11-20:

$$DU = \frac{\text{average weighted low quarter catch}}{\text{average weighted system catch}} \times 100 \quad (\text{eq. 11-252})$$

which substituting for the example problem (fig. 11-95, part 15) is:

$$DU = \frac{0.42}{0.50} \times 100 = 84\% \quad (\text{eq. 11-253})$$

This is a reasonable value and is independent of the speed of revolution.

Plot the volume (or depth) of each catch against distance from the pivot (fig. 11-97). Such a plot is useful for spotting problem areas, improperly located nozzles, and malfunctioning sprinklers. Usually there is excess water near each water-driven drive unit where the water is distributed as part of the pattern.

If the system is operating on an undulating or sloping field and is not equipped with pressure or flow regulators, DU will vary with the lateral position. The DU will remain nearly constant if the differences in elevation (ft) multiplied by 0.43 (to convert to an equivalent lb/in²) do not exceed 20 percent of the pressure at the end sprinkler. Thus, for the example test, the line position would have minimal effect on the DU since the pressure at the end sprinkler was 60 pounds per square inch and the maximum elevation differences were only 25 feet, equivalent to 11 pounds per square

inch, which is only 18 percent of 60 pounds per square inch.

The E_q can be determined if the pivot point is equipped with an accurate flow measuring device. To find the average low quarter application rate use the average weighted low quarter of the catches expressed as a depth per revolution. The average depth of water applied per revolution is calculated by re-arranging equation 11-12 and plugging in data computed on figure 11-96 in parts 11, 14, and 4. Using equation 11-12, the depth applied per revolution is:

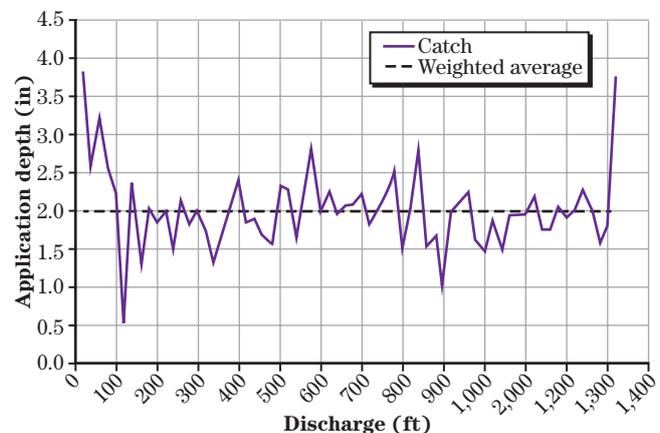
$$d = \frac{(31.4)(1,150)}{(453)(152)} = 0.52 \text{ in} \quad (\text{eq. 11-254})$$

Since R_e equals the average weighted catch divided by the gross depth, d , by substituting equation 11-30 gives:

$$E_q = DU \left(\frac{\text{average weighted catch}}{d} \right) = 84 \left(\frac{0.50}{0.52} \right) = 81\% \quad (\text{eq. 11-255})$$

in which $O_e = 1.0$.

Figure 11-97 Sample profile of container catch from a center pivot sprinkler evaluation test.



The small difference between DU of 84 percent and E_q of 81 percent indicates that evaporation losses are quite small and within the limits of measurement accuracy. The system flow rate and E_q can be estimated without a flow meter at the inlet. This is done by first estimating the gross application by adding the average catch depth and the estimated evaporation, which for the data recorded in figure 11–96, parts 15 and 17, is $0.50 + 0.02 = 0.52$ in per revolution. The flow in gallons per minute, which was distributed through the sprinkler, can be estimated by:

$$\text{Distributed flow} = \frac{453 \times \text{area (acres)} \times \text{gross application (in/rev)}}{\text{time per revolution (h)}} \quad (\text{eq. 11-256})$$

which for the recorded data is:

$$\begin{aligned} \text{Distributed flow} &= \frac{450(152)(0.52)}{31.4} \\ &= 1,133 \text{ gal/min} \quad (\text{eq. 11-257}) \end{aligned}$$

If water from the drive motor was not distributed, it must be added to the distributed flow to obtain the total system flow. The E_q is then computed as before by using the calculated system flow. For the recorded data the drive water was included in the distributed flow and need not be computed. However, if it had not been included in the distributed flow, it should be estimated by:

$$\text{Drive flow} = \frac{\text{sum of drive unit numbers} \times \text{gpm flow from end water motor}}{\text{Number of drive units}} \quad (\text{eq. 11-258})$$

For the 15 drive motors and a flow rate of 13.5 gpm from the end water drive motor:

$$\begin{aligned} \text{Drive flow} &= \frac{120 \times 13.5}{15} \\ &= 108 \text{ gal/min} \quad (\text{eq. 11-259}) \end{aligned}$$

(iv) *Runoff*

The computation of E_q is meaningful only if there is little or no runoff. Runoff or ponding may occur near the moving end of the system (fig. 11–98). Increasing the system's speed will reduce the depth per application and often prevent runoff; however, on some clay-

type soils, decreasing the system's speed and allowing the surface to become drier between irrigations will improve the soil infiltration characteristics and reduce runoff even though the depth per application is increased.

Therefore, both increasing and decreasing the speed should be considered. Other methods for reducing surface runoff include:

- Using an implement called a pitter, which scrapes indentations in the furrows followed by small dikes every 2 or 3 feet.
- Reducing the total depth of water applied per week by turning the system off for a period after each revolution (automatic stop devices are available for many systems). This allows the surface soil to become drier between irrigations and thus have a higher infiltration capacity. Careful planning is required to avoid extensive underirrigation that may reduce crop yields.
- Decreasing sprinkler nozzle diameters to decrease the system capacity and application rate. All the nozzles must be changed to maintain uniformity.
- Increasing system pressure and reducing nozzle sizes throughout the system to maintain the same system flow rate. This decreases the aver-

Figure 11–98 Runoff in furrows at the downstream end of a center-pivot lateral



age drop size, lessens drop impact, and thereby reduces surface sealing that restricts infiltration.

- Using special nozzles with pins to reduce drop sizes by breaking up the sprinkler jets.
- Adherence to conservation practices that will limit runoff of water from fields. Contour farming, conservation tillage, terrace construction, and conservation cropping should all be considered.

623.1113 References

- Allen, R.G., L.S. Pereira, D. Raes, M. Smith. 1998. Crop evapotranspiration, Irrigation and Drainage Paper 56, FAO, Rome, Italy. 300 pages.
- Brater, E.F., and H.W. King. 1976. Handbook of hydraulics. McGraw-Hill book company, New York, NY.
- Chu, T.S., D.L. Moe. 1972. Hydraulics of center pivot systems. Amer. Soc. Agricul. Eng. Trans. 15(5):894–896.
- Doorenbos, J., and W.O. Pruitt. 1984. Guidelines for predicting crop water requirements. FAO Irrig. and Drain. Paper 24. United Nations. Rome, Italy. 144 pages.
- Flammer, G.H., R.W. Jeppson, and H.F. Keedy. 1982. Fundamental principles and applications of fluid mechanics. Utah State Univ., Logan, UT. 364 pp.
- Irrigation Association. 2011. Center pivot design. Falls Church, VA. 203 p.
- Keller, J, and R.D. Bliesner. 1990. Sprinkle and trickle irrigation. AVI Books, Van Nostrand Reinhold, New York, NY. 652 pp.
- Merriam, J.L., and J. Keller. 1978. Farm irrigation system evaluation: a guide for management. Biological and irrigation engineering department, Utah State Univ., Logan, UT.
- Morris, H.M., and J.M. Wiggert. 1972. Applied hydraulics in engineering. 2nd ed. Ronald Press Co., New York, NY.
- Sneed, R.E. and R.G. Allen. 2011. Hydraulics of irrigation systems. Chapter 7, sixth edition, Irrigation Association, Falls Church, VA.
- Streeter, V.L., and E.B. Wylie. 1979. Fluid mechanics. McGraw-Hill, New York, NY.
- Uni-Bell Plastic Pipe Association. 1980. Handbook of PVC pipe design and construction. Uni-Bell Plastic Pipe Association, Dallas, TX. 312 pp.

Winward, T.W., and R.W. Hill. 2007. Catch-can performance under a line-source sprinkler. *Trans. of the Amer. Soc. of Agricul. and Bio. Engin.* Vol. 50(4): 1–9.

Appendix A

Symbols and Abbreviations

A	design area (acres, ha)	I'	preliminary application rate (in/h, mm/h)
B	nozzle size (1/64 in, mm)	I _i	instantaneous application rate (in/h, mm/h)
BHP	brake horsepower (HP, kW)	I _t	approximate actual application rate from a traveling sprinkler (in/h, mm/h)
C	friction coefficient of pipe	I _x	maximum application rate (in/h, mm/h)
CE	present annual energy cost of system operation (\$)	i	annual interest rate (decimal)
CE'	annual energy cost of overcoming head loss (\$)	J	head loss gradient (ft/100 ft, m/100 m)
CI	coarseness index (%)	J _a	allowable head loss gradient (ft/100 ft, m/100 m)
CRF	capital recovery factor	K	resistance coefficient of fitting or valve
CU	coefficient of uniformity (%)	K _{cp}	discharge coefficient of a center pivot
CU _a	coefficient of uniformity for alternate sets (%)	K _d	combined sprinkler and nozzle discharge coefficient
D	inside diameter of pipe (in, mm)	K _s	coefficient or function of I, S ₁ and k _d
d _n	net depth of application (in, mm)	L	length of pipe (ft, m)
d _g	gross depth of application (in, mm)	L'	length of pivot to last drive unit (ft, m)
d'	daily gross depth of application required during peak moisture use period (in, mm)	M	irrigation system cost (\$)
DU	distribution uniformity (%)	MAD	management allowable depletion (%)
DU _a	distribution uniformity for alternate sets (%)	N	number of outlets
E	elevation difference (ft, m)	N _n	minimum usual number of sprinklers operating
E _h	application efficiency of lower half (%)	N _R	Reynolds number
E _p	pump efficiency (%)	N _x	maximum usual number of sprinklers operating
E _q	application efficiency of the low quarter (%)	n	number of years in life cycle
e	equivalent annual rate of energy escalation (decimal)	P	nozzle operating pressure (lb/in ² , kPa)
EAE (e)	equivalent annualized cost factor of escalating energy	P _a	average sprinkler pressure (lb/in ² , kPa)
ET	crop water consumption (in/d, mm/d)	P _{cp}	inlet pressure measured at the top of the pivot point (lb/in ² , kPa)
F	multiple outlet reduction coefficient	P _{cv}	pressure loss at the control valve (lb/in ² , kPa)
f	time allowed for completion of one irrigation (days)	P _e	pressure change due to elevation (lb/in ² , kPa)
h _e	total head change due to elevation (ft, m)	P _f	pressure loss due to pipe friction (lb/in ² , kPa)
h _f	total head loss due to pipe friction (ft, m)	P _m	pressure required at lateral inlet (lb/in ² , kPa)
h _{fl}	limit of friction loss in length of pipe (ft, m)	P _n	minimum sprinkler pressure (lb/in ² , kPa)
h _e	head change due to elevation (ft, m)	P _r	pressure required to lift water by the riser height (lb/in ² , kPa)
I	average application rate (in/h, mm/h)		

P_x	maximum sprinkler pressure (lb/in ² , kPa)	S_a	angular segment wetted by sprinkler jet (degrees)
PW(e)	present worth of escalating energy costs (\$)	S_c	spacing of sprinklers along laterals (ft, m)
Q	system discharge capacity (gal/min, l/sec)	S_l	spacing of laterals along mainline (ft, m)
Q_r	pivot lateral flow rate at r (gal/min, l/sec)	S_r	sprinkler spacing on a center pivot lateral (ft, m)
Q_s	total system capacity (gal/min, l/sec)	T	actual operating time (h/day)
q	sprinkler discharge (gal/min, l/sec)	t	wetted radius (ft, m)
q_a	average sprinkler discharge (gal/min, l/sec)	TDH	total dynamic head (ft, m)
q_g	end gun discharge (gal/min, l/sec)	U	present annual power cost (\$)
q_r	sprinkler discharge at r (gal/min, l/sec)	U'	equivalent annual energy cost (\$)
R	maximum radius irrigated when corner system or end sprinkler is in operation (ft, m)	V	velocity of flow (ft/s, m/s)
R_e	effective portion of the applied water (%)	v	travel speed of end drive unit (ft/s, m/s)
R_w	radius of pivot to the location of the weighted average elevation (ft, m)	w	wetted width of water pattern (ft, m)
r	radius from pivot to point under study (ft, m)	W	tow-path spacing (ft, m)
S	travel speed (ft/min, m/min)	Wa	soil water-holding capacity (in/ft, mm/m)
		WHP	water horsepower (HP, kW)
		X	length of smaller pipe (ft/100 ft, m/100 m)
		Y	length of pipe of specified diameter
		ω	portion of circle receiving water (degrees)

Appendix B

Unit Conversions

0.3048	m per ft	Temperature conversions:	
25.4	mm per inch		
2.471	acres per ha	°C	(°F – 32)/1.8
43,560	ft ² per acre		
3.785	liters per gallon	°F	1.8(°C) + 32
7.481	gallons per ft ³		
1,233	m ³ per acre-ft		
15.85	gallons per ft per l/sec		
448.9	gallons per ft per ft ³ /sec		
6.89	kPa per lb/in ²		
100	kPa per bar		
101.3	kPa per atmosphere		
14.7	lb/in ² per atmosphere		
1	centibar per kPa		
2.31	ft (water head) per lb/in ²		
9.81	kPa per m (water head)		
0.746	kW per HP		

Appendix C

Plastic Pipe Specifications

Sprinkle irrigation systems are commonly built with plastic pipe, of which there are various types and specifications. Standards for the design and operation of pipelines are available from various professional organizations such as American Society of Agricultural and Biological Engineers (ASABE) and American Water Works Association (AWWA). Some of the material in this appendix is based on material in American Society of Agricultural Engineers (ASAE) standard S376.

Some of the most common types of plastic pipe are polyvinyl chloride (PVC), acrylonitrile-butadiene-styrene (ABS), and polyethylene (PE). ABS pipes are often used for buried drains and drainage pipes. Unlike most metal pipes, these plastic pipe materials are immune to almost all types of corrosion, whether chemical or electrochemical. The resistance to corrosion is a significant benefit when chemigation is practiced in a pressurized irrigation system.

The dimension ratio (DR) of a plastic pipe is the ratio of diameter (ID or OD) to the wall thickness: PVC, ABS, and some PE are OD based, while some PE pipe is ID based. There are several standard dimension ratios (SDR) for pipe, each with its own pressure rating (at 23 °C). Some pipe sizes correspond to iron pipe size (IPS) industry standards and others to plastic irrigation pipe (PIP) industry standards. The standard dimension ratio (SDR) is defined as:

$$\text{SDR} = \frac{D}{t} \quad (\text{eq. 11C-1})$$

where:

- D = diameter of the pipe
- t = wall thickness with the same units as D.

D may be either the outside or inside diameter, depending on the manufacturer. Different types of PVC, ABS, and PE compounds exist, some of which are stronger than others. The hydrostatic design stress (S) is used to indicate the strength of the pipe material. Values for S vary from 6,900 to 13,800 kPa for PVC, and from 3,400 to 5,500 kPa for PE.

The relationship between SDR, hydrostatic design stress (S), pounds per square inch, and pressure rating (PR), pounds per square inch is defined by ISO standard 161/1-1978:

$$\text{PR} = \frac{2S}{\text{SDR}-1} = \frac{2S}{\left(\frac{\text{OD}}{t}-1\right)} \quad \text{for OD-based pipe} \quad (\text{eq. 11C-2})$$

and

$$\text{PR} = \frac{2S}{\text{SDR}+1} = \frac{2S}{\left(\frac{\text{ID}}{t}+1\right)} \quad \text{for ID-based pipe} \quad (\text{eq. 11C-3})$$

The pressure rating of plastic pipe (especially PVC) decreases rapidly with increasing temperature of the pipe and or water. For example, at about 109 degrees Fahrenheit (43 °C), the PVC pressure rating drops to one-half of the nominal value at 73 degrees Fahrenheit (23 °C) and almost the same amount for PE. PE pipe temperature can easily reach 109 degrees Fahrenheit on a sunny day.

Values for hydrostatic pressure (S) and modulus of elasticity (E) are given in the table 11C-1 for common compounds of PVC, PE, and ABS, as well as for aluminum and steel.

Example The pressure rating of PVC 1220 pipe with a nominal diameter of 3 inches (75 mm) (inside diameter of 3.284 inches (83.4 mm)) and a SDR of 32.5 would be (for OD-based SDR) (using equation 11C-2):

$$\begin{aligned} \text{PR} &= \frac{2(2,000)}{32.5-1} \\ &= 127 \text{ lb/in}^2 \text{ (875 kPa)} \end{aligned} \quad (\text{eq. 11C-4})$$

Common pressure definitions used in the industry for PVC pipe include Class 160, Class 200, Schedule 40, Schedule 80, and Schedule 120 (listed in order of increasing strength and decreasing SDR). The higher the schedule, the thicker the walls for a given nominal pipe diameter. Class 160 and 200 refer to 160 and 200 pounds per square inch pipe. The schedule 40 and 80 specifications were originally developed for iron pipes. Schedule 80 is seldom used in irrigation because its pressure rating is much higher than the maximum pressures found in most irrigation systems.

For pipe schedules, the maximum allowable operating pressure is approximately equal to:

$$P = \frac{\text{Schedule } SE_j}{1,000} \quad (\text{eq. 11C-5})$$

where:

- P = operating pressure (lb/in²)
 S = allowable stress in the pipe material (lb/in²)
 E_j = joint efficiency
 schedule = schedule (e.g., 40, 80, 120, etc.).

Joint efficiency (joint quality factor) for PVC is approximately 1.00 due to the fact that it is seamless.

The maximum working pressure in a plastic pipe should normally be about 70 percent of the pipe's pressure rating, unless special care is taken in design and operation such that surges and excessive pressure fluctuations will not occur.

As another example of using the equations, the thickness of the 3-inch IPS pipe in the example would have to be at least

$$t = \frac{ID}{\frac{2S}{PR} - 1} = \frac{3.284}{\frac{2(2,000)}{125} - 1} = 0.106 \text{ in (2.7 mm)} \quad (\text{eq. 11C-6})$$

for the pipe to withstand the 125 pounds per square inch pressure with some factor of safety (the value for S includes a factor of safety).

If the pipe is to be capable of withstanding 250 pounds per square inch, then according to equation 11C-6) the thickness should be 0.22 inches (5.4 mm), and the SDR

Table 11C-1 Hydrostatic pressure (S) and modulus of elasticity (E) for common compounds of PVC, PE, and ABS, as well as for aluminum and steel

Pipe Material	ASTM No. or Std. Code	S		E	
		(lb/in ²)	(kPa)	(lb/in ²)	(kPa)
Steel (seamless)	3003-H14	14,000	97,000	10,600,000	73,140,000
	5050-H34	18,000	124,000		
	5086-H32	35,000	241,000		
PVC	1120, 1220, 2120	2,000	13,800	406,000	2,800,000
	2116	1,600	11,000		
	2112	1,250	8,600		
	2110	1,000	6,900		
PE	3408	800	5,500	102,000	700,000
	3406, 3306, 2306	625	4,300		
	2305	500	3,400		
ABS	1316	1,600	11,000	305,000	2,100,000
	2112	1,250	8,600		
	1210	1,000	6,900		
Steel		~60,000	~414,000	~28,000,000	~193,000,000

would be $3.284/0.22 = 15$. This pipe would need to be twice as thick to have twice the pressure rating.

Tables C-3 and C-4 list inside diameters for PVC pipe having hydrostatic design pressure of 2,000 pounds per square inch (13,800 kPa), which is characteristic of 1120, 1220, 2120 plastic compounds.

Table 11C-2 Common abbreviations for pipe specifications

Abbreviation	Meaning
ABS	acrylonitrile-butadiene-styrene
DR	dimension ratio
ID	inside diameter
IPS	iron pipe size
ISO	International Organization for Standardization
OD	outside diameter
PE	polyethylene
PIP	plastic irrigation pipe
PR	pressure rating
PVC	polyvinyl chloride
SDR	standard dimension ratio

Table 11C-3 Computed inner diameters for PVC pipe for various SDRs and pressure ratings, for S = 2,000 lb/in² (13,800 kPa)

	SDR:	11	13.5	17	21	26	32.5	41	51	64	81
	PR lb/in ²	400	320	250	200	160	125	100	80	63.5	50
Nom Diam	OD	ID									
(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)
IPS											
0.5	0.840	0.687	0.716	0.741	0.760	0.775	0.788	0.799	0.807	0.814	0.819
0.75	1.050	0.859	0.894	0.926	0.950	0.969	0.985	0.999	1.009	1.017	1.024
1	1.315	1.076	1.120	1.160	1.190	1.214	1.234	1.251	1.263	1.274	1.283
1.25	1.660	1.358	1.414	1.465	1.502	1.532	1.558	1.579	1.595	1.608	1.619
1.5	1.900	1.555	1.619	1.676	1.719	1.754	1.783	1.807	1.825	1.841	1.853
2	2.375	1.943	2.023	2.096	2.149	2.192	2.229	2.259	2.282	2.301	2.316
2.5	2.875	2.352	2.449	2.537	2.601	2.654	2.698	2.735	2.762	2.785	2.804
3	3.500	2.864	2.981	3.088	3.167	3.231	3.285	3.329	3.363	3.391	3.414
4	4.500	3.682	3.833	3.971	4.071	4.154	4.223	4.280	4.324	4.359	4.389
5	5.563	4.552	4.739	4.909	5.033	5.135	5.221	5.292	5.345	5.389	5.426
6	6.625	5.420	5.644	5.846	5.994	6.115	6.217	6.302	6.365	6.418	6.461
8	8.625	7.057	7.347	7.610	7.804	7.962	8.094	8.204	8.287	8.355	8.412
10	10.750	8.795	9.157	9.485	9.726	9.923	10.088	10.226	10.328	10.414	10.485
12	12.750	10.432	10.861	11.250	11.536	11.769	11.965	12.128	12.250	12.352	12.435
16	16.000	13.091	13.630	14.118	14.476	14.769	15.015	15.220	15.373	15.500	15.605
18	18.360	15.022	15.640	16.200	16.611	16.948	17.230	17.464	17.640	17.786	17.907
20	20.400	16.691	17.378	18.000	18.457	18.831	19.145	19.405	19.600	19.763	19.896
24	24.000	19.636	20.444	21.176	21.714	22.154	22.523	22.829	23.059	23.250	23.407
PIP											
4	4.130	3.379	3.518	3.644	3.737	3.812	3.876	3.929	3.968	4.001	4.028
6	6.140	5.024	5.230	5.418	5.555	5.668	5.762	5.840	5.899	5.948	5.988
8	8.160	6.676	6.951	7.200	7.383	7.532	7.658	7.762	7.840	7.905	7.959
10	10.200	8.345	8.689	9.000	9.229	9.415	9.572	9.702	9.800	9.881	9.948
12	12.240	10.015	10.427	10.800	11.074	11.298	11.487	11.643	11.760	11.858	11.938
14	14.280	11.684	12.164	12.600	12.920	13.182	13.401	13.583	13.720	13.834	13.927
15	15.300	12.518	13.033	13.500	13.843	14.123	14.358	14.554	14.700	14.822	14.922
18	18.701	15.301	15.930	16.501	16.920	17.262	17.550	17.789	17.968	18.117	18.239
21	22.047	18.038	18.781	19.453	19.947	20.351	20.690	20.972	21.182	21.358	21.503
24	24.803	20.293	21.128	21.885	22.441	22.895	23.277	23.593	23.830	24.028	24.191
27	27.953	22.871	23.812	24.664	25.291	25.803	26.233	26.589	26.857	27.079	27.263

Table 11C-4 Computed inner diameters for PVC pipe for various SDRs and pressure ratings S = 13,800 kPa (2,000 lb/in²) (mm)

	SDR	11	13.5	17	21	26	32.5	41	51	64	81
	PR lb/in ²	400	320	250	200	160	125	100	80	63.5	50
Nom diam (in)	PR kPa: OD (mm)	2760 ID (mm)	2208 ID (mm)	1725 ID (mm)	1380 ID (mm)	1104 ID (mm)	862.5 ID (mm)	690 ID (mm)	552 ID (mm)	438 ID (mm)	345 ID (mm)
IPS											
0.5	21.34	17.5	18.2	18.8	19.3	19.7	20.0	20.3	20.5	20.7	20.8
0.75	26.67	21.8	22.7	23.5	24.1	24.6	25.0	25.4	25.6	25.8	26.0
1	33.40	27.3	28.5	29.5	30.2	30.8	31.3	31.8	32.1	32.4	32.6
1.25	42.16	34.5	35.9	37.2	38.1	38.9	39.6	40.1	40.5	40.8	41.1
1.5	48.26	39.5	41.1	42.6	43.7	44.5	45.3	45.9	46.4	46.8	47.1
2	60.33	49.4	51.4	53.2	54.6	55.7	56.6	57.4	58.0	58.4	58.8
2.5	73.03	59.7	62.2	64.4	66.1	67.4	68.5	69.5	70.2	70.7	71.2
3	88.90	72.7	75.7	78.4	80.4	82.1	83.4	84.6	85.4	86.1	86.7
4	114.30	93.5	97.4	100.9	103.4	105.5	107.3	108.7	109.8	110.7	111.5
5	141.30	115.6	120.4	124.7	127.8	130.4	132.6	134.4	135.8	136.9	137.8
6	168.28	137.7	143.3	148.5	152.2	155.3	157.9	160.1	161.7	163.0	164.1
8	219.08	179.2	186.6	193.3	198.2	202.2	205.6	208.4	210.5	212.2	213.7
10	273.05	223.4	232.6	240.9	247.0	252.0	256.2	259.7	262.3	264.5	266.3
12	323.85	265.0	275.9	285.8	293.0	298.9	303.9	308.1	311.2	313.7	315.9
16	406.40	332.5	346.2	358.6	367.7	375.1	381.4	386.6	390.5	393.7	396.4
18	466.34	381.6	397.3	411.5	421.9	430.5	437.6	443.6	448.1	451.8	454.8
20	518.16	423.9	441.4	457.2	468.8	478.3	486.3	492.9	497.8	502.0	505.4
24	609.60	498.8	519.3	537.9	551.5	562.7	572.1	579.9	585.7	590.6	594.5
PIP											
4	104.90	85.8	89.4	92.6	94.9	96.8	98.4	99.8	100.8	101.6	102.3
6	155.96	127.6	132.9	137.6	141.1	144.0	146.4	148.3	149.8	151.1	152.1
8	207.26	169.6	176.6	182.9	187.5	191.3	194.5	197.2	199.1	200.8	202.1
10	259.08	212.0	220.7	228.6	234.4	239.2	243.1	246.4	248.9	251.0	252.7
12	310.90	254.4	264.8	274.3	281.3	287.0	291.8	295.7	298.7	301.2	303.2
14	362.71	296.8	309.0	320.0	328.2	334.8	340.4	345.0	348.5	351.4	353.8
15	388.62	318.0	331.0	342.9	351.6	358.7	364.7	369.7	373.4	376.5	379.0
18	475.01	388.6	404.6	419.1	429.8	438.5	445.8	451.8	456.4	460.2	463.3
21	559.99	458.2	477.0	494.1	506.7	516.9	525.5	532.7	538.0	542.5	546.2
24	630.00	515.5	536.7	555.9	570.0	581.5	591.2	599.3	605.3	610.3	614.4
27	710.01	580.9	604.8	626.5	642.4	655.4	666.3	675.4	682.2	687.8	692.5

Appendix D

Field Test for Determining Infiltration Rate and Required Surface Storage Under Sprinklers

Infiltration characteristics of soils under sprinkler irrigation can be determined either by ponding or by sprinkling the soil surface. The ponding method is easier, but sprinkling tests provide better, more representative information for simulating center pivot irrigations. Conducting field infiltration tests using either method is time consuming, so selecting test sites that can provide the most useful data is important. Infiltration tests should normally be conducted in the same area that will be irrigated by the proposed center-pivot system and in the circular area that will be served by the moving end of the lateral, where application rates will be highest. Soil and ground cover conditions should be selected to represent the worst-case conditions expected during actual operation; for example, under conditions of a relatively smooth, bare surface with little surface storage and on the steeper slopes of the field and with soil surface crusting resulting from prior irrigation or precipitation.

Two or three complete infiltration tests are usually sufficient. The application rates during these tests should bracket the peak application rates expected in the outer spans of the center pivot system. A relatively simple test involves selecting a spray nozzle that is similar to those proposed for the center pivot lateral. The nozzle is operated individually and can be supplied from a water container transported in the back of a pickup truck or pulled behind a tractor. A typical test will last usually no more than one hour before runoff occurs. At higher application rates, the time will be much shorter. For a 15 gallons per minute nozzle, which is relatively large, a 20-minute test will require about 300 gallons of water. An electric or gasoline powered pump can be used to supply the water pressure. A pressure regulator upstream of the nozzle should be used to keep discharge constant during the test.

Discharge during the test should be measured using a graduated bucket and stop watch. Application rate to different parts of the soil should be measured by placing catch cans on a sufficient grid to measure the location where the application pattern is highest. Often, one or two radial “legs” (lines) of containers on a 3-foot spacing is sufficient.

The test is begun and a timer is used to monitor the time during the test. The operator observes when both ponding and runoff begin to occur at different catch

can locations within the water pattern. These times and locations are noted. If the application pattern has sufficient variability with distance, three or more ponding times (t_p) can be observed during one test. In tests using nozzles that have a relatively uniform pattern with distance, several tests using more than one size of nozzle may be required to provide enough observations of application rates.

The application rate I at each of the locations where t_p is recorded can be calculated after the completion of the test by dividing the depth of water captured in an adjacent container by the length of the test in hours. When converting volume of water measured in a container into depth, it is important to use the area for the top of the container. For example, to convert 900 milliliters (ml) into a depth for a container that has a 10-inch top diameter, one would make the following calculation:

$$\begin{aligned}d_i &= \frac{\text{Volume of catch}}{\text{Area of container throat}} \\ &= \frac{4(900 \text{ ml})(1 \text{ cm}^3/\text{ml})}{\pi[(10 \text{ in})(2.54 \text{ cm/in})]^2} \left(\frac{1 \text{ in}}{2.54 \text{ cm}} \right) \\ &= 0.70 \text{ in}\end{aligned}\tag{eq. 11D-1}$$

where:

d_i = application depth

The application rate, I , is computed by dividing the depth of water caught by a container (d_i) by the time of the test. Often the time of the test, t_{test} , is expressed in minutes, but the application rate is expressed in inches per hour:

$$I = 60 \left(\frac{d_i}{t_{\text{test}}} \right)\tag{eq. 11D-2}$$

where:

I = application rate during a sprinkler test (in/h or mm/h)

d_i = depth of water caught by the container (in or mm)

t_{test} = test duration (min)

In the example, if the duration of the test were 20 minutes, then the application rate would be:

$$\begin{aligned} I &= 60 \left(\frac{d_i}{t_{\text{test}}} \right) \\ &= 60 \left(\frac{0.70}{20} \right) \\ &= 2.1 \text{ in/hr} \end{aligned} \quad (\text{eq. 11D-3})$$

Figure 11D-1 illustrates an infiltration versus time of ponding curve that was developed from three points of data taken from a field test using a single nozzle as described. The three points of application rate, I , and time until ponding, T_p , were plotted on an X-Y graph and a curve was drawn through these points.

The curve shown in figure 11D-1 can be used to determine the estimated application rate that will cause ponding at a particular time, or it can be used to predict the time at which a specific application rate will cause ponding. The application rate can be converted into an application depth as:

$$d_i = I \left(\frac{t_p}{60} \right) \quad (\text{eq. 11D-4})$$

where:

d_i = application depth, in or mm
 I = application rate, in/h or mm/h
 t_p = time until ponding, min

Two example points are shown on figure 11D-2 for the same curve as in figure 11D-1. These points indicate that:

- an application rate of 3.2 in/h (81 mm/h) will pond water in just 5 minutes time
- a lower application rate of 1.3 in/h (34 mm/h) will not pond for 30 minutes.

Using equation 11D-4, the infiltration depth at time of ponding (at 5 min) for the 3.2 inches per hour rate will be:

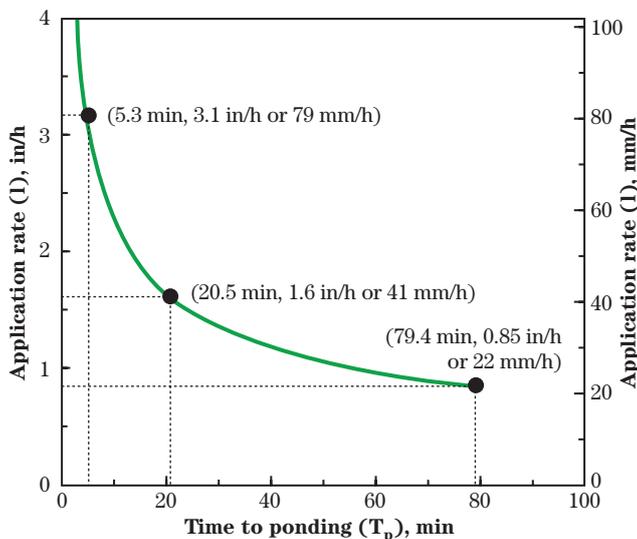
$$\begin{aligned} d_i &= I \left(\frac{t_p}{60} \right) \\ &= 3.2 \left(\frac{5}{60} \right) \\ &= 0.27 \text{ in (8 mm)} \end{aligned} \quad (\text{eq. 11D-5})$$

At the lower application rate, infiltration depth at ponding (at 30 min) is:

$$\begin{aligned} d_i &= I \left(\frac{t_p}{60} \right) \\ &= 1.3 \left(\frac{30}{60} \right) \\ &= 0.65 \text{ in (17 mm)} \end{aligned} \quad (\text{eq. 11D-6})$$

This illustration shows that over twice as much water can be infiltrated (0.65 vs. 0.27 in) before ponding occurs by reducing the application rate. The application rate is reduced by increasing the wetted diameter, w , of the sprinkler pattern. When the time of ponding is estimated to occur prior to the end of the wetting event, an equation for approximating the required SS is:

Figure 11D-1 Plot of application rate vs. the time of ponding from field measurements (Keller and Bliesner 1990)



$$SS_{\text{req}} = (t_{\text{wet}} - t_p) \left(\frac{I_a - I_{\text{pt}}}{60} \right) \quad (\text{eq. 11D-7})$$

where:

- SS_{req} = required depth of surface storage to prevent runoff, in or mm
- t_{wet} = total time of wetting, min from equation 11-158
- t_p = time at which ponding begins, min
- I_a = average application rate, in/h or mm/h over the wetting period (i.e., overpass of the pivot lateral)
- I_{pt} = application rate that creates ponding at time t_{wet} (at the end of the overpass)

Equation 11D-7 uses an approximate estimate of the infiltration capacity of the soil during the period of ponding (from t_p to t_{wet}) that is the maximum application rate that will not cause ponding at t_{wet} . That value is taken from figure 11D-2 for the overpass time.

Example calculation 1

It can be estimated whether the center pivot nozzling configuration from sample calculation 11-19, in which w is 30 feet, will cause runoff. The time of application at the end of the lateral (at 1,270 ft) was 5.0 minutes for a speed of 6.0 feet per minute. The application rate was calculated as 4.8 inches per hour. This was a peak application rate. The average application rate across W can be estimated as 0.8 times the peak, or 4.8 (0.8) is 3.8 inches per hour in this case (eq. 11-229 can be used).

From figure 11D-2, for t_p is 5 minutes, the maximum rate of application without ponding within 5 minutes is read as 3.2 inches per hour. This rate is less than I is 3.8 inches per hour average application rate that is to be applied. Therefore, some ponding is estimated to occur, and, without surface storage, some runoff may result.

If consistent surface storage can be developed and sustained, an approximate estimate of the surface storage that would be required to avoid runoff can be determined by finding the time at which the 3.8 inches per hour average application rate is estimated to just begin ponding. From figure 11D-2, that time is estimated to be at t_p is 3.5 minutes. This time can also be

determined from the regression equation developed in the next section.

If the water application time will be 5 minutes, but ponding is estimated to occur at 3.5 minutes under the 3.8 inches per hour application rate, then surface storage will need to be relied upon from 3.5 minutes until 5 minutes. An approximate estimate of the infiltration capacity of the soil during this final 1.5 minutes is to take the maximum application rate that will not cause ponding at 5 minutes (which is t_{wet}). From figure 11D-2, that rate is 3.2 inches per hour. The water application over the final 1.5 minute period that is in excess of the estimated infiltration rate is then 3.8 minus 3.2 is 0.6 inch per hour. Applying equation 11D-7, an approximation of the required SS is:

$$\begin{aligned} SS_{\text{req}} &= (5.0 - 3.5) \left(\frac{3.8 - 3.2}{60} \right) \\ &= 0.015 \text{ in (0.4 mm)} \end{aligned} \quad (\text{eq. 11D-8})$$

The 0.015 inches (0.4 mm) represents very little surface storage requirement. However, if on a slope, even a small amount of infiltration excess, without adequate surface storage, can concentrate into erosive rivulets. The total application depth during the overpass, from equation 11D-4, is 3.8 inches per hour (5/60) minutes are 0.32 inches (8 mm).

If the application rate were increased to 5 inches per hour, then, from figure 11D-2, ponding is estimated to occur at about 2 minutes into the overpass. Therefore, surface storage is needed during the last 3 minutes of the 5-minute nozzle overpass. In this case, the required surface storage is estimated to be:

$$\begin{aligned} SS_{\text{req}} &= (t_{\text{wet}} - t_p) \frac{I_a - I_{\text{pt}}}{60} \\ &= (5.0 - 2.0) \left(\frac{5 - 3.2}{60} \right) \\ &= 0.09 \text{ in (2.3 mm)} \end{aligned} \quad (\text{eq. 11D-9})$$

The total application depth during this overpass is 5 inches per hour times 5 minutes is 0.42 inches (10.6 mm).

If the application rate were the same as in the initial calculations (3.8 in/h), but the lateral rotation speed

were slowed to apply 0.9 inches (23 mm) per pass, then the rotation time would be 22 hours times 0.9 inches divided by 0.31 inches is 64 hours (the 22 hr is associated with applying the 0.31 in depth). From equation 11-233, the speed of the center pivot lateral at the end (1,270 ft from the pivot) for a 64-hour rotation time is:

$$\begin{aligned} \text{Speed}_{1270} &= \frac{2\pi r}{60 t_{\text{rotation}}} \\ &= \frac{2\pi(1,270)}{(60 \text{ min/h})(64 \text{ h})} \\ &= 2.1 \text{ ft/min} \end{aligned} \quad (\text{eq. 11D-10})$$

The wetting time, also referred to as the infiltration opportunity time, for a nozzle at 1,270 feet is:

$$\begin{aligned} t_{\text{wet}} &= \frac{w}{\text{Speed}_r} \\ &= \frac{30 \text{ ft}}{2.1 \text{ ft/min}} \\ &= 14.3 \text{ min} \end{aligned} \quad (\text{eq. 11D-11})$$

At 14.3 minutes, the application rate for no ponding, I_{pt} , is, from figure 11D-2 (or from the regression equation), I_{pt} is 1.92 inches per hour. Previously, the time of ponding at the application rate of 3.8 inches per hour was determined from figure 11D-2 to be at 3.5 minutes. Therefore, required surface storage is estimated to be:

$$\begin{aligned} \text{SS}_{\text{req}} &= (t_{\text{wet}} - t_p) \left(\frac{I_a - I_{\text{pt}}}{60} \right) \\ &= (14.3 - 3.5) \left(\frac{3.8 - 1.92}{60} \right) \\ &= 0.34 \text{ in (8.6 mm)} \end{aligned} \quad (\text{eq. 11D-12})$$

This surface storage requirement of 1/3 inch is substantial and represents nearly 40 percent of the gross application depth. Severe erosion may occur if the surface storage is not insured. This example illustrates the important effect of lateral speed (and irrigation dosage) on the potential for runoff. With daily rotation time, little or no surface storage is estimated to be required, whereas at a 2.5- to 3-day rotation time, more than 1/3 inch of surface storage is required.

Growers are often reluctant to speed up center pivots and reduce rotation cycle time. Reasons given are the increase in evaporation from the canopy or exposed soil, because the surface is wet more of the time, or because the wheel tracks have less time to dry between passes. However, the grower needs to weigh the loss of evaporation against the water lost by runoff and associated erosion of soil. In addition, surface runoff from a center pivot will often be intercepted by wheel tracks and can exacerbate rutting and traction problems.

(a) Developing an equation for infiltration capacity

Sometimes it is convenient to represent the time-to-ponding curve in figures 11D-1 and 11D-2 using an equation. Usually an exponential-type of curve is required:

$$I = k_p (t_p)^p \quad (\text{eq. 11D-13})$$

where:

- I = average application rate to create ponding at time T_p , in/h or mm/h
- k_p = time-to-ponding coefficient that is fitted to the data, in/h or mm/h
- t_p = time to ponding, min
- p = time-to-ponding exponent that is fitted to the data

The value for p can be calculated by selecting two points from the curve from figure 11D-1:

$$p = \frac{\ln(I_1) - \ln(I_2)}{\ln(t_{p1}) - \ln(t_{p2})} \quad (\text{eq. 11D-14})$$

where:

- I_1 = application rate from figure 11D-1 at $T_p = T_{p1}$, in/h or mm/h
- I_2 = application rate from Fig 11-D1 at $T_p = T_{p2}$, in/h or mm/h
- t_{p1} = time of ponding for application rate I_1 , min
- t_{p2} = ponding time for application rate I_2 , min

The value for k_p can be calculated as:

$$k_p = \frac{I}{(t_p)^p} \quad (\text{eq. 11D-15})$$

where:

I and t_p = any point on the application rate – ponding curve (fig. 11D-1)

p = equation 11D-14

As an example, using two of the points from figure D-1, I_1 is 3.12 inches per hour at t_{p1} is 5.3 minutes and I_2 is 1.6 inches per hour at t_{p2} is 20.5 minutes. Therefore:

$$\begin{aligned} p &= \frac{\ln(I_1) - \ln(I_2)}{\ln(t_{p1}) - \ln(t_{p2})} \\ &= \frac{\ln(3.12) - \ln(1.6)}{\ln(5.3) - \ln(20.5)} \\ &= \frac{1.13 - 0.47}{1.668 - 3.02} \\ &= -0.48 \end{aligned} \quad (\text{eq. 11D-14})$$

Parameter, p , will always have a negative value since the application rate versus time of ponding curve decreases with time. The value for k_p is calculated as:

$$\begin{aligned} k_p &= \frac{I}{(t_p)^p} \\ &= \frac{3.1}{(5.3)^{-0.48}} \\ &= 6.9 \end{aligned} \quad (\text{eq. 11D-15})$$

Therefore, the equation for the soil shown in figures 11D1 and 11D-2 is:

$$I = 6.9t_p^{-0.48} \quad (\text{eq. 11D-16})$$

where:

T_p = minutes

I = in/h

(b) Minimum required W

Equation 11-158, which relates wetted diameter, w , to lateral speed and wetting time, can be combined with equation 11D-4 to estimate the minimum required w for no runoff. If equation 11D-13 is inserted into equation 11D-1 for I , the result is:

$$d_i = \frac{k_p}{60} (t_p)^{p+1} \quad (\text{eq. 11D-17})$$

where:

d_i = infiltrated depth, in or mm

k_p = time-to-ponding coefficient that is fitted to the data, in/h or mm/h

t_p = time to ponding, min

p = time-to-ponding exponent that is fitted to the data

Equation 11D-17 can be inverted to solve for t_p as:

$$t_p = \left(\frac{60 d_i}{k_p} \right)^{\frac{1}{p+1}} \quad (\text{eq. 11D-18})$$

Because the infiltration depth at imminent runoff, d_i , is equal to d_{g-ss} , where d_g is gross application depth, then:

$$t_p = \left(\frac{60 (d_g - ss)}{k_p} \right)^{\frac{1}{p+1}} \quad (\text{eq. 11D-19})$$

Similarly, equation 11-158) can be inverted to solve for w , where lateral speed in the equation is replaced by equation 11-159), so that w is $2\pi r$ times t_{wet} divided by $60 t_{rotation}$. Because t_{wet} is the time that any point on the soil surface receives water, t_{wet} can be set equivalent to t_p , the time until ponding, so that the system will just avoid having any runoff. The two derived expressions can be combined to form the following equation to estimate a minimum wetted width of the wetting pattern perpendicular to the pivot lateral:

$$W_{min} = \frac{2\pi r \left(\frac{60 (d_g - SS)}{k_p} \right)^{\frac{1}{p+1}}}{60 t_{rotation}} \quad (\text{eq. 11D-20})$$

where:

- w_{\min} = minimum width of wetting pattern perpendicular to the lateral, ft or m
 SS = available surface storage, in or mm
 d_g = gross irrigation requirement during irrigation interval, in or mm
 k_p = time-to-ponding coefficient that is fitted to the data, in/h or mm/h
 p = time-to-ponding exponent that is fitted to the data
 t_{rotation} = time for one complete rotation of the center pivot, h

Technically, the d_g in equation 11D–20 can be reduced to account for the evaporation and drift of spray before the water reaches the soil surface. However, the evaporation loss fraction is typically less than 5 percent for a center pivot system and the soil parameters used in equation 11D–20 (k_p , p, and SS) are sufficiently uncertain so that refining the value for d_g is unnecessary. Because d_g for periods of no precipitation is equal to $ET_c t_{\text{rotation}}/24$, equation 11D–20 shows that as the time of rotation increases (slower lateral speed) the required w will increase.

Example calculation D2:

The minimum W can be calculated for example calculation D1, where 0.31 inches of water (d_g) are to be applied each 24 hours (i.e., daily irrigation) and lateral length is 1,270 feet. Assuming there are 0.08 inches (2 mm) of surface storage, then:

$$\begin{aligned} w_{\min} &= \frac{2\pi r \left(\frac{60(d_g - SS)}{k_p} \right)^{\frac{1}{p+1}}}{60t_{\text{rotation}}} \\ &= \frac{2\pi(1,270) \left(\frac{60(0.31 - 0.08)}{6.9} \right)^{\frac{1}{-0.48+1}}}{60(22)} \\ &= 23 \text{ ft} \end{aligned} \quad (\text{eq. 11D-21})$$

Therefore, the system is estimated to function without runoff as long as W is greater than 23 feet. This is possible using most types of flat plate spray nozzles on straight drops. A minimum W is 23 feet only results due to the benefit of the 0.08 inches of surface storage, SS.

If the equation were to be solved assuming no surface storage ($SS=0$), the result is $W = 41$ feet, which is substantially greater. This illustrates the important role that SS can play on soils that are prone to surface runoff.

The example was for a 22-hour rotation time. In many situations, the center pivot lateral speed is reduced and t_{rotation} increased to reduce the wetting frequency and to reduce the evaporation losses that can occur from frequently wetted soil or canopy. For example, for corn crops, a 3.5-day rotation is commonly used. In this case, the d_g for $f = 3.5$ days would be $d_g = 0.31 \times 3.5 = 1.09$ inches.

If equation 11D–20 is recalculated for $d_g = 1.09$ inches and $t_{\text{rotation}} = 3.5 \times 22 = 77$ hours (only 22 h/day are used to account for downtime), and with $SS = 0.08$ inches, the result is:

$$\begin{aligned} w_{\min} &= \frac{2\pi r \left(\frac{60(d_g - SS)}{k_p} \right)^{\frac{1}{p+1}}}{60t_{\text{rotation}}} \\ &= \frac{2\pi(1,270) \left(\frac{60(1.09 - 0.08)}{6.9} \right)^{\frac{1}{-0.48+1}}}{60(77)} \\ &= 113 \text{ ft} \end{aligned} \quad (\text{eq. 11D-22})$$

Therefore, for this soil, one would need to use sprinklers having a w greater 114 feet at the end of the lateral if one were to apply 1.09 inches of water per application each 3.5 days.

Equation 11D–20 illustrates that nozzles or nozzle systems on boom drops can have progressively smaller w at distances closer to the pivot, because the radius r is in the numerator of the equation. The equation also illustrates that speeding up a center pivot lateral, and reducing the depth of application each pass can have tremendous impact on reducing runoff potential for a given w .