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Section 15 **Irrigation**

Chapter 11

Sprinkle Irrigation

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Chapter 11

Sprinkle Irrigation

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 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 operate while moving 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 sprinklers, and gun sprinklers. The dominant continuous-move systems are center-pivot and traveling sprinklers.

With carefully designed periodic-move and fixed systems, water can be applied uniformly at a rate based on the intake rate of the soil, thereby preventing runoff and consequent damage to land and to 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.

Adaptability

Sprinkle irrigation is suitable for most crops. It is 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 (iph). 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.

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.

Advantages

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

1. Small, continuous streams of water can be used effectively.
2. Runoff and erosion can be eliminated.
3. Problem soils with intermixed textures and profiles can be properly irrigated.
4. Shallow soils that cannot be graded without detrimental results can be irrigated without grading.
5. Steep and rolling topography can be easily irrigated.
6. Light, frequent waterings can be efficiently applied.
7. Crops germinated with sprinkler irrigation may later be surface irrigated with deeper applications.
8. Labor is used for only a short period daily in each field.
9. Mechanization and automation are practical to reduce labor.
10. Fixed systems can eliminate field labor during the irrigation season.
11. Unskilled labor can be used because decisions are made by the manager rather than by the irrigator.
12. Weather extremes can be modified by increasing humidity, cooling crops, and alleviating freezing by use of special designs.
13. 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.
14. Salts can be effectively leached from the soil.
15. High application efficiency can be achieved by a properly designed and operated system.

Disadvantages

Important disadvantages of sprinkle irrigation are:

1. High initial costs must be depreciated. For simple systems these costs, based on 1980 prices, range from $75 to $150 per acre; for mechanized and self-propelled systems, from $200 to $300; and for semi and fully automated fixed systems from $500 to $1,000.
2. Cost of pressure development, unless water is delivered to the farm under adequate pressure, is about $0.20 per acre-ft of water for each pound per square inch (psi) of pressure, based on $0.75/gal for diesel or $0.06/KWH for electricity.
3. Large flows intermittently delivered are not economical without a reservoir, and even a minor fluctuation in rate causes difficulties.
4. Sprinklers are not well adapted to soils having an intake rate of less than 0.15 inches per hour (iph).
5. Windy and excessively dry locations appreciably lower sprinkler irrigation efficiency.
6. Field shapes, other than rectangular, are not convenient to irrigate especially with mechanized sprinkle systems.
7. Cultural operations must be meshed with the irrigation cycle.
8. Surface irrigation methods on suitable soils and slopes have higher potential irrigation efficiency.
9. Water supply must be capable of being cut off at odd hours when the soil moisture deficiency is satisfied.
10. Careful management must be exercised to obtain the high potential efficiency of the method.
11. Systems must be designed by a competent specialist with full consideration for efficient irrigation, economics of pipe sizes and operation, and convenience of labor.
12. When used in overhead sprinklers, irrigation water that has high concentrations of bicarbonates may affect the quality of fruit.
13. Saline water may cause problems because salt may be absorbed by the leaves of some crops.

Sprinkle irrigation can be adapted to most climatic conditions where irrigated agriculture is feasible. Extremely high temperatures and wind velocities, however, 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 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) = 1.3 mmhos/cm and containing 140 ppm sodium and 245 ppm chloride. In contrast, little or no damage has occurred from the use of waters having an EC_w as high as 4.0 mmhos/cm 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 very 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 1 revolution per minute (rpm) or faster are also recommended under such conditions.

If overhead sprinklers must be used, it may not be possible to grow certain sensitive crops such as beans or grapes. 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 and leaching requirements for various crops, water qualities, and soils.

Types of Systems

There are 10 major types of sprinkle 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 use either small or gun sprinklers. The major types of continuous-move systems are center-pivots, traveling gun or boom sprinklers, and linear-move.

Periodic-Move

Hand-Move Lateral

The hand-move portable lateral system is composed of either portable or buried mainline pipe with valve outlets at various spacings for the portable laterals. These laterals are of aluminum tubing with quick couplers and have either center-mounted or end-mounted riser pipes with sprinkler heads. This system is used to irrigate more area than any other system, and it is used on almost all crops and on all types of topography. A disadvantage of the system is its high labor requirement. This system is the basis from which all of the mechanized systems were developed. Figure 11-1 shows a typical hand-move sprinkler lateral in operation.

To reduce the need for labor the hand-move system can be modified by the addition of a tee to each sprinkler riser that is used to connect a 50-ft, 1-in-diameter, trailer pipeline with a stabilizer and another riser with a sprinkler head at the end. This modification reduces the number of hand-move laterals by half; however, the system is more difficult to move than the conventional hand-move lateral.

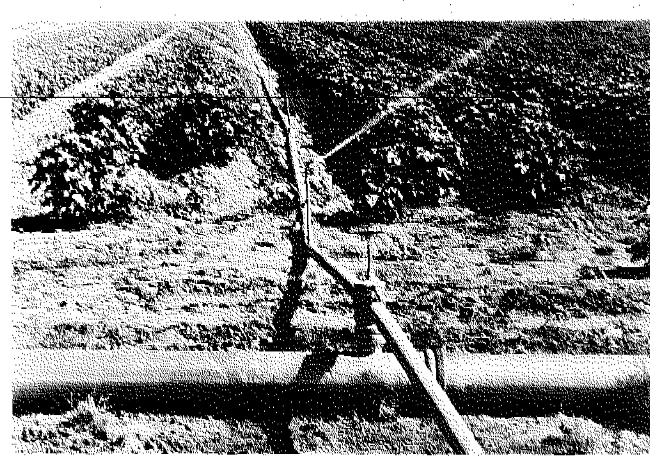


Figure 11-1.—Hand-move sprinkler lateral in operation.

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. 11–2). By draining the pipe through automatic quick drain valves, a 20- to 30-horsepower tractor can easily pull a quarter-mile 4-inch-diameter lateral.

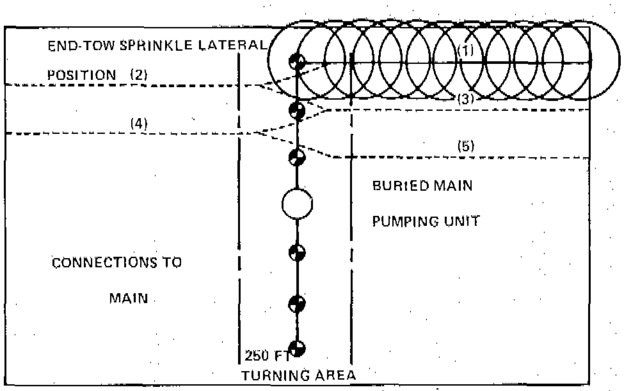


Figure 11–2—Schematic of move sequence for end-tow.

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-ft-wide turning area is required along the length of the mainline (fig. 11–2). The turning area 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 (fig. 11–2) 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 4 rows of a low growing crop that the tractor can drive over without causing much damage.

Side-Roll Lateral

A side-roll lateral system 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. 11–3). The lateral line forms the axle for the wheels, and when it is twisted 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 with no physical obstructions. The diameter of the wheels should be selected so that the lateral clears the crop and so that the specified lateral move distance is a whole number of rotations of the line, e.g., for a 60-ft move use 3 rotations of a 76.4-in-diameter wheel.

Figure 11-3.—Side-roll sprinkler lateral in operation.

Side-roll laterals up to 1,600 ft long are 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 one-fourth mile long are recommended. Typically, 4- or 5-in-diameter aluminum tubing is used. For a standard quarter-mile lateral on a close-spaced crop at least 3 lengths of pipe to either side of a center power unit should be 0.072-in heavy walled aluminum tubing. For longer lines and in deep-furrowed row crops or on steep topography more heavy walled tubing should be used, enabling the laterals to roll more smoothly and uniformly and with less chance of breaking.

A well designed side-roll lateral should have quick drains at each coupler. All sprinklers should be provided with a self leveler so that regardless of the position at which the lateral pipe is stopped each sprinkler will be upright. 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 tag lines are sometimes added to heavy walled 5-in side-roll lines. 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.

Side-Move Lateral

Side-move laterals 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 ft above the ground and the wheel carriages are spaced 50 ft apart. A trail tube with 11 sprinklers mounted at 30-ft intervals is pulled behind each wheel carriage. Thus, the system wets a strip 320 ft 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 ft. Small (60 to 100 gpm) gun sprinklers mounted at every other carriage will irrigate a 150-ft-wide strip, and a quarter-mile-long lateral can irrigate 4.5 acres per setting. Application rates, however, are relatively high (approximately 0.5 iph).

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. A major inconvenience of these mechanical move systems occurs, however, 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. Unfortunately, the mechanical move laterals cannot be readily disassembled; therefore, each one must be deadheaded back to its starting position. This operation is quite time consuming, especially where trail tubes are involved.

Fixed Sprinkler

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 (fig. 11–4), buried or permanent laterals, and sequencing valve laterals. Most fixed sprinkler systems have small sprinklers spaced 30 to 80 ft apart, but some systems use small gun sprinklers spaced 100 to 160 ft apart.

Solid-Set Portable

Solid-set portable systems are 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 also moved from field to field to germinate such crops as lettuce, which are then furrow irrigated. Moving the laterals into and out of the 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

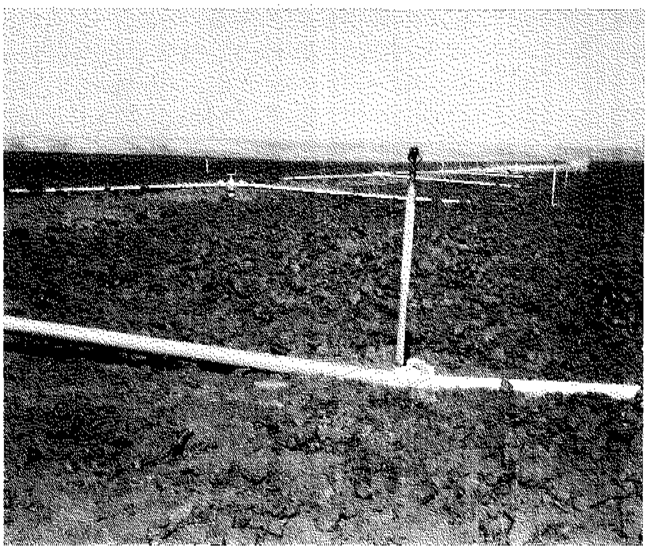


Figure 11-4.—Solid-set sprinkler laterals connected to buried mainline.

mechanical lifter. The procedure is reversed when returning the laterals to the field for the next season.

Buried Laterals

Permanent, buried laterals are placed underground 18 to 30 inches deep with only the riser pipe and sprinkler head above the surface. Many systems of this type are used in citrus groves, orchards, and field crops.

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. Most 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 automated by the use of electric or air valves 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 (or giant) sprinklers have 5/8-in 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 many can be set to irrigate a part circle (fig. 11-5).

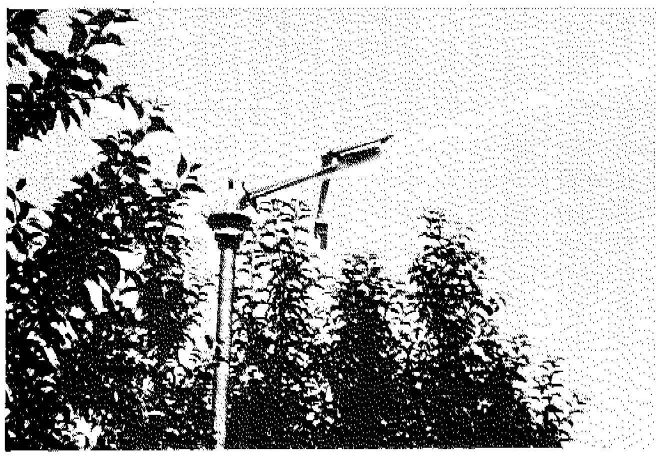


Figure 11-5.—Part circle gun sprinkler with rocker arm drive in operation.

Boom sprinklers have a rotating 110- to 250-ft 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 ft in diameter (fig. 11-6).

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, however, are considerably less expensive and are simpler to operate; consequently, there are more gun than boom sprinklers in use. Gun and boom sprinklers usually discharge more than 100 gpm and are operated individually rather than as sprinkler-laterals. A typical sprinkler discharges 500 gpm and requires 80 to 100 psi operating pressure.

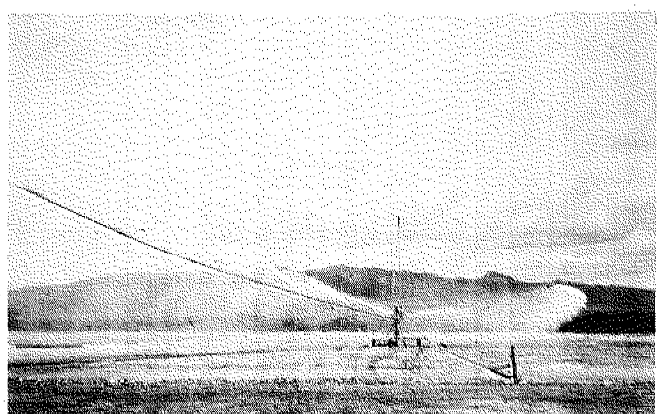


Figure 11-6.—Boom sprinkler in operation.

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 the soil surface and create runoff problems. Therefore, these sprinklers are most suitable for coarse-textured soils with high infiltration rates and for relatively mature crops that need only supplemental irrigation. Gun and boom sprinklers are not recommended for use in extremely windy areas because their distribution patterns 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. Boom sprinklers are unstable and can tip over when being towed over rolling or steep topography.

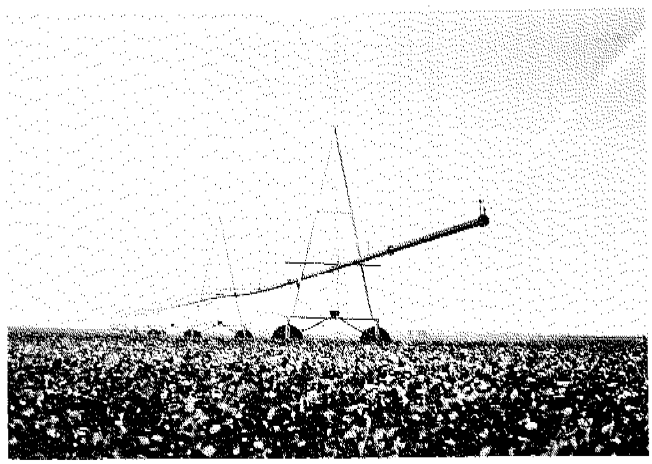


Figure 11-7.—Outer end of center-pivot lateral in operation.

Continuous-Move Lateral

Center-Pivot

The center-pivot system sprinkles water from a continuously moving lateral pipeline. The lateral is fixed at one end and rotates to irrigate a large circular area. The fixed end of the lateral, called the "pivot point," is connected to the water supply. The lateral consists of a series of spans ranging in length from 90 to 250 ft and carried about 10 ft above the ground by "drive units," which consist of an "A-frame" supported on motor driven wheels (fig. 11-7).

Devices are installed at each drive unit to keep the lateral in a line between the pivot and end-drive unit; the end-drive unit is set to control the speed of rotation. The most common center-pivot lateral uses 6-in pipe, is a quarter mile long (1,320 ft), 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 ft and as long as a half mile are available.

The moving lateral pipeline is fitted with impact, spinner, or spray-nozzle sprinklers to spread the water evenly over the circular field. The area to be irrigated by each sprinkler set at a uniform sprinkler spacing along the lateral becomes progressively larger toward the moving end. Therefore, to provide uniform application the sprinklers must be designed to have progressively greater discharges, closer spacings, or both, toward the moving end. Typically, the application rate near the moving end is about 1.0 iph. This exceeds the intake rate of many soils except for the first few minutes at the beginning of each irrigation. To minimize surface ponding and runoff, the laterals are usually rotated every 10 to 72 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, water pistons, water spinners and turbines, hydraulic oil motors, and air pistons. The first pivots were powered by water pistons; however, electric motors are most common today because of their speed, reliability, and ability to run backwards and forwards.

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 in the irrigated area. 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, the resulting runoff causes erosion and puddles that may interfere with the uniform movement of the lateral around the pivot point. If these systems are used on square subdivisions, some means of irrigating the four corners must be provided, or other uses made of the area not irrigated. In a 160-acre quarter-section subdivision, about 30 acres are not irrigated by the center-pivot system unless the pivot is provided with a special corner irrigating apparatus. With some corner systems only about 8 acres are left unirrigated.

Most pivot systems are permamently installed in a given field. But in supplemental irrigation areas or for dual cropping, it is practical to move a standard quarter-mile center-pivot lateral back and forth between two 130-acre fields.

Traveling Sprinkler

The traveling sprinkler, or traveler, is a high-capacity sprinkler fed with water through a flexible hose; it is 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 giant gun-type 500-gpm sprinkler that is mounted on a moving vehicle and wets a diameter of more than 400 ft. The vehicle is 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 lay-flat hose that is connected to the water supply pressure system. The typical hose is 4 inches in diameter and is 660 ft. long, allowing the unit to travel 1,320 ft unattended (fig. 11–8). After use, the hose can be drained, flattened, and wound onto a reel.

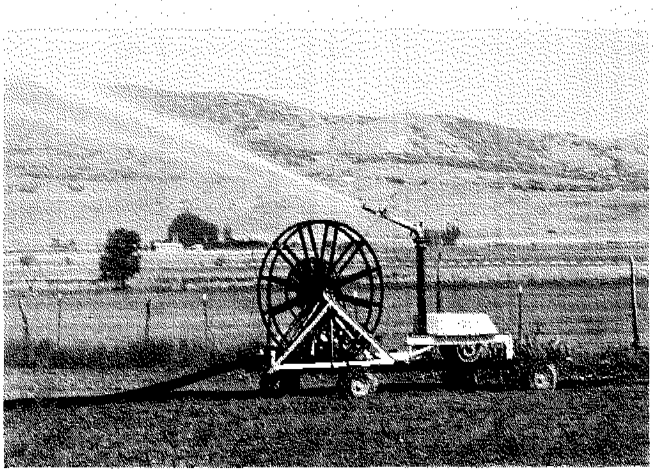


Figure 11–8.—Hose-fed traveling gun-type sprinkler in operation.

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.

Some travelers are equipped with boom sprinklers instead of guns. Boom sprinklers have rotating arms 60 to 120 ft long from which water is discharged through nozzles as described earlier.

As the traveler moves along its path, the sprinkler wets a strip of land about 400 ft 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. Frequently a part-circle sprinkler is used; the dry part of the pattern is over the towpath so the unit travels on dry ground (fig. 11–9).

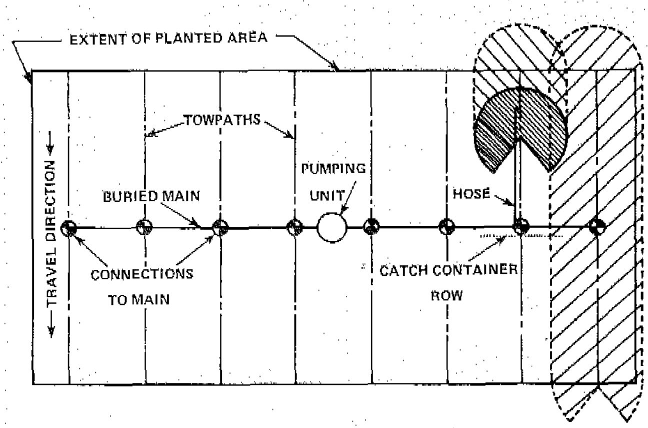


Figure 11–9.—Typical layout for traveling sprinklers showing location of the line of catch containers used for evaluating the distribution uniformity.

Figure 11–9 shows a typical traveling sprinkler layout for an 80-acre field. The entire field is irrigated from 8 towpaths each 1,320 ft long and spaced 330 ft apart.

Traveling sprinklers require the highest pressures of any system. In addition to the 80 to 100 psi required at the sprinkler nozzles, hose friction losses add another 20 to 40 psi 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 discussed under gun and boom sprinklers; however, because they are moving, traveling sprinklers have a higher uniformity and lower application rate than guns and booms. Nevertheless, the application uniformity of travelers is only fair in the central portion of the field, and 100- to 200-ft-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 for efficient operation. Measured water distribution from these systems has shown the highest uniformity coefficients of any system for single irrigations under windy conditions.

Systems that pump water from open ditches must be installed on nearly level fields. Even if the system is supplied by a flexible hose, the field must be fairly level in order for the guidance system to work effectively.

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 and across both sides of the water supply line. Since the center-pivot lateral operates in a circle, it automatically ends each irrigation cycle at the beginning of the next, but because the linear-move lateral moves from one end of the field to the other it must be driven or towed back to the starting position. However, the linear-move system can irrigate all of a rectangular field, whereas the center-pivot system can irrigate only a circular portion of it.

Other Sprinkle Systems

Because of the recent concerns about availability and cost of energy, interest has revived in the use of perforated pipe, hose-fed sprinklers run on a grid pattern, and orchard systems. They afford a means of very low pressure (5 to 20 psi) sprinkle irrigation. Often, gravity pressure is sufficient to operate the system without pumps. Furthermore, inexpensive low-pressure pipe such as unreinforced concrete and thin-wall plastic or asbestos cement can be used to distribute the water. These systems do have the disadvantage of a high labor requirement when being moved periodically.

Perforated Pipe

This type of sprinkle irrigation has almost become obsolete for agricultural irrigation but continues to be widely used for home lawn systems. Perforated pipe systems spray water from 1/16-in-diameter or smaller holes drilled at uniform distances along the top and sides of a lateral pipe. The holes are sized and spaced so as to apply water uniformly between adjacent lines of perforated pipeline (fig. 11-10). Such systems can operate effectively at pressures between 5 and 30 psi, but can be used only on coarse-textured soils such as loamy sands with a high capacity for infiltration.

Figure 11-10.—Perforated pipe lateral in operation.

Hose-Fed Sprinkler Grid

These systems use hoses to supply individual small sprinklers that operate at pressures as low as 5 to 10 psi. They can also produce relatively uniform wetting 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.

Orchard Sprinkler

A small spinner or impact sprinkler 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 psi, and typically the diameter of coverage is between 15 and 30 ft. They are located under the tree canopies to provide approximately uniform volumes of water for each tree. Water should be applied fairly evenly to areas wetted, although some soil around each tree may receive little or no irrigation (fig. 11-11). The individual sprinklers can be supplied by hoses and periodically moved to cover several positions or a sprinkler can be provided for each position.

Planning Concepts

A complete farm sprinkle system is a system planned exclusively for a given area or farm unit on which sprinkling will be the primary method of water application. Planning for complete systems includes consideration of crops and crop rotations used, water quality, and the soils found in the specified design area.

A farm sprinkle-irrigation system includes sprinklers and related hardware; laterals, submains, mainlines; pumping plant and boosters; operation-control equipment; and other accessories required for the efficient application of water. Figure 11-12 shows a periodic-move system with buried mainlines and multiple sprinkler laterals operating in rotation around the mainlines.

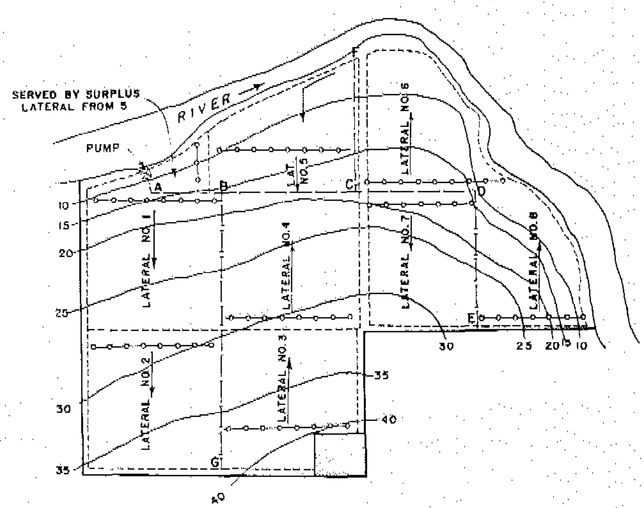


Figure 11-12.—Layout of a complete periodic hand-move sprinkle system. The odd-shaped area of 72 acres illustrates the subdivision of the design area to permit rotation to all areas except one small tract near the pumping location. Number of sprinklers required per acre, 1.5; number of settings for each lateral per irrigation, 10; required number of sprinklers, 72 × 1.5 = 108; total sprinklers required for the eight laterals, 124. Lateral 8 will require an intermediate pressure-control valve.

Figure 11-11.—Orchard sprinkler operating from a hose line.

Large farm systems are usually made up of several field systems designed either for use on several fields of a farm unit or for movement between fields on several farm units. Field systems are planned for stated conditions, generally for preirrigation, for seed germination, or for use in specialty crops in a crop rotation. 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 or semiportable.

Failure to recognize the fundamental difference between field and farm systems, either by the planner or the owner, has led to poorly planned systems of both kinds. In between these two is the incomplete farm system, initially used as a field system but later intended to become a part of a complete farm system.

Failure to anticipate the capacity required of the ultimate system 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 since he may not always be informed as to whether future expansion is intended, however, he has a responsibility to inform the owner of possible considerations for future development when he prepares a field-system plan.

Preliminary Design

The first six steps of the design procedure outlined below are often referred to as the preliminary design factors. Some of these steps are discussed in more detail in other chapters.

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 following instructions in Chapter 3, *Planning Farm Irrigation Systems.*

2. From the local irrigation guide, determine the depth or quantity of water to be applied at each irrigation. If there is no such guide, follow instructions in Chapter 1, *Soil-Plant-Water Relations*, to compute this depth.

3. Determine from the local irrigation guide the average peak period daily consumptive use rates and the annual irrigation requirements for the crops to be grown. The needed information is available. The procedure is discussed more fully in Technical Release No. 21, *Irrigation Water Requirements*.

4. Determine from the local irrigation guide design-use frequency of irrigation or shortest irrigation period. The procedure is discussed more fully in Chapter 1. This step is often not necessary for fully automated fixed systems or for center-pivot systems.

5. Determine capacity requirements of the system as discussed in Chapter 3, *Planning Farm Irrigation Systems*.

6. Determine optimum water-application rate. Maximum (not necessarily optimum) rates are obtainable from the local irrigation guide.

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

8. For periodic move and fixed sprinkle systems:

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

b. Estimate number of sprinklers operating simultaneously, required to meet system capacity requirements.

c. Determine the best layout of main and lateral lines for simultaneous operation of the approximate number of sprinklers required.

d. Make necessary final adjustments to meet layout conditions.

e. Determine sizes of lateral line pipe required.

f. Compute maximum total pressure required for individual lateral lines.

9. For continuous-move sprinkle systems:

a. Select the type of sprinkle nozzle desired.

b. Set the minimum allowable nozzle pressure.

c. Determine the desired system flow rate.

d. Select the type of system drive, i.e., electric, hydraulic.

e. Determine the maximum elevation differences that will be encountered throughout the movement of the system.

f. Select the system pipe (or hose) diameter based on economic considerations.

g. Calculate the system inlet pressure required to overcome friction losses and elevation differences and provide the desired minimum nozzle pressure.

10. Determine required size of mainline pipe.

11. Check mainline pipe sizes for power economy.

12. Determine maximum and minimum operating conditions.

13. Select pump and power unit for maximum operating efficiency within range of operating conditions. The selection of a pump and power plant is discussed in Chapter 8, *Irrigation Pumping Plants*.

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

Figure 11–13 is useful for organizing the information and data developed through carrying out these steps. Section V is set up specifically for periodic-move and fixed-sprinkle systems. It can be modified slightly for continuous-move systems by replacing parts a, b, and c with:

a. Maximum application rate (iph)

b. Time per revolution (or per single run) (hr)

c. Speed of end tower (or of machine) (ft/min)

Figure 11–13 contains four columns that can be used for different crops or for different fields on the same farm.

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

Capacity Requirements

The required capacity of a sprinkle system depends on the size of the area irrigated (design area), the gross depth water applied at each irrigation, and the net operating time allowed to apply this depth. The capacity of a system can be computed by the formula:

$$Q = \frac{453\ Ad}{fT} \qquad (11\text{–}1)$$

Where

Q = system discharge capacity (gpm)
A = design area (acres)
d = gross depth of application (in)
f = time allowed for completion of one irrigation (days)
T = actual operating time (hr/day)

I. Crop (Type)				
(a) Root depth (ft)				
(b) Growing season (days)				
(c) Water use rate (in/day)				
(d) Seasonal water use (in)				
II. Soils (Area)				
(a) Surface texture Depth (ft) Moisture capacity (in/ft)				
(b) Subsurface texture Depth (ft) Moisture capacity (in ft)				
(c) Mositure capacity (in)				
(d) Allowable depletion (in)				
(e) Intake rate (iph)				
III. Irrigation				
(a) Interval (days)				
(b) Net depth (in)				
(c) Efficiency (%)				
(d) Gross depth (in)				
IV. Water requirement				
(a) Net seasonal (in)				
(b) Effective rain (in)				
(c) Stored moisture (in)				
(d) Net irrigation (in)				
(e) Gross irrigation (in)				
(f) Number of irrigations				
V. System capacity				
(a) Application rate (iph)				
(b) Time per set (hrs)				
(c) Settings per day				
(d) Days of operation per interval				
(e) Preliminary system Capacity (gpm)				

Figure 11-13.—Factors for preliminary sprinkle irrigation system design.

For center-pivot systems and fully automatic fixed systems, it is best to let d equal the gross depth required per day and f = 1.0. To allow for some breakdown or moving of systems, T can be reduced by 5 to 10 percent from the potential value of 24 hr.

Of major importance are f and T because they have a direct bearing on the capital investment per acre required for equipment. From equation 1 it is obvious that the longer the operating time (fT) the smaller the required system capacity and, therefore, the 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. With these systems irrigation frequency should be based on maintaining optimum soil-plant-water conditions rather than on allowing soil moisture depletion levels that are a compromise between labor requirements, capital costs, and growing conditions (as recommended in Chapter 1).

Before a sprinkle 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. Also the farmer should understand the amount of labor required to run the sprinkle system so that this operation interferes minimally with other farming operations.

Areas that have several soil zones that vary widely in water-holding capacity and infiltration rate can be subdivided on the basis of the water needed at each irrigation (fig. 11-14) for all systems except center pivots. It is easier to operate center-pivot sprinklers as though the entire field has the soil with the lowest water-holding capacity and 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. Otherwise, they may be computed from Technical Release No. 21, *Irrigation Water Requirements* and Chapter 1, *Soil-Plant-Water Relationships*.

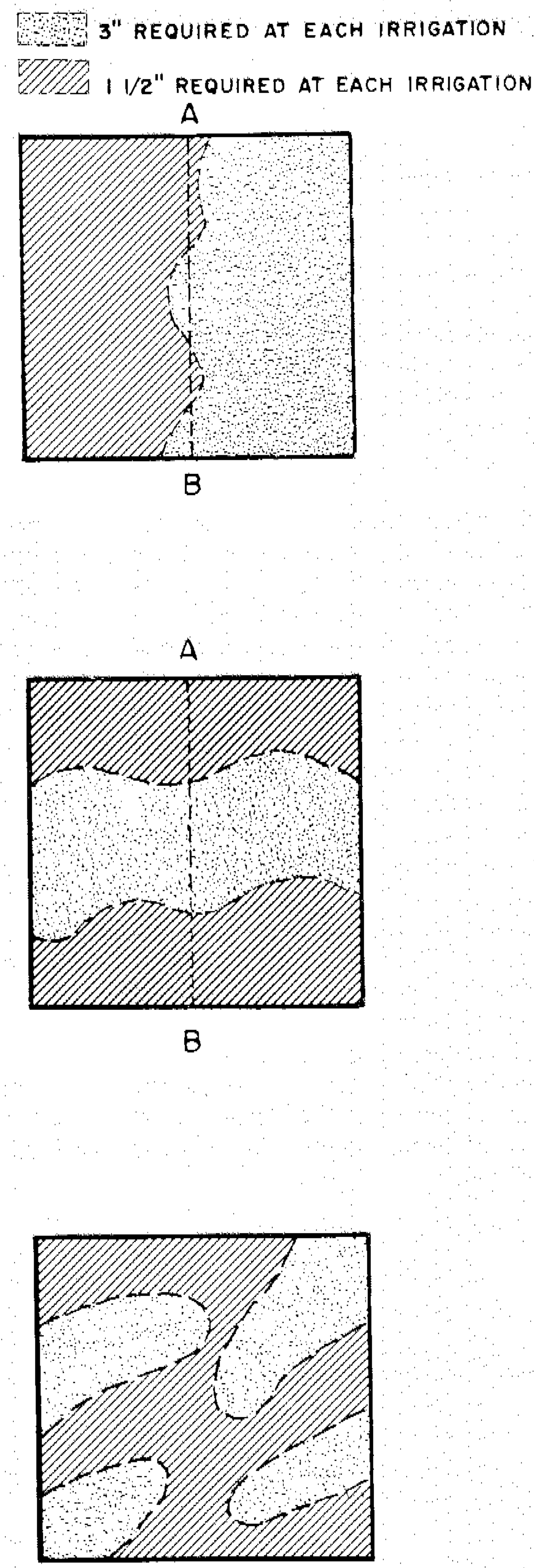


Figure 11-14.—Subdivision of design areas having different soil zones.

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

Given:
- 40 acres of corn (A)
- Design moisture use rate: 0.20 in/day
- Moisture replaced in soil at each irrigation: 2.4 in
- Irrigation efficiency: 70%
- Gross depth of water applied (d): 2.4/0.70 or 3.4 in a 70% efficiency
- Irrigation period (f): 10 days in a 12-day interval
- System to be operated 20 hr/day (T)
- 3.0 in required at each irrigation
- 1.5 in required at each irrigation

A The design area can be served by a mainline as indicated by the dotted line. Laterals can operate on both sides, but must run twice as long on the 3.0-in zone and twice as often on the 1.5-in zone, or else separate laterals must be designed for each zone with different water application rates. In either case the frequency of irrigation would be two times on the 1.5-in zone for each time on the 3.0-in zone.

B The system is designed for a uniform soil area using the 1.5-in water-application rate. Once during the early growing season, the lateral or laterals could be operated twice as long on the 3.0-in zone, but the entire area would be irrigated at the frequency required for the 1.5-in zone during peak-moisture-use periods.

C Again the system would be designed for the 1.5-in zone. For deep-rooted crops, the entire area might be given a 3.0-in application for the first irrigation in the spring. However, this would mean some sacrifice in water-application efficiency.

Calculation using equation 1:

$$Q = \frac{453\ Ad}{fT} = \frac{453 \times 40 \times 3.4}{10 \times 20} = 308 \text{ gpm}$$

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-frequency period as shown in the local irrigation guide or determined by the procedure in Chapter 1.

System-capacity requirements for an area in a crop rotation are calculated to satisfy the period of water use. Therefore, 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 with crop acreages as follows:
- 10 acres Irish potatoes, last irrigation May 31;
- 2.6-inch application lasts 12 days in May (peak period);
- 30 acres corn, last irrigation August 20;
- 2.9-inch application lasts 12 days in May;
- 3.4-inch application lasts 12 days in July (peak period);
- 50 acres alfalfa, irrigated through frost-free period;
- 3.6-inch application lasts 12 days in May;
- 4.3-inch application lasts 12 days in July (peak period);
- Irrigation period is 10 days in 12-day irrigation interval;
- System is to be operated 16 hr per day.
- Calculations using equation 1:
- Capacity requirements for May when all three crops are being irrigated.

Irish potatoes $$Q = \frac{453 \times 10 \times 2.6}{10 \times 16} = 74 \text{ gpm}$$

Corn $$Q = \frac{453 \times 30 \times 2.9}{10 \times 16} = 246 \text{ gpm}$$

Alfalfa $$Q = \frac{453 \times 50 \times 3.6}{10 \times 16} = 510 \text{ gpm}$$

Total for May = 830 gpm

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

Corn $$Q = \frac{453 \times 30 \times 3.4}{10 \times 16} = 289 \text{ gpm}$$

Alfalfa $$Q = \frac{453 \times 50 \times 4.3}{10 \times 16} = 609 \text{ gpm}$$

Total for July = 898 gpm

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 and after the peak use-period.

If highly saline irrigation water is to be used on salt sensitive crops (when the conductivity of the irrigation water is more than half the allowable conductivity of the drainage water), it is advisable to provide a portion of the annual leaching requirement at each irrigation. Thus, 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 Technical Release No. 21.

It is not wise to irrigate under extremely windy conditions, because of poor uniformity and excessive 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.

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 often are optimum with system capacities about 20 percent lower than are specified for conventional periodic-move systems in the same area. Underirrigation is best achieved by using a longer interval between irrigations than is normally recommended for optimum yields.

Fixed Systems

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

Ordinary Irrigation.—Some fixed systems are installed in permanent crops, and relatively long irrigation intervals are used. 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-hr day, 7-day week basis. These systems may be used to apply fertilizers and other chemicals and can be controlled by hand valves.

High Frequency.—If the system is designed to apply irrigations once or twice a day to control soil temperatures 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 always be consuming water at the peak potential evapotranspiration rate. By contrast, under lower frequency irrigation, as the soil moisture decreases the consumptive use rate falls below the peak potential rate. A major purpose for such a system is to keep the crop performing at a peak rate to increase quality and yield. Clearly, crops that do not respond favorably to uniform high soil moisture conditions are not particularly good candidates for solid set systems. High frequency systems can be hand valve operated. However, automatic valve systems can be used to apply fertilizers and chemicals.

Crop Cooling.—Very 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 they are nearly dry, then reapplied. This generally requires having 1/4 to 1/6 of the system in operation simultaneously and cycling the system once every 15 to 40 min depending on system capacity, crop size, and climatic conditions. For example, a system for cooling trees might be operated 6 out of every 30 min so that 1/5 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 BTU of latent heat released per pound of water during the actual freezing of the water. In addition, a small amount of heat (one BTU per pound of water per degree Fahrenheit temperature drop) 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 mph an application rate of 0.15 iph (65 gpm per acre) should provide overhead freeze protection down to a dew point temperature of 20°F. For every degree above or below a dew point temperature of 20°F the application rate can be decreased or increased by 0.01 iph (4.3 gpm per acre).

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°F, use under-tree sprinkler systems with every other sprinkler operating and over-crop systems of limited capacity that can be rapidly sequenced. Such systems may use only 25 to 30 gpm per acre.

Bloom Delay.—Bloom delay is a means of cold protection wherein woody plants are cooled by sprinkling during the dormant season to delay budding until there is little 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 iph is about as low as can be practically achieved with ordinary impact sprinklers. Operating half of such a system simultaneously requires 22 to 26 gpm per acre.

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. Therefore, it is advisable to allow some reserve capacity (time) and use the same system capacity as for a conventional periodic-move system.

High Frequency.—Where high frequency irrigation is used for the same purposes described above, 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.

Limited Irrigation.—On crop-soil systems where there is 5.0 in or more water storage capacity, limited irrigation 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 the peak use periods when the system capacity is inadequate to meet crop moisture withdrawal rates.

Light, frequent watering of the topsoil plus the gradual withdrawal of moisture from the subsoil can produce optimum crop yield when the system capacity is limited. But when subsoil moisture is inadequate, light, frequent irrigation resulting in heavy moisture losses from evaporation may be an inefficient use of a limited supply of water and may also increase salinity. Under these conditions, deeper less frequent irrigations may produce better yields.

System capacities as low as 60 percent of the recommended value for ordinary periodic-move systems may be adequate. But before determining the area that can be irrigated with a limited flow rate, a careful soil-moisture budget account should be constructed for the peak-use period.

Depth of Application

The calculated depth of application should be obtained for the crop-soil-water relationships at the proposed system location. Whenever possible, the depth should be based on local experience or on irrigation guides. In the absence of these, Chapter 1 can be used to gain an insight into the computation process.

Water-Holding Capacity

Soils of various textures have varying abilities to retain water. Except in the case of required periodic leaching, any irrigation beyond the field capacity of the soil is an economic loss. Table 11-1, which was taken from Chapter 1, gives typical ranges of available water-holding capacities of soils of different textures (field capacity minus permanent wilting point) and is presented here for convenience. If local data are not available, the listed averages may be used as a guide.

The total amount of soil water available for plant use in any soil is the sum of the available water-holding capacities of all horizons occupied by plant roots.

Table 11-1.—Range in available water-holding capacity of soils of different texture [1]

	Inches of water per foot of depth	
	Range	Average
1. Very coarse texture—very coarse sands	0.40 to 0.75	0.5
2. Coarse texture—coarse sands, fine sands, and loamy sands	0.75 to 1.25	1.0
3. Moderately coarse texture—sandy loams	1.25 to 1.75	1.5
4. Medium texture—very fine sandy loams, loams, and silt loams	1.50 to 2.30	2.0
5. Moderately fine texture—clay loams, silty clay loams, and sandy clay loams	1.75 to 2.50	2.2
6. Fine texture—sandy clays, silty clays, and clays	1.60 to 2.50	2.3
7. Peats and mucks	2.00 to 3.00	2.5

[1] Chapter 1, Section 15, *Soil-Plant-Water Relationships.*

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 restrictions, table 11-2 can be used as a guide to estimating the effective root depths of various crops.

The values given are averages selected from several references. They represent the depth at which crops will get most of their needed water when they are grown in a deep, well-drained soil that is adequately irrigated.

Application Depth and Frequency

For periodic-move, and low-frequency continuous-move systems such as traveling sprinklers, 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 (SMD) within the root zone should not fall below 50 percent of the total available-water-holding capacity. This is a management-allowed deficit, MAD = 50%. It is also desirable to bring the moisture level back to field capacity with each irrigation; therefore, the duration of each irrigation is identical.

In humid regions it is necessary to allow for rains during the irrigation period; however, the 50 percent limitation on soil moisture depletion should be followed for design purposes.

Local soil conditions, soil management, water management, and economic considerations determine the amount of water used in irrigating and the rate of water application. The standard design approach has been to determine the amount of water needed to fill the entire root zone 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 has been to assume MAD = 50%, then take the number of inches of water in the root zone reservoir that can be extracted and, using the daily consumptive use rate of the plant, determine how long this supply will last. Such an approach is useful only as a guide to irrigation requirements because many factors affect the amount of irrigation water and the timing of applications for optimal design and operation of a system.

Table 11-2. Effective crop root depths that would contain approximately 80 percent of the feeder roots in a deep, uniform, well-drained soil profile [1]

Crop	Root depth (ft)	Crop	Root depth (ft)
Alfalfa	4.0 to 6.0	Parsnip	2.0 to 3.0
Almonds	2.0 to 4.0	Passion fruit	1.0 to 1.5
Apple	2.5 to 4.0	Pastures (annual)	1.0 to 2.5
Apricot	2.0 to 4.5	Pastures (perennial)	1.0 to 2.5
Artichoke	2.0 to 3.0	Pea	1.5 to 2.0
Asparagus	6.0	Peach	2.0 to 4.0
Avocado	2.0 to 3.0	Pear	2.0 to 4.0
Banana	1.0 to 2.0	Pepper	2.0 to 3.0
Barley	3.0 to 3.5	Plum	2.5 to 4.0
Bean (dry)	1.5 to 2.0	Potato (Irish)	2.0 to 3.0
Bean (green)	1.5 to 2.0	Potato (sweet)	2.0 to 3.0
Beans (lima)	3.0 to 5.0	Pumpkin	3.0 to 4.0
Beet (sugar)	1.5 to 2.5	Radish	1.0
Beet (table)	1.0 to 1.5	Safflower	3.0 to 5.0
Berries	3.0 to 5.0	Sorghum (grain and sweet)	2.0 to 3.0
Broccoli	2.0		
Brussel sprout	2.0	Sorghum (silage)	3.0 to 4.0
Cabbage	2.0	Soybean	2.0 to 2.5
Cantaloup	2.0 to 4.0	Spinach	1.5 to 2.0
Carrot	1.5 to 2.0	Squash	2.0 to 3.0
Cauliflower	2.0	Strawberry	1.0 to 1.5
Celery	2.0	Sugarcane	1.5 to 3.5
Chard	2.0 to 3.0	Sudangrass	3.0 to 4.0
Cherry	2.5 to 4.0	Tobacco	2.0 to 4.0
Citrus	2.0 to 4.0	Tomato	2.0 to 4.0
Coffee	3.0 to 5.0	Turnip (white)	1.5 to 2.5
Corn (grain and silage)	2.0 to 3.0	Walnuts	5.5 to 8.0
Corn (sweet)	1.5 to 2.0	Watermelon	2.0 to 3.0
Cotton	2.0 to 6.0	Wheat	2.5 to 3.5
Cucumber	1.5 to 2.0		
Eggplant	2.5		
Fig	3.0		
Flax	2.0 to 3.0		
Grapes	1.5 to 3.0		
Lettuce	0.5 to 1.5		
Lucerne	4.0 to 6.0		
Oats	2.0 to 2.5		
Olives	2.0 to 4.0		
Onion	1.0		

[1] Soil and plant environmental factors often offset normal 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.

Intake and Optimum Application Rates

The rate at which water should be applied depends on:

1. 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.

2. 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.

3. The amount of time it takes for irrigation to achieve efficient use of available labor in coordination with other operations on the farm.

4. The application rate adjusted to the number of sprinklers operating in the best practical system layout.

Chapter 1 has a discussion of intake rates and the effects of slope, vegetation, and soil condition. The rate of application should be planned so 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.

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 millimeters (mm) and have terminal falling velocities ranging from about 6 to 30 ft/s, respectively. With a typical fall distance equivalent to about 10 to 20 ft, most drops come close to reaching their respective terminal velocities. Table 11–3 presents terminal velocities and kinetic energies associated with different drop sizes.

Drop size is reduced as pressure increases (fig. 11–15), or as nozzle size decreases. Drop sizes can also be reduced by using means other than high pressures to cause jet breakup.

Table 11–3. Terminal velocities and kinetic energies associated with different size raindrops

Drop size (mm)	Volume (mm^3)	Terminal velocity (ft/s)	Kinetic energy values: in relation to a 1.0-mm drop	Kinetic energy values: per inch of rain, $ft\text{-}lb/ft^2$
0.5	0.066	5.92	0.0324	2.8
1.0	0.523	12.55	1.0	12.7
1.5	1.77	17.40	6.5	24.5
2.0	4.19	21.20	22.75	36.3
2.5	8.19	23.95	57.0	46.4
3.0	14.2	25.90	115.7	54.2
3.5	22.5	27.40	205.0	60.6
4.0	33.5	28.51	332.0	65.5
4.5	47.8	29.30	499.0	69.3
5.0	65.5	29.80	707.5	71.7

Some such devices are the use of pins penetrating the jet near the nozzle orifice; using sharp orifices instead of tapered nozzles; using triangular, rectangular, or oval orifices; and using impinging jets. Because of escalating energy costs the interest in obtaining small drops without high pressures has been accelerated.

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 11–16 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 iph. The reduction in infiltration rate on the freshly tilled, heavy-textured soil approached the maximum level about 20 min after the beginning of the application.

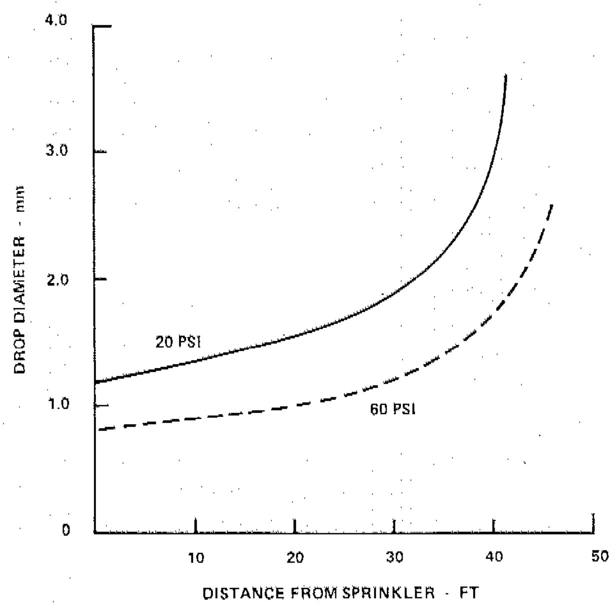


Figure 11–15.—Drop sizes at various distances from a standard 5/32-in nozzle operating at 20 and 60 psi.

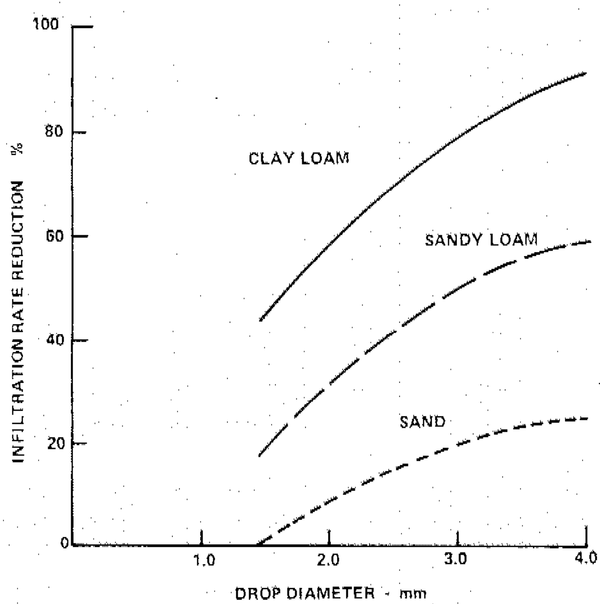


Figure 11–16.—Relation of infiltration rate reduction due to sprinkling three different soils at an application rate of approximately 0.5 iph.

Impact sprinklers produce a circular wetted area. At any one moment, all of the water in the jet lands in a small segment of the total wetted area. Usually the application rate on the area exceeds the 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 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. These particles are carried into the soil by the infiltrating water, causing vertical erosion, surface sealing, and compaction.

The average application rate from a sprinkler is computed by:

$$I = \frac{96.3 \times q}{S_\ell \times S_m} \qquad (11\text{–}2)$$

where

I = average application rate (iph)
q = sprinkler discharge (gpm)
S_ℓ = spacing of sprinklers along the laterals (ft)
S_m = spacing of laterals along the mainline (ft)

Typically, an impact sprinkler with a 5/32-in nozzle operating at 50 psi and discharging 5 gpm would be spaced on a 30- by 50-ft spacing. From equation 2 the average application rate is 0.32 iph.

To compute the average instantaneous application rate (I_i) for a sprinkler having a radius of throw (R_j) and wetting an angular segment (S_a) equation 2 can be modified to:

$$I_i = \frac{96.3 \times q}{\pi (R_j)^2 \times S_a / 360^\circ} \qquad (11\text{–}2a)$$

If the above sprinkler produced a wetted radius of R_j = 45 ft and the jet stream wetted an angular segment of $S_a = 6^\circ$, then I_i = 4.5 iph. This is considerably higher than the infiltration rate of most any agricultural soil except during the first moments of an irrigation.

Increasing sprinkler pressures or applying other means to reduce drop size also tends to decrease the instantaneous application rate. 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. A good rotational speed for the jet at the periphery of the wetted area is 5 ft/sec, which is a typical walking speed of 3.5 mph. Thus a typical impact sprinkler that produces a 90- to 100-ft wetted diameter should rotate about once a minute. However, a gun sprinkler that wets an area over 400 ft in diameter should turn only once every 4 to 5 min.

Periodic-Move and Fixed Systems

In all cases, the selected water-application rate must fall somewhere between the maximum and minimum values set forth at the beginning of the section.

The local irrigation guide gives 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 11–4 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 about 25 percent. For grasses and alfalfa the values may be increased about 25 percent. In addition, application rates should be reduced 25 percent for gun sprinklers, because they produce an abundance of large diameter drops and have high instantaneous application rates.

For most irrigated crops, the minimum practical rate of application to obtain reasonably good distribution and high efficiency under favorable climatic conditions is about 0.15 iph. If high temperatures and high wind velocities are common, the minimum application rate will be higher. The establishment of minimum application rates for local conditions requires experience and judgment.

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 usually 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 mealtimes leave most of the day for other work. For fixed systems (especially automated ones) any number of changes per day can be made.

Table 11-4.—Suggested maximum application rates for sprinklers for average soil, slope, and tilth

Soil texture and profile	0–5% Slope (in/hr)	5–8% Slope (in/hr)	8–12% Slope (in/hr)	12–16% Slope (in/hr)
1. Coarse sandy soil to 6 ft	2.0	1.5	1.0	0.50
2. Coarse sandy soils over more compact soils	1.5	1.0	0.75	0.40
3. Light sandy loams to 6 ft	1.0	0.80	0.60	0.40
4. Light sandy loams over more compact soils	0.75	0.50	0.40	0.30
5. Silt loams to 6 ft	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 loams	0.15	0.10	0.08	0.06

Continuous-Move Systems

Traveling sprinklers, like periodic-move systems, are usually managed to apply relatively deep irrigations. Furthermore, drop sizes tend to be large so values from Table 11-4 should be reduced by 25 percent for use as guides to selecting maximum application rates for traveling sprinklers.

It is practical to apply frequent, light applications with center-pivot and linear-move systems. With light applications, up to 0.5 in of the applied water can be stored in small depressions on the soil surface. Because of this, the peak application rates near the end of center-pivot or linear-move laterals operating on a 1- or 2-day cycle can often be more than 100 percent greater than specified in Table 11-4 and not cause runoff on slopes of less than 8 percent. This is fortunate because it is difficult to nozzle center-pivot systems that have a maximum application rate of much less than 1.0 iph.

Sprinkle Irrigation Efficiency

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

1. Variation of individual sprinkler discharge along lateral lines can be held to a minimum by proper lateral design.

2. Variation in moisture distribution within the sprinkler-spacing area is caused primarily by wind movement. For periodic move, fixed, and traveling sprinklers this can be partially overcome by closely spacing sprinklers or tow paths to meet adverse wind conditions. In addition to the variation caused by wind, there is always a 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 a serious problem because the sprinklers are spaced close together along the lateral, and the lateral is continuously moving.

3. Loss of water by direct evaporation from the spray increases as temperature and wind velocities increase and as drop size and application rate decrease.

4. Evaporation from the soil surface before the water reaches the plants decreases proportionally as greater depths of water are applied.

Uniformity

Distribution uniformity (DU) is a useful term for placing a numerical value on the uniformity of application. The DU indicates the uniformity of infiltration throughout the field.

$$\text{DU} = \frac{\text{Average low-quarter depth of water received}}{\text{Average depth of water received}} \times 100 \qquad (11\text{–}3)$$

The average low-quarter depth of water received is the average of the lowest one-quarter of the measured values where each value represents an equal area.

Another parameter that is used continuously to evaluate sprinkle irrigation uniformity is the uniformity coefficient developed by Christiansen[1]:

$$\text{CU} = 100\left(1.0 - \frac{\Sigma X}{mn}\right) \qquad (11\text{–}4)$$

where

X = absolute deviation of the individual observations from the mean (in)

[1] *Christiansen, J. E. 1942. Irrigation by sprinkling. University of California. Bull. No. 670.*

m = mean depth of observations (in)
n = number of observations

The test data for CU > 70% usually form a typical bell-shaped normal distribution and are reasonably symmetrical around the mean. Therefore CU can be approximated by:

$$CU \cong \frac{\text{Average low-half depth of water received}}{m} \times 100 \qquad \textbf{(11–4a)}$$

and the relationship between DU and CU can be approximated by:

$$CU = 100 - 0.63\,(100 - DU) \qquad \textbf{(11–5a)}$$

or

$$DU = 100 - 1.59\,(100 - CU) \qquad \textbf{(11–5b)}$$

Some of the things that affect uniformity tend to average out during a series of irrigation applications. Other aspects of nonuniformity tend to concentrate, that is, the same areas tend to be over- or under-irrigated during each irrigation application. Obviously, the major concern is with those aspects that concentrate in the problem areas.

Components of nonuniformity in sprinkle irrigation systems that tend to smooth out are:

1. Uneven operation of the sprinklers. 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.

2. Uneven travel speed for moving sprinklers or time of set for stop-start 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 stop-start systems will generally smooth out randomly, especially if care is taken to alternate between day and night sets.

The following tend to concentrate unevenness:

1. Differences in sprinkler discharges throughout the system caused by elevation and friction loss.

2. Surface movement of water (both micro- and macro-runoff). 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 about 1 iph, which is excessive for many soils.

3. 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 ft past the end of a 1,320 ft center-pivot lateral constitutes more than 13 percent of the area wetted of the system. The outer 100 ft of a 160-acre field irrigated with a giant sprinkler constitutes 15 percent of the field area. Tipping the risers inward along the outer lateral sets and using part-circle sprinklers on lateral ends where medium and small sprinklers are used can greatly improve the uniformity along the field edges.

Uneven aerial distribution of water has both a tendency to smooth out and a tendency to concentrate, resulting from 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. In general, close sprinkle spacings give higher uniformities irrespective of wind conditions. Continuously moving a sprinkler is similar to having an infinitely close sprinkler spacing along the direction of travel. Thus, 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. Although the concept of low values is relative, values of DU < 72% (CU < 83%) are generally considered as being low even for general field and forage crops. For higher value crops DU > 80% (CU > 88%) are recommended.

The sprinkler's physical characteristics as well as nozzle size and pressure affect its 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 the following sections. However, when test data are not available in general planning for the most common periodic-move sprinkler spacings, tables 11–5 through 11–8 can be used to obtain estimated values 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 lateral spacing for the pair of irrigations. The uniformity of a pair of irrigations using alternate sets can be approximated by:

$$CU_a = 10\sqrt{CU} \qquad \textbf{(11–6a)}$$

or

$$DU_a = 10\sqrt{DU} \qquad \textbf{(11–6b)}$$

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. Thus, 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. With proper nozzling $CU > 94\%$, $DU > 90\%$ can be expected in the area under the system hardware in relatively level fields. The same high uniformities can be maintained even on steep, undulating fields if flow control nozzle sprinklers or other means of countering elevation effects by regulating pressure, flow, or system speed are used. 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.

Water Loss

Although efforts are often concentrated on evaluating systems by dealing with uniformity problems, loss of water 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 perhaps the greatest cause of loss in any irrigation system. Other major causes of losses associated with sprinkle irrigation are:

1. Direct evaporation from droplets and from wet soil surfaces and transpiration from unwanted vegetation.
2. Wind drift.
3. Leaks and system drainage.

Wind drift and evaporation losses may be less than 5 percent when irrigating a crop with a full vegetative canopy in low winds. More commonly, wind drift and evaporation losses range between 5 and 10 percent. However, under very severe conditions they can be considerably greater. Figure 11–17 has been developed 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-hr applications. The fine-spray curves are based on 3/16-in nozzles operating at 60 psi in a 40- x 60-ft spacing. The coarse spray is for 3/16-in nozzles operating at 30 psi in a 30- x 60-ft spacing.

To use figure 11–17, 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 the following method:

$$CI = \frac{P^{1.3}}{B} \qquad \textbf{(11–7)}$$

where

P = Nozzle operating pressure (psi)
B = Nozzle size (64ths of an inch)

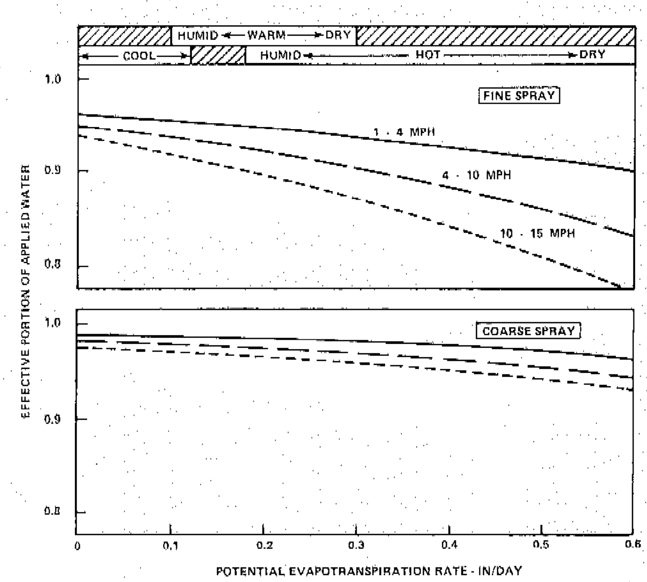


Figure 11-17.—Effective portion of water applied, R_e, by sprinkling with fine and coarse sprays in different wind conditions and with different potential evapotranspiration rates on crops with full canopies.

If the value of $CI \leq 7$ the spray is coarse, and the lower portion of figure 11-17 should be used to find R_e. If $CI \geq 17$ then the spray is 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:

$$R_e = \frac{(CI-7)}{10}(R_e)_c + \frac{(17-CI)}{10}(R_e)_f \qquad (11\text{–}8)$$

where R_e = Effective portion of applied water
$(R_e)_c$ = R_e value found if the coarse spray curves are used
$(R_e)_f$ = R_e value found if the fine spray curves are used

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 have been known to have leakage and drainage losses of up to 10 percent.

Inherent to scheduling is the evaluation of the system to determine its efficiency and to locate potential areas for upgrading system performance. With scheduling and careful management the following improvements in irrigation efficiency appear reasonable.

1. Increases of 20 to 40 percent or more are feasible when irrigation water is plentiful, when there is supplemental rain, and when soils have low water-holding capacities.
2. Increases of 5 to 15 percent are often possible for high water-holding capacity soils and of 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.
3. 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 most increase efficiencies by 10 percent. Scheduling may be very 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 can be further reduced.

Application

Perhaps the most often used irrigation efficiency term is application efficiency (E_a). This is the ratio of the average depth of irrigation water stored in the root zone to the average depth of irrigation water applied.

The E_a only indicates the losses, since it merely shows the fraction of applied water stored within the root zone that is potentially accessible for evaporation and transpiration. Thus, E_a does not indicate the adequacy of the irrigation and, with exaggerated underirrigation, it can equal 100 percent.

To be more useful, an irrigation efficiency concept should combine some measure of uniformity, of adequacy of irrigation, and of losses. Such a concept is application efficiency of the low quarter (E_q). 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:

$$E_q = DU \times R_e \qquad (11\text{–}9)$$

where

E_q = Application efficiency of the low quarter (%)

DU = Distribution uniformity (%)
R_e = Effective portion of applied water from figure 11-17.

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 will remain below field capacity. 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 is extravagant for low-value field and forage crops. For such crops an application efficiency based on the average low-half depth is more appropriate.

For design purposes, the application efficiency of the low half (E_h) can be estimated by:

$$E_h = CU \times R_e \qquad (11\text{–}10)$$

When E_h is used to estimate d, needed to replace a given SMD, only about 20 percent of the area will remain below field capacity.

The range of probable E_q and E_h values for the various types of sprinkle systems are:

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

The above 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 estimates. Obviously, considerably lower values would be obtained with poor management or where systems are poorly designed or ill-suited to the prevailing conditions.

Design Procedure

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 and quantity, weather, crops, and soils. The farmer should be consulted about financial, labor, and management capabilities. Once the data on the farm's resources have been assembled, the system selection, layout, and hydraulic design process can proceed.

The four major components in a sprinkle system are shown in figure 11-18. The design process should begin with the sprinkler selection then continue with the system layout, followed by the design of the lateral, mainline, and pumping plant. To make a rational system selection, it may be necessary to design and analyze two or more systems and the farmer should carefully study the system ultimately selected.

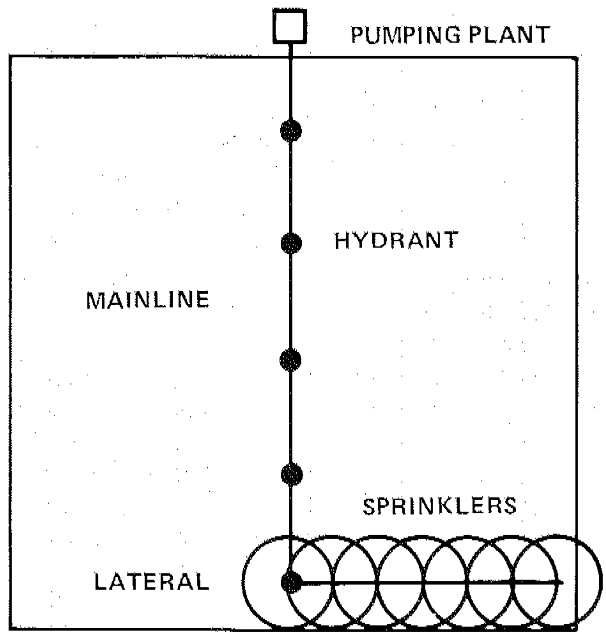


Figure 11-18.—Basic sprinkle system components.

Periodic-Move and Fixed Systems

The basic strategy for designing all periodic-move and fixed systems is the same as for hand-move systems. 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 those of 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 and their position in relation to irrigated crops. The different classifications, with the characteristics and adaptability of each, are given in table 11-5.

Sprinkler Selection

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 that are not even multiples of 10 ft are practical, and low discharge sprinklers set at wide spacings are chosen for economic reasons.

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. The sprinkler giving the most economical overall system should be selected if soil surface sealing and infiltration are not limiting factors. Quite often, however, when bare soil surfaces must be sprinkled, sprinklers having nozzles between 5/64 and 9/64 in and operating at pressures over 50 psi must be used.

Under-tree systems may require low trajectory sprinklers to reduce foliar wetting and interference. Under-tree sprinkling is required when the irrigation water is of such low quality that it will cause leaf burn. Variations in sprinkler design imposed by tree spacings and tree shapes are not detailed here. In general, however, sprinklers that produce an E-type pattern by throwing 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 very windy areas, low-angle sprinklers with a trajectory of 18° to 21° produce better results than high-angle sprinklers with 25° to 28° trajectories. Many sprinkler manufacturers have compromised on a trajectory angle of between 22° and 24° 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.

Distribution Uniformity.—The degree of uniformity obtainable depends primarily on the moisture-distribution pattern of the sprinkler and on the spacing of the sprinklers. Figure 11-19 shows the distribution pattern and precipitation profiles obtained from a typical double-nozzle sprinkler operating at proper pressure with no wind.

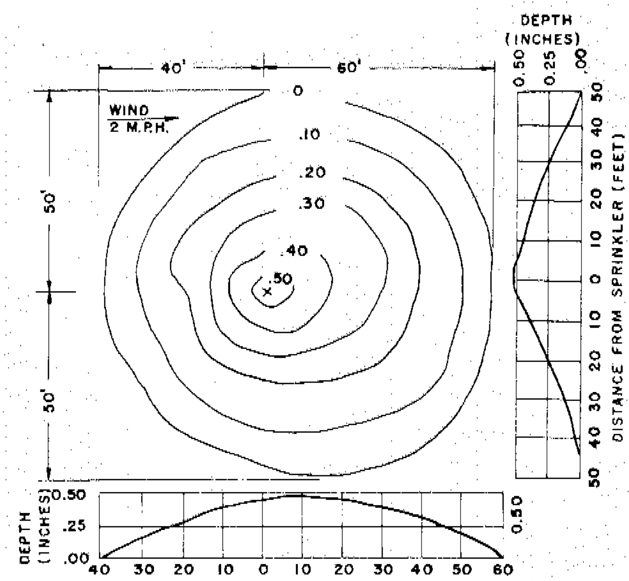


Figure 11-19.—Distribution pattern and precipitation profiles from a typical double-nozzle sprinkler operating under favorable conditions.

Each type of sprinkler has certain precipitation profile characteristics that change as nozzle size and operating pressure change. Each has an optimal range of operating pressures for each nozzle size. All manufacturers of revolving sprinklers 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 affect the profile as follows:

Table 11-5.—Classification of sprinklers and their adaptability

Type of sprinkler	Low pressure 5–15 psi	Moderate pressure 15–30 psi	Intermediate pressure 30–60 psi	High pressure 50–100 psi	Hydraulic or giant 80–120 psi	Under-tree long-angle 10–50 psi	Perforated pipe 4–20 psi
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.	Design 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.
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] wide.
Recommended minimum application rate	0.40 inch per hour.	0.20 inch per hour.	0.25 inch per hour.	0.50 inch per hour.	0.65 inch per hour.	0.33 inch per hour.	0.50 inch per hour.
Jet characteristics (assuming proper pressure-nozzle size relations)	Waterdrops are large due to low pressure.	Waterdrops are fairly well broken.	Waterdrops are well broken over entire wetted diameter.	Waterdrops are well broken over entire wetted diameter.	Waterdrops are extremely well broken.	Waterdrops are fairly well broken.	Waterdrops are large due to low pressure.
Moisture distribution pattern (assuming proper spacing and pressure-nozzle size relations)	Fair.	Fair to good at upper limits of pressure range.	Very good.	Good *except* where wind velocities exceed 4 miles per hour.	Acceptable in calm air. Severely distorted by wind.	Fairly good. Diamond pattern recommended where laterals are spaced more than one tree interspace.	Good rectangular pattern.
Adaptations and limitations.	Small acreages. Confined to soils with intake rates exceeding 0.50 inch per hour and to good ground cover on medium- to coarse-textured soils.	Primarily for under-tree sprinkling in orchards. Can be used for field crops and vegetables.	For all field crops and most irrigable soils. Well adapted to over-tree sprinkling in orchards and groves and to tobacco shades.	Same as for intermediate 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 rates.	For all orchards or citrus groves. In orchards where wind will distort over-tree sprinkler patterns. In orchards where available pressure is not sufficient for operation of over-tree sprinklers.	For low-growing crops only. Unsuitable for tall crops. Limited to soils with relatively high intake rates. Best adapted to small acreages of high-value crops. Low operating pressure permits use of gravity or municipal supply.

1. At the lower side of the specified pressure range for any nozzle, the water remains in large drops. When pressure falls too low, the water from the nozzle falls in a ring a distance away from the sprinkler, giving a poor precipitation profile (fig. 11-20A).

2. Within the desirable range, the sprinkler should produce the precipitation profile shown in figure 11-20B.

3. On the high side of the pressure range, the water from the nozzle breaks up into fine drops and settles around the sprinkler (fig. 11-20C). Under such conditions the profile is easily distorted by wind.

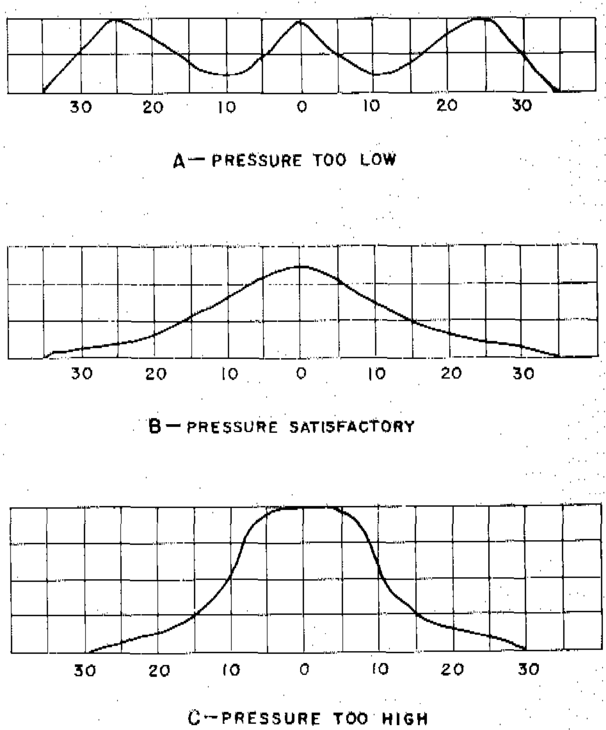


Figure 11-20.—Effect of different pressures on precipitation profiles for a typical double-nozzle sprinkler.

Wind distorts the application pattern, and the higher the wind velocity, the greater the distortion. Figure 11-21 shows test results of an intermediate double-nozzle sprinkler operating under a wind velocity of 10.7 mph. This distortion must be considered when selecting the sprinkler spacing.

The depth of water applied to an area surrounding a revolving sprinkler varies with the distance from the sprinkler. Thus, to obtain a reasonably high uniformity of application, water from adjacent sprinklers must be added. Figure 11-22 illustrates the depth of distribution obtained by overlapping.

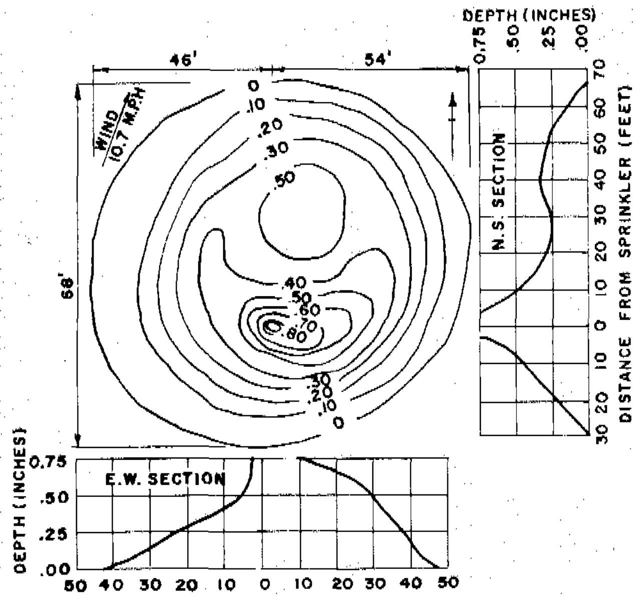


Figure 11-21.—Effect of wind on distribution pattern and precipitation profiles from a typical intermediate double-nozzle sprinkler.

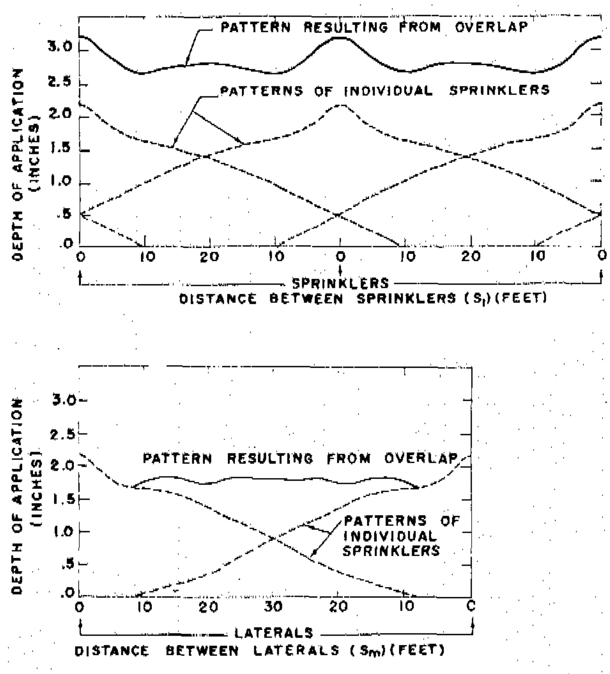


Figure 11-22.—Example of the distribution patterns between sprinklers along the lateral and between laterals.

Manufacturers of sprinklers specify a wetted diameter 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 nozzling, pressure, and physical characteristics produce different precipitation profiles. Figure 11-23 shows a stylized set of potential sprinkler profiles and optimum spacings.

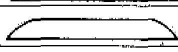
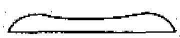
SPRINKLER PROFILE		RECOMMENDED SPACING AS A PERCENTAGE OF DIAMETER		
TYPE	SHAPE	SQUARE	TRIANGULAR EQUILATERAL	RECTANGULAR SHORT x LONG
A		50	50	40 x 60 to 65
B		55	66	40 x 60
C		60	65	40 x 60 to 65
D		40 70 (FAIR)	70 to 75	40 x 70 to 75
E		40 80 (FAIR)	80	40 x 80

Figure 11-23.—Christiansen's geometrical sprinkler profiles and optimum spacings as a percentage of the effective wetted diameter.

Certain sprinklers under specific conditions produce a typical precipitation profile as shown in figure 11-23. 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, size of the nozzle, speed and uniformity of rotation and characteristics of the driving mechanism such as the shape, angle, and frequency of the spoon and lever action. 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.

Profile types A, B, and C (fig 11-23) are characteristic of sprinklers having two or more nozzles. Profile types C and D are characteristic of single-nozzle sprinklers at the recommended pressures.

Profile type 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 type profile. The vanes increase the diameter of throw, but pressures must be increased by 10 to 15 psi to keep the dip in the center of the profile from becoming too low.

The spacing recommendations in figure 11-23 should give acceptable application uniformities when a realistic effective 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 cross wind (fig. 11-21). The diameter of throw of a sprinkler as listed in the manufacturer's brochure is often for no wind and to the farthest droplet from the sprinkler. Under field operating conditions with 0-3 mph wind, such diameters should be shortened by 10 percent from the listed figure to obtain the effective diameter. Effective diameters should be further reduced for winds exceeding 3 mph. A reduction of 2.5 percent for each mph over 3 pmh is a fair estimate for the usual range of wind conditions under which sprinklers are operated.

Generally, highest uniformities are obtained at spacings of 40 percent or less of the diameter, but such close spacings raise both precipitation rates and costs. Overly conservative or optimistic spacings between lines can result in poor uniformities of coverage. Certain profile types, notably D and E, have a narrow range at high uniformity for extended spacing between lines. Thus the uniformity can change drastically with changes in wind speed. Unfortunately, with D and E profiles the uniformity can actually decrease as wind velocity decreases because of too much overlap.

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

1. Rectangular spacing of 40 by 67 percent of the effective diameter based on the average wind speed during the setting.
2. Square spacing of 50 percent of the effective

diameter based on average wind speed during the setting.

3. Equilateral triangular spacing of 62 percent of the effective diameter based on average wind speed during the setting.

Application Uniformity.—Obviously the spacing of sprinklers along the lateral (S_l) and along the main (S_m) affects the amount of overlap and, consequently, the uniformity and depth of application. Figure 11-24 shows the data from a typical field test. (The procedure for collecting the data is presented at the end of this section.) The basic catch data that were measured in milliliters have been converted to the application rates in inches per hour received at each location. Obviously, these rates are equivalent to depths when computing DU and CU values.

Figure 11-25 shows the data gathered between sprinklers 5 and 6 from figure 11-24 overlapped to simulate a 50-ft lateral spacing, S_m = 50 ft. The sprinklers were spaced 30 ft apart on the lateral, S_l = 30 ft; thus, the sprinkler spacing is referred to as a 30- by 50-ft spacing. The right side catch is added to the left side catch; the totals at each point represent a complete 1-hour irrigation for a 30- by 50-ft spacing. For the simulated 50-ft lateral spacing, the total catch at all 15 grid points is 3.97, which gives:

$$\text{Average catch rate} = \frac{3.97}{15} = 0.265 \text{ iph}$$

The average of the lowest one-quarter of the catch rates (use 4 out of 15) is:

$$\text{Average low quarter rate} =$$

$$\frac{0.20 + 0.22 + 0.22 + 0.23}{4} = 0.218 \text{ iph}$$

and from equation 3:

$$DU = \frac{0.218}{0.265} \times 100 = 82\%$$

To estimate the CU, from the mean one must determine the total deviations (X) by summing the deviations of the individual observations as shown by the numbers in parentheses on figure 11-25. The sum of these deviations is 0.51 and from equation 4:

$$CU = 100\left(1.0 - \frac{0.51}{0.26 \times 15}\right) = 87\%$$

As mentioned earlier, the CU can be approximated from the average low-half and mean values of the observations by equation 4a:

$$CU \cong \frac{1.6/7}{0.26} \times 100 = 88\%$$

Or, the CU can be approximated from the DU = 82% by equation 5a:

$$CU \cong 100 - 0.63\,(100 - 82) = 89\%$$

The deviations between the approximated values of CU and the value computed by equation 4 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-ft lateral move, the effect on uniformity of the other move distances can also be evaluated from the field test data. Table 11-6 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 11-24 parts 8 and 10. Comparison of percentage values illustrates the problem of choosing a representative or minimum site. Some other sites in the field undoubtedly were poorer and some were better than the tested site; therefore, computed uniformities are not universally applicable, but they are useful for evaluating the system. 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

Table 11-6.—DU and CU values of four standard sprinkler spacings for areas between sprinklers 5 and 6 and sprinklers 4 and 5 (fig. 11-24)

Test area criteria	Sprinkler spacing (feet)			
	30 × 40	30 × 50	30 × 60	30 × 60 alt [1]
	Area between sprinklers 5 and 6			
DU	81	84	64	91
CU	87	87	75	93
	Area between sprinklers 4 and 5			
DU	79	76	50	82
CU	86	89	70	91

[1] The alternate set values are the same as for a 30 × 30-ft spacing.

1. Location *Field C-22*, observer *JLM*, date *9-30-75*
2. Crop *Tomatoes*, root zone depth *4.0* ft, MAD *50%*, MAD *4.4* in
3. Soil: texture *clay loam*, available moisture *2.2* in/ft, SMD *4.4* in
4. Sprinkler: make *Rain Bird*, model *29B*, nozzles *5/32* by ____ in
5. Sprinkler spacing *30* by *50 ft*, 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%*, riser height *18* in
8. Actual sprinkler pressure and discharge rate:

	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 or sec)	*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

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

Container grid spacing *10* by *10* ft

Test: start *2.55 pm*, stop *4:30 pm*, duration *1* hr *35* min = *1.58* hr

___	___	___	*32* / *.10*	*68* / *.21*	*77* / *.24*	*90* / *.28*	*73* / *.23*	*66* / *.21*	*9* / *.03*	___	*ml* / *iph*	___
___	___	___	*35* / *.11*	*66* / *.21*	*84* / *.26*	*100* / *.31*	*100* / *.31*	*52* / *.16*	*3* / *.01*	___	___	___
___	___	___	*32* / *.10*	*50* / *.16*	*70* / *.22*	*104* / *.32*	*99* / *.31*	*48* / *.15*	*12* / *.04*	___	___	___
___	___	___	*31* / *.10*	*74* / *.23*	*88* / *.27*	*104* / *.32*	*86* / *.27*	*56* / *.17*	*11* / *.03*	___	___	___
___	___	___	*27* / *.08*	*64* / *.20*	*80* / *.25*	*96* / *.30*	*112* / *.35*	*62* / *.19*	*9* / *.03*	___	___	___
___	___	___	*20* / *.06*	*49* / *.16*	*59* / *.19*	*107* / *.33*	*87* / *.27*	*36* / *.11*	*13* / *.04*	___	___	___

11. Evaporation container: initial *2.15* final *2.10* loss *0.05* in
12. Sprinkler pressures: max *45* psi; min *39* psi, ave *40* psi
13. Comments: *Test duration was too short. Depths caught measured in 1000-ml graduated cylinder. Wind velocities are less than normal.*

Figure 11-24—Sprinkler-lateral irrigation evaluation.

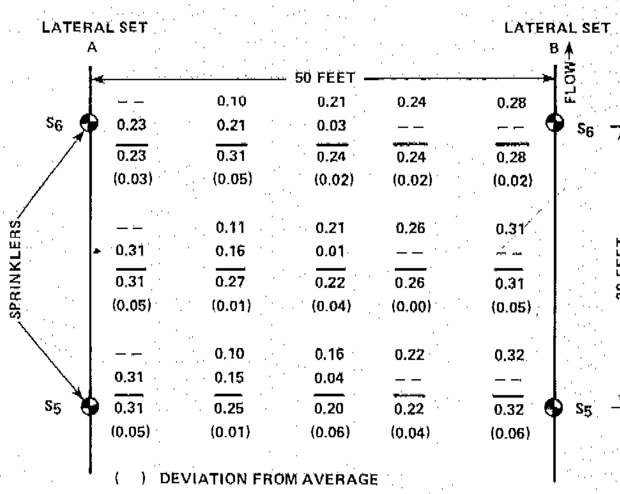


Figure 11-25.—Combined catch pattern in inch per hour between sprinklers 5 and 6 for a 50-ft lateral spacing.

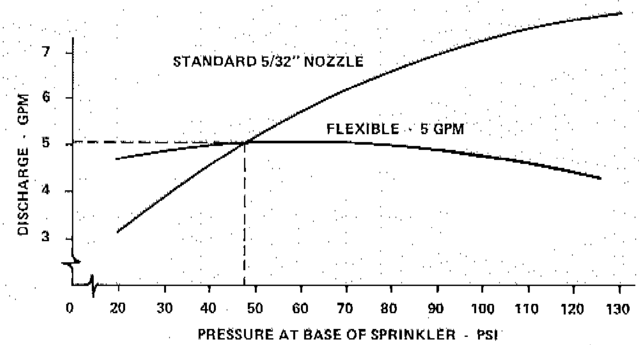


Figure 11-26.—Comparison of pressure versus discharge relationship for a standard fixed nozzle and a special flexible orifice nozzle.

of ±1 to 2 percent. In addition, the normal variation of the uniformity values can be approximated by:

$$\pm[0.2\ (100 - CU)]\%;\ \text{or}\ \pm[0.2\ (100 - DU)]\%$$

Nozzle discharge varies with the nozzle pressure unless special flexible orifice nozzles are used to control the flow. Figure 11-26 shows the relationship between discharge and pressure for a typical fixed 5/32-in nozzle that gives 5 gpm at 48 psi and for a flexible orifice nozzle designed to give 5 gpm, regardless of pressure. Unfortunately, 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 of each sprinkler. Therefore, unless the difference in pressures throughout the system is expected to exceed 25 percent of the desired average operating pressure, it is best to use standard fixed nozzles and no flow-control devices.

The flexible orifice nozzles maintain constant flow without causing a pressure drop of at least 10 to 15 psi, which is typical of the flow or pressure control devices used at the base of sprinklers. This is an important advantage when operating pressures are lower than 50 psi and maintaining a reasonably high nozzle pressure is necessary to have adequate jet breakup and range of throw. However, when pressures are above 80 psi, 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 the sprinklers.

When flexible orifice nozzles are used, the DU and CU test values should be multiplied by approximately 0.95 to obtain the system uniformities. When they are not used, the pressure variations throughout the system cause the overall uniformity of the system to be lower than the uniformity in the test area. An estimate of the system DU and CU can be computed from the maximum, minimum, and average system pressures by:

$$\text{System DU} = \text{DU} \times \left(1 - \frac{P_x - P_n}{5\ P_a}\right) \quad \textbf{(11–11a)}$$

and

$$\text{System CU} = \text{CU} \times \left(1 - \frac{P_x - P_n}{8\ P_a}\right) \quad \textbf{(11–11b)}$$

where

P_x = the maximum sprinkler pressure (psi)
P_n = the minimum sprinkler pressure (psi)
P_a = the average sprinkler pressure (psi)

Using the data from figure 11-24, part 12 with the test DU = 82%:

$$\text{System DU} = 82 \times \left(1 - \frac{45 - 39}{5 \times 40}\right) = 80\%$$

and with the test CU = 87%:

$$\text{System CU} = 87 \times \left(1 - \frac{45 - 39}{8 \times 40}\right) = 85\%$$

The leading manufacturers of sprinklers are continually field testing their products, and data are available on several sprinklers operating under various field conditions. When planning sprinkle irrigation systems, request such 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 operating conditions.

Spacing.—The basic criterion governing the selection of spacing for any given sprinkler nozzle-pressure and wind combination is the uniformity of distribution desired. In general, a CU of about 85 percent is recommended for delicate and shallow-rooted crops such as potatoes and most other vegetables. A CU above 75 percent is generally adequate for deep-rooted field crops such as alfalfa, corn, cotton, and sugar beets. Tree and vine crops that have deep spreading root systems can be adequately irrigated if the CU is above 70 percent. When applying chemicals through the system, however, a CU above 80 percent is recommended. When systems have low CUs due to wind, chemicals should be applied only during calm periods.

Table 11-7 gives a more useful meaning to the concept of CU. From table 11-7, if a sprinkle system has a CU of 86 percent, for each inch of gross application received by the crop or soil, 80 percent of the area would receive at least 0.85 in. If the CU were only 70 percent, 80 percent of the area would receive at least 0.68 in. To apply a net application of 1.0 in to at least 80 percent of the area with a system having a CU of 86 percent, a gross of 1.0 divided by 0.85 = 1.18 in plus wind drift and evaporation losses must be applied. With a CU of only 70 percent, a gross after drift and evaporation losses of 1.0 divided by 0.68 = 1.47 in would be required.

Figure 11-27 illustrates the relation between rainfall area and depth of water applied at the CU values discussed above. Both 70 and 86 percent CU values leave 20 percent of the area underirrigated, and 80 percent of the area adequately or overirrigated. However, this requires a gross application of approximately 25 percent more water with the 70 percent CU than with the 86 percent CU. Data for constructing figure 11-27 were taken from table 11-7.

Table 11-7.—Minimum depth of water applied per 1.0 in gross application for various values of CU and percentages of land area adequately irrigated

CU percent	Percent of area adequately irrigated: 95	90	85	80	75	70	65	60
	(inch)							
90	0.79	0.84	0.87	0.89	0.92	0.93	0.95	0.97
86	.71	.78	.82	.85	.88	.91	.93	.96
82	.63	.71	.77	.81	.85	.88	.91	.94
78	.55	.65	.71	.77	.81	.86	.89	.93
74	.46	.58	.66	.73	.78	.83	.88	.92
70	.38	.52	.61	.68	.75	.80	.86	.91

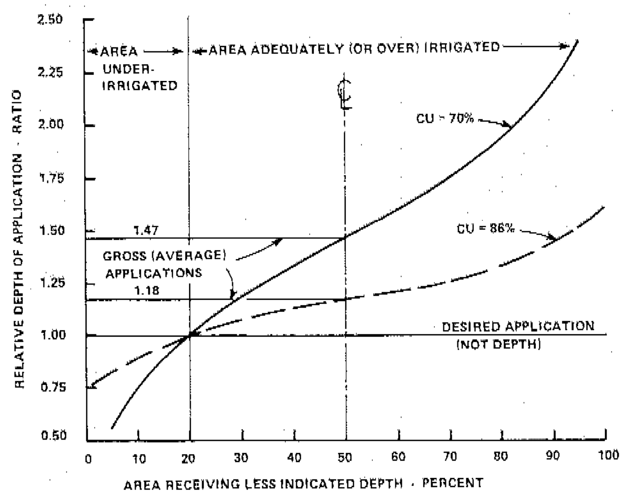


Figure 11-27.—Relationships between surface area and depth of water applied for CU values of 70 and 86 percent when 20 percent of the area is underirrigated and the remaining 80 percent of the area is adequately (or over) irrigated.

When any given CU value is used as the irrigation application efficiency, the area adequately irrigated will be approximately 80 percent, i.e., note that the values under the 80 percent adequacy column correspond almost perfectly with the values under the CU column.

When three or more adjacent laterals are operated simultaneously in a fixed or block-move system, the wind drift and evaporation losses are minimized and essentially all of the water is applied effectively. Therefore, table 11-7 can be used to approximate overall irrigation efficiency for "block system" layouts.

Table 11-8 gives a better understanding of CU and shows the relative productivity, especially when dealing with shallow-rooted vegetative crops such as forage crops. According to table 11-8, almost optimum yields may be obtained with a system having a low CU. For example, with a CU of 90 percent and 90 percent of the area adequately irrigated, 99 percent of optimum 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. 11-17). With a CU of only 70 percent, 97 percent of the optimum yields 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. If only 1.19 times the adjusted net were applied only 65 percent of the area would be adequately irrigated (table 11-7) and only 90 percent of optimum yields might be expected (table 11-8).

Table 11-8.—Relative percentages of optimum productivity (where overwatering does not reduce yields) for various values of CU and percentages of land area adequately irrigated

CU	Percent of area adequately irrigated							
percent	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

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

The nozzle sizes and pressures given in the tables for each spacing will give application rates (I) that fall within 0.02 iph of rates indicated by the column headings. Equation 2 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 following ranges.

Nozzle sizes	Pressure range[1]
-inch-	-psi-
5/64 to 3/32	20 - 45
7/64 to 9/64	25 - 50
5/32 to 11/64	30 - 55
3/16 to 7/32	35 - 60

[1] When straightening vanes are used, add 5 psi.

The low side of the pressure ranges given above should be increased by 5 to 10 psi when sprinkling bare soils that tend to seal. High pressures should be avoided to save energy and eliminate excessive drift and evaporation losses.

Risers.—Straight riser pipe, located between the sprinkler head and the lateral line pipe, must be provided in order to remove the turbulence set up when the direction of flow is changed by diversion of a part of the flow to an individual sprinkler. If not removed, this turbulence will carry through the nozzle and cause a premature stream breakup, a reduced diameter of coverage, and hence a poorer distribution pattern. The length of pipe needed to remove turbulence varies with sprinkler discharge. Recommended *minimum* riser lengths follow:

Discharge, gpm	Risers	Discharge, gpm	Risers
Under 10	6-inch	50-120	18-inch
10-25	9-inch	more than 120	36-inch
25-50	12-inch		

Most crops exceed 12 in. in height so, except for clean cultivated orchards where low riser pipes are desirable for under-tree sprinkling, the choice will be the minimum height to clear the crop. Although some research studies indicate that 12 to 24 in 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 risers except when irrigating high-growing crops such as cotton and corn.

Discharge Requirement.—The required average discharge (q) of each sprinkler is a function of the water application rate (I) and the sprinkler spacing.

Table 11-9.—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 to 4 mph)

Sprinkler		Water application rate, iph ± 0.02 iph						
Spacing ft × ft	Operation	0.10	0.15	0.20	0.25	0.30	0.35	0.40
30 × 40	Nozzle, inch	3/32	3/32	7/64	1/8	9/64	5/32	9/64×3/32
	Pressure, psi	30	50	45	45	45	40	40
	CU, %	82	83	82	83	83	85	88
30 × 50	Nozzle, inch	3/32	7/64	1/8	9/64	5/32	11/64	11/64
	Pressure, psi	40	40	45	50	45	45	50
	CU, %	83	88	86	86	84	85	86
30 × 60	Nozzle, inch		1/8	9/64	5/32	11/64	3/16	3/16
	Pressure, psi		40	45	45	45	45	50
	CU, %		88	88	89	88	85	87
40 × 40	Nozzle, inch	7/64	1/8	9/64	1/8×3/32	5/32×3/32	5/32×3/32	5/32×1/8
	Pressure, psi	30	35	35	40	35	40	35
	CU, %	78	82	86	87	88	89	90
40 × 50	Nozzle, inch			5/32	5/32×3/32	5/32×3/32	11/64×3/32	3/16×3/32
	Pressure, psi			35	35	45	40	40
	CU, %			78	83	84	88	89
40 × 60	Nozzle, inch			5/32	11/64	3/16	13/64	7/32
	Pressure, psi			50	50	50	50	50
	CU, %			83	85	85	84	86
60 × 60	Nozzle, inch			3/16	13/64	7/32	7/32	1/4
	Pressure, psi			60	65	65	80	88
	CU, %			88	88	88	88	88

Table 11-10.—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)

Sprinkler		Water application rate, iph ± 0.02 iph						
Spacing ft × ft	Operation	0.10	0.15	0.20	0.25	0.30	0.35	0.40
	Nozzle, inch	3/32	3/32	7/64	1/8	9/64	5/32	9/64x3/32
30 × 40	Pressure, psi	30	50	45	45	45	40	40
	CU, %	82	85	85	82	83	84	85
	Nozzle, inch	3/32	7/64	1/8	9/64	5/32	11/64	11/64
30 × 50	Pressure, psi	40	40	45	50	45	45	50
	CU, %	70	75	84	84	84	87	85
	Nozzle, inch		1/8	9/64	5/32	11/64	3/16	3/16
30 × 60	Pressure, psi		40	45	45	45	45	50
	CU, %		80	84	84	84	85	86
	Nozzle, inch	7/64	1/8	9/64	1/8x3/32	5/32x3/32	5/32x3/22	5/32x1/8
40 × 40	Pressure, psi	30	35	35	40	35	40	35
	CU, %	80	83	83	83	84	87	86
	Nozzle, inch			5/32	5/32x3/32	5/32x3/32	11/64x3/32	3/16x3/32
40 × 50	Pressure, psi			35	35	45	40	40
	CU, %			76	76	76	83	84
	Nozzle, inch			4/32	11/64	3/16	13/64	7/32
40 × 60	Pressure, psi			50	50	50	50	50
	CU, %			77	81	83	84	85
	Nozzle, inch			3/16	13/64	7/32	7/32	1/4
60 × 60	Pressure, psi			60	65	65	80	68
	CU, %			80	82	83	84	84

Table 11-11.—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)

Sprinkler		Water application rate, iph ± 0.02 iph						
Spacing ft × ft	Operation	0.10	0.15	0.20	0.25	0.30	0.35	0.40
30 × 40	Nozzle, inch	3/32	3/32	7/64	1/8	9/64	5/32	5/32
	Pressure, psi	30	50	45	45	45	40	45
	CU, %	75	80	80	84	84	85	86
30 × 50	Nozzle, inch		7/64	1/8	9/64	5/32	11/64	11/64
	Pressure, psi		40	45	50	45	50	55
	CU, %		70	81	82	87	88	88
30 × 60	Nozzle, inch			9/64	5/32	11/64	3/16	3/16
	Pressure, psi			45	45	45	45	50
	CU, %			72	75	81	84	86
40 × 40	Nozzle, inch		1/8	9/64	5/32	11/64	11/64	3/16
	Pressure, psi		35	35	35	35	50	45
	CU, %		80	82	81	80	86	85
40 × 50	Nozzle, inch			5/32	5/32	11/64	3/16	13/64
	Pressure, psi			35	50	50	50	50
	CU, %			77	78	80	80	82
40 × 60	Nozzle, inch			5/32	11/64	3/16	13/64	7/32
	Pressure, psi			50	50	50	50	50
	CU, %			68	74	78	81	82
60 × 60	Nozzle, inch			3/16	13/64	7/32	7/32	1/4
	Pressure, psi			60	65	65	80	68
	CU, %			64	66	68	80	82

Table 11-12.—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)

Sprinkler Spacing ft × ft	Operation	Water application rate, in/h ± 0.02 in/h 0.10	0.15	0.20	0.25	0.30	0.35	0.40
30 × 40	Nozzle, inch	3/32	3/32	7/64	1/8	9/64	5/32	5/32
	Pressure, psi	30	50	45	45	45	40	45
	CU, %	69	72	73	75	76	82	85
30 × 50	Nozzle, inch			1/8	9/64	5/32	11/64	11/64
	Pressure, psi			45	50	45	50	55
	CU, %			74	77	80	81	84
30 × 60	Nozzle, inch			9/64	5/32	11/64	3/16	3/16
	Pressure, psi			45	45	45	45	50
	CU, %			60	65	75	80	83
40 × 40	Nozzle, inch			9/64	5/32	11/64	11/64	3/16
	Pressure, psi			35	35	35	50	45
	CU, %			70	72	76	81	84
40 × 50	Nozzle, inch			5/32	5/32	61/64	3/16	13/64
	Pressure, psi			35	50	50	50	50
	CU, %			55	60	70	75	77
40 × 60	Nozzle, inch			5/32	11/64	3/16	13/64	7/32
	Pressure, psi			50	50	50	50	50
	CU, %			64	70	73	74	75
60 × 60	Nozzle, inch						7/32	1/4
	Pressure, psi						80	68
	CU, %						66	75

The desired I depends on time per set, net depth to be applied per irrigation, and application efficiency. It is practical to change periodic-move laterals only once or twice per day unless they are automated. For one change per day, the time per set will be 24 hr minus the length of time required to change the lateral position, leaving a total of 23 to 23.5 hr. For two changes per day, set times will range between 11 and 11.5 hr.

Figure 11–28 shows a copy of figure 11–13 completed for a sample field of alfalfa and potatoes. Sample calculations 11–3 and 11–4 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 11–3.—Determine the net depth per irrigation, irrigation interval, irrigation efficiency, application rate, and sprinkler discharge requirement.

Given:

The information in parts I and II of figure 11–28 for alfalfa

An average wind of 4–10 mph

Assume:

The soil moisture depletion is MAD = 50%

There will be one change per day

The sprinkler spacing is 40 × 60 ft

Calculation:

For a MAD = 50%, the allowable soil water depletion is 50 percent of the total available water-holding capacity of the root zone which in this case is:

$$6 \text{ ft} \times 2.0 \text{ in/ft} \times \frac{50}{100} = 6.0 \text{ in}$$

The maximum allowable irrigation interval during the peak use period is

$$\frac{\text{allowable depletion (in)}}{\text{water use rate (in/day)}} = \frac{6.0}{0.30} = 20 \text{ days}$$

These are the maximum allowable depletion and corresponding maximum interval during the peak use period that will give the desired level of productivity. To fit the final system design, lesser net applications and correspondingly shorter intervals may be used.

The application efficiency can be estimated from the effective portion of the applied rate (R_e) and the uniformity of application. Assuming the spray will be midway between coarse and fine (from fig. 11–18) for a potential evapotranspiration rate of 0.3 in/day the effective portion, $R_e = \frac{(0.97 + 0.91)}{2} = 0.94$.

Because alfalfa is a relatively low value crop, an applied efficiency (E_h) based on the average low-half depth is appropriate, i.e., use CU. Assuming an E_h of 75 percent, the gross application would be:

$$\frac{6.0}{75/100} = 8.0 \text{ in}$$

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 hr. Thus the preliminary application rate is:

$$I' = \frac{8.0 \text{ in}}{23 \text{ hr}} = 0.35 \text{ iph}$$

From table 11–10 (4–10 mph winds) the anticipated CU = 84% on a 40- x 60-ft spacing and 0.34 iph. A more specific estimate of CU can often be obtained directly from a supplier. The expected application efficiency can now be estimated by equation 8:

$$E_h = CU \times R_e = 84 \times 0.94 = 79\%$$

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

$$\frac{6.0}{79/100} = 7.6 \text{ in}$$

and the required application rate is:

$$I = \frac{7.6 \text{ in}}{23 \text{ hr}} = 0.33 \text{ iph}$$

The required sprinkler discharge can now be calculated by equation 2:

$$q = \frac{I \times S_l \times S_m}{96.3}$$

$$= \frac{0.33 \times 40 \times 60}{96.3} = 8.22 \text{ gpm}$$

I. Crop (type)	*Alfalfa*	*Potatoes*	
(a) Root depth (ft)	*6*	*2.5*	*Table 11-2*
(b) Growing season (days)	*165*	*135*	*From*
(c) Water use rate (in/day)	*0.30*	*0.25*	*Irrigation*
(d) Seasonal water use (in)	*30.0*	*19.0*	*Guide*
II. Soils (area)			
(a) Surface texture Depth (ft) Moisture capacity (in/ft)	*Loam* *8* *2.0*	*Sandy* *loam* *4* *1.6*	*Table 11-1*
(b) Subsurface texture Depth (ft) Moisture capacity (in/ft)			
(c) Moisture capacity (in)	*12.0*	*4.0*	
(d) Allowable depletion (in)	*6.0*	*2.0*	*(50% of total)*
(e) Intake rate (iph)	*0.6*	*0.4*	*Table 11-4*
III. Irrigation			
(a) Interval (days)	*20*	*8*	
(b) Net depth (in)	*6.0*	*2.0*	
(c) Efficiency (%)	*79*	*75*	
(d) Gross Depth (in)	*7.6*	*2.7*	
IV. Water Requirement			
(a) Net seasonal (in)	*30*	*19*	
(b) Effective rain (in)	*3*	*2*	
(c) Stored moisture (in)	*5*	*2*	
(d) Net irrigation (in)	*22*	*15*	
(e) Gross irrigation (in)	*28*	*20*	
(f) Number of irrigations	*3 to 4*	*7 to 8*	
V. System capacity			
(a) Application rate (iph)	*0.33*	*0.23*	
(b) Time per set (hrs)	*23*	*11.5*	
(c) Settings per day	*1*	*2*	
(d) Days of operation per interval	*18*		
(e) Preliminary system capacity (gpm)			

Figure 11-28.—Preliminary sprinkler irrigation system design factors.

Sample calculation 11-4.—Determine irrigation efficiency and application rate.

Given:

The information in parts I and II of figure 11–28 for potatoes.

An average wind of 10–15 mph

Assume:

The soil moisture depletion is MAD = 50%

Side-roll laterals will be used and two changes per day will be made.

The sprinkler spacing is 40 x 50 ft

Calculation:

Determine $R_e = 0.92$ from figure 11–17 for ET = 0.25 in/day for 10–15 mph wind and average spray. 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 use DU as the measure of uniformity. This will leave approximately 10 percent of the area underwatered. Assuming an E_q of 67 percent the gross application would be:

$$\frac{2.0}{67/100} = 3.0 \text{ in}$$

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

$$I' = \frac{3.0 \text{ in}}{11.5 \text{ hr}} = 0.26 \text{ iph}$$

From table 11–11, (10–15 mph winds) the anticipated CU =78%. If alternate sets are used the improved CU_a can be estimated by equation 6a as:

$$CU_a = 10\sqrt{CU} = 10\sqrt{78} = 88\%$$

These are two processes that can be used to develop the expected E_q. An estimated DU_a can be determined by equation 5b as:

$$DU_a = 100 - 1.59\,(100 - CU_a)$$
$$= 100 - 1.59\,(100 - 88) = 81\%$$

and from equation 9:

$$E_q = 81 \times 0.92 = 75\%$$

The other method is to use table 11–7 with CU_a = 88% and find that for 90 percent of the area adequately irrigated 0.81 in is the minimum depth of water applied per 1.0 in of effective application so:

$$E_{(90\%\ \text{adequate})} = 0.81 \times 0.92 = 75\%$$

Obviously, if alternate sets had not been used the efficiency would have been much lower, i.e., about 60 percent for 90 percent adequacy. Also, if an efficiency of 75 percent is assumed and alternate sets are not used, the area adequately irrigated will only be 75 percent. This was determined by noting that 0.81 in is the minimum depth of water applied per 1.0 in of effective application with a CU of 78 percent and 75 percent adequacy in table 11–7.

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

$$\frac{2.0}{75/100} = 2.7 \text{ in}$$

and the required application rate is:

$$I = \frac{2.7 \text{ in}}{11.5 \text{ hr}} = 0.23 \text{ iph}$$

The required sprinkler discharge can now be computed by equation 2 as:

$$q = \frac{0.23 \times 40 \times 50}{96.3} = 4.78 \text{ gpm}$$

The production value of having 90 percent adequacy by using alternate sets vs. 75 percent adequacy can be demonstrated, assuming overwatering does not reduce yields. Table 11–8 gives relative percentages of optimum production for different CU and adequacy values. With a CU = 78% and 75 percent adequacy, the relative production is 95 percent and for a CU = 88% and 90 percent adequacy, it is 99 percent. Thus the use of alternate sets can be expected to improve yields by at least 4%. If, however, uneven watering decreases production or quality (due to leaching of fertilizer or waterlogging), the gross income differences may be considerably larger than 4 percent.

Nozzle Size and Pressure.—Table 11–13 is a list of the expected discharge and wetted diameters in conditions of no wind from typical 1/2- and 3/4-in bearing impact sprinklers with angles of trajectory between 22° and 28° and having standard nozzles

Table 11–13.—Nozzle discharge and wetted diameters for typical 1/2- and 3/4- inch bearing impact sprinklers with trajectory angles between 22° and 28° and standard nozzles without vanes [1]

Sprinkler pressure	Nozzle diameter—inch																	
	3/32		7/64		1/8		9/64		5/32		11/64		3/16		13/64		7/32	
psi	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		1.193		1.394	

[1] The use of straightening vanes or special long discharge tubes increases the wetted diameter by approximately 5%.
[2] Lines represent upper and lower recommended pressure boundaries.
[3] $q = K_d\sqrt{P}$.

without vanes. The various values in the table are for different nozzle sizes between 3/32- and 7/32-in and base of sprinkler pressures between 20 and 70 psi.

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

$$q = K_d \sqrt{P} \quad (11\text{–}12)$$

where

q = the sprinkler discharge (gpm)
K_d = the discharge coefficient for the sprinkler and nozzle combined
P = the sprinkler operating pressure (psi)

The K_d can be determined for any combination of sprinkler and nozzle if a P and a corresponding q are known. Because of internal sprinkler friction losses, K_d decreases slightly as q and P increase; 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 11–13.

Equation 12 can be rearranged to give:

$$q = q' \sqrt{P/P'} \quad (11\text{–}13a)$$

or

$$P = P'(q/q')^2 \quad (11\text{–}13b)$$

where the P' and q' are corresponding values that are known (from table 11–13 or a manufacturers table) and either q or P is not known.

Sample calculation 11–5 illustrates the procedure for determining the nozzle size and pressure required to obtain a given sprinkler discharge.

Sample calculation 11–5.—Determination of nozzle size and average operating pressure.

Given:

The sprinkler spacing of 40- by 60-ft and the average sprinkler discharge of q_a = 8.22 gpm for the alfalfa field considered in sample calculation 11–3.

Calculation:

From table 11–10, a sprinkler with a 13/64-in nozzle should be appropriate (see 0.35 ± 0.02 iph). Furthermore, from table 11–13 or from appropriate manufacturers charts, a 13/64-in nozzle will discharge 8.00 gpm at 45 psi and 8.44 gpm at 50 psi. Thus the average sprinkler pressure (P_a) which will give the required discharge can be interpolated as P_a = 47 psi.

Another way to estimate P_a is by equation 13.

$$P_a = 45 \left(\frac{8.22}{8.00}\right)^2 = 47 \text{ psi}$$

or by equation 12

$$P_a = \left(\frac{q_a}{K_d}\right)^2 = \left(\frac{8.22}{1.193}\right)^2 = 47 \text{ psi}$$

System Layout

Figure 11–29 shows general types of periodic-move sprinkle system layouts. Often the layout of a system will be simple, as in the case of small regularly shaped areas. On the other hand, large odd-shaped tracts with broken topography may present a complex engineering problem requiring alternate layouts and careful pipe-size analyses. The following paragraphs discuss 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. In the more complex layouts, considerable judgment must be exercised.

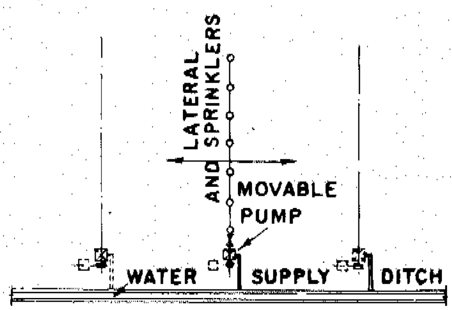
Number of Sprinklers Operated.—A system layout must provide for simultaneous operation of the average number of sprinklers that will satisfy the required system capacity determined by equation 1. This average number is computed as follows:

$$N_n = \frac{Q}{q_a} \quad (11\text{–}14a)$$

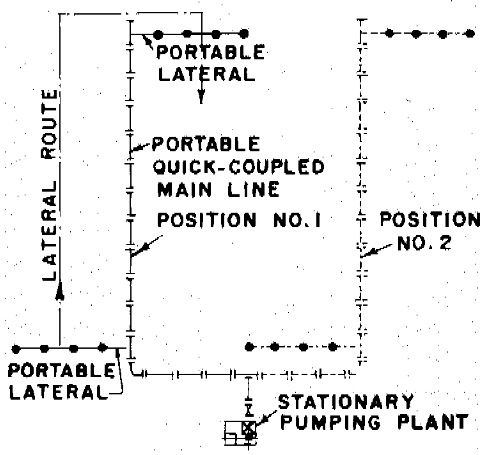
where

N_n = minimum average number of sprinklers operating
Q = system capacity from equation 1 (gpm)
q_a = average sprinkler discharge (gpm)

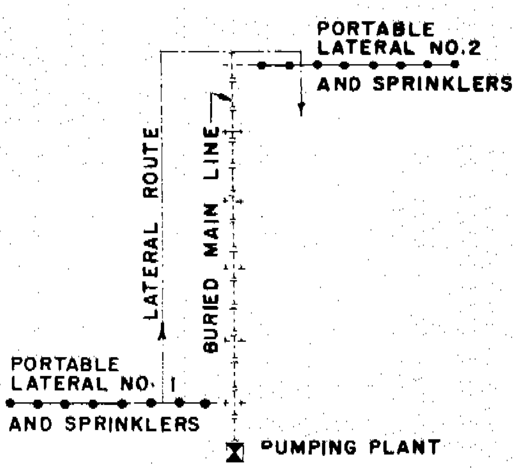
The variation in the number of sprinklers operated from time to time during an irrigation should be kept to a minimum to facilitate lateral routing



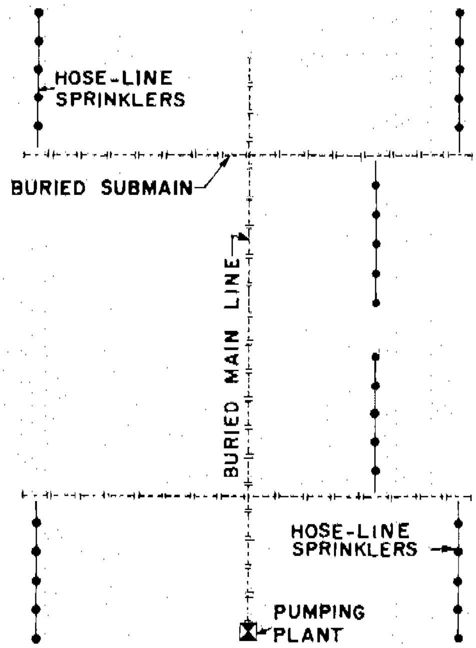
A–Fully portable sprinkler system with portable lateral and movable pumping plant.



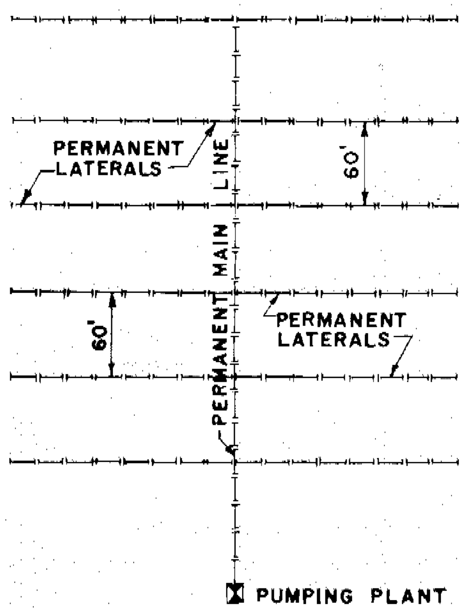
B–Portable laterals and main lines with stationary pumping plant.



C–Portable laterals, permanent buried main line, and stationary pumping plant.



D–Permanent mains and submains with portable hose lines.



E–Permanent main lines and laterals with movable or permanent sprinklers and quick-coupled riser pipes.

Figure 11-29.—General types of periodic-move sprinkle systems.

and to maintain a 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-ft intervals on the laterals. Furthermore, the spacing between laterals is usually at 40-, 50-, 60-, and 80-ft intervals along the mainline. Since whole laterals must be operated simultaneously, the preliminary system capacity determined by equation 1 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 × T) 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 needed 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.

Number of Lateral Settings.—The number of settings required for each lateral depends on the number of allowable sets per day and on the maximum number of days allowed for completing one irrigation during the peak-use period (f). 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 theoretical 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, however, may require additional lateral settings. Thus, more equipment is necessary if such areas are to be served within the allowable time period.

Lateral Layout.—Figure 11–30 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 variation in the discharge of individual sprinklers along the line. Normally this variation in discharge should not exceed 10 percent unless long term economic justification exists. Therefore, 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 head and static head, *will not exceed 20 percent of the average design operating pressure* for the sprinklers (P_a).

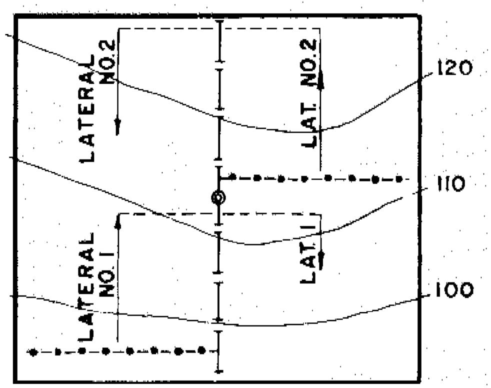
To meet this pressure-variation criteria, it is usually necessary to lay laterals across prominent land slopes (fig. 11–30A and B). Laid on level land or on the contour, a lateral of a given pipe size with a fixed average sprinkler-discharge rate (q_a) will thus be limited only to that length in which 20 percent of P_a is lost as a result of friction.

Running laterals uphill should be avoided wherever possible. Where they must be used, they need to be materially shortened unless pressure or flow regulators are used. Such a lateral of a given pipe size and fixed q_a 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. 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 because of friction.

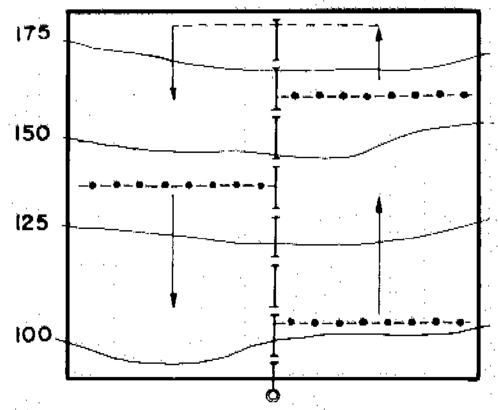
Running laterals downslope is often a distinct advantage, provided the slope is fairly constant and not too steep (see fig. 11–30C, D, E, and F). Because the difference in elevation between the two ends of the line causes a gain in head, laterals running downslope may be longer than lines laid on level ground.

While downslopes may permit longer laterals for a given pipe size or smaller pipe for a given length of lateral, such a layout does not usually permit split-line layout and lateral rotation about the mainline or submain. Thus labor costs may be higher.

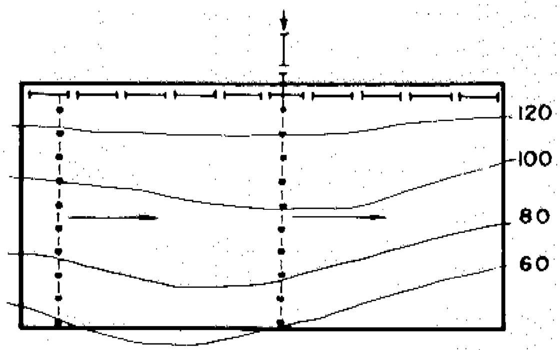
When the slope of the ground along the lateral is about equal to the slope of the friction loss, the pressure along the lateral is nearly constant. When the slope along the lateral increases for successive settings, intermediate control valves may be required to avoid building up excessive pressures and exceeding the variation limit.



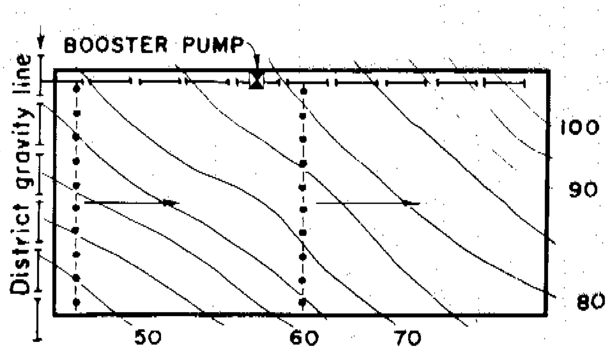
A–Layout on moderate, uniform slopes with water supply at center.



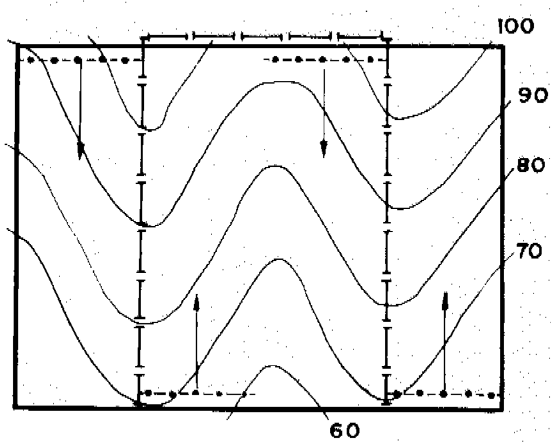
B–Layout illustrating use of odd number of laterals to provide required number of operating sprinklers.



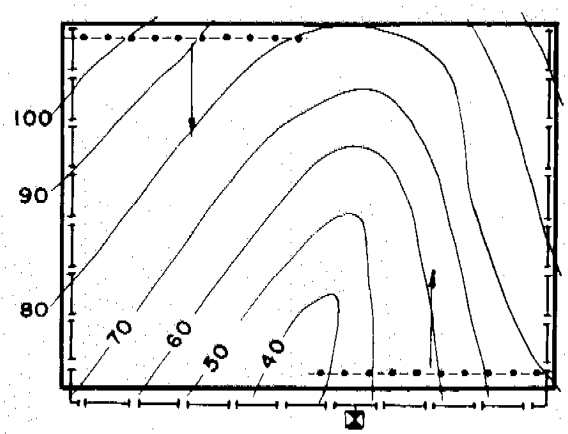
C–Layout with gravity pressure where pressure gain approximates friction loss and allows running lateral downhill.



D–Layout illustrating area where laterals have to be laid downslope to avoid wide pressure variation caused by running laterals upslope.



E–Layout with two main lines on ridges to avoid running laterals uphill.



F–Layout with two main lines on the sides of the area to avoid running the laterals uphill.

Figure 11–30.—Layouts of periodic-move sprinkle systems showing effects of topography on laterals.

Hand-move lateral lines need to be limited to one or two pipe sizes for simplicity of operation. The trend in recent years has been toward the use of a single pipe size.

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 1000 ppm of salts.

If lateral pipelines are to remain in a single design area and are not to be moved from field to field, they should be located so that they can be rotated around the mainline, thereby minimizing the hauling of pipe back to the starting point for subsequent irrigations (see fig. 11–29C).

Farming operations and row directions often influence the layout of laterals. Contoured row crops can be sprinkle irrigated only with hand-move or solid-set systems, which presents special problems such as difficulty in placing and moving lateral lines and getting 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 (S_m) will be variable 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.

Stripcropping has been used effectively in overcoming some of the difficulties arising from sprinkle irrigation of contoured row crops. The row crops are planted in strips equal in width to the lateral spacing. The alternating strips are equal in width to the lateral spacing at the mainline point of beginning but may vary considerably in width at points distant from the mainline. Laterals are laid on the contour along the outside of the row-crop strips as shown in figure 11–31A. In this method the hay crops as well as the row crop are irrigated. Advantages of this procedure are uniform coverage on the row-crop strips and the relative ease of moving the pipe on firmer footing and outside the areas of tall crops. Disadvantages are nonuniform coverage on the secondary hay crop and the necessity for carefully laying out the strips before planting each crop.

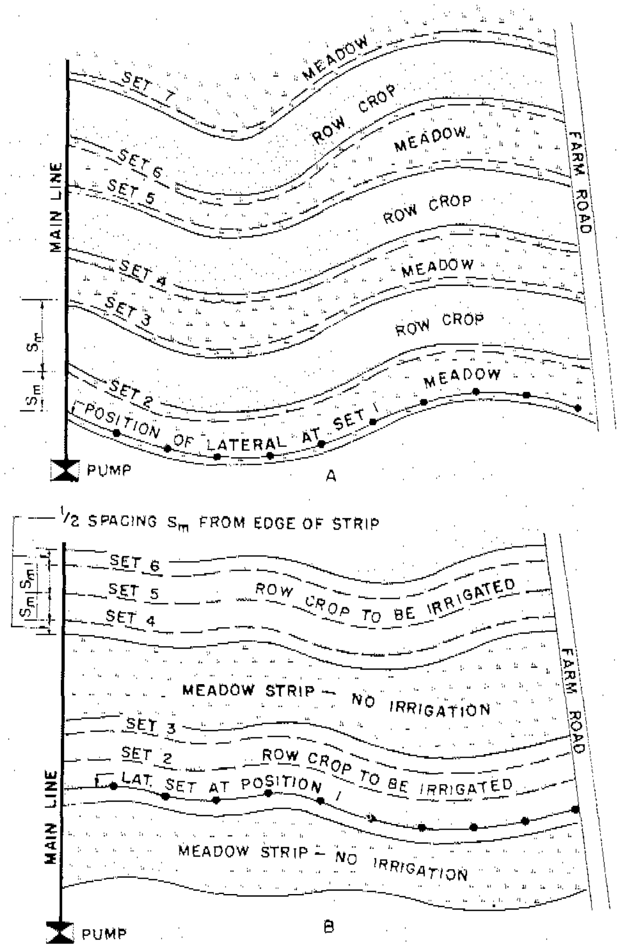


Figure 11–31.—Typical sprinkler lateral layouts on stripcropped areas.

When it is not desired to irrigate the hay crop, part-circle sprinklers may be used to irrigate the row crop alone or the row crop may be planted in strips equal in width to some multiple of S_m and the laterals operated entirely within the row-crop strips as shown in figure 11–31B. A disadvantage is in having to move the pipe when the upper part of the soil is saturated.

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.

Mainline Layout.—Figures 11–29 and 11–30 show various mainline configurations. 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 11–29C. This minimizes both pipe friction losses and the labor needed for hauling lateral pipe back to the starting point. The farmers' planting, cultural, and harvesting operations do not always permit a split-line operation, however. An example would be harvesting flue-cured tobacco over a period of several weeks while irrigation is still in progress. 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.

Location of Water Source and Pumping Plant.—If a choice in location of the water-supply source is possible, the source should be placed near the center of the design area. This results in the least cost for mainline pipe and for pumping. A choice of location of the water supply is usually possible only when a 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. Figure 11–12 illustrates the choice of pump locations between points A and F as follows:

With the pump at location A, line BC will carry water for 30 acres and line CF will carry water for 15 acres; with the pump at F, BC will carry water for 40 acres and CF will carry water for 72 acres. In this example, therefore, 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 lands, 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 discussed in more detail in Chapter 8, *Irrigation Pumping Plants*.

Adjustments to Meet Layout Conditions.—After completing the layout of main lines and laterals it is usually necessary to adjust one or more of the following:

Number of sprinklers operating, N
Water-application rate, I
Gross depth of each irrigation, d
Sprinkler discharge, q_a
Spacing of sprinklers, $S_l \times S_m$
Actual operating time per day, T
Days to complete one irrigation, f
Total operating time per irrigation, f × T
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 in this chapter, 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-intake rate of the soil and by the minimum water application rates practical for the design.

Since I is a function of q_a 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 frequency of irrigation can also be adjusted if further modification is needed. Spacing can be adjusted within limits to maintain a fixed I. Changes in spacing (S_l or S_m) can be made in 10-ft 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, f × T, to fit d.

Before the layout is made, T and f are assumed in computing Q by equation 1. If the total time of operation (T × f) 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 14a and replacing N_n with N_x:

$$Q = N_x \times q_a \qquad \textbf{(11-14b)}$$

Therefore, the final adjustment is to compute the total system capacity needed to satisfy maximum demands. Sample calculation 11-6 illustrates the problem of adjusting system capacity to meet layout requirements.

Sample calculation 11-6.—Determine system capacity and adjust operating conditions to meet layout requirements.

Given:

An 80-acre potato field with 1,320- by 2,640-ft dimensions

The information from figure 11-29 for potatoes and from sample calculation 11-4 gives d = 2.7 in; q_a = 4.78 gpm; 8-day irrigation interval during peak-use period; two 11.5-hr sets per day, and 40- by 50-ft sprinkler spacing.

Layout:

Preliminary system capacity by equation 1:

$$Q = \frac{453 \times Ad}{fT} = \frac{453 \times 80 \times 2.7}{8 \times 2 \times 11.5} = 532 \text{ gpm}$$

Minimum number of sprinklers by equation 14a:

$$N_n = \frac{Q}{q_a} = \frac{532}{4.78} = 112 \text{ sprinklers}$$

Design the layout with one mainline 1,320 ft long, through the center of the field with laterals 1,320 ft long to either side

With S_l = 40 ft, the number of sprinklers per lateral is: 1,320/40 = 33

The minimum whole number of laterals required is: 112/33 = 4

The number of lateral settings on each side of the mainline with

S_m = 50 ft is: 1,320/50 = 27.

The number of settings for each of the 4 laterals is:

2 × 27/4 = 14 for 2 laterals and 13 for 2 laterals

Time required to complete one irrigation is: f = 14/2 = 7 days

Adjustments:

With all 4 laterals operating, the maximum number of sprinklers running is: N_x = 4 × 33 = 132 sprinklers

The time required to complete one irrigation is: f = 14/2 = 7 days

The actual system capacity computed by equation 14b is:

$$Q = N_x \times q_a = 132 \times 4.78 = 631 \text{ gpm}$$

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 = 532 gpm by letting d = 2.4 in and reducing the irrigation interval to 7 days. This would require changing q_a to about 4.25 gpm (depending on the effect on E_q). 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 be more than offset by the added labor cost of more frequent irrigations.

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*.

Friction Losses in Laterals.—Friction loss is less for flow through a line with a number of equally spaced outlets than for flow through the length of a pipeline of a given diameter, because the volume of flow 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 used 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 (sprinklers in the line (N)).

The Hazen-Williams equation is commonly used for estimating the friction loss in sprinkler laterals and mainlines of various pipe materials:

$$J = \frac{h_f\,100}{L} = 1050\left(\frac{Q}{C}\right)^{1.852} D^{-4.87} \qquad \textbf{(11–15)}$$

where

J = head loss gradient (ft/100 ft)
h_f = head loss due to pipe friction (ft)
L = length of pipe (ft)
Q = flow rate in the pipe (gpm)
C = friction coefficient that is a function of pipe material characteristics
D = inside diameter of the pipe (in)

Typical values of C are:

Pipe	C
Plastic (4-in or larger)	150
(2- and 3-in)	140
Cement asbestos	140
Aluminum (with couplers every 30 ft)	130
Galvanized steel	130
Steel (new)	130
(15 years old)	100

Table 11–14 gives J values for portable aluminum pipe.

Christiansen's equation for computing the reduction coefficient (F) for multiple outlet pipelines where the first outlet is S_l from the mainline is:

$$F = \frac{1}{m+1} + \frac{1}{2N} + \frac{\sqrt{m-1}}{6N^2} \qquad \textbf{(11–16a)}$$

and where the first outlet is $S_l/2$ from the mainline:

$$F = \left(\frac{2N}{2N-1}\right)\left(\frac{1}{m+1} + \frac{\sqrt{m-1}}{6N^2}\right) \qquad \textbf{(11–16b)}$$

where

m = 1.852, velocity exponent of the Hazen-Williams formula
N = number of outlets in the line.

Table 11–15 shows values of F for different numbers of outlets.

Table 11–14.—Friction loss in ft/100 ft (J) in portable aluminum pipe with 0.050-in wall and couplings every 30 ft [1]

Flow rate (gpm)	2-in	3-in	4-in	5-in
10	0.40	0.05		
20	1.44	0.18	0.04	
30	3.05	0.39		
40	5.20	0.66	0.15	
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	3.62	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 Hazen-Williams formula (C = 130).

Table 11–15.—Reduction coefficients (F) for computing friction loss in pipe with multiple outlets

Number of outlets	F[1] (end)	F[2] (mid)	Number of outlets	F[1] (end)	F[2] (mid)
1	1.00	1.00	8	0.42	0.38
2	0.64	0.52	9	0.41	0.37
3	0.53	0.44	10–11	0.40	0.37
4	0.49	0.41	12–14	0.39	0.37
5	0.46	0.40	15–20	0.38	0.36
6	0.44	0.39	21–35	0.37	0.36
7	0.43	0.38	> 35	0.36	0.36

[1] F(end) is for 1st sprinkler S_l from main (end-riser pipe).
[2] F(mid) is for 1st sprinkler $S_l/2$ from main (mid-riser pipe).

The friction head loss (h_f) in a lateral can be computed by:

$$h_f = J\ F\ L/100 \qquad (11\text{–}17a)$$

and the pressure head loss (P_f) is

$$P_f = \frac{J\ F\ L}{231} = h_f/2.31 \qquad (11\text{–}17b)$$

Sample calculation 11–7.—Computation of lateral friction loss.

Given:
A 4-in lateral line 1,320 ft long with a 40-ft sprinkler spacing and sprinklers discharging 8 gpm.

Calculation:
The number of sprinklers is $N = 1{,}320/40 = 33$
The lateral discharge, $Q_\ell = 33 \times 8.00 = 264$ gpm
From table 11–15, $F = 0.37$ and by equation 15 or table 11–14, $J = 5.16$
By equation 17

$$h_f = J\ F\ L/100 = 5.16 \times 0.37 \times 1{,}320/100 = 24.5 \text{ ft} = 10.6 \text{ psi}$$

Laterals on Level Ground.—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:

$$J_a = \frac{0.20\ P_a \times 2.31}{L/100 \times F} \qquad (11\text{–}18a)$$

Using table 11–14 find the flow rate corresponding to the total lateral discharge and, 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).

To determine the pressure required at the mainline for single pipe size laterals:

$$P_m = P_a + 3/4\ P_f + P_r \qquad (11\text{–}19a)$$

and for dual pipe size laterals:

$$P_m = P_a + 2/3\ P_f + P_r \qquad (11\text{–}20a)$$

where

P_m = pressure required at the mainline end (lateral inlet pressure) (psi)
P_f = pressure loss due to pipe friction (psi)
P_r = pressure required to lift water up the riser, riser height/2.31 (psi)

Laterals Laid Uphill.—In figure 11–32, P_f may be equal to 20 percent of P_a minus the pressure required to overcome elevation P_e, which is the difference in elevation divided by 2.31. Therefore:

$$J_a = \frac{(0.20\ P_a - P_e) \times 2.31}{L/100 \times F} \qquad (11\text{–}18b)$$

For single pipe size laterals on uniform uphill slopes:

$$P_m = P_a + 3/4\ P_f + 1/2\ P_e + P_r \qquad (11\text{–}19b)$$

and for dual pipe size laterals:

$$P_m = P_a + 2/3\ P_f + 1/2\ P_e + P_r \qquad (11\text{–}20b)$$

Sample calculation 11–8 illustrates this procedure.

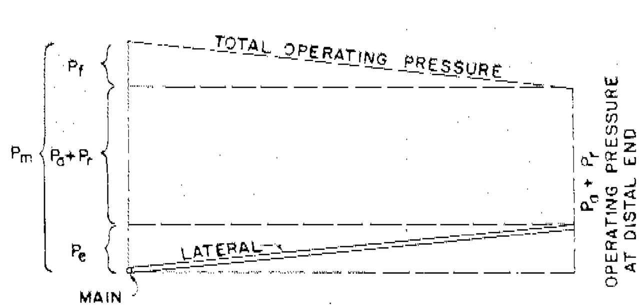


Figure 11–32.—Lateral laid uphill.

Laterals Laid Downhill.—In figure 11–33, the allowable P_f is $0.20\ P_a + P_e$ and for relatively mild slopes:

$$J_a = \frac{(0.20\ P_a + P_e) \times 2.31}{L/100 \times F} \qquad (11\text{–}18c)$$

However, on steep slopes where $P_e > 0.4\ P_a$, it is desirable to 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, $P_f = P_e$.

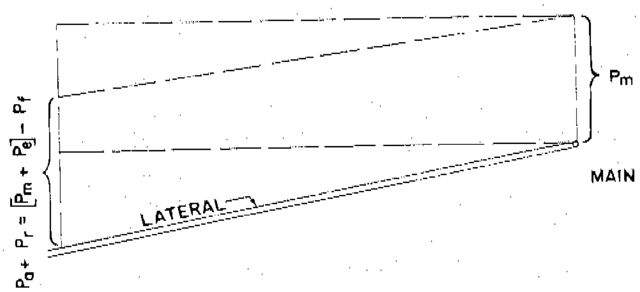


Figure 11-33.—Lateral laid downhill.

For single pipe size laterals on uniform downhill slopes:

$$P_m = P_a + 3/4\ P_f - 1/2\ P_e + P_r \qquad \textbf{(11-19c)}$$

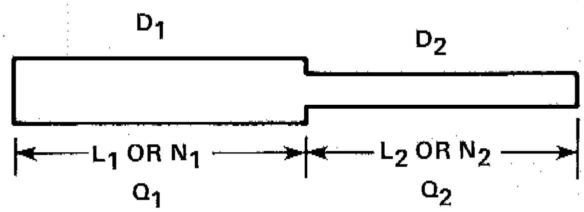
and for dual pipe size laterals:

$$P_m = P_a + 2/3\ P_f - 1/2\ P_e + P_r \qquad \textbf{(11-20c)}$$

Sample calculation 11–9 illustrates this procedure.

Laterals with Two Pipe Sizes.—Most farmers prefer lateral lines of a single pipe size for convenience. A few want to use two pipe sizes where their use 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 11–14 and 11–15 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 the following procedure:



1. Compute the allowable P_f for the total length of the line as described in the previous sections.
2. Convert this allowable P_f to J_a by using a form of equation 18 appropriate for the slope conditions.
3. With the total lateral line capacity (Q) and the J_a known, use table 11–14 to find the two pipe sizes required.
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 and then compute the total pressure loss due to friction for these lengths. The closed end of the multi-outlet line must be considered in all friction-loss calculations using equation 17. Should this loss fall above or below the allowable P_f, choose different values of L_1 and L_2 and repeat the procedure.
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 $Q_1 + Q_2$.
6. Find the loss in length L_2 for pipe diameter (D_1) containing N_2 sprinklers and discharging Q_2.
7. Then find the loss in length (L_2) of pipe diameter D_2 containing N_2 sprinklers and discharging Q_2.
8. Combine the losses as follows:

$$P_f = \text{Step 5} - \text{Step 6} + \text{Step 7}$$
$$= P_{f(1+2)}\ (\text{for } D_1) - P_{f(2)}\ (\text{for } D_1) + P_{f(2)}\ (\text{for } D_2) \qquad \textbf{(11-21)}$$

Sample calculation 11–8 illustrates this procedure.

Sample calculation 11–8.—Laterals laid out uphill—two pipe sizes.

Given:

Lateral consisting of 960 ft of portable aluminum irrigation pipe with 24 sprinklers spaced 40 ft apart, discharging at a rate of 12.5 gpm and operating at 44 psi.

Lateral capacity: Q = 300 gpm

Elevation difference = 9.0 ft (uphill) or P_e = 9.0/2.31 = 3.9 psi

Height of risers for corn: 8.0 ft

Find:

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

Calculation:

Referring to figure 11–32 determine the allowable J_a by equation 18b:

$$J_a = \frac{(0.20 \times 44 - 3.9) \times 2.31}{960/100 \times 0.37} = 3.19$$

Using the lateral capacity of Q = 300 gpm and J_a = 3.19, table 11–14 indicates that some 5-in and some 4-in pipe should be used.

Assuming 480 ft of 5-in and 480 ft of 4-in pipe:

D_1 = 5-in $\qquad$ D_2 = 4-in

L_1 = 480 ft L_2 = 480 ft
N_1 = 12 N_2 = 12
Q_1 = 150 gpm Q_2 = 150 gpm

Using equation 17b and tables 11–14 and 11–15 and assuming $D_1 = 5$ in for the entire length of the lateral, find the loss in $(L_1 + L_2) = 960$ ft containing $(N_1 + N_2) = 24$ sprinklers and discharging $(Q_1 + Q_2) = 300$ gpm:

$$P_{f(1+2)} \text{ (for } D_1) = \frac{2.15 \times 0.37 \times 960}{231} = 3.31 \text{ psi}$$

Next find the loss in $L_2 = 480$ ft of D_1 = 5-in pipe containing

$N_2 = 12$ sprinklers and discharging $Q_2 = 150$ gpm:

$$P_{f(2)} \text{ (for } D_1) = \frac{0.50 \times 0.39 \times 480}{231} = 0.48 \text{ psi}$$

And in a similar manner find the loss in the 4-in pipe:

$$P_{f(2)} \text{ (for } D_2) = \frac{1.81 \times 0.39 \times 480}{231} = 1.47 \text{ psi}$$

The friction loss for the dual pipe size line can now be determined by equation 21:

$$P_f = 3.31 - 0.48 + 1.47 = 4.3 \text{ psi}$$

This value is slightly lower than the allowable $P_f = 0.20\ P_a - P_e = 0.20 \times 44 - 3.9 = 4.9$ psi. Therefore, less 5-in pipe and more 4-in pipe can be used.

By assuming 400 ft of 5-in pipe containing 10 sprinklers and 560 ft of 4-in pipe containing 14 sprinklers, a repetition of the procedure results in:

$$P_f = 3.31 - 0.75 + 2.28 = 4.8 \text{ psi}$$

The pressure requirement at the mainline can now be determined by equation 20b:

$$P_m = 44.0 + (2/3 \times 4.8) + (1/2 \times 3.9) + \frac{8.0}{2.31}$$

$= 52.6$ psi

Sample calculation 11–9.—Laterals laid downhill.

Given:

Lateral consisting of 960 ft of portable aluminum irrigation pipe with 24 sprinklers spaced 40 ft apart, discharging at a rate of 12.5 gpm, and operating at 44.0 psi

Lateral capacity: $Q = 300$ gpm

Average downhill slope: 3.5 percent and 33.6 ft in total length of line

Height of risers for corn = 8 ft

Owner desires only one pipe size

Find:

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 main line

Calculation:

Assume the allowable P_f to be equal to the pressure gain due to elevation $P_e = \frac{33.6}{2.31} = 14.5$ psi

Convert the pressure gain due to elevation to an allowable head loss gradient (J_a) using equation 18c and letting $P_a = 0$:

$$J_a = \frac{(14.5) \times 2.31}{960/100 \times 0.37} = 9.43$$

Using a lateral capacity of 300 gpm, table 11–14 indicates some 3-in and some 4-in pipe will be required. Since the owner wishes to use only one pipe size, use all 4-in. The pressure loss due to friction resulting from the use of 4-in pipe by equation 17b is:

$$P_f = \frac{0.37 \times 6.54 \times 960}{231} = 10.1 \text{ psi}$$

The percent of pressure variation in the line is:

$$\frac{P_e - P_f}{P_a} = \frac{14.5 - 10.1}{44.0} = 10.0\%$$

If all 3-in pipe were used, the pressure loss due to friction would be 42.5 psi, and the resulting pressure variation would be:

$$\frac{P_f - P_e}{P_a} = \frac{42.5 - 14.5}{44.0} = 64\%$$

This is obviously outside the 20 percent limit. Thus a line consisting of all 3-in pipe should not be used.
Using equation 19c, to compute the pressure required at the mainline for a 4-in lateral:

$$P_m = 44.0 + (3/4 \times 10.1) - (1/2 \times 14.5) + \frac{8.0}{2.31} = 47.8 \text{ psi}$$

Laterals with Flow-Control Devices.—Flow or pressure control devices are used in lateral lines where the topography is too broken or too 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 line and the sprinkler head at each sprinkler outlet or special flow control nozzles as described earlier. They are 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. 11–34). 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 psi.

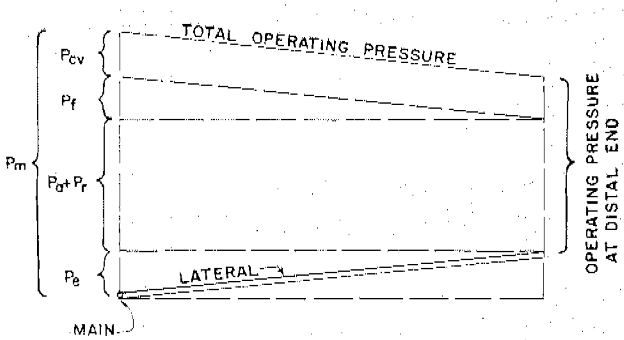


Figure 11–34.—Lateral with flow-control valves.

The pressure requirement at the main line for level fields is:

$$P_m = P_a + P_f + P_r + P_{cv} \tag{11–22a}$$

for uphill laterals:

$$P_m = P_a + P_f + P_e + P_r + P_{cv} \tag{11–22b}$$

and for downhill laterals:

$$P_m = P_a + P_f - P_e + P_r + P_{cv} \tag{11–22c}$$

Valve manufacturers furnish data on the pressure losses for different discharges through their valves (fig. 11–26). Sample calculation 11–10 illustrates the procedure involved in the design of a lateral line containing flow control nozzles.

Sample calculation 11–10.—Design of lateral with flow control nozzles.

Given:
A lateral 1,320 ft long; running up and down slopes on broken topography. The highest point in the line is 33 ft above the lateral inlet from the mainline. The lateral contains 44 sprinklers spaced at $S_\ell = 30$ ft with $q_a = 5.0$ gpm. The first sprinkler is 1/2 S_ℓ from the mainline.
Sprinklers with flexible orifice nozzles designed to discharge about 5 gpm between 40 and 80 psi as shown in figure 11–26 will be used.
The system will have 3-ft risers
The owner desires single pipe size laterals.
Find:
Pipe size and P_m required.
Calculation:
Pressure required to overcome elevation is:

$$P_e = \frac{33}{2.31} = 14.3 \text{ psi}$$

Let the allowable $P_f = 10$ psi, which is about 20 percent of the pressure that would be required for a standard 5/32-in nozzle discharging 5.0 gpm. The allowable head loss gradient for $P_f = 10$ psi is:

$$J_a = \frac{10.0 \times 2.31}{1,320/100 \times 0.36} = 4.86$$

From table 11–14 for $Q_\ell = 44 \times 5.0 = 220$ gpm it is determined that 4-in pipe will satisfy J_a. Using equation 17b:

$$P_f = \frac{0.36 \times 3.68 \times 1{,}320}{231} = 7.6 \text{ psi}$$

Typically, sprinkler regulating valves have a P_{cv} of between 10 and 15 psi; however, as mentioned earlier for flexible orifice nozzles, $P_{cv} = 0$. Substituting the lowest permissible operating pressure, 40 psi, for P_a in equation 22b:

$$P_m = 40.0 + 7.6 + 14.3 + \frac{3.0}{2.31} + 0 = 63.2 \text{ psi}$$

Hose-Fed Design.—Hose-fed systems for overlapped sprinkler grids and for orchard sprinklers (figs. 11–11 and 11–29D) require special design considerations; however, the design strategies discussed earlier in this section can be used. Each hose may be fitted with from 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. The average pressure along the manifold, however, 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 (fig. 11–29D), the hose line should be treated as an ordinary sprinkler lateral. Thus, equation 17b is used to find P_f and equation 19 is used to find P_m.

Friction losses in small diameter hoses can be estimated by:

$$J = \frac{h_f}{L/100} = 0.133 \frac{Q^{1.75}}{D^{4.75}} \text{ (for D < 5 in)} \qquad \textbf{(11–23a)}$$

This equation is derived by combining the Blasius equation and the Darcy-Weisbach formula for smooth pipes. Equation 23a gives good results for 5-in-diameter and smaller plastic pipe. For larger plastic pipes the Hazen-Williams equation 15 with C = 150 can be used; however, slightly more accurate estimates of friction loss can be obtained from:

$$J = \frac{h_f\ 100}{L} = 0.100 \frac{Q^{1.83}}{D^{4.83}} \text{ (for D > 5 in)} \qquad \textbf{(11–23b)}$$

Table 11–16 gives friction loss gradients for various sizes of hoses and hose bibs based on equation 23a.

Table 11–16.—Approximate friction loss gradients for plastic hoses and hose bibs[1]

Flow	Friction loss, psi/100 ft[2]			Hydrant loss, psi	
gpm	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.

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 iph. This limit in application rates materially reduces 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 it easy to read the discharge, spread, and operating pressure from the tables. Table 11–17 is an example. The designer should request such tables from the manufacturer when confronted with perforated-pipe-design problems.

Table 11-17.—Typical performance table for perforated pipelines[1]

Inlet pressure	Discharge and Spread	Pipe size = 5-in diameter Application rate = 1.0 iph																		
		Length of line (feet)																		
		50	100	150	200	250	300	350	400	450	500	550	600	650	700	750	800	850	900	950
(psi) 6	gpm	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	gpm	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	32	31	31	31	30	30	29	29	28	27
8	gpm	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	35	34	34	34	34	33	33	33	32	32	31	30	30
9	gpm	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	gpm	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	gpm	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	gpm	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	gpm	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	gpm	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	gpm	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	gpm	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	gpm	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	gpm	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	48	47	47	47	46	46	45	44	44	43
[illegible]	[illegible]	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	gpm	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	48	48	48	47	46	46	45

[1] Furnished by a manufacturer.

To illustrate the use of table 11–17, assume a lateral 750 ft long with S_m = 40 ft applying water at the rate of 1.0 iph. Since this table includes lateral lengths of 750 ft for 5-in pipe and an application rate of 1.0 iph, this size pipe may be used. Find the 750-ft column and follow the column downward until a spread of 42 ft is reached. A spread 2 ft greater than the lateral spacing is customarily used to provide a 1-ft overlap between laterals to prevent dry areas. At a 42-ft spread note that the lateral discharge is 364 gpm. Following a horizontal line to the left, the inlet pressure or pressure required at the mainline, is P_m = 15.0 psi.

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 4 different pipe sizes are often used. To determine friction loss use equation 23 to compute the P_f of a multisized lateral either following a procedure similar to that outlined in this section under subtopic *Laterals for Two Pipe Sizes* or the graphical procedures developed in Chapter 7, *Trickle Irrigation*.

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 Tables.—The Hazen-Williams equation is the most commonly used formula for computing friction loss in aluminum mainline pipes. Table 11–18 gives friction loss J values in ft/100 ft for portable aluminum irrigation pipe with typical mainline coupler losses assuming 30-ft pipe lengths.

Tables 11–19a and 11–19b give J values for SDR 41 PVC, IPS, and PIP (Class 100 psi) thermoplastic pipe used in typical sprinkle irrigation system mainlines. The values in these tables were computed using equation 23 which gives slightly more accurate estimates than the Hazen-Williams equation with C = 150 for smooth plastic pipe.

Table 11–18.—Friction loss J values in ft/100 ft of portable aluminum mainline pipe with couplers connecting 30-foot 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
1000			2.01	0.68	0.27
1100			2.39	0.81	0.33
1200			3.81	0.95	0.39
1300			3.26	1.10	0.45
1400			3.74	1.26	0.51
1500			4.25	1.44	0.58
1600			4.79	1.62	0.66
1800			5.96	2.01	0.82
2000			7.25	2.45	0.99
2200			8.64	2.92	1.18
2400				3.43	1.39
2600				3.98	1.61
2800				4.56	1.85
3000				5.18	2.10
3500					2.80
4000					3.58

[1]Based on 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 11–20 gives J values for welded steel pipe. The table is based on Skobey's formula, which is generally used for estimating friction in steel pipe

$$J = \frac{h_f\,100}{L} = \frac{K_f}{10}\,\frac{V^{1.9}}{(D/12)^{1.1}} \qquad \textbf{(11–24)}$$

Table 11-19a.—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 equation 23a)

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	0.43				
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	
1000		4.25	1.19	0.41	0.18
1100		5.07	1.41	0.49	0.21
1200		5.94	1.66	0.57	0.25
1300			1.92	0.66	0.29
1400			2.20	0.76	0.33
1500			2.50	0.86	0.38
1600			2.81	0.97	0.43
1700			3.14	1.08	0.48
1800			3.48	1.20	0.53
2000			4.23	1.46	0.64
2200			5.03	1.74	0.76
2400			5.90	2.04	0.89
2600				2.36	1.03
2800				2.70	1.18
3000				3.05	1.34
3200				3.45	1.51
3600				4.28	1.88
4000				5.19	2.28

[1] Nominal pipe diameter; inside diameter in parentheses.

Table 11-19b.—Friction loss J values in ft/100 ft of SDR 41, PIP, PVC (Class 100) thermoplastic pipe used for spinkle irrigation mainlines (based on equation 23b)

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		
1000	6.14	1.55	0.53		
1100		1.85	0.63	0.26	
1200		2.17	0.74	0.31	
1300		2.51	0.86	0.35	
1400		2.88	0.98	0.41	
1600		3.67	1.25	0.52	0.18
1800		4.56	1.55	0.64	0.22
2000		5.52	1.88	0.78	0.27
2200		6.58	2.24	0.93	0.32
2400			2.63	1.09	0.37
2600			3.04	1.26	0.43
2800			3.48	1.44	0.49
3000			3.95	1.64	0.56
3500				2.17	0.74
4000				2.77	0.94
4500				3.44	1.17
5000				4.17	1.42
5500					1.69
6000					1.98
6500					2.29
7000					2.63

[1] Nominal pipe diameter; inside diameter in parentheses.

where

K_f = Skobey's friction coefficient that is normally taken as 0.36 for 15-year-old welded steel.

V = flow velocity (ft/s)

Other types of pipe material such as asbestos-cement are available and practical for sprinkle 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.

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.

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 sprinkle system operation is supplied by pumping, the problem is

Table 11-20.—Friction loss in ft/100 ft (J), in mainlines of 8-to-12 year old welded steel pipe (based on Skobey's formula with $K_f = 0.36$)

Flow (gpm)	4-in [1]			5-in [1]		6-in [1]		7-in [1]		8-in [1]		10-in [1]	
	16-gage	14-gage	12-gage	14-gage	12-gage	14-gage	12-gage	14-gage	12-gage	14-gage	12-gage	14-gage	12-gage
40	0.150	0.155	0.169	0.048	0.052								
50	.218	.227	.246	.074	.080								
60	.300	.312	.339	.106	.113								
70	.393	.411	.444	.142	.151								
80	.558	.579	.628	.182	.193	0.074	0.079						
90	.677	.709	.768	.228	.242	.091	.096						
100	.810	.848	.920	.279	.296	.109	.115	0.052	0.054				
125	1.28	1.34	1.45	.425	.452	.172	.181	.079	.082				
150	1.76	1.83	1.99	.602	.640	.235	.249	.111	.116				
175	2.42	2.52	2.73	.807	.857	.323	.341	.148	.155	0.075	0.080		
200	3.04	3.17	3.44	1.04	1.10	.407	.429	.191	.200	.096	.100		
250	4.79	5.01	5.43	1.59	1.69	.643	.678	.292	.306	.152	.159	0.050	0.052
300	6.74	7.04	7.63	2.25	2.39	.903	.953	.414	.432	.215	.223	.070	.072
350	8.99	9.41	10.2	3.01	3.23	1.21	1.27	.555	.579	.287	.297	.095	.097
400	11.5	12.1	13.1	3.88	4.12	1.55	1.63	.714	.746	.369	.381	.120	.124
450	14.4	15.3	16.3	4.85	5.16	1.94	2.04	.894	.934	.458	.476	.150	.155
500	17.6	18.6	19.9	5.93	6.30	2.36	2.49	1.09	1.14	.559	.580	.183	.189
600				8.38	8.91	3.39	3.57	1.54	1.61	.801	.834	.263	.271
700				11.2	11.9	4.51	4.76	2.07	2.16	1.07	1.11	.352	.361
800				14.5	15.4	5.79	6.10	2.67	2.79	1.37	1.42	.450	.464
900						7.28	7.68	3.34	3.48	1.73	1.79	.573	.584
1000						8.90	9.38	4.08	4.26	2.11	2.18	.694	.712
1200						12.5	13.2	5.76	6.02	3.04	3.07	.977	1.00
1400								7.73	8.07	3.98	4.14	1.30	1.35
1600								9.96	10.4	5.13	5.33	1.68	1.74
1800										6.43	6.66	2.12	2.17
2000										7.86	8.18	2.62	2.65
2500										12.0	12.5	3.97	4.05
3000												5.52	5.74

[1] Outside diameters.

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 ft, 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 very 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 excessive water hammer. This is particularly important in PVC and cement-asbestos pipelines. NI PVC pipe design, mainline velocities should be limited to 5.0 ft/s. With SDR-41 PVC pipe, the surge pressure is approximately equal to 12.4 psi for each 1.0 ft/s velocity change.

Design with 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 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.

Design with Split-Line Layout.—The split-line layout consists of two or more laterals rotated around the mainline or submains. Its purpose is twofold: (1) to equalize the load at the pump regardless of lateral position, and (2) to minimize the haulback of lateral pipe to the beginning point.

Figure 11-35 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 carried 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, thus the flow for the entire length of main 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 $H_{f2}+E_2$. Note that the elevation difference between B and C (E_2) in figure 11-35 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 mains fed from 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 follows:

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.

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.

3. Determine the proportionate lengths for L_1 for the two pipe sizes as follows:

$$H_{f1} = XJ_2 + (L_1 - X)J_1 \qquad \textbf{(11-24a)}$$

where

H_{f1} = limit of friction loss in length of pipe (ft)

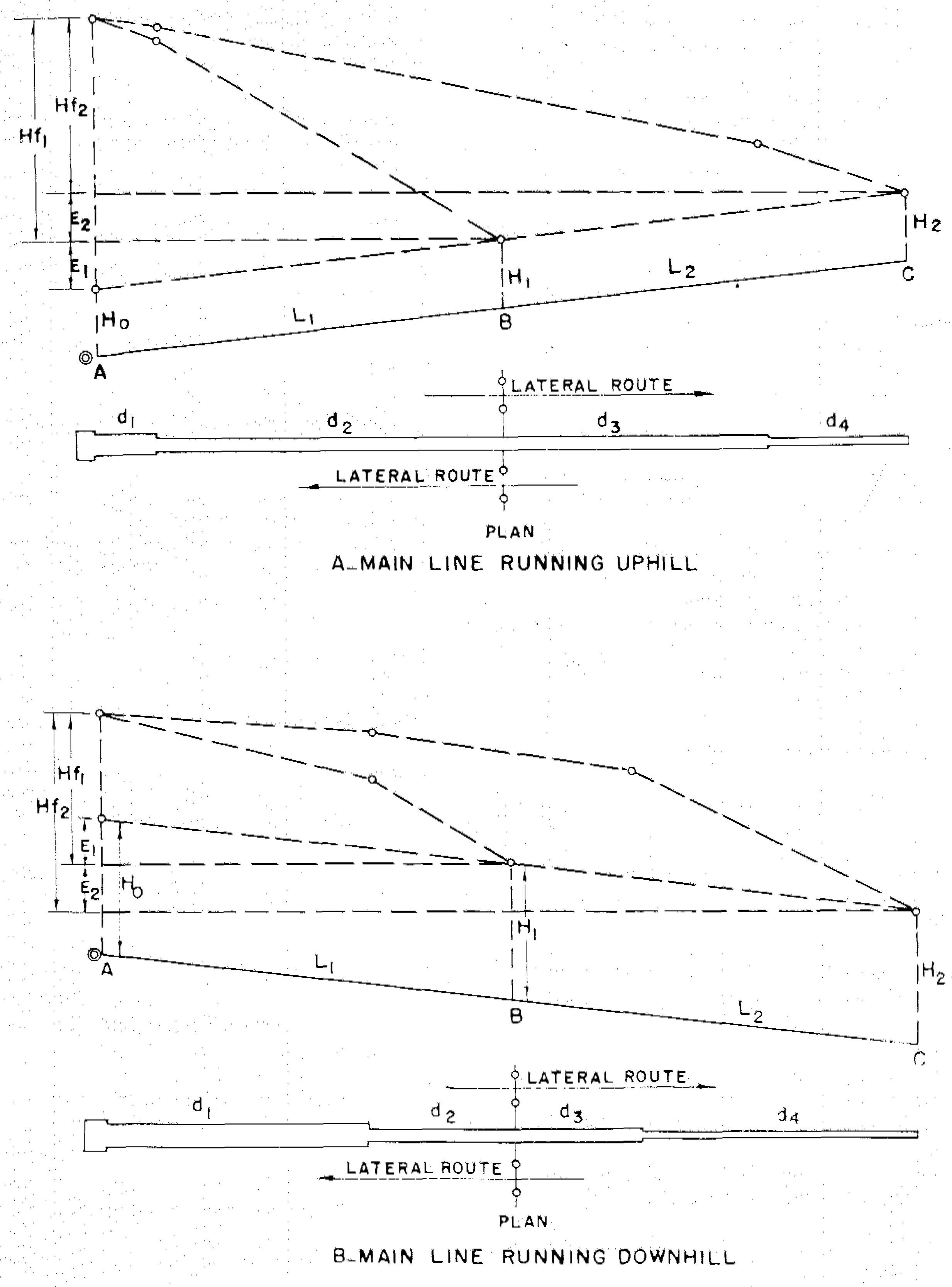


Figure 11-35.—Design of mainline with twin laterals, split-line operation.

X = length of smaller pipe (ft/100 ft)
J_2 = friction loss gradient in smaller pipe (ft/100 ft)
$(L_1 - X)$ = length of larger pipe (ft/100 ft)
J_1 = friction loss gradient in larger pipe (ft/100 ft)

Solving equation 24a for X gives:

$$X = \frac{H_{f1} - J_1 L_1}{J_2 - J_1} \quad \textbf{(11–24b)}$$

4. Determine the pipe size requirements for length L_2 by:

$$H_{f2} = J_1 L_{d1} + J_2 L_{d2} + J_3 (L_2 - Y) + J_4 Y \quad \textbf{(11–25a)}$$

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, and J_4 – friction loss gradients in respective pipe diameters, D_1, D_2, D_3, and D_4 (ft/100 ft)

Solving equation 25a for Y gives:

$$Y = \frac{H_{f2} - J_1 L_{d1} - J_2 L_{d2} - J_3 L_2}{J_4 - J_3} \quad \textbf{(11–25b)}$$

Sample calculation 11–11 illustrates the problem of mainline design when two laterals are operated in a split-line manner.

Sample calculation 11–11.—Uphill mainline with twin lateral split-line operation.

Given:
Refer to figure 11–35A.
Q, capacity of system: 500 gpm
Length of supply line (water source to design area): 440 ft aluminum pipe (30-ft sections)
L, length of mainline (within design area): 1,200 ft aluminum pipe (30-ft sections)
L_1 = 600 ft L_2 = 600 ft
$H_0 = H_1 = H_2$ = 125 ft (head required to operate laterals)
$E_1 = E_2$ = 7.0 ft (elevation difference in mainline assuming uniform slope).
Total allowable head loss due to friction: 33.0 ft.

Find:
Smallest pipe sizes for both supply line and mainline that will limit friction head to 33.0 ft.

Calculation:
Assume 6-in diameter of supply line
From table 11–18, friction loss in 6-in pipe for 500 gallons per minute = 2.27 ft per 100 ft
Friction loss in 440-ft supply line = 4.4 × 2.27 = 10.0 ft

Then H_{f2} = 33.0 − 10.0 = 23.0 ft and $H_{f1} = H_{f2} + E_2$ = 23.0 + 7.0 = 30.0 ft

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 = 500 gpm and L_1 = 600 ft

Average loss through length $L_1 = H_{f1} \div L_1/100$

$$= \frac{30.0}{6} = 5.0 \text{ ft/100 ft}$$

From table 11–18, 5- and 6-in pipe are indicated for D_2, friction loss in 5-in pipe, J_2 = 5.54 ft/100 ft and for D_1, friction loss in 6-in pipe, J_1 = 2.27 ft/100 ft. Let X = length of D_2, then 600 − X = length of D_1 and by equation 24b:

$$X = \frac{30.0 - (2.27 \times 600/100)}{5.54 - 2.27} \times 100$$
$$= 500 \text{ ft}$$

Use 500 ft of 5-in pipe and 600 − 500 = 100 ft of 6-in pipe. When one lateral is operating from position A and the other is operating from position C, Q = 250 gpm.

The average loss through length $L_2 = H_{f2} \div$

$$L_2/100 = \frac{23.00}{6} = 3.83 \text{ ft/100 ft. From table}$$

11–14, 4- and 5-in pipe are indicated.

For D_4, friction loss in 4-in pipe, J_4 = 4.66 ft/100 ft; for D_3 and D_2, friction loss in 5-in pipe, $J_3 = J_2 = 1.53$ ft/100 ft; and for D_1, friction loss in 6-in pipe, $J_1 = 0.63$ ft/100 ft.

Let Y = length of D_4, then 600 − Y = length of D_3 pipe, and by equation 25b:

$$Y = \frac{23.0 - (0.63 \times 100/100) - (1.53 \times 500/100) - (1.53 \times 600/100)}{(4.66 - 1.53)} \times 100 = 177 \text{ ft}$$

Use 180 ft of 4-in pipe, 600 − 180 = 420 ft of 5-in pipe in L_2. Thus the mainline will consist of:

100 ft of 6-in pipe
500 + 420 = 920 ft of 5-in pipe
180 ft of 4-in pipe

Similar calculations should be made for different assumed values of allowable friction head loss (H_f) to determine the most economical pipe sizes.

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. 11–36).

No simple mathematical formulas can be used to determine the minimum pipe sizes. Approximations can be made, however, by inspection and by 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.

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 loss and will coincide with the straight line at each control point as shown on the profile in figure 11–36.

The mainline thus 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.

Design of 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 11–11. Figure 11–37 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 on figure 11–37.

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: (1) the seasonal hours of operation, and (2) 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. Then the annual cost of pumping against friction head is low and a reduction in mainline pipe sizes would ordinarily be justifiable. On the other hand, in an area where full season operation is required and power costs are high, pumping against friction head is much more costly. An increase in mainline pipe sizes is often required to achieve 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 very small pipe is used the fixed cost will be low, but the operating cost of overcoming friction losses in the pipe will be large. As the pipe diameter is increased the fixed costs will also increase, but the power costs will decrease. The optimum pipe size is the one for which the fixed plus 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

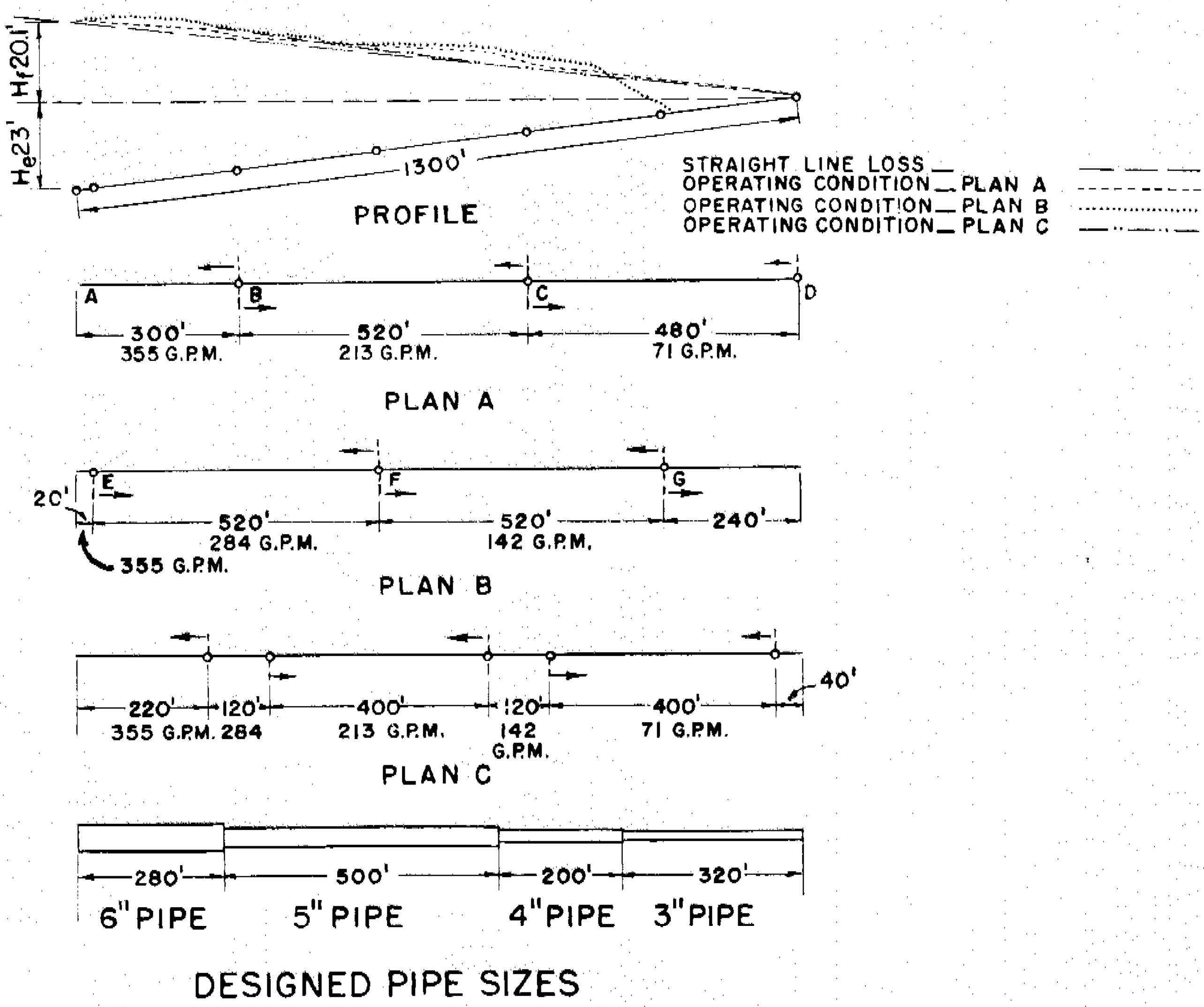


Figure 11-36.—Design of an uphill mainline with five 71 gpm laterals, split-line operation assuming the allowable friction head loss is 20.1 ft and the elevation difference is 23 ft.

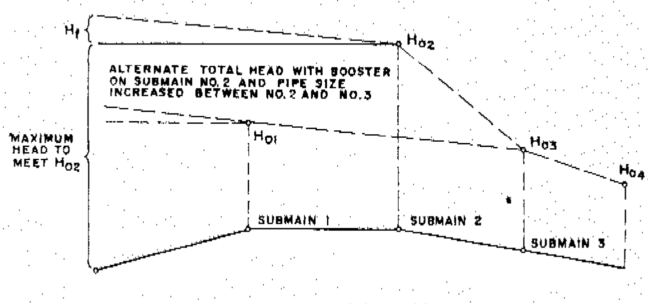


Figure 11-37.—Maximum operating conditions with submains.

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 the following equations for $e \neq i$:

$$PW(e) = \left[\frac{(1+e)^n - (1+i)^n}{(1+e) - (1+i)}\right] \times \left[\frac{1}{(1+i)^n}\right] \quad (11\text{–}26)$$

and

$$EAE(e) = \left[\frac{(1+e)^n - (1+i)^n}{(1+e) - (1+i)}\right] \times \left[\frac{i}{(1+i)^n - 1}\right] \quad (11\text{–}27)$$

The standard capital recovery factor is computed by:

$$CRF = \frac{i\,(1 + i)^n}{(1 + i)^n - 1} \qquad (11\text{–}28)$$

where

- e = decimal equivalent annual rate of energy escalation
- i = time value of unsecured money to the developer or the decimal equivalent annual interest rate
- n = number of years in the life cycle
- PW(e) = present worth factor of escalating energy costs, taking into account the time value of money over the life cycle.
- EAE(e) = equivalent annual cost factor of escalating energy, taking into account the time value of money over the life cycle.
- CRF = uniform series annual payment (capital recovery factor), which takes into account the time value of money and depreciation over 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 11–21 gives the necessary factors for either a present worth or an annual life-cycle cost analysis. The table gives factors for 9 percent 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 PW(0%) is the present worth factor of nonescalating energy, taking into account the time value of money over the life cycle.

The expected life of different mainline pipe materials is:

Portable aluminum	10–20 yr
Coated welded steel	10–20 yr
PVC plastic	20–40 yr
Cement-asbestos	20–40 yr

However, because of obsolescence, life cycles of n = 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 power units is:

Diesel	15.0 BPH hrs/U.S. gallon
Gasoline (water cooled)	10.5 BPH hrs/U.S. gallon
Tractor fuel	8.5 BPH hrs/U.S. gallon
Butane-propane	9.5 BPH hrs/U.S. gallon
Natural gas	8.5 BPH hrs/100 cubic feet
Electric	1.20 BPH hrs/kwh @ meter

The factors presented in Table 11–21 can be used with the present annual power costs (U) and the cost of the irrigation system (M) to estimate the following:

1. The present worth of energy escalating at 9 percent per year is equal to U × PW(9%).
2. The equivalent annual cost (U') of energy escalating at 9 percent per year is U' = U × EAE (9%).
3. The annual fixed cost of the irrigation system is M × CRF.
4. The present worth of nonescalating energy is U × PW(0%).
5. In addition, it is obvious that the annual cost of nonescalating energy is equal to U.
6. The 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 here 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.

Economic Pipe Selection Chart.—The following example demonstrates how the chart is constructed:

Step 1.—The necessary economic data must be obtained.

a. For a 20 percent time value of money and expected life cycle of aluminum mainline pipe of 15 years from table 11–21, CRF = 0.214 and EAE(9%) = 1.485.

Table 11-21.—Present worth and annual economic factors for assumed escalation in energy costs of 9 percent and 13.5 percent 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	0.132	0.118	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	10.960	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	5.848	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	4.193	4.676	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	1.306	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	4.000

b.

Nominal diameter	Price/100 ft	Annual fixed cost/100 ft (0.214 × price/100 ft)
5-in	$150	$32.10
6-in	$200	$42.80
8-in	$250	$53.50
10-in	$300	$64.20
12-in	$350	$74.90

c. Diesel fuel @ $1.05/gal gives $0.07/BHP-hr

d. Estimated hours of operation/year are 1,000

e. 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 11-22.

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:

a. The present annual cost of energy is:

$$U = \frac{1000 \text{ hr/yr} \times \$0.07\text{/BHP-hr}}{0.75 \text{ WHP/BHP}} \quad (11\text{–}29)$$

U = $93.33/WHP-year

b. The equivalent annual cost of energy at EAE (9%) = 1.485 is:

$$U' = 1.485 \times \$93.33\text{/WHP-year}$$
$$= \$138.60\text{/WHP-year}$$

Table 11-22.—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

Step	Item	Adjacent pipe sizes Nominal diameters (inches)			
		5–6	6–8	8–10	10–12
2	Yearly fixed-cost difference - $/100	10.70	10.70	10.70	10.70
4	Water horse power (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

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 11–22 and an example calculation for 6–8 in pipe is:

$$\text{WHP (6–8)} = \frac{\$10.70/100 \text{ ft-yr}}{\$138.60/\text{WHP-yr}} \qquad \textbf{(11–30)}$$

$$= 0.077 \text{ WHP/100 ft}$$

Step 5.—The head loss difference (ΔJ) between adjacent pipe sizes needed to obtain the above WHP is presented in table 11–22 and an example calculation for an assumed system flow rate, Q = 1,000 gpm is:

$$\Delta J(6\text{–}8) = \frac{0.077 \text{ WHP/100 ft} \times 3{,}960}{1{,}000 \text{ gpm}}$$

$$= 0.31 \text{ ft/100 ft}$$

Step 6.—The flow rates (q) that would produce the required ΔJ between adjacent pipe sizes are shown in table 11–22. These flow rates can be determined by trial and error using J values from pipe friction loss calculators or tables. For example, to get J(8–10) = 0.31 ft/100 ft at q = 450 gpm from table 11–18:

$$J(8) = 0.46 \text{ ft/100 ft}$$
$$J(10) = 0.15 \text{ ft/100 ft}$$
$$\Delta J(8\text{–}10) = 0.31 \text{ ft/100 ft}$$

To obtain ΔJ values 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 11–38 (see the open circles).

Step 8.—Draw lines—with a slope equal to the exponent for Q or V in the pipe friction equation used—through each of the points plotted in step 7. 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.

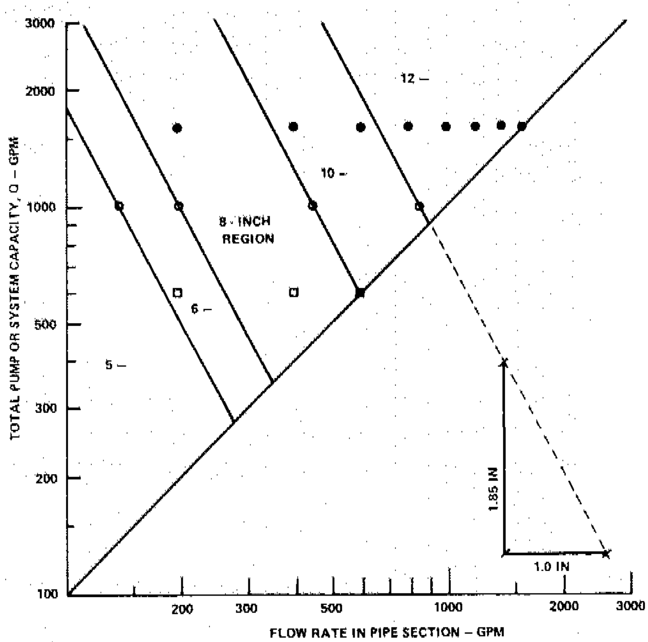


Figure 11–38.—Economic pipe selection chart for portable aluminum pipe with C=130, CRF=0.214, and U' =$138.60/WHP-year.

Figure 11–38 shows the complete economic pipe size selection chart. The circles on the 2 × 2 cycle log-log graph paper at a system flow rate Q = 1,000 gpm represent the pipeline flow rates (q) found in step 6 and presented in the last line of table 11–22.

Changing any of the economic factors will shift the lines in the chart shown in figure 11–38. 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 vs. 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.

Design of Economical Mainline.—The negative sloping lines on figure 11–38 represent all the possible Q vs. 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 vs. 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 11–12. Use of economic pipe selection chart.

Given:

For system layouts refer to figure 11–39.

For economic pipe selection chart refer to figure 11–38.

Find:

The most economical pipe sizes for systems (a) and (b), using portable aluminum pipe with the economic parameters considered in developing figure 11–38.

Calculation:

System (a)

A pipe system that is to deliver 200 gpm to each of eight different hydrants as shown in figure 11–39A. The pump discharge is $Q = 8 \times 200$ gpm = 1,600 gpm, which is also the flow rate in the first section of pipe. The flow rate in the pipe will decrease by 200 gpm at each outlet, with the final section carrying only 200 gpm. The solid dots plotted on figure 11–38 are the Q vs. 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 11–39A. Since 12-in pipe is the largest size considered in setting up the chart, the 12-in region is exaggerated. If 14-in pipe had been considered, perhaps some of the flows would have fallen above the 12-in region.

System (b)

Assume a system has three 200-gpm outlets so that Q = 600 gpm as shown in figure 11–39B. The square symbols plotted on figure 11–38 are the Q vs. q points representing the system. The flow rates and recommended pipe sizes for each reach are shown on figure 11–39B. If q = 200 gpm in the smaller system, 6-in pipe should be installed, and in the larger system 8-in pipe is recommended. If q = 600, the larger system should have 10-in pipe; the smaller only requires 8-in pipe. This is because the added power cost to offset friction for a given q increases with Q.

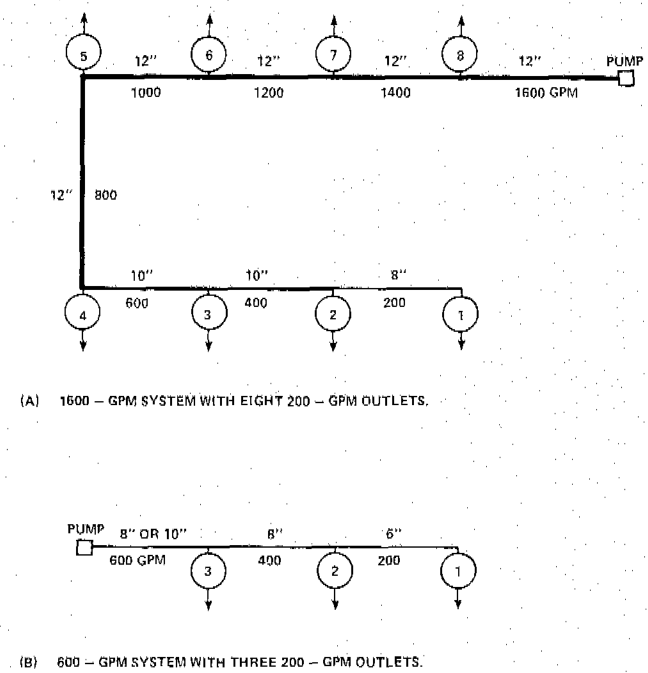


Figure 11–39.—Flow systems with pipe sizes selected from the economic pipe size selection chart shown in figure 11–38.

The preceding examples and solutions shown in figure 11–39B 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 above. 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: (a) sub-branch, parallel, or branched series pipelines, and (b) 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 11–38 must be adjusted downward, the adjustments are direct and yield the most economical pipe sizes for the new conditions. Sample calculation 11–34 demonstrates the use of these adjustments.

Pipe Diameter Selection.—Various designers may use different methods to size sprinkler system mainlines. The recommended technique is as follows:

1. Economic method—Selection of the least amount of fixed plus power costs as described in the section on Life-Cycle Costs.

2. Unit head-loss method—Setting a limit on the head loss per unit length, for example 2.0 ft/100 ft.

3. Velocity method—Setting a limit on the velocity.

4. 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 11-38 or by merely comparing the fixed plus power costs of the most reasonable combination of pipe sizes. In the following example all of the selection methods are compared. This sample problem demonstrates the value of the economic chart method.

Sample calculation 11-13.—Comparison of pipe-size selection methods.

Given:

For system layout refer to figure 11-40

Aluminum pipe and cost data used in previous section on *Life-Cycle Costs.*

Find:

Pipe size selection based on:

1. Economic method.
2. Head loss gradient of 2 ft/100 ft or less.
3. Maximum flow velocity of 7 ft/s or less.
4. Mainline friction head loss of 15 percent of P_a = 50 psi or 17.3 ft.

Calculations:

Selection by head loss gradient:—Select pipe sizes from table 11-18 so that the head loss gradient (J) will be less than but as close to 2 ft/100 ft as possible for each reach of pipe. This results in a total head loss of 21.4 ft 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 ft/s as possible for each section of pipe. This results in a total head loss of 39.7 ft due to pipe friction as shown in table 11-23. Velocity limitations for each size of pipe were computed by:

$$V = 0.4085 \frac{Q}{D^2} \qquad (11\text{-}31)$$

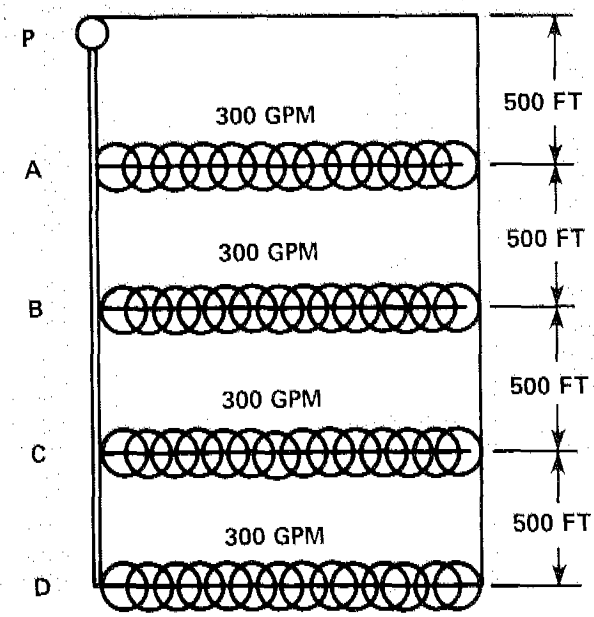


Figure 11-40.—System layout for sample calculation 11-13, as shown in table 11-23.

where

V = velocity of flow in pipe (ft/s)
Q = flow rate (gpm)
D = inside diameter of pipe (in)

Selection by percent head loss method.—Select pipe sizes so that the total head loss does not exceed 17.3 ft. For a beginning point, let the maximum unit head loss be 2.0 psi/100 ft. This will be the same as for the head loss gradient method in which the total head loss is 21.4 ft. 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-in 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 ft as shown in table 11-23.

Selection by economic method.—Select pipe sizes that will require the least amount of pumping (fuel) plus annual fixed (investment) costs as discussed earlier under Life-Cycle Costs. In this simple example the set of practical pipe diameter combinations that should be considered are:

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 a downstream section.

The economic pipe selection chart presented as figure 11–38 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 ft due to pipe friction as shown in table 11–23.

Table 11–23.—Data for sample calculation 11–13 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	2.0
A–B	900	500	12	0.23	1.2
B–C	600	500	10	0.26	1.3
C–D	300	500	8	0.22	1.1
				Total	5.6
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

It may be surprising that such large pipe diameters are called for by the economic method in the above 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 get the annual fixed cost. The annual energy cost (CE′) is equal to the total head loss (H_f) times the annual energy cost per unit of head loss. The CE′ can be computed by:

$$CE' = \frac{EAE\ U\ Q_s}{3{,}960} H_f \qquad (11\text{–}32)$$

where

CE′ = annual energy cost of head loss ($)
EAE = equivalent annual cost factor of escalating energy
U = present annual cost of energy from equation 29 ($/WHP-year)
Q_s = total system capacity (gpm)
H_f = total head loss due to pipe friction (ft)

Table 11–24 shows a comparison of the total annual costs for the different pipe size combinations presented in table 11–23.

From table 11–24 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 11–24 for section C–D in figure 11–40 in which the flow rate is only 300 gpm. However, the total system capacity must be used in equation 32 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_s = 1,200 gpm.

For systems with downhill or branching mainlines the pipe size selection is more complex. As a beginning point, however, 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 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 11–14.

Table 11-24.—Comparison of total annual costs for different pipe size combinations for section C-D of sample calculation 11-13 (Pipe selection for section C-D)

Method (or size for C-D)	Initial capital (dollars)	Annual fixed cost[1] (dollars)	Total H (feet)	Annual energy[2] (dollars)	Annual total (dollars)
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 11-21 for n = 15 years and i = 20%.
[2] CE′ = $42 for each foot of head loss as computed by equation 32 in which Q_s = 1,200 gpm, H_f = 1.0 ft; U = $93.33/WHP-year from equation 29 for 1,000 hr/yr, $0.07/BHP-hr and 75% pump efficiency; and EAE = 1.485 from table 11-21 for n = 15 yr, i = 20% and r = 9%.

Sample calculation 11-14.—Mainline pipe selection for a system with submains.

Given:

The economic pipe selection chart presented in figure 11-38 for aluminum pipe

A project with 4 small center pivots as shown in figure 11-41. The flow rate of each center pivot is 200 gpm.

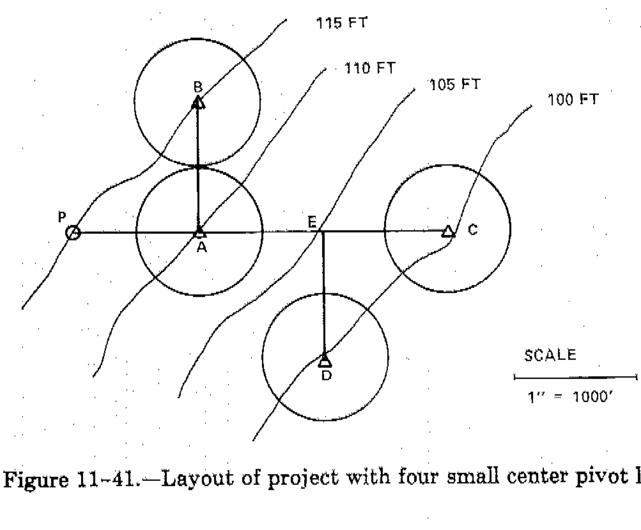


Figure 11-41.—Layout of project with four small center pivot laterals.

Find:

The most economical pipe sizes for the system

Calculations:

First select the pipe sizes from figure 11-37 and compute the friction loss in each pipe section as in table 11-25. 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 $H_f + \Delta E$, 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, however, may be reduced if the velocity limitations are not exceeded. The excess head at C is equal to the difference between the $H^f + \Delta E1$ between P-B and P-C which is 8.7 − (−2.6) = 11.3 ft. The same amount of excess head occurs at D.

Replacing the 6-in pipe in sections E-C and E-D with 5-inch pipe still results in excess heads of 5.4 ft at C and D (see the center section of table 11-26). Therefore, a portion of the 8-in pipe in section A-E can be reduced to 6-in pipe. The length (X) of 6-in pipe that will increase the head loss by 5.4 ft can be computed by equation 24b as:

$$X = \frac{H_{f1} - J_1 L_1}{J_2 - J_1} \times 100$$

$$= \frac{5.4}{1.50 - 0.37} \times 100 = 478 \text{ ft}$$

Replacing 478 ft of 8-in pipe with 6-in pipe in section A-E eliminates the excess head at inlets C and D as indicated in the bottom portion of table 11-26.

Table 11-25.—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

Table 11-26.—Location of critical pivot lateral inlet and trimming sequence for sample calculation 11-14

Pipe sections	H_f (ft)	$\Delta E1$ (ft)	$H_f + \Delta E1$ (ft)	Excess (ft)
Using pipe sizes selected from 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	4.5 + 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	−15	8.7	0
P-A-E-D	4.5 + 9.1 + 10.1 = 23.7	−15	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.

Portable Versus Buried Mainlines.—Use of buried mainlines is restricted to areas that are to be irrigated permanently, whereas portable mainlines can 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. They 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 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. Thus, for the same length and size of mainline, the annual fixed cost for buried mainlines is usually lower than that for portable lines. There is a considerable saving 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.

When making an economic comparison between two mainline pipe materials, first develop a layout and select sets of pipe diameters using the economic methods described earlier for each pipe material, and then determine the total annual cost (fixed, energy, maintenance, labor) of the mainline portion of each system.

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, thus 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 they 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.

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 Chapter 8, *Irrigation Pumping Plants*.

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.

Losses in Fittings and Valves.—Allowance must be made for friction losses in all elbows, tees, crossings, reducers, increasers, adapters, and valves placed in laterals, mainlines, or submains and in the suction line. Where deep-well turbine pumps are used, losses in the column must be considered. Pump manufacturers make allowances for losses in the pump itself.

Losses in fittings and valves are computed by:

$$h_f = K \frac{V^2}{2g} \qquad (11\text{–}33)$$

where

h_f = friction head loss (ft)
K = resistance coefficient for the fitting or valve

$\frac{V^2}{2g}$ = velocity head for a given discharge and diameter (ft)

Values of the resistance coefficient (K) may be taken from table 11–27 for irrigation pipe or table 11–28 for standard pipe fittings and valves. The velocity head may be computed by:

$$\frac{V^2}{2g} = 0.002592 \frac{Q^2}{D^4} = \frac{Q^2}{386\ D^4} \qquad (11\text{–}34)$$

where

Q = flow rate (gpm)
D = inside diameter of pipe (in)

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-x6-x6-in reducing side outlet tee has an inflow of 1,000 gpm and outflows of 400 gpm from the side outlet and 600 gpm through the body. The three respective velocity heads are 0.64 ft for the inlet, 0.32 ft for the side outlet, and 0.69 ft for the line flow through the body. Therefore, when estimating h_f for the side outlet flow, use the velocity head of 0.64 ft (since it is larger than 0.32 ft) and K = 1.0 from table 11–27 to obtain $h_f = 0.64 \times 1.0 = 0.64$ ft (by eq. 33). For the line flow $h_f = 0.5 \times 0.69 = 0.35$ ft.

Table 11–29 gives velocity heads for inside diameters in whole inch increments. Actual inside pipe diameters are usually different, but these table values give satisfactory results for most practical purposes. The values of K are only approximations for the fittings in general, inasmuch as the inside diameters of fittings vary as well.

Figure 11–42 is a nomograph that can be used to simplify estimating losses in fittings and valves. Sample calculation 11–15 demonstrates the use of the nomograph.

Table 11-27.—Values of resistance coefficient (K) for irrigation pipe fittings and valves [1]

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, Milpitos, Calif.

Sample calculation 11–15.—Use of nomograph for estimating fitting losses.

Given:
The nomograph for estimating fitting losses, figure 11–42
Mainline: Q = 450 gpm; D = 6 in
Fitting: Plate valve

Find:
The head loss resulting from the valve

Calculations:
From table 11–27 K = 2.0

Start from the left on the nomograph with 6-in pipe diameter passing through 450 gpm on the flow rate line. This line intersects the third scale at a flow velocity of 5.1 ft/s.

Draw a line from the flow velocity through the pivot point to intersect the velocity head at 0.38 ft.

Draw a line from this velocity head through K = 2.0 to the right-hand scale and reach the head loss, h_f = 0.76 ft.

Static Head.—Static head is the vertical distance (ΔE1) the water must be raised or lowered between the water source and the point of discharge. Static head may be plus or minus.

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 head values. 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, the velocity head seldom exceeds 1 ft and therefore may be disregarded.

Total Dynamic Head.—The total dynamic head (TDH) is the sum of the following:

Pressure head required to operate lateral (P_m), ft
Friction head losses in mainline and submains (H_f), ft
Friction head losses in fittings and valves (Σh_f), ft
Total static head including suction lift (ΔE1), ft

Table 11-28.—Values of resistance coefficient (K) for standard pipe fittings and valves

Fitting or valve	Nominal diameter							Source or authority
	3-in	4-in	5-in	6-in	7-in	8-in	10-in	
Elbows:								
Regular flanged 90°	0.34	0.31	0.30	0.28	0.27	0.26	0.25	Pipe friction manual [1]
Long radius flanged 90°	.25	.22	.20	.18	.17	.15	.14	Hydraulic Institute
Long radius flanged 45°	.19	.18	.18	.17	.17	.17	.16	..........do..........
Regular screwed 90°	.80	.70						..........do..........
Long radius screwed 90°	.30	.23						..........do..........
Regular screwed 45°	.30	.28						..........do..........
Bends:								
Return flanged	0.33	0.30	0.29	0.28	0.27	0.25	0.24	Pipe friction manual [1]
Return screwed	.80	.70						Hydraulic Institute
Tees:								
Flanged line flow	.16	.14	.13	.12	.11	.10	.09	..........do..........
Flanged branch flow	.73	.68	.65	.60	.58	.56	.52	..........do..........
Screwed line flow	.90	.90						..........do..........
Screwed branch flow	1.20	1.10						..........do..........
Valves:								
Globe flanged	7.0	6.3	6.0	5.8	5.7	5.6	5.5	..........do..........
Globe screwed	6.0	5.7						..........do..........
Gate flanged	.21	.16	.13	.11	.09	.075	.06	..........do..........
Gate screwed	.14	.12						..........do..........
Swing check flanged	2.0	2.0	2.0	2.0	2.0	2.0	2.0	..........do..........
Swing check screwed	2.1	2.0						..........do..........
Angle flanged	2.2	2.1	2.0	2.0	2.0	2.0	2.0	..........do..........
Angle screwed	1.3	1.0						..........do..........
Foot	.80	.80	.80	.80	.80	.80	.80	..........do..........
Strainers-basket type	1.25	1.05	.95	.85	.80	.75	.67	..........do..........
Other								
Inlets or entrances:								
Inward projecting	0.78		All diameters					King's Handbook [1]
Sharp cornered	.50		All diameters					..........do..........
Slightly rounded	.23		All diameters					..........do..........
Bell-mouth	.04		All diameters					..........do..........
Sudden enlargements	$K = \left(1 - \frac{d_1^2}{d_2^2}\right)^2$ where d_1 = diameter of smaller pipe							S.I.A. Handbook [2]
Sudden contractions	$K = 0.7\left(1 - \frac{d_1^2}{d_2^2}\right)^2$ where d_1 = diameter of smaller pipe							S.I.A. and King

[1] King, Horace Williams, and Ernest F. Brater, 1963. Handbook of Hydraulics. McGraw Hill Book Co., Inc.
[2] Pair, Claude H., Walter W. Hinz, Crawford Reid, and Kenneth R. Frost. 1975. Sprinkler Irrigation. Sprinkler Irrigation Assoc. Brantwood Publishers, Inc.

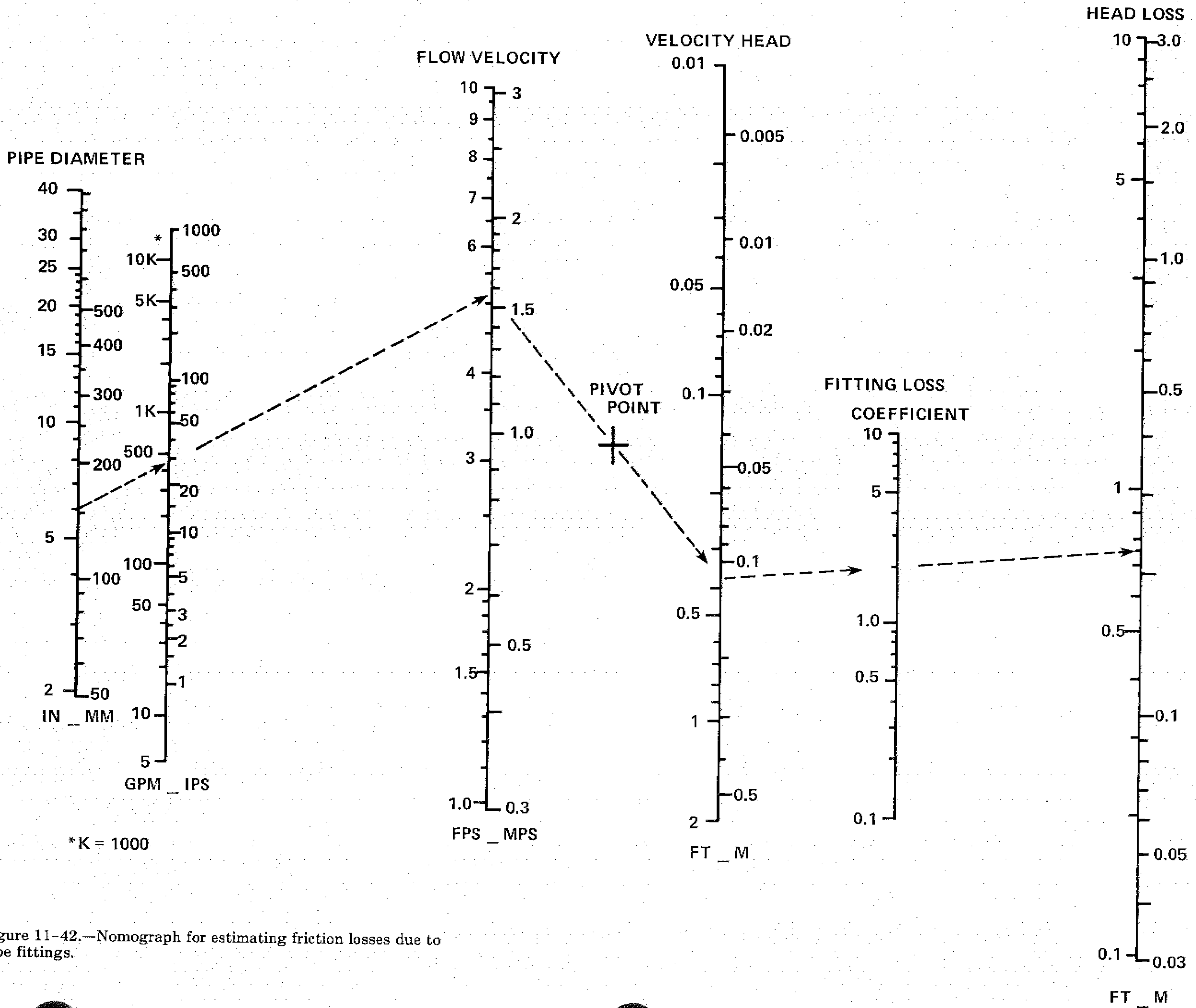


Figure 11-42.—Nomograph for estimating friction losses due to pipe fittings.

Table 11-29. Values of velocity head ($V^2/2g$) in feet, for different diameters and flow rates

	Inside diameter (in)								
Flow (gpm)	2	3	4	5	6	7	8	10	12
100	1.62	0.32	0.10	0.04	0.02				
150	3.64	0.72	0.23	0.09	0.04				
200	6.48	1.28	0.40	0.17	0.08				
250		2.00	0.63	0.26	0.12				
300		2.88	0.91	0.37	0.18	0.10	0.06		
350		3.92	1.24	0.51	0.24	0.13	0.08		
400		5.12	1.62	0.66	0.32	0.17	0.10		
450		6.48	2.05	0.84	0.40	0.22	0.13		
500		8.00	2.53	1.04	0.50	0.27	0.16	0.06	
550		9.68	3.06	1.25	0.60	0.33	0.19	0.07	
600			3.64	1.49	0.71	0.39	0.23	0.09	
650			4.28	1.75	0.84	0.46	0.27	0.11	
700			4.96	2.03	0.98	0.53	0.31	0.13	0.06
750			5.69	2.33	1.12	0.61	0.36	0.15	0.07
800			6.48	2.65	1.28	0.69	0.41	0.17	0.08
850			7.31	2.99	1.44	0.78	0.46	0.19	0.09
900			8.20	3.36	1.62	0.87	0.52	0.21	0.10
1000				4.15	2.00	1.08	0.64	0.26	0.13
1100				5.02	2.42	1.31	0.77	0.31	0.15
1200				5.97	2.88	1.55	0.92	0.37	0.18
1300				7.01	3.38	1.82	1.07	0.44	0.21
1400				8.12	3.92	2.11	1.25	0.51	0.25
1500				9.33	4.50	2.43	1.42	0.58	0.28
1600					5.12	2.75	1.64	0.66	0.32
1800					6.48	3.49	2.01	0.84	0.41
2000					8.00	4.32	2.53	1.04	0.50
2200					9.68	5.22	3.06	1.25	0.61
2400						6.22	3.64	1.49	0.72
2600						2.29	4.28	1.75	0.84
2800						8.46	4.96	2.03	0.98
3000						9.71	5.69	2.33	1.12
3200							6.47	2.65	1.28

Miscellaneous losses (for safety) usually taken as 0.2 H_f, ft

Sample calculation 11-16 demonstrates the computation of the TDH for a simple sprinkle system.

Sample calculation 11–16.—Determining the TDH for a sprinkle system.

Given:

The system layout shown in figure 11-43

Lateral: Flow rate 300 gpm, P_m = 50 psi

Mainline: PVC plastic pipe, IPS, SDR, 41

System Capacity: Q = 900 gpm

Find:

The total dynamic head (TDH) required at the pump discharge.

Calculations:

In figure 11-43 the critical lateral is at D and the pressure head required at the inlet is:

$P_m \times 2.31 = 50 \times 2.31 = 115.5$ ft

The friction loss in the mainline between P and D using J values from table 11-19a is:

Section P-B	0.98 × 1000/100	= 9.8 ft
Section B-C	1.67 × 500/100	= 8.4
Section C-D	0.47 × 500/100	= 2.4
Total		H_f = 20.6 ft

The friction head loss in the fittings based on K values from table 11-27 and velocity head values from table 11-29:

Velocity heads are:

Section P-B	0.52 ft
Section B-C	0.71 ft
Section C-D	0.18 ft
4-in hydrant	0.91 ft

The fitting losses in section P-B:		
1 check valve	1.3 × 0.52	= 0.7 ft
2 mitered elbows	2 (0.6 × 0.52)	= 0.6
4 hydrants (off)	4 (0.3 × 0.52)	= 0.6
1 line flow tee	0.5 × 0.52	= 0.3
The fitting losses in section B-C:		
4 hydrants (off)	4 (0.3 × 0.71)	= 0.9
1 line flow tee	0.5 × 0.71	= 0.4
The fitting losses in section C-D:		
4 hydrants (off)	4 (0.3 × 0.18)	= 0.2
The fitting loss of D:		
1 hydrant with opener	7.5 × 0.91	= 6.8
Total		h_f = 10.5 ft

The static head between P and D is

Section P-B	1.5% × 1,000/100	= 15.0
Section B-D	1.0% × 1,000/100	= 10.0
Total		ΔE1 = 25.0

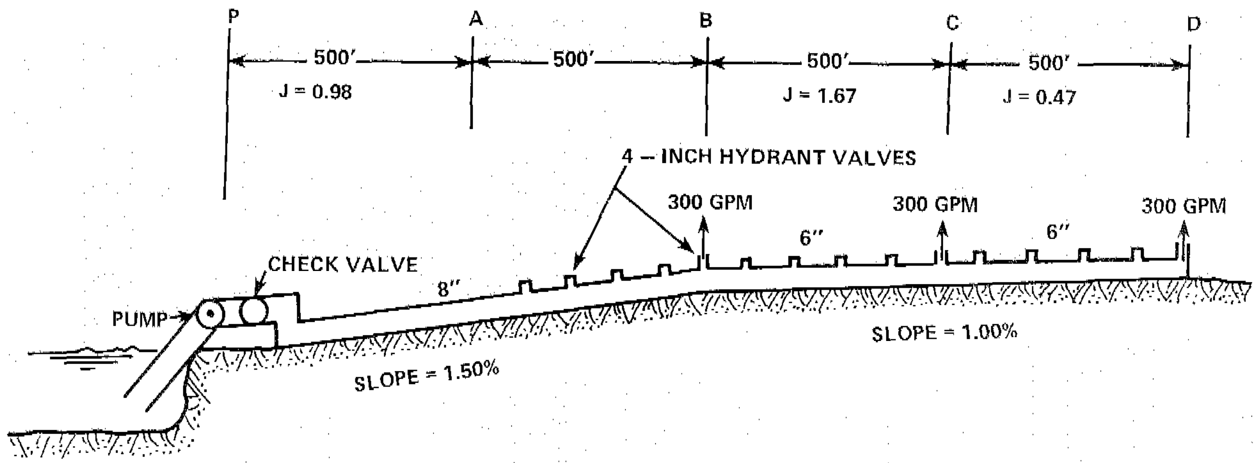


Figure 11-43.—Sprinkle system mainline layout.

The miscellaneous losses are estimated to be:

$0.2 \times H_f = 0.2\ (20.6) = \underline{\quad 4.1}$

TDH $= 175.7$ ft

Special 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. Therefore, 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 (as explained below); however, neither spacing nor pressure should be decreased below those normally accepted as standard. The alternative to operating at low pressures may be either adding a pump to the system or not watering certain high portions of the fields.

Since the sprinkler spacing on the lateral line is fixed, 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 12 and the average application rate for a given sprinkler discharge at a given sprinkler spacing as given by equation 2. Combining equation 12 and 2 and rearranging the terms yields:

$$S_m = \frac{96.3\ K_d \sqrt{P}}{I - S_\ell} \qquad \textbf{(11–35a)}$$

where

S_m = lateral spacing on main (ft)
K_d = discharge coefficient for the sprinkler and nozzle combined
P = sprinkler operating pressure (psi or ft)
I = average application rate (iph)
S_ℓ = sprinkler spacing on lateral (ft)

By holding I and S_ℓ constant, equation 35a may be reduced to:

$$S_m = K_s \sqrt{P} \qquad \textbf{(11–35b)}$$

where

K_s = a constant that is a function of I, S_ℓ, 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_m and P are automatically set and K_s

can be solved very simply from equation 35b. 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 35b, using the K_s as determined above, and the pressure head available at the lateral inlet. For example, a standard lateral inlet pressure of 50 psi and a lateral move of 60 ft are selected for a given gravity sprinkler irrigation system. Thus $K_s = 60/\sqrt{50} = 8.48$. When the pressure at the head of the lateral is only 45 psi because of insufficient elevation differentials, the lateral spacing should be $S_m = 8.48\sqrt{45} = 57$ ft to give the same average application rate. For 40 psi, the spacing should be 54 ft; for 30 psi, 47 ft; and for 20 psi, 38 ft.

The above procedures have been found useful for the design of the lateral line spacing of gravity 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 pressures selected furnish sufficient jet breakup and sprinkler rotation.

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 Chapter 8, *Irrigation Pumping Plants.*

Horsepower Required.—The horsepower required to operate a sprinkler system can be computed by:

$$BHP = \frac{Q_s \times TDH}{3{,}960\ E_p/100} \qquad \textbf{(11–36)}$$

where

BHP = brake horsepower required to operate pump (hp)
Q_s = system capacity (gpm)
TDH = total dynamic head (ft)
E_p = pump efficiency (%)

Seasonal Power Cost.—The annual cost of power to operate the pumping unit can be computed by:

$$CE = \frac{UQ_s\ TDH}{3{,}960} \qquad (11\text{–}37)$$

where

CE = present annual energy cost to operate system ($)
U = present annual cost of energy from equation 29 ($/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 (from table 11–21 or equation 27).

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. Data from the field evaluation of a periodic move sprinkle system were presented in figure 11–24. The procedure for collecting the data follows:

Information Required.—The desired information includes:

1. Duration of normal irrigations.
2. Spacing of sprinklers along lateral lines.
3. Spacing of lateral lines along mainlines.
4. Measured depths of water caught in catch containers at a test location.
5. Duration of the test.
6. Water pressures at the sprinkler nozzles at the test location and along laterals throughout the system.
7. Rate of flow from the tested sprinklers.
8. Additional data specified on figure 11–44.

It is useful to know what wetting patterns the operation produces at different pressures and also to know operating pressures at the pump and along the mainline and laterals. General study of data obtained in the field enables determination of system DU and E_q. 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.

1. Location ____________________, observer ____________________, date ____________________
2. Crop ______________________________, root zone depth ____ ft, MAD ____ %, MAD ____ in
3. Soil: texture ______________________________, available moisture ____ in/ft, SMD ____ in
4. Sprinkler: make ______________________________, model ____, nozzles ____ by ____ in
5. Sprinkler spacing ____ by ____ ft, irrigation duration ________ hr
6. Rated sprinkler discharge ____ gpm at ____ psi giving ________ in/hr
7. Lateral: diameter ____ in, slope ____ %, riser height ________ in
8. Actual sprinkler pressure and discharge rates:

	Sprinkler location number on test lateral					end
Initial pressure (psi)						
Final pressure (psi)						
Catch volume (gal)						
Catch time (min or sec)						
Discharge (gpm)						

9. Wind: direction relative to
   Part 10: initial ______, during ______, final ______
   Speed (mph): initial ______, during ______, final ______
10. Container grid test data in units of ____, volume/depth ________ ml/in
    Container grid spacing ____ by ____ ft
    Test: start ____, stop ____, duration ____ hr ____ min = ________ hr

11. Evaporation container: initial ________ final ________ loss ________ in
12. Sprinkler pressures: max ____ psi; min ____ psi, ave ____ psi
13. Comments ____

Figure 11–44.—Sprinkler-lateral irrigation evaluation.

Equipment Needed.—The equipment the evaluator needs is:

1. A pressure gauge (0-100 psi) with pitot tube attached (See fig. 11–45.)
2. A stopwatch or watch with an easily visible second hand.
3. A large container clearly marked (1 gal or larger for large sprinklers).
4. A 4-ft length of flexible hose of inside diameter appreciably larger than the outside diameter of nozzles. (See fig. 11–46.)
5. From 50 to 100 (or more depending on sprinkler size) catch containers such as 1-qt oil cans or plastic freezer cartons.
6. A measuring stick (or ruler) to measure depth, or a 500-ml graduated cylinder to measure water caught in containers.
7. A soil probe or auger.
8. A 50- or 100-ft tape for measuring distances in laying out catch container grid.
9. A shovel for smoothing spots to set containers and for checking soil, root, and water penetration profiles.

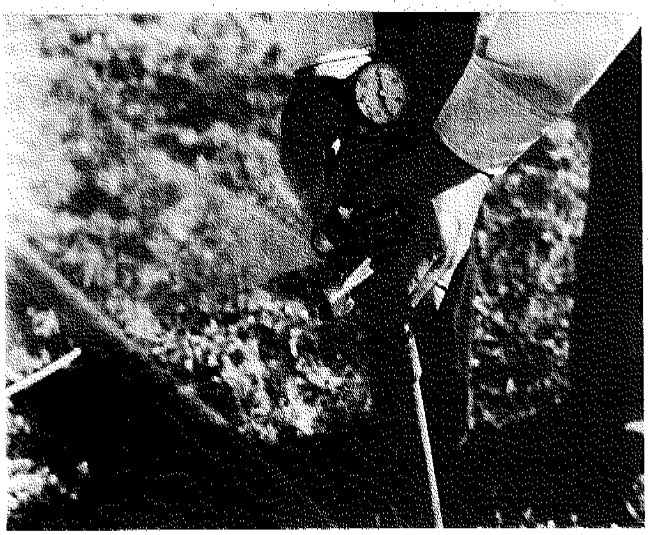


Figure 11-45.—Measuring pressure at sprinkler nozzle with gage connected to pitot tube.

Figure 11-46.—Measuring sprinkler discharge using a hose to direct the water into a container.

10. A form (fig. 11-44) for recording data.

11. Manufacturers' sprinkler performance charts showing the relationship between discharge, pressure, and wetted diameter plus recommended operating pressure ranges.

12. A set of drill bits ranging from 3/64- to 1/4-in in diameter in increments of 1/64-in to check nozzle wear.

Field Procedure.—The information obtained from the following field procedure should be entered in a data sheet similar to figure 11-44.

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. 11-47). On a flat field the most representative pressure is at about 40 percent of the distance from the inlet to the terminal end.

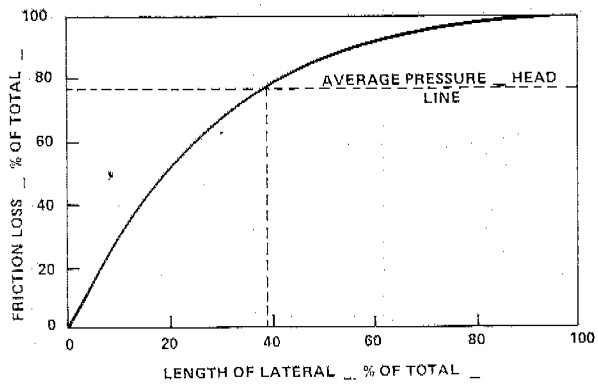


Figure 11-47.—Loss of pressure due to friction along a lateral having only one size of pipe.

2. Set out at least 24 catch containers (see pattern in fig. 11-48) on a grid having a spacing not to exceed 10- by 10-ft for testing along a single lateral line. The catch containers' 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 dotted grid lines in fig. 11-48.)

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. 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 other lateral spacings.

Each container 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

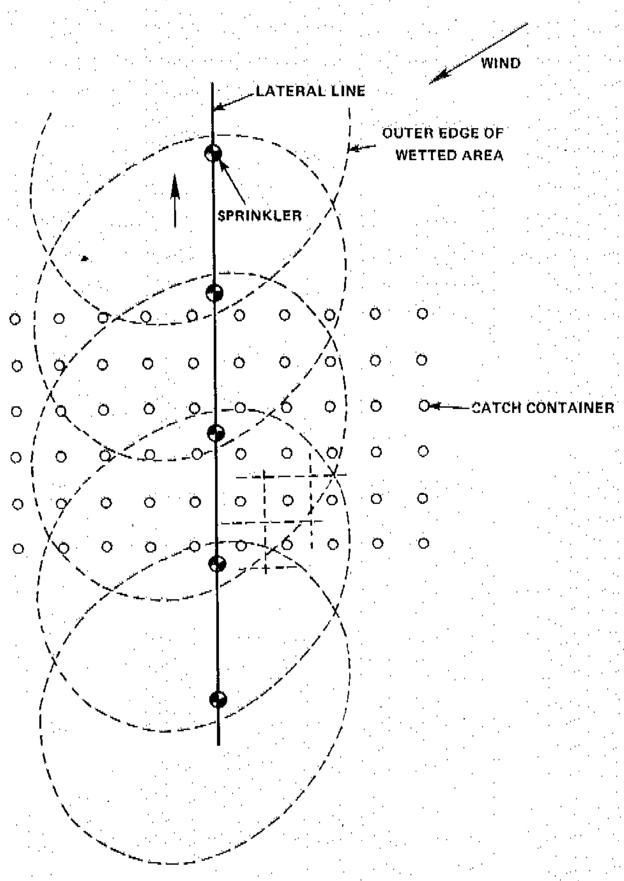


Figure 11–48.—Layout of catch containers for testing the uniformity of distribution along a sprinkler lateral line.

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-qt oil cans, 200 ml corresponds to 1 in. in depth. Other suitable catch containers may be square or cylindrical plastic freezer containers with sides tapered slightly for nesting, or any similar container.

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. (See fig. 11–44; part 10.)

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 parts 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.

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 in part 8. When measuring sprinkler pressures (fig. 11–45), the pitot tube must be centered in the jet, which must 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-in from the sprinkler nozzle.

Also in part 8, 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 (fig. 11–46). 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.) Often the measured sprinkler discharge rate is 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 syphoning action. You can 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. (See fig. 11–44, 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 0.5 in of water in the containers.

Measure the depth of water in all the containers 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. For long runs, where maximum depths exceed 2 in., a measuring stick provides suitable accuracy up to ± 0.1 in.

Use of Field Data.—Use of the data was discussed in connection with the test data presented in figure 11–24. The general procedure for analyzing the data is:

1. Convert the depths or volumes of water caught in the containers to application rates and record them (iph) 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. 11–25), as if it were a subsequent set, to simulate different lateral spacings. 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 very close lateral spacings, water may overlap from as many as four lateral positions. The simulation of overlapping discussed above is not recommended where winds are likely to change appreciably between subsequent lateral sets. It is most useful for 24-hour sets.

2. To determine whether sprinklers are operating at acceptable efficiency, evaluate system DU and CU using equations 3, 4, and 11. The system DU is based on the average rate or depth recorded for the lowest one-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 be approximately equal to 100 − system DU. (A similar relationship exists for CU.)

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 gage 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 7 and 8 for computing E_q and E_h) can be determined from the field data by:

$$R_e = \frac{\text{average catch rate (or depth)}}{\text{application rate (or depth)}} \qquad \textbf{(11–38a)}$$

$$R_e = \frac{\text{average catch rate}}{96.3\ q/(S_\ell \times S_m)} \quad \textbf{(11–38b)}$$

where

q = average sprinkler discharge rate (gpm)
S_ℓ = sprinkler spacing on the lateral (ft)
S_m = lateral spacing along the main (ft)

Traveling Sprinkle System

A typical traveling sprinkle system consists of the following major components: pumping plant, mainline, flexible hose, traveler unit, and gun sprinkler (fig. 11–8). 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*.

Sprinkler and Traveler Selection

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; towpath length, potential towpath spacings and number of paths for each potential spacing; wind conditions; crop characteristics; and the mechanical properties of the soil.

Sprinkler Variables.—Gun sprinklers used in most travelers have trajectory angles ranging between 18° and 32°. 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 mph, but drop impact is quite severe and may be detrimental to all but the sturdiest crops and coarsest soils. For average conditions trajectories between 23° and 25° 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 towpath 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 11–30 for gun sprinklers with 24° angles of trajectory and tapered nozzles. The wetted diameter would increase, or decrease, about 1 percent for each 1° 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 11–30.

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. 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:

$$I_t = \frac{96.3\ q}{\pi\,(0.9_t)^2} \times \frac{360}{\omega} \quad \textbf{(11–39)}$$

Table 11-30.—Typical discharges and wetted diameters for gun sprinklers with 24° angles of trajectory and tapered nozzles operating when there is no wind

Sprinkler pressure	Tapered nozzle size (in) 0.8		1.0		1.2		1.4		1.6	
	Sprinkler discharge and wetted diameter									
psi	gpm	ft	gpm	ft	gpm	ft	gpm	ft	gpm	ft
60	143	285	225	325	330	365	—	—	—	—
70	155	300	245	340	355	380	480	435	—	—
80	165	310	260	355	380	395	515	455	675	480
90	175	320	275	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	520
120	205	350	320	395	465	440	630	500	825	535

where

I_t = approximate actual application rate from a traveling sprinkler (iph)
q = sprinkler discharge (gpm)
t = wetted radius (ft)
ω = portion of circle receiving water (degrees)

This is similar to equation 2. 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 11-30 in equation 39, the actual application rates from 0.8-in and 1.6-in nozzles operating full-circle at 80 psi are 0.26 iph and 0.44 iph, respectively. Using ring nozzles that would reduce the wetted diameters by about 5 percent would increase the application rate to approximately 0.29 iph and 0.49 iph, respectively. For a tapered nozzle operating with a 25° dry wedge as in figure 11-9, the application rates would be increased to 0.33 iph and 0.56 iph, respectively.

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 ± 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:

1. Hose pull, which varies with hose size, soil type, terrain, and condition of the towpath.
2. Water pressure and flow rate.
3. 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.
4. The characteristics of the power unit on the traveler must be matched to the requirements of hose pull and other factors enumerated above for operation at a constant speed.

Many of the above 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 on bare, sandy soils. On sticky soils, the towpaths should be left 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 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.

Towpath 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 mph, CU's were 70 to 75 percent in the central portion of the fields for towpath 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 ft on each end of most fields are not irrigated as well as the center of the field. This underirrigation can be essentially eliminated, as discussed earlier, by allowing the sprinkler to stand for a period of time at the end of the towpaths. The above 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 11–49 shows a comparison between a traveling and a set gun sprinkler application pattern measured across the towpath. The traveling sprinkler produces a uniform pattern in low winds. From figure 11–49, it is evident that a towpath 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 towpaths.

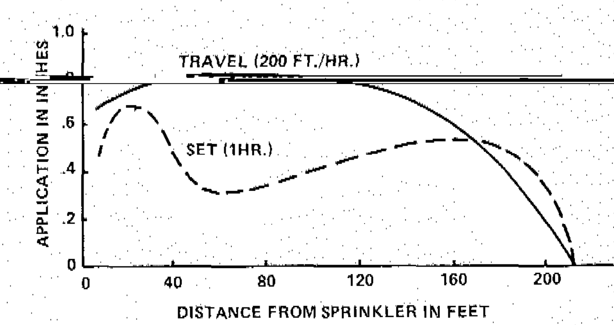


Figure 11–49.—Typical application patterns of a traveling and a set gun sprinkler operating in very low wind.

Table 11–31 gives recommended towpath spacings for 23° to 25° trajectory sprinklers as a function of wetted diameter and anticipated average wind velocities. These towpath spacings will ensure full coverage midway between towpaths. 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 mph, 20° to 21° trajectory angles should be used. Where winds are negligible, 26° to 28° trajectories will give the best results.

Table 11–31. Recommended towpath 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	—	—

Travel speed.—The travel speed should be set to traverse the length of the towpath so that there will be little down time with either one or two setups per day. Some typical travel speeds are:

1. For a 1,320-ft 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/(11 × 60) = 2 ft/min. For one setup per day it should be between 0.9 and 1.0 ft/min.

2. For a 1,320-ft 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 towpath as described earlier under system layout. In each case with average sized gun sprinklers having an effective wetted diameter of 400 ft, the travel speed for one setup per day should be approximately:

$$\frac{1{,}320 \text{ ft} - 400 \text{ ft}}{60 \text{ min/hr} \, [23 \text{ hr} - 2(1) \text{ hr}]} \cong 0.75 \text{ ft/min}$$

This allows for a 1-hr set time, 200 ft from the field boundary at each end of the towpath. With half-hour set times and two setups per day the travel speed should be approximately 1.5 ft/min.

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:

$$d = \frac{1.605\ q}{W\ S} \qquad \textbf{(11–40)}$$

where

- d = gross depth of application (in)
- q = sprinkler discharge (gpm)
- W = towpath spacing (ft)
- S = travel speed (ft/min)

To obtain the net depth assume an E_q between 55 and 67 percent or an E_h between 65 and 77 percent.

Rate of Irrigation Coverage.—The rate of irrigation coverage is a function of travel speed and towpath spacing. Some useful rate of coverage formulas are:

$$\text{acres covered per hour} = \frac{W\ S}{726} \qquad \textbf{(11–41a)}$$

$$\text{acres irrigated per 1/4-mile long run} = \frac{W}{33} \qquad \textbf{(11–41b)}$$

Friction Losses in Hose and Traveler.—Hose-fed traveling sprinklers must have hoses that are long (typically 660 ft), flexible, tough skinned, and capable of withstanding high pressures. High-pressure traveler hoses are made in 2.5- to 5-in diameters. They are about 5 times as expensive as pipe and often have a 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 following relatively small diameter hoses are used for the following ranges of flow:

Hose flow rate range (gpm)	Nominal inside diameter of lay-flat hose (in)
Up to 150	2.5
100 to 300	3
250 to 600	4
400 to 750	4.5
500 to 1,000	5

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 11–32 gives estimated pressure losses for lay-flat hose operating at approximately 100 psi. Friction loss can be estimated by equation 23 when the actual inside 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. Thus equation 23 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 psi. 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 11–9

Assumed irrigation efficiency of the low half: E = 70%

Low winds—ranging between 0 and 5 mph

Peak moisture-use rate 0.22 in/day

A corn crop to be grown on sandy soil on which the allowable application rate is 1 iph and allowable moisture depletion is 3 in.

Irrigation over the field boundaries is both permissible and practical.

Find:

The required sprinkler, nozzle, and operating pressures

The system layout

The pressure required at the hose inlet

Calculation:

The potential towpath spacings for the 2,640-ft width of the field are:

Table 11-32.—Estimated pressure head loss gradients for lay-flat irrigation hose operating at approximately 100 psi

Flow rate	Nominal inside diameter (in)									
	2.5		3		4		4.5		5	
	Pressure head loss gradient per 100 ft of hose									
gpm	psi	ft	psi	ft	psi	ft	psi	ft	psi	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

Number of towpaths	Spacing
7	380 ft
8	330 ft
9	290 ft
10	260 ft
11	240 ft

If two travelers are used, there should be an even number of towpaths.

For the crop and soil conditions, no special consideration need be given to application rate or droplet impact.

With an E_h = 70% and a peak moisture use rate of 0.22 in/day the average gross depth of application per day during peak use periods must be:

$$d = 0.22/(70/100) = 0.32 \text{ in/day}$$

and by equation 1 the system capacity must be at least:

$$Q = \frac{453 \text{ Ad}}{\text{fT}} \qquad \textbf{(11–1)}$$

$$= \frac{453 \times 80 \times 0.32}{1 \times 23} = 504 \text{ gpm}$$

From table 11–30 a 24° gun sprinkler with a 1.4-in tapered bore nozzle will discharge 515 gpm at 80 psi and produce a 455-ft wetted diameter.

From table 11–31 the towpath spacing can be 75 percent of the wetted diameter in winds up to 5 mph. For a 455-ft wetted diameter this would be 340 ft. The nearest acceptable potential towpath spacing for the design at hand is 330 ft. Thus eight tow paths will be required as shown in figure 11–9.

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 × 0.32 = 2.56 in. From equation 40 the required travel speed is:

$$S = \frac{1.605 \text{ q}}{\text{W d}} \qquad \textbf{(11–40)}$$

$$= \frac{1.605 \times 515}{330 \times 2.56} = 0.98 \text{ ft/min}$$

The time required to travel the 1,320-ft length of each towpath is:

$$\frac{1{,}320}{0.98 \times 60} = 22.5 \text{ hr}$$

This is a reasonable design. In practice the travel speed would probably be adjusted to as close to 1 ft/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 ft to 23 hrs by letting S = 0.96

ft/min. The required sprinkler discharge by equation 40 would then be:

$$q = \frac{2.56 \times 330 \times 0.96}{1.605} = 505 \text{ gpm}$$

This agrees with the minimum system capacity found earlier by equation 1.

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-in diameter hose proved to be the most economical size for the 515-gpm design flow rate.

From table 11–32 the estimated pressure head loss gradient for the lay-flat irrigation hose is 2.1 psi/100 ft. Using equation 23 as a basis for inter- [illegible]

$$2.1\left(\frac{515}{500}\right)^{1.75} \times \frac{660}{100} = 14.6 \text{ psi}$$

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 ft/min will be 7.5 psi. In addition the automatic shut-off valve has 3.5 psi loss.

The hose inlet pressure required for the traveling sprinkler is:

Sprinkler pressure	80.0 psi
Friction loss in hose	14.6
Pressure loss in traveler	7.5
Automatic shut-off valve	3.5
Riser height (10 ft)	4.3
Required hose inlet pressure	109.9 psi

System Layout

Figure 11–9 shows a typical traveling sprinkler system layout. In the design and layout of traveling sprinkler systems the following general criteria should be considered:

1. With unrestricted water supplies it is usually desirable to design the system to operate at least 20 hr per day during peak-use periods.

2. Traveling systems should normally be designed to require only one and at most two "setups" per day. (Travelers operate unattended until they reach the end of a towpath at which time the traveler and hose must be moved and set up for a new run in the next towpath.)

3. The maximum operating time should be 23 hr/day for systems requiring only one setup per day and 22 hr/day for 2 setups per day.

4. Whenever possible, systems should be designed for the traveler to begin and end at the field boundary as shown in figure 11–9. Sometimes it is not advisable or practical to irrigate over the field boundaries at the ends of the towpaths, and the sprinklers must be started 150 to 200 ft inside of the field boundaries. In such cases, a better irrigation can be applied by allowing the traveling sprinkler to stand 1 hr at each end for once-a-day setups on 1/4-mile towpaths, and 30 minutes at each end for twice a day setups. For longer towpaths this time should be increased and for shorter towpaths [illegible] towpath length.

5. If practical, where prevailing winds exceed 5 mph, towpaths should be laid out so they do not line up with the prevailing wind direction.

6. Towpaths should be laid out in the same direction as the rows, usually following the contours of steeply sloping fields.

7. The actual application rate from full circle traveling gun sprinklers ranges from about 0.3 iph for sprinklers discharging 300 gpm to 0.6 iph for 1,000 gpm units. Therefore, where infiltration is apt to be a problem, a large number of low discharge sprinklers is preferable to a few large units.

8. The width of the field should be divided by a series of integers to obtain a potential set of towpath spacings provided that irrigation outside of the field boundaries is permitted (see 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.

9. The final design layout will be a compromise between the above factors so that the number of towpaths is a multiple of the number of sprinklers; the spacing between towpaths 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.

Center-Pivot Design

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, 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 nozzling or any mechanical aspects of the machine.

A step-by-step general design procedure is presented in *Types of Systems* 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 presented as figure 11–13.

The main advantages of center-pivot sprinkle irrigation machines are:

1. Water delivery is simplified through the use of a stationary pivot point.
2. Guidance and alignment are controlled at a fixed pivot point.
3. Relatively high water application uniformities are easily achieved with moving sprinklers.
4. After completing one irrigation, the system is at the starting point for the next irrigation.
5. Irrigation management is improved by accurate and timely application of water.
6. Accurate and timely applications of fertilizers and other chemicals can be made in the irrigation water.
7. 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-pivot machines, however, have some definite disadvantages. As with all irrigation machines, in order 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, this is done by irrigating 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-ft which irrigates a 125 to 140 ac circular field depending on how far water is thrown from the end sprinklers. From an irrigation standpoint, center-pivots have the following disadvantages:

1. When the pivot point is in the center of a square field, only 125 to 132 ac of the 160-ac 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 and complexity.
2. The application rate at the outer edge of the irrigated circle will range between 1 and 8 iph depending on the nozzle configuration.
3. To reduce or eliminate runoff problems associated with these high application rates, use light, frequent applications on all but the most sandy soils or cracked clays. Thus, 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.
4. 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.
5. Elevation differences can be large between lateral ends that point up or down hill, resulting in wide variations in discharge.

System Capacity

The required system capacity can be computed by equation 1, as discussed in the section under *Capacity Requirement for Center Pivots*. It is often desirable to compute the unit system capacity required for different moisture use rates. If a 24-hr-per-day, 7-day-per-week operation is assumed, equation 1 can be reduced to:

$$Q = 18.9\, A\, d' \qquad (11\text{–}42a)$$

or

$$Q = \frac{R^2\, d'}{734} \qquad (11\text{–}42b)$$

where

Q = system capacity required (gpm)
A = design area (acres)
d′ = daily gross depth of application required during peak moisture use rate period (in)

R = maximum radius irrigated when corner system or end sprinkler is in operation (ft)

The unit system capacity, gpm/acre, can be obtained by letting A = 1. To accommodate breakdowns, time to move the system or shutdowns to accommodate electric load management:

$$Q = \frac{453\ Ad'}{T} \tag{11-42c}$$

where

T = average actual operating time (hr/day)

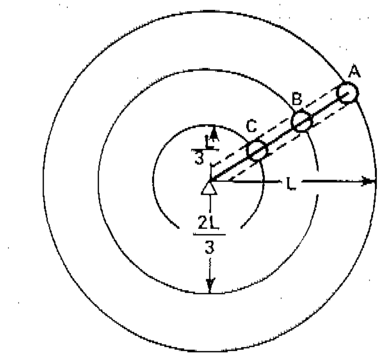
To determine the gross depth of irrigation (d) per revolution of a center pivot use equation 1.

Application Intensity

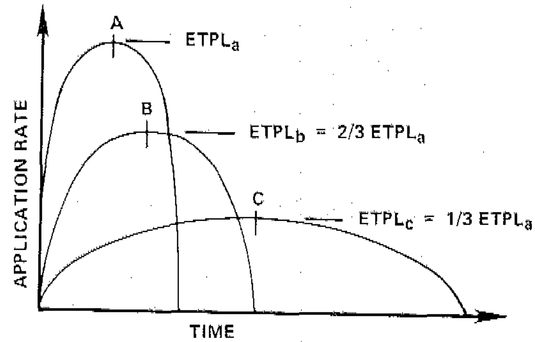
The geometrical characteristics of the center-pivot system are such that the application rate must increase with the distance from the stationary pivot point to obtain a uniform depth of application (fig. 11-50). As a result, the application rates, especially near the moving end of the lateral, often 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 11-50. A stationary water application pattern can be transformed into a moving one by dividing the pattern base width by the speed of the pivot. For the 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.

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 ft^2/day covers most of the practical combinations



A) AERIAL VIEW OF CENTER PIVOT FIELD WITH UNIFORM WIDTH OF WETTED STRIP.



B) WATER APPLICATION RATES AT DIFFERENT POINTS ALONG PIVOT LATERAL.

Figure 11-50.—Water application rates at different points along a center pivot with uniform width of wetted strip.

of ETP and L. As an example, for ETP = 0.30 in/day and L = 1/4 mile, the value of ETPL = 33 ft^2/day. The advantage of using the parameter ETPL can be demonstrated by referring to figure 11-50. The ETPL = 33 ft^2/day at the outer edge of the pivot, ETPL = 22 ft^2/day along the circular path at 2/3 L and 11 ft^2/day at 1/3 L. If the pivot were lengthened to 1,866 ft to irrigate twice as much area, the ETPL along the outer edge would be increased to 47 ft^2/day. Thus, 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.

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:

$$I = \frac{2(96.3)\ r\ Q}{R^2 w} \qquad (11\text{–}43a)$$

and

$$I_x = \frac{4}{\pi} \quad \frac{2\ (96.3)\ r\ Q}{R^2 w} \qquad (11\text{–}43b)$$

$$= \frac{245\ r\ Q}{R^2 w}$$

where

- I = the average application rate at any point r (iph)
- r = radius from pivot to point under study (ft)
- I_x = the maximum application rate at any point r (iph)
- Q = system capacity (gpm)
- R = maximum radius irrigated by center pivot (ft)
- w = wetted width of water pattern (ft)

nomenon. For example, in figure 11–51 the shaded portion depicts the potential runoff. 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.

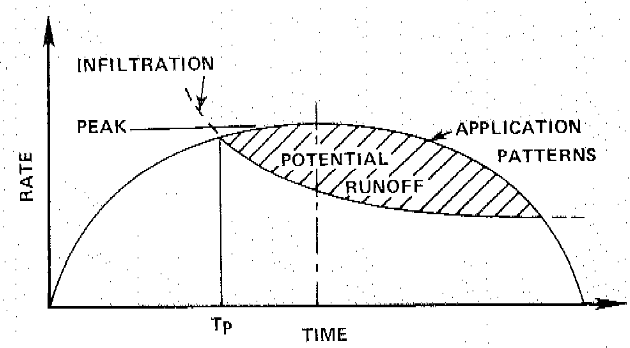


Figure 11–51.—Intersection between a typical elliptical pattern of water application rate under a center pivot and a potential infiltration curve.

When field experience is not available for center-

and irrigation demand factors and independent of the travel speed.

Infiltration Rate.—General soil infiltration characteristics for sprinkler systems are presented in table 11–4. The table values can often be increased by over 100 percent when applying light, daily irrigations with a center-pivot system.

Surface storage is important in minimizing runoff from center-pivot systems. For example, assume daily irrigations of d′ = 0.30 in are applied and 0.1 in can be stored on the surface. Then only 0.2 in must be infiltrated while the system is overhead to prevent runoff. Potential values of surface storage are:

Slope (%)	Potential surface storage (in)
0–1	0.5
1–3	0.3
3–5	0.1

Pitting or diking implements can be used to increase surface storage.

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 phe-

figure 11–52 can be used as a guide to identifying potential runoff problems. In general, soils above the 0.3 iph contour are questionable for center-pivot irrigation; soils lying between the 0.3- and 0.5-iph contour require careful design and management, and soils below the 0.5-iph contour are ideal for center-pivot irrigation. Additional and somewhat contradictory criteria are shown by the dotted lines. Obviously, figure 11–52 should only be used as a "first approximation" since factors other than soil texture affect the infiltration capacity of soils. Field trials may be needed to determine intake rates for center-pivot design.

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 mm 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 and cause vertical erosion. Numerous studies have been conducted to investigate the problem of raindrop impact energy and soil surface sealing in relation to infiltration and runoff; how-

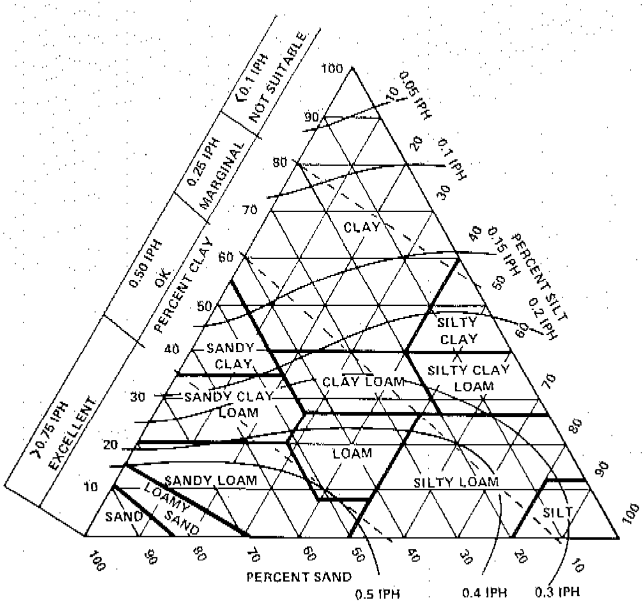


Figure 11-52.—Soil triangle showing proportions of sand, silt, and clay for different soil textures plus general infiltration rate contours.

ever, no satisfactory quantitative relation has been established.

The hydraulic permeability of the soil surface seal is a function of drop size (fig. 11-16). Larger raindrops 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. 11-15.) 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 very small drops.

The ultimate consequence of raindrop impact is that the wetted radius produced by a sprinkler 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 the 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 and settle and have vertical erosion of fine particles.

Sprinkler-Nozzle Configuration

The sprinkler-nozzle configuration used for most center-pivot laterals is one of the following:

1. *Uniform spacing* of 30 to 40 ft between sprinklers, with the discharge increasing in proportion to the distance from the pivot (fig. 11-53).
2. *Uniform sprinkler discharge*, with the distance between sprinklers decreasing from 30 ft near the pivot to 5 ft in inverse proportion to the distance from the pivot.
3. A *combination* of (1) and (2).

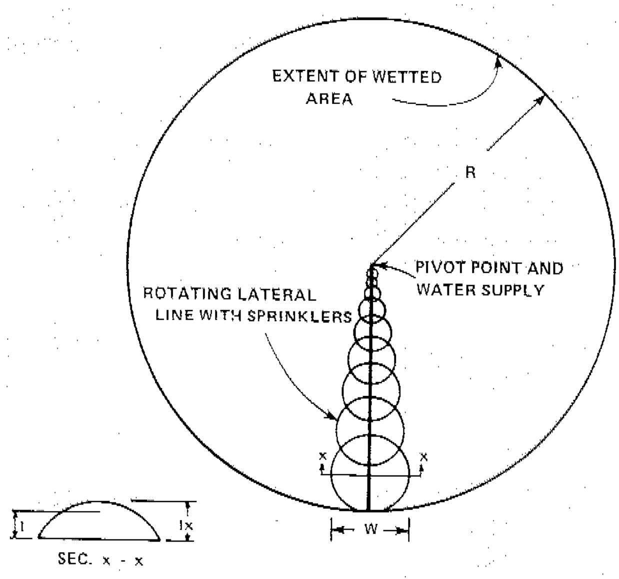


Figure 11-53.—Watering characteristics of center-pivot irrigation machines.

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 and 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-ft sprinkler spacing along the first third of the lateral, a 20-ft spacing along the middle third and a 10-ft spacing along the last third of the lateral. Thus, the outlets can be uniformly spaced at 10-ft intervals along the lateral. To vary the sprinkler spacing merely close off some of the outlets with pipe plugs. Thus, 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 to:

1. Determine the discharge required from each sprinkler to apply a uniform application of water throughout the irrigated area.
2. Then, starting with a design pressure at either end determine the pressure available at each sprinkler outlet.
3. From the required discharge and available pressure, select the appropriate nozzle size in accordance with equation 12.

Sprinkler Discharge.—The sprinkler discharge required at any outlet along a center-pivot lateral can be computed by:

$$q_r = r\, S_r\, \frac{2Q}{R^2} \qquad (11\text{-}44)$$

where

q_r = sprinkler discharge required at r (gpm)
r = radius from pivot to outlet under study (ft)
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)
Q = system capacity (gpm)
R = maximum radius effectively irrigated by the center pivot (ft)

Sprinkler Configurations.—The pressures and wetted widths produced by the sprinkler configurations commonly used on center-pivot laterals are presented in table 11-33. Impact sprinklers operating at the low end of the pressure range produce large droplets that may cause excessive soil sealing. "Breakup pins" can be used to remedy this, but the pins reduce the wetted width of the patterns about 25 percent.

Table 11-33.—Nozzle pressure and pattern width range for various center-pivot sprinkler configurations

Type	Pressure range (psi)	Pattern width range[1] (ft)
Fixed spray nozzles[2]	15-30	20-45
Uniform discharge with rotating sprinklers	20-55	75-90
Combination spacing with rotating sprinklers	25-60	80-110
Uniform spacing with rotating sprinklers	60-90	150-175

[1] At outer end of radius.
[2] All nozzle spacing arrangements.

The fixed spacing nozzles produce narrow pattern widths and consequent high application rates (see eq. 43). Thus their use is limited to high infiltration soils or to nearly level fields with good potential for surface water storage. Spray nozzles produce small drops that do not cause surface sealing but are subject to high wind drift losses. Some fixed spray nozzles, however, are available that produce coarser sprays to reduce wind drift problems. While low pressure is an advantage of fixed spray nozzles in terms of energy use, it will cause water distribution problems because of sensitivity to pressure changes resulting from lateral rotation over uneven topography.

The large nozzles used for uniform spacing produce a wide pattern and coarse drops. 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 can be used to maintain the desired discharge.

Angle of Trajectory.—Rotating sprinklers with various angles of trajectory are available for use on center-pivot laterals. High trajectory (23° to 27°) sprinklers normally used for periodic-move and fixed systems often result in excessive drift losses when placed high above the ground along center-pivot laterals. Trajectory angles of center-pivot sprinklers recommended to minimize drift losses range between 6° and 18°, with the low end of the range being preferable in high winds. Table 11–34 shows drift losses obtained from some typical field can test data for center pivots with different nozzle configurations. An analysis of the data in the table gives the following averages: low angle has 12 percent loss in 10-mph wind, spray has 17 percent loss in 6-mph wind, and high angle has 29 percent loss in 10-mph wind.

End-Gun Operation.—The designer can compute the capacity of the end gun sprinkler (q_g) by equation 44 letting S_r equal 90 percent of the radius wetted by the end gun and r equal the lateral pipe length (L) plus $S_r/2$.

Table 11–34.—Drift losses from field evaluations of center pivots with different nozzle configurations

Nozzle configuration	Trajectory angle	Wind (mph)	Temperature (°F)	Drift loss (%)
Spray	—	3	80	20
Combination	6°	7	80	15
Combination	6°	7	88	10
Combination	23°	7	90	18
Spray	—	9	95	25
Combination	6°	10	86	3
Uniform discharge	6°	10	88	17
Combination	6°	12	86	7
Combination	low	4	83	6
Spray	—	6	90	14
Spray	—	8	92	10
Uniform spacing	high	8	86	41
Uniform spacing	high	9	86	13
Combination	low	12	90	19
Uniform spacing	high	13	91	36
Uniform spacing	high	13	92	39
Uniform discharge	low	16	91	16

Part-circle sprinklers should be used and the angle should be set as shown in figure 11–54 for the best coverage on most systems.

Large end-gun sprinklers can add significantly to the area irrigated by a center pivot. For example, by adding an additional 100 ft of radius to a 1,320-ft system the area covered will be increased from 125 to 145 ac; however, where end guns are used only in the field corners, the effect of the on-off operation must be considered. If the gun discharge exceeds 20 percent of the normal system discharge, the effect on the quality of irrigation on the larger inner field area should be carefully considered. Some of the other problems are that water distribution from end guns is often severely affected by wind, booster pumps are required on all of the lower pressure nozzling configurations, and the high application intensity that is typically found under end guns may be detrimental to the soil tilth and crop.

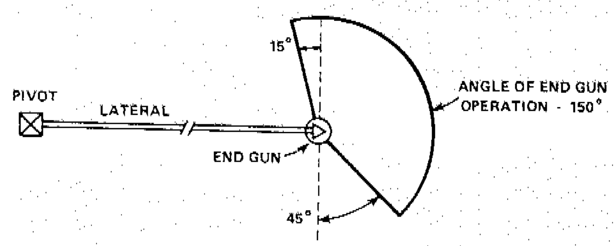


Figure 11–54.—Top view of end-gun sprinkler wetting pattern showing recommended angle of operation.

Lateral Hydraulics

The discharge per unit length of lateral increases linearly along center-pivot laterals as described by equation 44. Therefore, the hydraulic characteristics of center-pivot laterals are different than for periodic-move or linearly moving sprinkler laterals that were discussed earlier.

Lateral Flow Rate.—The flow rate at any point along a center-pivot lateral can be computed by:

$$Q_r = Q\left(1 - \frac{r^2}{R^2}\right) \qquad (11\text{–}45)$$

where

Q_r = lateral flow rate at r (gpm)
r = radius from pivot to point under study (ft)

Q = system capacity (gpm)
R = maximum radius effectively irrigated by the center pivot (ft)

The end-gun flow rate can be computed by setting r equal to the length of the lateral pipe (L) and R equal to L plus 90 percent of the radius wetted by the end gun to obtain:

$$q_g = Q\,(1 - \frac{L^2}{R^2}) \qquad \textbf{(11–46)}$$

where

q_g = the end gun discharge (gpm)
L = the length of the lateral pipe (ft)

(An alternative method for computing end gun discharge using equation 44 is described above.)

Lateral Friction Loss.—The pipe friction loss for a center-pivot lateral can be computed by combining equations 16 and 17 to obtain:

$$(H_f)_{cp} = 10.50\ F\ R\ (\frac{Q}{C})^{1.852}\ D^{-4.87}$$

The reduction coefficient is F = 0.543 for center-pivot laterals that have a large number of uniformly increasing discharges per unit length, therefore:

$$(H_f)_{cp} = 5.7\ L\ (\frac{Q}{C})^{1.852}\ D^{-4.87} \qquad \textbf{(11–47)}$$

where

$(H_f)_{cp}$ = the pipe friction loss in the center-pivot lateral (ft)
L = the length of the lateral pipe that must be equal to the maximum radius wetted by the center pivot (ft)
Q = inlet flow rate or system capacity (gpm)
C = the friction coefficient that usually is taken as 130 for galvanized steel and 145 for epoxy-coated steel
D = inside diameter of the pipe (in)

Equation 47 assumes that there is uniformly increasing discharge per unit length along the pipe; thus, when a very large gun sprinkler is installed on the moving end, special adjustments must be made. For ordinary end guns, however, the effectively irrigated radius (R) can be substituted for L in equation 47 to compute $(H_f)_{cp}$. To compute the pipe friction loss in systems with very large end-gun volumes in proportion to the volume of water for the rest of the system so that L is considerably less than the maximum radius (R) effectively irrigated by the center pivot, $(H_f)_{cp}$ can be computed as follows:

1. Determine $(H_f)_R$ by letting L = R in equation 47.
2. Determine $(H_f)_{R-L}$ by letting: $Q = q_g$, and $L = r_g$ where r_g is the radius from the pivot to the end gun, i.e., L = R − L
3. Then:

$$(H_f)_{cp} = (H_f)_R - (H_f)_{R-L} \qquad \textbf{(11–48a)}$$

The above procedure can be expressed in a single formula for systems with end guns as:

$$(H_f)_{cpg} = 5.7\ R'\ (\frac{Q}{C})^{1.852}\ D^{-4.87} \qquad \textbf{(11–48b)}$$

where

$$R' = R - [(R - L)\,(1 - \frac{L^2}{R^2})^{1.852}]$$

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 (eq. 45) 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 drive units.

The best trade-off between fixed and operating costs can be based on a unit-length analysis as described in sample calculation 11–13. If several center-pivot systems are designed using the same economic and hydraulic parameters, a chart such as figure 11–38 can be developed for the selection of center-pivot pipe using economic parameters.

When more than one pipe size is used for a center-pivot lateral a procedure similar to the one leading to equation 22 for laterals with two pipe sizes should be used. The main point to keep in mind is that equation 47 assumes that discharge increases uniformly per unit length along the pipe so that there is no flow past the section under study.

Thus, to compute the $(H_f)_{cp}$ with two or more pipe sizes all friction loss computations must be made with lengths of pipe that include the distal end. Furthermore, for systems with end guns, the distal end is at the limit of the radius effectively irrigated. The conceptual difference between equation 48b and equation 22 is that there is no pipe and consequently no pipe friction loss past the end gun in the latter equation.

Application Uniformity and Depth.—Very 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, i.e., 18, 30, 42, 54 hr, etc. This will ensure that the pivot experiences different wind conditions as the lateral passes over a given site from one irrigation to the next.

To determine the travel speed of the end-drive unit for a given number of hours per rotation:

$$v = \frac{2 \pi L'}{60 f T} \qquad \textbf{(11–49)}$$

where

- v = the travel speed of the end drive unit (ft/s)
- L′ = length from the pivot to the last drive unit (if there is an overhang, L′ will be less than the pipe length) (ft)
- f = time allowed for completion of one irrigation (days)
- T = actual operating time (hr/day)

As mentioned earlier, the gross depth of application can be determined by equation 1.

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 speeded up when pointing downhill and 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.

The center-pivot lateral acts as one giant sprinkler, and the general relationship between discharge and inlet pressure can be approximated by:

$$Q_2 = K_{cp} \sqrt{P_{cp2}} = Q_1 \left(\frac{P_{cp2}}{P_{cp1}} \right)^{1/2} \qquad \textbf{(11–50)}$$

where

- Q = system discharge (gpm)
- K_{cp} = the discharge coefficient of the system
- P_{cp} = the lateral pipe inlet pressure measured at the top of the pivot point (psi or ft)

The value of K_{cp} can be computed letting Q and P_{cp} be the design values in equation 50.

Sample calculation 11–18.—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 = 130 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/day when operating an average of 22 hr/day
- Nozzling: Combination spacing of rotating sprinklers with a minimum pressure of 45 psi at the end of the lateral.

Find:

- The system capacity, Q
- The discharge of a sprinkler at r = 1,200 ft from the pivot where the sprinkler spacing, S_r = 10 ft
- The average application rate 1,200 ft from the pivot, I
- The lateral flow rate at r = 1,200 ft
- The required discharge rate of the end gun, q_g
- The pipe friction loss, $(H_f)_{cp}$
- The end drive unit travel speed for making a lateral rotation every 66 hours of continuous operation
- The depth of application with a 66-hr cycle time

Calculations:

The area irrigated, assuming the end-gun sprinkler is always on, is:

$$A = \frac{\pi\ 1400^2}{43560} = 141.4 \text{ ac}$$

By equation 42c the system capacity should be:

$$Q = \frac{453\ Ad'}{T}$$

$$= \frac{453 \times 141.4 \times 0.30}{22} = 873 \text{ gpm}$$

The discharge of a sprinkler at r = 1,200 ft can be determined by equation 44 as:

$$q_r = r\ S_r\ \frac{2\ Q}{R^2}$$

$$= \frac{1200 \times 10 \times 2 \times 873}{(1400)^2} = 10.7 \text{ gpm}$$

Interpolating from table 11–13 this would require a nozzle slightly larger than 7/32 in operating at 45 psi with $w \cong 107$ ft.

The average application rate at r = 1,200 ft by equation 43a is:

$$I = \frac{2\ (96.3)\ r\ Q}{R^2\ w}$$

$$= \frac{2(96.3) \times 1200 \times 873}{(1400)^2 \times 107} = 0.96 \text{ iph}$$

The lateral flow rate past r = 1,200 ft is computed by equation 45 as:

$$Q_r = Q\ (1 - \frac{r^2}{R^2})$$

$$= 873\ (1 - \frac{(1200)^2}{(1400)^2}) = 232 \text{ gpm}$$

The required end-gun discharge is computed by equation 46 as:

$$q_g = Q\ (1 - \frac{L^2}{R^2})$$

$$= 873\ (1 - \frac{(1300)^2}{(1400)^2}) = 120 \text{ gpm}$$

The pipe friction loss can be computed directly by equation 48b or in a three-step process by equation 47 and 48a. The three step process starting with equation 47 gives:

$$(H_f)_R = 5.7\ R\ (\frac{Q}{C})^{1.852}\ D^{-4.87}$$

$$= 5.7 \times 1400\ (\frac{873}{130})^{1.852}\ (6.36)^{-4.87}$$

$$= 33.2 \text{ ft}$$

and

$$(H_f)_{R-L} = 5.7 \times 100\ (\frac{120}{130})^{1.852}\ (6.36)^{-4.87} = 0.1 \text{ ft}$$

Therefore, by equation 48a

$$(H_f)_{cp} = (H_f)_R - (H_f)_{R-L} = 33.2 - 0.1 = 33.1 \text{ ft}$$

The above computations point out that $(H_f)_{cp}$ can be computed directly by substituting R for L in equation 47 for end guns where $q_g < 1/4Q$. This is demonstrated by the insignificance of the computed $(H_f)_{R-L} = 0.1$ ft as compared to $(H_f)_{cp} = 33.1$ ft.

The speed at which the end drive unit must travel to complete a cycle in 66 hours can be determined by equation 49 as:

$$v = \frac{2\ \pi\ L'}{60\ fT}$$

$$= \frac{2\ \pi\ 1260}{60 \times 66} = 2.0 \text{ ft/min}$$

The gross depth of application with a 66-hr cycle time by equation 1 is:

$$d = \frac{Q\ f\ T}{453\ A}$$

$$= \frac{873 \times 66}{453 \times 141.44} = 0.90 \text{ in}$$

And the net depth of application assuming E_q = 80% is:

$$\text{net depth/irrigation} = \frac{E_q\, d}{100} = \frac{80 \times 0.90}{100} = 0.72 \text{ in}$$

Operating Pressures

The minimum pressure, inlet pressure, and end-gun pressures for center-pivot systems should all be examined.

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 sprinkler-nozzle configuration to avoid producing a watering pattern that will [illegible] minimum recommended operating pressures that are available for the various sprinkle-nozzle configurations should be followed.

Inlet Pressure.—The inlet pressure required at the base of the pivot point is equal to the sum of the following pressure heads, elevation differences, and friction losses:

1. Minimum sprinkler pressure.
2. 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 negative. In rolling fields use the elevation difference between the pivot and the highest point in the field.
3. Height of the pivot lateral above the ground.
4. Friction loss in lateral pipe plus 10 percent to cover miscellaneous losses.
5. 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; therefore, a valve is unnecessary. End guns may also need to be shut on and off to water the corners without wetting roadways running along the field.

End-Gun Pressure.—End-gun pressures should be at least 50 psi and preferably above 65 psi 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 to provide the necessary pressure.

Elevation-Discharge Relationship

When a center-pivot system is used on a sloping field the sprinkler pressures vary as the lateral rotates. Typical nozzling configurations are designed to give uniform water application when the lateral is on a contour, but pressure or flow control devices are not usually provided. Thus, when the lateral is pointing uphill the individual sprinkler discharges drop causing the system discharges to decrease, and when pointing downhill the discharges increase.

Discharge Variations.—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 [illegible] be represented by a weighted average elevation location for the entire lateral:

$$R_w = \frac{L}{3Q}(2Q + q_g) \qquad \textbf{(11–51a)}$$

which can also be computed by:

$$R_w = \frac{2L}{3} + \frac{L}{3}\left(1 - \frac{L^2}{R^2}\right) \qquad \textbf{(11–51b)}$$

where

R_w = radius from the pivot to the location of the weighted average elevation (ft)
L = the length of the lateral pipe (ft)
Q = system capacity (gpm)
q_g = the end gun discharge (gpm)
R = maximum radius effectively irrigated by the center pivot (ft)

To estimate the overall effect of elevation changes, 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 (± slope) × R_w. From this the variations in Q can be computed by equation 50 as demonstrated in sample calculation 11–19.

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.

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 11–19. Pivot inlet pressure and end-gun booster pump design.

Given:
- The pivot information from sample calculation 11–18
- The field has a uniform 2 percent slope
- The lateral is 10 ft above the ground

Find:
- The inlet pressure required at the base of the pivot
- The booster pump horsepower required to provide a gun pressure of 65 psi
- The system discharges when the lateral is pointing uphill and downhill assuming the system is designed for Q = 873 gpm when the lateral is on the contour

Calculations:

The inlet pressure at the base of the pivot should be:

Minimum nozzle pressure (45 psi)	= 104.0 ft
Elevation difference (1,300 × 2%)	= 26.0
Height of pivot lateral	= 10.0
Friction loss in pipe[1]	= 33.1
Plus 10% minor loss	= 3.3
Inlet valve loss (3.5 psi)	= 8.0
Required inlet pressure	= 184.4 = 80 psi

[1] *This is quite high and an economic analysis might indicate the use of larger pipe.*

To operate the end gun at 65 psi and to take care of valve and plumbing friction losses (5 psi), the pressure of the end of the lateral should be boosted by:

45 to 70 = 25 psi = 58 ft

The horsepower required for a 65 percent efficient booster pump can be computed by equation 36 as:

$$BHP = \frac{q_g \times H}{3960\ E_p/100}$$

$$= \frac{120 \times 58}{3960 \times 65/100} = 2.7 \text{ hp}$$

The effect of [illegible]

constant is computed by equation 50. The average nozzle pressure variation can be approximated by the elevation changes at the weighted average elevation radius (R_w). The R_w can be determined by equation 51a:

$$R_w = \frac{L}{3Q}(2Q + q_g)$$

$$= \frac{1300}{3(873)}[2(873) + 120]$$

$$= 926 \text{ ft}$$

The elevation 926 ft from the pivot will vary ± 0.02 × 926 = 18.5 ft.

If the lateral was designed for Q = 873 gpm at an inlet pressure of 184.4 ft, the flow variation can be computed by equation 50 as follows: First subtract the height of the pivot since this does not vary with flow and compute K_{cp} as:

$$K_{cp} = \frac{Q}{\sqrt{P_{cp}}} = \frac{873}{\sqrt{184.4 - 10}} = 66.1$$

Then compute Q when the lateral points uphill:

$$(Q)up = 66.1\sqrt{184.4 - 10 - 18.5} = 825 \text{ gpm}$$

And when the lateral is downhill:

$$(Q)dn = 66.1\sqrt{184.4 - 10 + 18.5} = 918 \text{ gpm}$$

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.

Some considerations as to machine suitability are:

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 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.

Field Test Data

It is good practice to occasionally test the performance of a center-pivot system to check the uniformity of application and flow characteristics.

Information Required.—Center-pivot systems are propelled by using diverted water or such independent power sources as electricity, oil hydraulics, or compressed air to move the lateral. If water is used, it must be included as part of the total water applied; this somewhat lowers computed values of water use efficiency. When the water discharging from the pistons or turbines is distributed as an integral part of the irrigation pattern, its effectiveness should be included in DU; otherwise, it should be ignored in the DU computations but should be included in computing E_q.

The procedures and logic are similar for evaluating all types of sprinkle 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 systems.

The following information is required for evaluating center-pivot irrigation systems.

1. Rate of flow for the total system.
2. Rate of flow required to propel the system if it is water driven.
3. Depth of water caught in a radial row of catch containers.
4. Travel speed of end-drive unit.
5. Lateral length to end-drive unit and radius of the portion of the field irrigated by the center pivot.
6. Width of the wetted strip at end-drive unit.
7. Operating pressure and diameter of largest sprinkler nozzles at the end of the lateral.
8. 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.
9. Additional data indicated on figure 11–55.

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.

Equipment Needed.—The equipment needed is essentially the same as for the full evaluation of rectangular sprinkler-lateral systems.

1. A pressure gauge (0–100 psi) with pitot attachment (fig. 11–44).
2. A stopwatch or watch with an easily visible second hand.
3. From 60 to 100 (depending on the lateral length) catch containers such as 1-quart oil cans or plastic freezer cartons.
4. A 250-ml graduated cylinder to measure volume of water caught in the containers.
5. A tape for measuring distances in laying out the container row and estimating the machine's speed.
6. A soil probe or auger.
7. A hand level and level rod to check differences in elevation.
8. A shovel for smoothing areas in which to set catch containers and for checking profiles of soil, root, and water penetration.
9. Figure 11–55 for recording data.
10. Manufacturer's nozzle specifications giving discharge and pressure and the instructions for setting machine's speed.
11. For water-driven machines which do not incorporate the drive water into the sprinkler patterns, a 2- to 5-gal bucket and possibly a short section of flexible hose to facilitate measuring the drive water discharge.

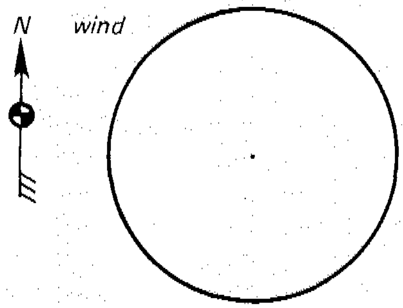
Field procedure.—Fill in the data blanks of figure 11–55 while conducting the field procedure. In a field having a low-growing crop or no crop, test the system when the lateral is in the position at which the differences in elevation are least. In tall-growing crops, such as corn, test the system where the lateral crosses the access road to the pivot point.

1. Location ____________, observer ____________, date & time ____________

2. Equipment: make ____________, length ____ ft, pipe diameter ____ in

3. Drive: type ____________ speed setting ____ %, water distributed? ____

4. Irrigated area = $\dfrac{3.14\ (\text{wetted radius} \_\_\_\_ \text{ft})^2}{43{,}560}$ = ____ acres

5. 

*Mark position of lateral, direction of travel, elevation differences, wet or dry spots and wind direction.

Wind ____ mph, temperature ____ °F

Pressure: at pivot ____ psi

at nozzle end ____ psi

Diameter of largest nozzle ____ in

Comments: ____________

6. Crop: condition ____________, root depth ____ ft

7. Soil: texture ____________, tilth ____________, avail. moisture ____ in/ft

8. SMD: near pivot ____ in, at 3/4 point ____ in, at end ____ in

9. Surface runoff conditions at 3/4 point ____, and at end ____

10. Speed of outer drive unit ____ ft per ____ min = ____ ft/min

11. Time per revolution = $\dfrac{(\text{outer drive unit radius} \_\_\_\_ \text{ft})}{9.55\ (\text{speed} \_\_\_\_ \text{ft/min})}$ = ____ hr

12. Outer end: water pattern width ____ ft, watering time ____ min

13. Discharge from end drive motor ____ gal per ____ min = ____ gpm

14. System flow meter ____ gallons per ____ min = ____ gpm

15. Average weighted catches:

System = $\dfrac{(\text{sum all weighted catches} \_\_\_\_)}{(\text{sum all used position numbers} \_\_\_\_)}$ = ____ ml = ____ in

Low 1/4 = $\dfrac{(\text{sum low 1/4 weighted catches} \_\_\_\_)}{(\text{sum low 1/4 position numbers} \_\_\_\_)}$ = ____ ml = ____ in

16. Minimum daily (average daily weighted low 1/4) catch:

$\dfrac{(\_\_\_\_ \text{hrs operation/day}) \times (\text{low 1/4 catch} \_\_\_\_ \text{in})}{(\_\_\_\_ \text{hrs/revolution})}$ = ____ in/day

17. Container catch data in units of ____, volume/depth ____ ml/in

Span length ____ ft, container spacing ____ ft

Evaporation: initial ____ ml ____ ml

final ____ ml ____ ml

loss ____ ml ____ ml, ave ____ ml = ____ in

Figure 55.—Center pivot sprinkle irrigation evaluation.

Span No.	Container			Span No.	Container		
	Position number	× Catch =	Weighted catch		Position number	× Catch =	Weighted catch
	1				37		
	2				38		
	3				39		
	4				40		
	5				41		
	6				42		
	7				43		
	8				44		
	9				45		
	10				46		
	11				47		
	12				48		
	13				49		
	14				50		
	15				51		
	16				52		
	17				53		
	18				54		
	19				55		
	20				56		
	21				57		
	22				58		
	23				59		
	24				60		
	25				61		
	26				62		
	27				63		
	28				64		
	29				65		
	30				66		
	31				67		
	32				68		
	33				69		
	34				70		
	35				71		
	36				72		

Sum all: used position numbers ____________________, weighted catches ____________

Sum low 1/4: position numbers ____________________, weighted catches ____________

Figure 11–55.—Center pivot sprinkle irrigation evaluation (Cont.).

1. Set out the catch containers along a radial path beginning at the pivot, with a convenient spacing no wider than 30 ft; a 15- or 20-ft spacing is preferable. 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, etc. For example, if the span length is 90 ft, use a 30-ft or 22.5-ft spacing. This simplifies the catchment layout since measurements can be made from each wheel track and the spacing related to the span, i.e., 4th span + 50 ft. Obviously, containers should not be placed in wheel tracks or where they would pick up waste 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.

As an example, a typical layout between wheel tracks for 90-ft spans and any type of drive would be:

a. Place the first container 5 ft downstream from the pivot.

b. Set containers 2, 3, and 4 at 22.5-ft intervals. The fourth container is now 17.5 ft from the wheel track of the first span.

c. Repeat the above 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. Frequently, the containers under the first one or two spans are omitted with little adverse effect on the evaluation. A number should be assigned to each container position with a sequential numbering system beginning with 1 at the container position nearest the pivot point. Even the locations not having containers under the first spans should be numbered.

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.

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 $60/(2 \times 3.14) = 9.44$.)

a. 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.

b. 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.

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.

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.

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 11–55. 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-min period and calculate the rate per minute. To convert from cubic feet per second (or acre-inches per hour) to gallons per minute, multiply by 450.

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 ml corresponds to a depth of 1.0 in. 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 11–20.—Using center-pivot field test data.

Given:

The field data presented in figure 11–56.

Find:

Evaluate the system using the field data

Calculation:

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 described earlier and figure 11–56 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.

For the average minimum weighted catch, an unknown number of containers that represents the low 1/4 of the irrigated area must be used. The low 1/4 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 1/4 of the catch is then found by dividing the sum of the low 1/4 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:

$$DU = \frac{\text{average weighted low quarter catch}}{\text{average weighted system catch}} \times 100 \qquad (11\text{–}3)$$

which for the example problem (fig. 11–56, part 15) is:

$$DU = \frac{0.42}{0.50} \times 100 = 84\%$$

This is a reasonable value and is independent of the speed of revolution.

It is useful to plot the volume of catch against distance from the pivot (fig. 11–57). 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 (in feet) multiplied by 0.43 (to convert to an equivalent psi) 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 psi and the maximum elevation differences were only 25 ft, equivalent to 11 psi, which is only 18 percent of 60 psi.

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 one-quarter of the catches expressed as a depth per revolution. The average depth of water applied per revolution is calculated from equation 1 and from data computed on figure 11–56 in parts 11, 14, and 4. The depth applied per revolution is:

$$d = \frac{31.4 \times 1150}{453 \times 152} = 0.53 \text{ in}$$

Since the R_e = (the average weighted catch)/d, equation 9 gives

$$E_q = DU \times \frac{\text{average weighted system catch}}{d}$$

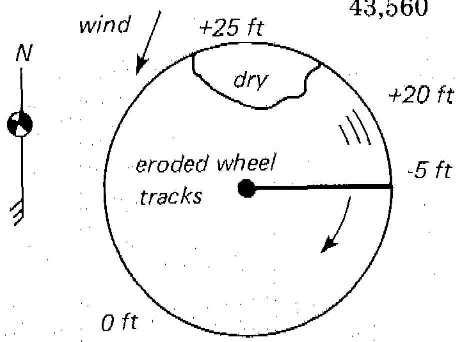
$$= 84 \times \frac{0.50}{0.53} = 79\%$$

The small difference between DU of 84 percent and E_q of 79 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 11–56, parts 15 and 17, is 0.50 + .02 = 0.52 in

1. Location: *Field F202*, observer *JK*, date & time *8-12-71 p.m.*
2. Equipment: make *HG 100*, length *1375* ft, pipe diameter *6 5/8* in
3. Drive: type *water* speed setting *—%*, water distributed? *yes*

4. Irrigated area $= \dfrac{3.14\ (\text{wetted radius } 1450 \text{ ft})^2}{43{,}560} = 152$ acres

5. 

*Mark position of lateral, direction of travel, elevation differences, wet or dry spots and wind direction.

Wind *6* mph, temperature *90*°F

Pressure: at pivot *86* psi

at nozzle end *60* psi

Diameter of largest nozzle *1/2* in

Comments: *Sprinklers operating OK but end part circle sprinklers out of adjustment*

6. Crop: condition *corn, good except north edge*, root depth *4* ft
7. Soil: texture *sandy loam*, tilth *poor*, avail. 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. Time per revolution $= \dfrac{(\text{outer drive unit radius } 1350 \text{ ft})}{9.55\ (\text{speed } 4.5 \text{ ft/min})} = 31.4$ hr

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* gallons per *10* min = *1150* gpm
15. Average weighted catches:

System $= \dfrac{(\text{sum all weighted catches } 256{,}255)}{(\text{sum all used position numbers } 2044)} = 125 \text{ ml} = 0.50 \text{ in}$

Low 1/4 $= \dfrac{(\text{sum low 1/4 weighted catches } 53{,}416)}{(\text{sum low 1/4 position numbers } 518)} = 104 \text{ ml} = 0.42 \text{ in}$

16. Minimum daily (average daily weighted low 1/4) catch:

$$\frac{(24 \text{ hr operation/day}) \times (\text{low 1/4 catch } 0.42 \text{ in})}{(31.4 \text{ hr/revolution})} = 0.32 \text{ in/day}$$

17. Container catch data in units of *ml*, volume/depth *250* ml/in

Span length *90* ft, container spacing *22.5* ft

Evaporation:	initial	*150* ml	*150* ml
	final	*−147* ml	*−145* ml
	loss	*3* ml	*5* ml, ave *4* ml = *0.016* in

Figure 11–56.—Center-pivot sprinkle irrigation evaluation.

Span No.	Container			Span No.	Container		
	Position number	× Catch =	Weighted catch		Position Number	X 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*	*4366*
1	2			*10*	38	*127*	*4826*
1	3			*10*	39	*115*	*4485*
1	4			*10*	40	*147*	*5880*
2	5			*11*	41	*127*	*5207*
2	6			*11*	42	*122*	*5124*
2	7			*11*	43	*118*	*5074*
2	8			*11*	44	*144*	*6336*
3	9	*141*	*1269*	*12*	45	*112*	*5040*
3	10	*160*	*1600*	*12*	46	*124*	*5704*
3	11	*122*	*1342*	*12*	47	*126*	*5922*
3	12	*130*	*1560*	*12*	48	*151*	*7248*
4	13	*143*	*1859*	*13*	49	*120*	*5880*
4	14	*150*	*2100*	*13*	50	*122*	*6100*
4	15	*134*	*2010*	*13*	51	*115*	*5865*
4	16	*123*	*1968*	*13*	52	*143*	*7436*
5	17	*144*	*2448*	*14*	53	*124*	*6572*
5	18	*138*	*2484*	*14*	54	*114*	*6156*
5	19	*135*	*2565*	*14*	55	*115*	*6325*
5	20	*107*	*4140*	*14*	56	*160*	*8960*
6	21	*122*	*2562*	*15*	57	*120*	*6840*
6	22	*114*	*2508*	*15*	58	*110*	*6380*
6	23	*115*	*2645*	*15*	59	*109*	*6431*
6	24	*138*	*3312*	*15*	60	*117*	*7020*
7	25	*109*	*2725*	*16*	61	*85*	*5185*
7	26	*113*	*2938*	*16*	62	*194*	*12028*
7	27	*114*	*3078*	*16*	63	*148*	*9324*
7	28	*126*	*3528*	*End*	64	*82*	*5248*
8	29	*116*	*3364*		65	*12*	*omit*
8	30	*107*	*3210*		66		
8	31	*122*	*3782*		67		
8	32	*140*	*4480*		68		
9	33	*117*	*3861*		69		
9	34	*105*	*3570*		70		
9	35	*111*	*3885*		71		
9	36	*125*	*4500*		72		

Sum all: used position number *2044*, weighted catches *256,255*

Sum low 1/4: position numbers *514*, weighted catches *53,416*

Figure 11-56.—Center pivot sprinkle irrigation evaluation. (Cont.)

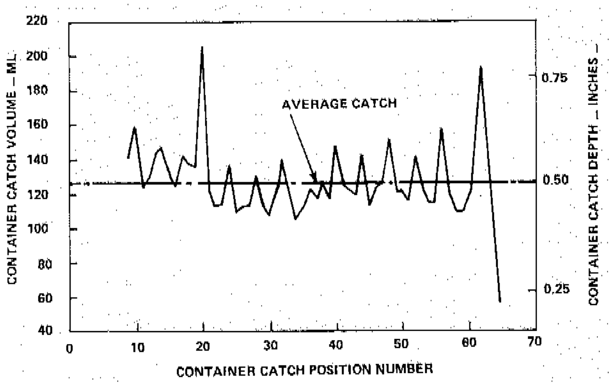


Figure 11-57.—Profile of container catch from center-pivot sprinkler evaluation test.

per revolution. The flow in gpm, which was distributed through the sprinkler, can be estimated by:

$$\text{Distributed flow} = \frac{453 \times \text{area (acres)} \times \text{gross application (in/rev)}}{\text{time per revolution (hr)}}$$

which for the recorded data is:

$$\text{Distributed flow} = \frac{450 \times 152 \times 0.52}{31.4}$$

$$= 1{,}133 \text{ gpm}$$

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 computed 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:

$$\text{Drive flow} = \frac{\text{sum of drive unit numbers} \times \text{gpm flow from end water motor}}{\text{Number of drive units}}$$

For the 15 drive motors and a flow rate of 13.5 gpm from the end water drive motor:

$$\text{Drive flow} = \frac{120 \times 13.5}{15} = 108 \text{ gpm}$$

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. 11-58). 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 runoff include:

1. Using an implement called a pitter, which scrapes indentations in the furrows followed by small dikes every 2 or 3 ft.
2. 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.

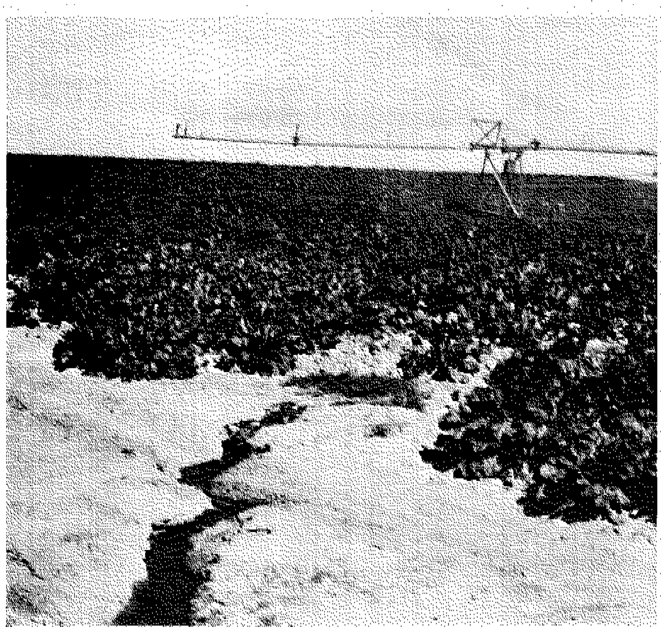


Figure 11-58.—Runoff near the moving end of a center-pivot lateral.

3. Decreasing sprinkler nozzle diameters to decrease the system capacity and application rate. All the nozzles must be changed to maintain uniformity.

4. Increasing system pressure and reducing nozzle sizes throughout the system to maintain the same system flow rate. This decreases the average drop size, lessens drop impact, and thereby reduces surface sealing that restricts infiltration.

5. Using special nozzles with pins to reduce drop sizes by breaking up the sprinkler jets.

6. Adherance to conservation practices that will limit runoff of water from fields. Contour farming, conservation tillage, terrace construction, and conservation cropping should all be considered.

Linear-Move System

Self-propelled linear-move laterals are among the latest innovations on the sprinkle irrigation market. The linear-move system must be fed by a hose pipe, 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, the uniformity of application is very high under linear-move systems. Application rates are also usually high because it is attractive economically to irrigate as much area as possible with each lateral.

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.

Application Rate.—Assuming that the application pattern under the sprinklers is elliptical, the average and maximum application rates under a linear-move lateral are:

$$I = \frac{93.3\ q}{S_\ell\ w} = \frac{96.3\ Q}{w\ L} \qquad (11\text{–}52a)$$

and

$$I_x = \frac{4}{\pi}\,\frac{96.3\ q}{S_\ell\ w} = \frac{122.6\ q}{S_\ell\ w} \qquad (11\text{–}52b)$$

where

- I = the average application rate (iph)
- q = the sprinkler discharge (gpm)
- S_ℓ = the 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 = the maximum application rate (iph)

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.

The average gross depth of water applied per irrigation can be computed by equation 1.

Special Uses of Sprinkle Systems

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.

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 for those chemicals that are approved for application in irrigation water by sprinklers and on what crops the chemicals may be used.

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 required, 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 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. First, 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. Second, 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 sprinkle system has been properly designed and is properly operated, fertilizer distribution will be acceptable.

Injection Techniques.—The simplest way to apply fertilizer through a sprinkle system is to introduce the solution into the system at the suction side of a centrifugal pump (fig. 11–59). 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 for rinsing. If a closed pressure-type container is used, such as one of the several fertilizer applicators on the market, 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.

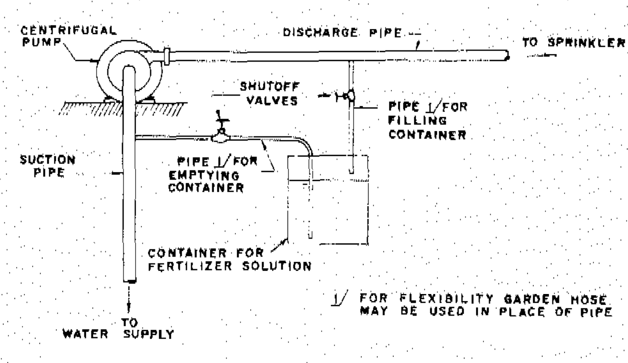


Figure 11–59.—A method for adding fertilizers in solution to a centrifugal pump system.

Fertilizer can also be added to sprinkler systems with a small high-pressure pump such as a gear or paddle pump (fig. 11–60). If a spray rig for orchards is available, the fertilizer solution can be pumped

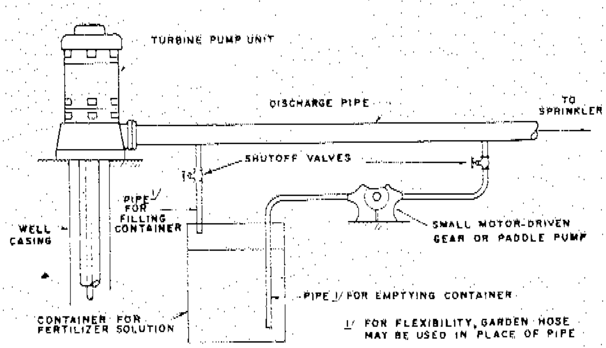


Figure 11-60.—A method for adding fertilizers to a turbine pump system using a small gear or paddle pump.

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 one 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 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, thus creating a flow through 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 gear or paddle pump unit and it has the advantage of simplicity and freedom from moving parts.

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 very convenient to handle with pumps and gravity flow from bulk storage tanks. They 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 singly or in combination 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. Sprinker 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 they will hold relatively large quantities of micronutrients.

Only traces of many micronutrient materials can be dissolved in clear liquids. It is important that the irrigation water volume and velocity be sufficient to maintain the fertilizers in suspension or solution, in order to ensure proper dispersion and uniform distribution.

Materials commonly used for application through sprinkle systems are: urea-ammonium nitrate solutions, ammonium nitrate, ammonium sulfate, urea (potential NH_3 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 sprinkle systems include: magnesium sulfate, zinc sulfate and zinc chelates, manganese sulfate and manganese chelates, copper sulfate and copper chelates, iron sulfate and iron chelates, Solubor (boron), and molybdenum.

Materials that should *not* be applied through sprinkle 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 superphosphate 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), and phosphoric acid or any acid (causes corrosion and precipitation).

Fertilizer Applications

For periodic-move and fixed sprinkle 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 the soil. During the second interval, the fertilizer in 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 root zone. 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 since this determines 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 as follows: (1) galvanized steel, (2) phosphobronze, (3) yellow brass, (4) aluminum, and (5) stainless steel. There are several grades of stainless steel, the best of which are relatively immune to corrosion. Protection is afforded by (a) diluting the fertilizer and (b) minimizing the period of contact with immediate, thorough rinsing after the application of chemicals. Avoid using materials containing heavy metals.

The steps in table 11–35 are for estimating the fertilizer application through a sprinkle system. Examples included are for applying urea-ammonium nitrate with 32 percent N and weighing 11.0 lb/gal through a 1/4-mile side-roll with 60 ft moves and through a 1/4 mile center pivot.

Applying Soil Amendments

Various soluble soil amendments, such as gypsum, sulphuric 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.

Applying Pesticides

Pesticides include herbicides, insecticides, fungicides, rodenticides, fumigants, and similar substances. The sale and use of these materials are 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, do not use or experiment with them through sprinkle systems. Many people believe there is great potential for this method of pest control, especially through center-pivot and fixed systems, but more research is needed.

Table 11-35.—Steps for estimating fertilizer application through sprinkle systems

Step	Periodic move	Continuous move
1. Decide on amount of nitrogen to apply	40 lb/ac	30 lb/ac
2. Select kind of nitrogen fertilizer and % N	32%	32%
3. Determine gallons (or pounds) per acre[1]	11.4 gal/ac	8.5 gal/ac
4. Determine number of acres irrigated per set or turns[2]	1.82 ac	125.7 ac
5. Determine the gallons (or pounds) required per set or turn	20.7 gal	1,068 gal.
6. Determine the length of the application time[3]	1 hr	24 hr
7. Calculate the required fertilizer solution injection rate[4]	21 gph	44.5 gph

[1] Dry fertilizers must be dissolved and put in a liquid form in order to be injected continuously into the system (40/0.32)/11 = 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.

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.

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; for pH adjustment and for 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. Wastewaters from food processing plants generally require more extensive pretreatment such as removal of solids, greases, and oils and adjustments in pH.

Design Considerations

Major concerns for land application of wastewaters with sprinkle systems are that the wastewater be of good quality and be 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 iph. The total application per week can vary between 1 and 4 in, with the higher application during the summer months. There should be a rest period between applications, however.

Woodland 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, it is important to 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 lb/ac per year for corn to 700 lb/ac per year for coastal Bermudagrass. Nitrogen application in excess of plant use can result in leaching of nitrate and pollution of the ground water.

Hardware

Most land disposal sprinkle systems use single-nozzle sprinklers. This reduces nozzle clogging problems and also results in a lower application rate. If systems are designed to operate during freezing temperatures, sprinklers that will operate under these conditions should be selected. 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. Where 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 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. Effluents 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.

Frost Protection

Sprinkle irrigation can be used for frost protection as discussed in *Capacity Requirements* for fixed systems. 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. The application rate and system capacity requirements for different levels of protection were presented earlier. Since an application rate of about 0.1 iph is usually sufficient, small single-nozzle sprinklers are satisfactory; however, double-nozzle sprinklers can be used by plugging one nozzle. Nozzle sizes from 3/32 to 1/4 in have been successfully used for overhead frost protection, with the size depending on the spacing.

Short-duration, light-radiant frosts (down to 28° or 29° F) can be protected against with under-tree misting or by cycling an overhead system with 2- to 4-min applications every 4 to 8 mins so that half the system is always operating. Such systems require about 25 to 30 gpm per acre, half as much water as is needed through continuously operating full coverage systems.

Usually wind speeds are very low during periods when frost protection is possible. Therefore, wetted diameters taken from manufacturers' catalogues or from table 11–13 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 as shown in figure 11–22. Sprinkler pressures should be maintained on the high side of the recommended operating range, and rotation speeds of impact sprinklers should be 1 rpm or faster for best results.

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 water available to be frozen, the temperature will be held at 32°F, higher than 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°F. 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°. Therefore, for adequate protection, one should continue to apply water until the air temperature is above 32°F, 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 with 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°. 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.

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 nine 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 sensitive 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°F the buds will show signs of development. The rate of development increases as the temperature increases until the ambient air temperature reaches 77°F. Thereafter the rate of development does not change appreciably with increasing temperature. The energy accumulation associated with bud development 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 discussed in *Capacity Requirements for Fixed Systems*.

The amount of evaporative cooling that takes place on bare limbs depends on: (a) the temperature of the tree buds, (b) the difference in vapor pressure between the bud surface and the air, and (c) the rate at which evaporated water is removed from the boundary layer by diffusion or by wind currents. 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:

1. Overtree 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.

2. Starting the sprinkler on the day when the mathematical model predicts winter rest is completed minimizes guesswork, provides maximum protection, and saves water.

3. 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.

4. In the early spring, less water is required to provide adequate cooling and protection. Water can be saved if (a) the off portion of the watering cycle is long in the early spring and is decreased as daytime temperatures rise, (b) a smaller nozzle is used in impact sprinklers in the early spring, and (c) pump output is low in the early spring and is increased as daytime temperatures rise.

5. Impact sprinklers, with 9/64-in nozzles on spacings of 40 x 50 ft operating at 40 psi and cycled on and off each 2 min have given good protection under most conditions.

6. 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.

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 2 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. The small amounts of water intermittently applied cool the air and plant, raise the humidity, and in theory improve the produce 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. The management and value of cooling systems, however, need further study.

On low crops and vines, a 3-min application at 0.1 iph every 15 min has usually been adequate to reduce temperature 10° to 20°F when the humidity is 20 to 40 percent and the air temperature is over 95°F. On larger trees, a 6-min application every 30 to 36 min has been satisfactory. Foliar cooling is possible only with *very high* quality water. The capacity requirements and system design procedures of fixed systems that are designed for foliar cooling are discussed in *Capacity Requirements for Fixed Systems.*

System design procedures follow the general guidelines presented in *Design Procedures.*

Installation and Operation of Sprinkle Systems

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, the dealer, the 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 that includes a map of the design area or areas showing the location of the water supply and pumping plant; the location of supply lines, main lines, and submains; the location and direction of movement of lateral lines; the spacing of sprinklers; and the pipe sizes and length of each size required. While it is not necessary to furnish the farmer with 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 SCS engineers, and then purchase equipment that is entirely different from that specified in the plans. While SCS personnel do not have any responsibility for or control over the purchase of sprinkler equipment by the farmer, it is important, nevertheless, to emphasize to the farmer the necessity of purchasing a satisfactory system. A sprinkle 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 main lines and laterals, the spacing of sprinklers, the movement of lateral lines, the time of lateral operation, and the maintenance of design operating pressures. He also should be shown how to estimate soil-moisture conditions in order to determine when irrigation is needed and how much water should be applied.

Ideally, irrigation scheduling should be managed so that optimum 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. Computerized scheduling services based on climatic demand prove to be an ideal tool for managing sprinkle systems.

Appendix

Sprinkle Abbreviations

A	design area (acres)
B	nozzle size (1/64 in)
BHP	brake horsepower (hp)
C	friction coefficient of pipe
CE	present annual energy cost of system operation ($)
CE′	annual energy cost of overcoming head loss ($)
CI	coarseness index (%)
CRF	capital recovery factor
CU	coefficient of uniformity (%)
CU_a	coefficient of uniformity for alternate sets (%)
D	inside diameter of pipe (in)
d	gross depth of application (in)
d′	daily gross depth of application required during peak moisture use period (in)
DU	distribution uniformity (%)
DU_a	distribution uniformity for alternate sets (%)
E	elevation difference (ft)
E_h	application efficiency of lower half (%)
E_p	pump efficiency (%)
E_q	application efficiency of the low quarter (%)
e	equivalent annual rate of energy escalation (decimal)
EAE(e)	equivalent annualized cost factor of escalating energy
ET	crop water consumption (in/day)
F	multiple outlet reduction coefficient
f	time allowed for completion of one irrigation (days)
H_e	total head change due to elevation (ft)
H_f	total head loss due to pipe friction (ft)
$H_{f\ell}$	limit of friction loss in length of pipe (ft)
h_e	head change due to elevation (ft)
h_f	head loss due to pipe friction (ft)
I	average application rate (iph)
I′	preliminary application rate (iph)
I_i	instantaneous application rate (iph)
I_t	approximate actual application rate from a traveling sprinkler (iph)
i	annual interest rate (decimal)
J	head loss gradient (ft/100 ft)
J_a	allowable headloss gradient (ft/100 ft)
K	resistance coefficient of fitting or valve
K_{cp}	discharge coefficient of a center pivot
K_d	combined sprinkler and nozzle discharge coefficient
K_f	Skobey friction coefficient
K_s	coefficient or function of I, S_ℓ and k_d
L	length of pipe (ft)
L′	length of pivot to last drive unit (ft)
M	irrigation system cost ($)
MAD	management allowable depletion (%)
N	number of outlets (may be laterals off mainline or sprinklers operating off laterals)
N_n	minimum usual number of sprinklers operating
N_x	maximum usual number of sprinklers operating
n	number of years in life cycle
P	nozzle operating pressure (psi)
P_a	average sprinkler pressure (psi)
P_{cp}	inlet pressure measured at the top of the pivot point (psi)
P_{cv}	pressure loss at the control valve (psi)
P_e	pressure change due to elevation (psi)
P_f	pressure loss due to pipe friction (psi)
P_m	pressure required at lateral inlet (psi)
P_n	minimum sprinkler pressure (psi)
P_r	pressure required to lift water up risers (psi)
P_x	maximum sprinkler pressure (psi)
PW(e)	present worth of escalating energy costs ($)
Q	system discharge capacity (gpm)
Q_r	pivot lateral flowrate at r (gpm)
Q_s	total system capacity (gpm)
q	sprinkler discharge (gpm)
q_a	average sprinkler discharge (gpm)
q_g	end gun discharge (gpm)
q_r	sprinkler discharge at r (gpm)
R	maximum radius irrigated when corner system or end sprinkler is in operation (ft)
R_e	effective portion of applied water (%)
R_w	radius of pivot to the location of the weighted average elevation (ft)
r	radius from pivot to point under study (ft)
S_a	angular segment wetted by sprinkler jet (degrees)
S_ℓ	spacing of sprinklers along laterals (ft)
S_m	spacing of laterals along mainline (ft)
S_r	sprinkler spacing on pivot lateral (ft)

T	actual operating time (hr/day)
t	wetted radius (ft)
TDH	total dynamic head (ft)
U	present annual power cost ($)
U′	equivalent annual energy cost ($)
V	velocity of flow (ft/s)
v	travel speed of end drive unit (ft/s)
W	towpath spacing (ft)
w	wetted width of water pattern (ft)
WHP	water horsepower (hp)
ω	portion of circle receiving water (degrees)
X	length of smaller pipe (ft/100 ft)
Y	length of pipe of specified diameter

Sprinkle Equations

11-1 $$Q = \frac{453\ Ad}{fT}$$

11-2 $$I = \frac{96.3 \times q}{S_l \times S_m}$$

11-2a $$I_i = \frac{96.3 \times q}{\pi (R_j)^2 \times S_a/360°}$$

11-3 $$DU = \frac{\text{Average low-quarter depth of water received}}{\text{Average depth of water received}} \times 100$$

11-4 $$CU = 100\ (1.0 - \frac{\Sigma X}{mn})$$

11-4a $$CU \cong \frac{\text{Average low-half depth of water received}}{m} \times 100$$

11-5a $$CU = 100 - 0.63\ (100 - DU)$$

11-5b $$DU = 100 - 1.59\ (100 - CU)$$

11-6a $$CU_a = 10\ \sqrt{CU}$$

11-6b $$DU_a = 10\ \sqrt{DU}$$

11-7 $$CI = \frac{P^{1.3}}{B}$$

11-8 $$R_e = \frac{(CI-7)}{10} (R_e)_c + \frac{(17-CI)}{10} (R_e)_f$$

11-9 $$E_q = DU \times R_e$$

11-10 $$E_h = CU \times R_e$$

11-11a $$\text{System } DU = DU \times (1 - \frac{P_x - P_n}{5\ P_a})$$

11-11b $$\text{System } CU = CU \times (1 - \frac{P_x - P_n}{8\ P_a})$$

11-12 $$q = K_d \sqrt{P}$$

11-13a $$q = q' \sqrt{P/P'}$$

11-13b $$P = P' (q/q')^2$$

11-14a $$N_n = \frac{Q}{q_a}$$

11-14b $$Q = N_x \times q_a$$

11-15 $$J = \frac{h_f\ 100}{L} = 1050\ (\frac{Q}{C})^{1.852} D^{-4.87}$$

11-16a $$F = \frac{1}{m+1} + \frac{1}{2N} + \frac{\sqrt{m-1}}{6N^2}$$

11-16b $$F = (\frac{2N}{2N-1})(\frac{1}{m+1} + \frac{\sqrt{m-1}}{6N^2})$$

11-17a $$h_f = JFL/100$$

11-17b $$P_f = \frac{JFL}{231} = h_f/2.31$$

11-18a $$J_a = \frac{0.20\ P_a \times 2.31}{L/100 \times F}$$

11-18b $$J_a = \frac{(0.20\ P_a - P_e) \times 2.31}{L/100 \times F}$$

11-18c $$J_a = \frac{(0.20\ P_a + P_e) \times 2.31}{L/100 \times F}$$

11-19a $$P_m = P_a + 3/4\ P_f + P_r$$

11-19b $$P_m = P_a + 3/4\ P_f + 1/2\ P_e + P_r$$

11-19c $$P_m = P_a + 3/4\ P_f - 1/2\ P_e + P_r$$

11-20a $P_m = P_a + 2/3\ P_f + P_r$

11-20b $P_m = P_a + 2/3\ P_f + 1/2\ P_e + P_r$

11-20c $P_m = P_a + 2/3\ P_f - 1/2\ P_e + P_r$

11-21 $P_f = P_{f(1+2)}$ (for D_1) $- P_{f(2)}$ (for D_1) $+ P_{f(2)}$ (for D_2)

11-22a $P_m = P_a + P_f + P_r + P_{cv}$

11-22b $P_m = P_a + P_f + P_e + P_r + P_{cv}$

11-22c $P_m = P_a + P_f - P_e + P_r + P_{cv}$

11-23a $J = \frac{h_f}{L/100} = 0.133 \frac{Q^{1.75}}{D^{4.75}}$ (for D < 5 in)

11-23b $J = \frac{h_f\ 100}{L} = 0.100 \frac{Q^{1.83}}{D^{4.83}}$ (for D > 5 in)

11-24 $J = \frac{h_f\ 100}{L} = \frac{K_f}{10} \frac{V^{1.9}}{(D/12)^{1.1}}$

11-24a $H_{f1} = X\ J_2 + (L_1 - X)\ J_1$

11-24b $X = \frac{H_{f1} - J_1 L_1}{J_2 - J_1}$

11-25a $H_{f2} = J_1\ L_{d1} + J_2 L_{d2} + J_3\ (L_2 - Y) + J_4 Y$

11-25b $Y = \frac{H_{f2} + J_1 L_{d1} - J_2 L_{d2} - J_3 L_{d2}}{J_4 - J_3}$

11-26 $PW(e) = [\frac{(1+e)^n - (1+i)^n}{(1+e) - (1+i)}] \times [\frac{1}{(1+i)^n}]$

11-27 $EAE(e) = [\frac{(1+e)^n - (1+i)^n}{(1+e) - (1+i)}] \times [\frac{i}{(1+i)^n - 1}]$

11-28 $CRF = \frac{i(1+i)^n}{(1+i)^n - 1}$

11-29 $U = \frac{1{,}000 \text{ hr/yr} \times \$0.07/\text{BHP-hr}}{0.75 \text{ WHP/BHP}}$

11-30 $WHP(6-8) = \frac{\$10.70/100 \text{ ft-yr}}{\$138.60/\text{WHP-yr}} = 0.077 \text{ WHP/100 ft}$

11-31 $V = 0.4085 \frac{Q}{D^2}$

11-32 $CE' = \frac{EAE\ U\ Q_s}{3{,}960} H_f$

11-33 $h_f = K \frac{V^2}{2g}$

11-34 $\frac{V^2}{2g} = 0.002592 \frac{Q^2}{D^4} = \frac{Q^2}{386\ D^4}$

11-35a $S_m = \frac{96.3\ K_d \sqrt{P}}{I - S_l}$

11-35b $S_m = K_s \sqrt{P}$

11-36 $BHP = \frac{Q_s \times TDH}{3{,}960\ E_p/100}$

11-37 $CE = \frac{U\ Q_s\ TDH}{3{,}960}$

11-38a $R_e = \frac{\text{average catch rate (or depth)}}{\text{application rate (or depth)}}$

11-38b $R_e = \frac{\text{average catch rate}}{96.3\ q/(S_l \times S_m)}$

11-39 $I_t = \frac{96.3\ q}{\pi(0.9t)^2} \times \frac{360}{\omega}$

11-40 $d = \frac{1.605\ q}{W\ S}$

11-41a acres covered per hour $= \frac{W\ S}{726}$

11-41b acres irrigated per 1/4-mile run $= \frac{W}{33}$

11-42a $Q = 18.9\ A\ d'$

11-42b $Q = \frac{R^2 d'}{734}$

11-42c $Q = \frac{453A\ d'}{T}$

11-43a $I = \frac{2(96.3)\ r\ Q}{R^2\ w}$

11-43b $I_x = \frac{4}{\pi} \frac{2(96.3) r\ Q}{R^2\ w}$

11-44 $q_r = r\ S_r \frac{2\ Q}{R^2}$

11-45 $Q_r = Q\ (1 - \frac{r^2}{R^2})$

11-46 $q_g = Q(1 - \frac{L^2}{R^2})$

11-47 $(H_f)_{cp} = 5.7\ L\ (\frac{Q}{C})^{1.852} D^{-4.87}$

11-48a $(H_f)_{cp} = (H_f)_R - (H_f)_{R-L}$

11-48b $(H_f)_{cpg} = 5.7\ R'\ (\frac{Q}{C})^{1.852}\ D^{-4.87}$

11-49 $v = \frac{2\ \pi\ L'}{60\ fT}$

11-50 $Q_2 = K_{cp} \sqrt{P_{cp2}} = Q_1\ (\frac{P_{cp_2}}{P_{cp_1}})^{1/2}$

11-51a $R_w = \frac{L}{3Q}(2Q + q_g)$

11-51b $R_w = \frac{2L}{3} + \frac{L}{3}(1 - \frac{L^2}{R^2})$

11-52a $I = \frac{96.3q}{S_l\ w} = \frac{96.3\ Q}{wL}$

11-52b $I_x = \frac{4}{\pi} \frac{96.3\ q}{S_l\ w} = \frac{122.6\ q}{S_l\ w}$

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