11.1 Introduction

At this point we know how crops use water and have determined the amount of irrigation needed in the near term. We understand how much water can be supplied from ground and surface water sources. We need to know how to apply that water to our field. Many producers have chosen to utilize sprinkler irrigation. So now we need to determine how sprinkler systems operate and think about how to manage them for efficient water use. Questions to answer include how large of a sprinkler nozzle is required, how rapidly does the system apply water, and therefore, how many hours should I operate the system? How much pressure does our pump need to provide? What do we need to do to achieve uniform distribution of water across the field?

Irrigation water is often applied using sprinkler systems. In fact, much of the growth in irrigated area in the U.S. during the past two decades has been due to development of sprinkler irrigation. Sprinkler irrigation has expanded because of the ability to irrigate many crops and landscapes efficiently that could not be irrigated effectively with surface irrigation. Advancements in controller technology have allowed automation of some sprinkler systems to further enhance efficiency and minimize labor inputs. This chapter focuses on the fundamentals of sprinkler irrigation while the following chapters focus on specific types of sprinkler systems.

The National Engineering Handbook from the USDA-NRCS (2016) and the chapter by Martin et al. (2007) are references that provide detailed analysis, description of standard practices, and equipment specifications for sprinkler systems.

11.2 System Components

Sprinkler devices, frequently called heads (Figure 11.1), are the nucleus of sprinkler systems. Sprinkler devices consist of a sprinkler body that may be stationary or rotate due to water pressure. The water exits through a nozzle installed in the sprinkler body. The nozzle is smaller than the pipe leading to the sprinkler or the sprinkler body itself. The small diameter causes pressure to build in the pipe and sprinkler body. The discharge, flow rate, of water through the nozzle is related to the amount of pressure and the diameter or size of the nozzle.

One sprinkler shown in Figure 11.1 is an impact sprinkler because the water from the nozzle sprays onto the spoon of the sprinkler arm. The impact of the jet on the spoon causes the arm to rotate away from the jet. The arm is connected to a spring that stores energy as the arm rotates. The spring decelerates the arm rotation, eventually causing the arm to stop. The energy stored in the spring is then released to accelerate in the opposite direction. As the arm returns to its original position it strikes the sprinkler body. This impact causes the sprinkler body to rotate through a small angle.

Many impact sprinklers use two nozzles. The nozzle that causes the sprinkler arm to rotate is the drive or range nozzle (Figure 11.1). The second nozzle often has a slit to enhance breakup of the water jet. This is called a spreader nozzle and it increases the amount of water applied close the sprinkler while the range nozzle throws water further.
Impact sprinklers were invented in the 1930s and became the standard type of sprinkler device. Spray head devices were later developed where the jet impinges onto a plate or pad (Figure 11.1). The jet is divided into either several streams or a smooth surface of water. Some devices spray onto pads that rotate or vibrate due to the impact of the water jet. Spray pad devices are used extensively on center pivot and linear-move irrigation systems.

Low-angle impact sprinklers and spray heads were developed for systems that position the device above the crop. The low angle reduces drift and evaporation. Large or high-volume gun sprinklers are operated at a high pressure and are designed to throw water hundreds of feet. Only one gun is generally used at a time. The gun often travels across the field in a continuous motion. Some sprinklers are also made to rotate throughout part of a circle. The part-circle sprinkler has a special mechanism so that a latch engages when the sprinkler has rotated to the desired angle. It then rotates in the opposite direction to the original position. The part-circle sprinkler has been very useful at the edges of fields, on guns, and in landscape and turf applications where irregularly shaped areas are irrigated.

The nozzle is used to build pressure causing a water jet to discharge from the device. Several properties of that jet are important for successful operation of a sprinkler system. It is desirable to have nozzles that throw water as far as possible using as little pressure as possible. In addition, it is desirable for the droplet to breakup so that the application is uniform. Large drops are often desirable because they have smaller drift or evaporation issues; however, large droplets can pack unprotected soil surfaces. Trade-offs often occur as some criteria are contradictory.
Many types of nozzles have been developed to accommodate these objectives (Figure 11.2). The original, and still popular, nozzle was the straight bore nozzle. It is usually made of brass and machined to be very smooth to reduce turbulence in the nozzle. The hole in the center of the nozzle matches commercially available drill bit sizes. Small plastic inserts called straightening vanes are sometimes used upstream of the nozzle to reduce turbulence and increase the distance of throw. Vanes are frequently built into the body of spray devices.

In the 1970s an energy crisis occurred causing the cost of sprinkler irrigation to increase dramatically. As illustrated in Chapter 8, decreasing pump pressure can reduce operating costs. When straight bore nozzles are operated at low pressure, the jet does not breakup very well leading to poor uniformity and soil compaction. As a result, low-pressure nozzles were developed. Some are shown in Figure 11.2.

Water is supplied to the lateral from a pipeline called a mainline (Figure 11.3). The sprinkler lateral may be located below the ground surface as with solid-set and turf irrigation systems. For some systems, the lateral lays on the soil surface, while for continuously moving systems the lateral is carried above the soil surface by a series of towers. A smaller diameter pipe—the riser—is used to conduct water from the lateral to the sprinkler device for some systems (Figure 11.3). Risers are primarily used to position the sprinkler above the crop and/or structural elements of the irrigation system to prevent canopy or structural interference with the jet.

Water is supplied to the lateral with the mainline (Figure 11.3) which is an enclosed pipeline conveying water from the source at the inlet of the mainline to outlet of the mainline at the lateral. The mainline may serve several laterals simultaneously. The mainline is
under pressure for the duration of the time required to irrigate the field. It must be protected from pressure surges, vacuums, and other factors to prevent damage or leaks. The mainline is generally larger in diameter than the lateral since it may carry more water than a single lateral, and the pressure loss due to friction would be larger for the mainline than for a lateral of equal length.

Many systems are designed so that sprinklers are spaced at equal intervals along the lateral. The spacing along the lateral is denoted $S_L$, while the distance along the mainline between successive laterals, or sets of the same lateral, is denoted $S_m$ (Figure 11.3). Sprinklers may be laid out in a rectangular or square orientation. For some permanently installed sprinkler systems heads may be placed in a triangular orientation as shown in Figure 11.3. In this orientation the sprinklers are placed an equal distance $S$ from adjacent sprinklers in an equilateral orientation.

The diameter of coverage of the individual sprinkler is a critical property for the system (Figure 11.3). Sprinklers and laterals need to be placed close enough to overlap providing uniformity; therefore, sprinklers and laterals are spaced closer than the diameter of coverage. The crosshatched areas in Figure 11.3 are representative areas for computing the rate and uniformity of water application. The area for the equilateral triangular orientation is $A = 0.433 S^2$ while the area for rectangular or square orientations is $A = S_m \times S_L$.

Figure 11.3. Components and layout of typical sprinkler systems.
11.3 Sprinkler Performance

The performance of sprinkler systems depends on the operation of individual sprinkler heads. The goal of sprinkler irrigation is to apply water uniformly at a rate that does not cause runoff or erosion. The system should meet crop water requirements and attain the highest practical efficiency—and of course must be cost-effective.

The discharge, or volume flow rate of water, leaving the nozzle is important and can be described by:

$$q_s = 29.82 \cdot C_d \cdot D^2 \cdot \sqrt{P}$$

(11.1)

where:
- $q_s$ = discharge through the nozzle (gallons per minute, gpm),
- $C_d$ = discharge coefficient for the sprinkler head,
- $D$ = inside diameter of the nozzle orifice (inches),
- $P$ = pressure of the water at the inlet to the sprinkler device (pounds per square inch, psi); and
- 29.82 is a unit conversion and geometric constant.

Example 11.1

The discharge from a sprinkler depends on the pressure at the nozzle and the diameter of the nozzle orifice. Would a 20% increase in nozzle diameter produce more flow than a 20% increase in pressure?

Given: A straight bore nozzle is used in a sprinkler. The discharge is 10 gpm.

Solution:

Let $q_{s1} = 10$ gpm be the initial flow rate.

Use Equation 11.1 to develop a term called the discharge ratio where 2 denotes the new condition and 1 the original condition.

$$\frac{q_{s2}}{q_{s1}} = \left(\frac{D_2}{D_1}\right)^2 \cdot \frac{\sqrt{P_2}}{\sqrt{P_1}}$$

For a 20% increase in diameter $D_2 = 1.2 \cdot D_1$ and $P_2 = P_1$

$$q_{s2} = q_{s1} \left(\frac{1.2 \cdot D_1}{D_1}\right)^2 = 1.44 \cdot q_{s1} = 14.4 \text{ gpm}$$

So, a 20% increase in diameter provides a 44% increase in flow.

For a 20% increase in pressure $P_2 = 1.2 \cdot P_1$ and $D_2 = D_1$

$$q_{s2} = q_{s1} \sqrt{\frac{1.2 \cdot P_1}{P_1}} = 1.1 \cdot q_{s1} = 11 \text{ gpm}$$

So, a 20% increase in pressure only changes the discharge by 10%.

Changing the nozzle size increases flow more than an equal percentage change of pressure.

The value of the discharge coefficient is about 0.96 but depends on the design of the nozzle and sprinkler head. The inside diameter of nozzles is customarily referred to as the nozzle size. Performance for a range of nozzle sizes and pressures is summarized in Table 11.1 for straight bore nozzles. Some manufacturers produce nozzles sized by the diameter in 64ths of an inch; others may use 128ths of an inch. For example, a nozzle diameter of one-quarter inch is referred to as a size of 16 (Table 11.1) or 32 depending on which system is used. Table 11.1 represents the typical discharge for a broad range of sprinkler nozzles. The discharge from a specific design of nozzle and sprinkler may vary from data presented in Table 11.1. Data from the relevant manufacturer should be used for specific systems. The total discharge from a sprinkler head with two nozzle outlets is the sum of the discharge from each nozzle for that pressure. The discharge for pressures between those listed in Table 11.1 can be determined by interpolation.
The second important characteristic of sprinkler performance is the diameter of coverage (also referred to as wetted diameter) as illustrated in Figures 11.3 and 11.4. The diameter of coverage is the maximum diameter wetted by the sprinkler at a rate that is significant for the intended use of the sprinkler. For example, the diameter of coverage for agricultural sprinklers is usually determined to be the maximum radial distance where the water application rate equals 0.01 inches per hour. Usually, the wetted diameter is measured in an indoor laboratory with no wind. The diameter of coverage is affected by the design of the sprinkler body and nozzle. Representative diameters of coverage are given in Table 11.2 for impact sprinklers with straight bore nozzles. The data are for sprinklers where the water jet exits from the sprinkler head at an angle of 23° above the horizon for the range nozzle. The diameter may vary for other designs and should be determined from data by the manufacturer. The diameter of coverage also depends on the height of the device above the crop or the ground surface; therefore, the intended usage of the device is important.

The straightening vanes shown in Figure 11.2 are used to reduce turbulence in the sprinkler barrel; thus, producing a larger diameter of coverage. Straightening vanes increase the diameter of coverage from 5% to as much as 20% depending on the design of the sprinkler head and the specific nozzle.

Nozzles are designed to operate within a specified pressure range. When used outside that range the performance changes in an undesirable way. The patterns shown in Figure 11.5 illustrate the impact of pressure on the distribution of water. When the pressure is within the proper range, the pattern is nearly elliptical with distance from the sprinkler. When the pressure is too high the water jet breaks up into a high percentage of small drops. In some cases, the jet atomizes into very small drops.

<table>
<thead>
<tr>
<th>Nozzle Size</th>
<th>Nozzle Pressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>in</td>
<td>25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100</td>
</tr>
<tr>
<td>3/32</td>
<td>1.2 1.4 1.6 1.7 1.8 1.9</td>
</tr>
<tr>
<td>7/64</td>
<td>1.7 1.9 2.0 2.2 2.3 2.4 2.6</td>
</tr>
<tr>
<td>1/8</td>
<td>2.2 2.5 2.7 2.9 3.0 3.2 3.4 3.5 3.6 3.8 3.9 4.0</td>
</tr>
<tr>
<td>9/64</td>
<td>2.8 3.1 3.4 3.6 3.8 4.0 4.2 4.4 4.6 4.8 5.0 5.1</td>
</tr>
<tr>
<td>5/32</td>
<td>3.5 3.9 4.2 4.5 4.7 5.0 5.2 5.5 5.7 5.9 6.1 6.3</td>
</tr>
<tr>
<td>11/64</td>
<td>4.3 4.7 5.1 5.4 5.7 6.0 6.3 6.6 6.9 7.2 7.4 7.6</td>
</tr>
<tr>
<td>3/16</td>
<td>5.1 5.6 6.0 6.4 6.8 7.2 7.5 7.9 8.2 8.5 8.8 9.1</td>
</tr>
<tr>
<td>13/64</td>
<td>6.0 6.5 7.1 7.6 8.0 8.4 8.9 9.2 9.6 10.0 10.3 10.7</td>
</tr>
<tr>
<td>7/32</td>
<td>6.9 7.6 8.2 8.8 9.3 9.8 10.3 10.7 11.2 11.6 12.0 12.4</td>
</tr>
<tr>
<td>15/64</td>
<td>7.9 8.7 9.4 10.1 10.7 11.2 11.8 12.3 12.8 13.3 13.8 14.2</td>
</tr>
<tr>
<td>1/4</td>
<td>9.0 9.9 10.7 11.4 12.1 12.8 13.4 14.0 14.6 15.1 15.7 16.2</td>
</tr>
<tr>
<td>17/64</td>
<td>10.0 11.2 12.1 12.9 13.7 14.4 15.1 15.8 16.5 17.1 17.7 18.3</td>
</tr>
<tr>
<td>9/32</td>
<td>11.0 12.5 13.5 14.5 15.4 16.2 17.0 17.7 18.5 19.2 19.8 20.5</td>
</tr>
<tr>
<td>5/16</td>
<td>14.0 15.5 16.7 17.9 19.0 20.0 21.0 21.9 22.8 23.6 24.5 25.3</td>
</tr>
<tr>
<td>11/32</td>
<td>17.0 19.0 20.0 22 22 24 25 26 28 29 30 31 32 32 33 34</td>
</tr>
<tr>
<td>3/8</td>
<td>20.0 22.0 24 26 27 29 30 32 33 34 35 36 38 39 40 41</td>
</tr>
<tr>
<td>13/32</td>
<td>23.0 26.0 28 30 32 34 35 37 38 40 41 43 44 45 47 48</td>
</tr>
<tr>
<td>7/16</td>
<td>27.0 30.0 33 35 37 39 41 43 45 46 48 50 51 53 54 55</td>
</tr>
<tr>
<td>15/32</td>
<td>30.0 31.0 35 38 40 43 45 47 49 51 53 55 57 59 60 62 64</td>
</tr>
<tr>
<td>5/8</td>
<td>33.0 37 40 43 45 48 50 52 54 57 58 60 62 64 66 68</td>
</tr>
<tr>
<td>17/32</td>
<td>38.0 42.0 45 48 51 54 57 59 62 64 66 68 70 72 74 76</td>
</tr>
<tr>
<td>9/16</td>
<td>42.0 47 51 54 57 60 64 66 69 72 74 76 79 81 83 86</td>
</tr>
<tr>
<td>5/8</td>
<td>52.0 58 62 67 71 75 78 82 85 88 92 94 97 100 103 105</td>
</tr>
<tr>
<td>11/16</td>
<td>63.0 70 76 81 84 90 95 99 103 106 110 114 117 121 124 127</td>
</tr>
</tbody>
</table>
Table 11.2. Diameter of coverage (ft) for impact sprinklers with straight bore nozzles.\(^{[a]}\)

<table>
<thead>
<tr>
<th>Nozzle Size</th>
<th>Nozzle Pressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>in 64(^{th}) in</td>
<td>25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100</td>
</tr>
<tr>
<td>3/32</td>
<td>6 64 66 68 69 70 71 72</td>
</tr>
<tr>
<td>7/64</td>
<td>7 65 67 69 70 71 72 73</td>
</tr>
<tr>
<td>1/8</td>
<td>8 78 79 80 81 82 83 84 85 86 86 87 87</td>
</tr>
<tr>
<td>9/64</td>
<td>9 80 81 82 83 84 85 86 87 88 89 90 91</td>
</tr>
<tr>
<td>5/32</td>
<td>10 82 85 87 88 89 90 91 92 93 94 95 96</td>
</tr>
<tr>
<td>11/64</td>
<td>11 83 88 90 92 93 95 96 97 98 99 100 101</td>
</tr>
<tr>
<td>3/16</td>
<td>12 85 91 94 96 98 100 102 103 104 105 106</td>
</tr>
<tr>
<td>13/64</td>
<td>13 87 91 97 100 103 105 107 109 111 113 114 116 117</td>
</tr>
<tr>
<td>7/32</td>
<td>14 92 99 102 105 108 110 113 115 117 118 120 122</td>
</tr>
<tr>
<td>15/64</td>
<td>15 95 100 104 107 110 112 115 117 119 121 123 125</td>
</tr>
<tr>
<td>3/16</td>
<td>16 94 102 105 109 112 115 118 120 122 124 127 129</td>
</tr>
<tr>
<td>17/64</td>
<td>17 95 103 107 110 114 117 119 122 125 127 129 131</td>
</tr>
<tr>
<td>9/32</td>
<td>18 96 104 108 112 116 119 122 125 127 130 132 134</td>
</tr>
<tr>
<td>5/16</td>
<td>20 121 124 127 130 133 136 140 143 145 147 149 151</td>
</tr>
<tr>
<td>11/32</td>
<td>22 122 128 134 138 142 146 150 154 158 162 164 166 170 172 174 176</td>
</tr>
<tr>
<td>3/8</td>
<td>24 124 130 136 142 146 150 154 158 162 166 168 172 174 178 180 182</td>
</tr>
<tr>
<td>13/32</td>
<td>26 128 136 144 150 154 158 162 166 168 172 174 178 180 184 186 188</td>
</tr>
<tr>
<td>7/16</td>
<td>28 132 138 158 154 158 162 166 172 174 178 180 184 186 190 192 194</td>
</tr>
<tr>
<td>15/32</td>
<td>30 132 144 154 160 164 168 172 176 180 182 186 188 192 194 196 198</td>
</tr>
<tr>
<td>1/2</td>
<td>32 132 146 156 166 170 174 178 182 186 188 192 194 198 200 202 204</td>
</tr>
<tr>
<td>17/32</td>
<td>34 132 146 158 166 176 180 184 188 192 196 198 202 204 208 210 212</td>
</tr>
<tr>
<td>9/16</td>
<td>36 132 146 158 172 180 188 192 194 198 202 204 208 210 212 216 218</td>
</tr>
<tr>
<td>5/8</td>
<td>40 132 146 158 172 184 190 198 202 204 208 210 214 216 220 222 224</td>
</tr>
<tr>
<td>11/16</td>
<td>44 132 146 158 172 184 194 200 208 212 216 218 222 224 226 230 232</td>
</tr>
</tbody>
</table>

\(^{[a]}\) For a brass impact sprinkler where the exit angle of the range nozzle is 23° above the horizontal.
Small drops decelerate very quickly in the air and fall to the soil close to the sprinkler, giving a reduced diameter of coverage and higher application rate. When pressure is too low, the water jet does not breakup sufficiently and the sprinkler primarily wets an annular area located near the end of the diameter of coverage. Areas at the center of the circle receive little water. The diameter of coverage is also reduced with low pressures because the velocities of the droplets leaving the sprinkler are smaller. The net effect of low pressure is that a doughnut shaped pattern results with a dry area in the middle of the pattern near the sprinkler. Either too much or too little pressure will produce a poor distribution of water. The acceptable operating range for specific sprinklers is provided by the manufacturer and should be followed. Straightening vanes reduce droplet breakup, which can lead to a doughnut shaped pattern. Usually, the minimum operating pressure of sprinklers with vanes is higher than those without vanes to prevent the doughnut shaped pattern.

Sprinkler systems require that the water pattern from one sprinkler overlap with adjacent sprinklers. When the sprinklers are properly designed and located, the overlap pattern will be like that shown in Figures 11.3 and 11.6. The depth of water applied to a point is the sum of water from all sprinklers reaching that point. In Figure 11.6 the total depth would be \( d_1 + d_2 \) for the point shown. Some irrigators attempt to reduce costs by extending the spacing between laterals or between sprinklers on a lateral. When that is done, the overlap is inadequate and poor uniformity results. The upper portion of Figure 11.6 shows the water pattern where sprinklers are spaced a distance \( S_L \) between sprinklers. The

\[ \text{Figure 11.6. Illustration of the effect of sprinkler spacing on uniformity of water application.} \]
depth of application is relatively uniform. When the spacing is increased to $1.5 \times S_L$, the depth of application between the sprinklers decreases.

The lower and middle portions of Figure 11.6 show the three-dimensional distribution of water between sprinklers along and between laterals. The middle figure shows the distribution when sprinklers are spaced 40 ft apart along the lateral and 60 ft between laterals. The bottom figure shows the distribution when the spacing is increased to 50 ft along and 70 ft between laterals. The system was designed to apply 3 inches of water during a 10-hour application time with an operating pressure of 50 psi. The required sprinkler discharge for the 40 ft $\times$ 60 ft spacing is 7.48 gpm and 10.9 gpm for the 50 ft $\times$ 70 ft spacing. The diameter of coverage for the two spacings was 106 and 112 ft, respectively. The wider spacing leads to a poorer distribution with a peak depth centered in the representative area.

Overlap requirements have been developed for sprinkler systems. The recommendations depend on the wind speed and direction. Consider a plan view of the wetted pattern of a single sprinkler as shown in Figure 11.7. The pattern for calm conditions will be circular. As the wind speed increases the pattern is displaced downwind giving the elongated pattern. Note that the wetted pattern is not only displaced downwind, but also is narrower perpendicular to the direction of wind travel. This occurs because the wind blowing perpendicular to the water jet causes droplets to travel a curved path, originally perpendicular to the wind but later in a more downwind direction. The perpendicular wind may also cause the jet to breakup into a distribution with a higher percentage of smaller drops which do not travel as far.

The narrowing of the wetted pattern perpendicular to the wind direction has an important impact on sprinkler spacings and on the orientation of the lateral relative to the predominant wind during the irrigation season. The diagram in Figure 11.8 shows the effect of wind on two orientations of laterals relative to the wind direction. With no wind the individual sprinkler pattern is circular, and the laterals appear to have adequate overlap. When the laterals are oriented parallel...
to wind travel, the wind causes the wetted pattern from a sprinkler to narrow into a tighter pattern along the lateral. A dry zone may result between the laterals because of insufficient overlap. To adjust for this problem, more laterals would be needed with a smaller spacing between laterals. This leads to a more expensive system. When the laterals are oriented perpendicular to the wind as shown in Figure 11.8, the pattern of an individual sprinkler is still narrower due to the wind; however, now the spacing of sprinklers along the lateral is smaller than the spacing between laterals. Therefore, more overlap occurs and better uniformity results. At the same time, this is a more economical system because it is more efficient to install more sprinklers along a lateral, rather than install more laterals. The major point is that laterals should be laid out perpendicular to the pervading wind when possible.

The spacing of sprinklers and laterals depends upon wind conditions. Recommendations for maximum spacing of sprinklers along the lateral and between laterals is given in Table 11.3.

The rate of application from a sprinkler system is a major consideration. The representative areas for the rectangular and triangular sprinkler orientations shown in Figure 11.3 are used to compute the rate water is applied. One-fourth of the discharge from a sprinkler is applied into the rectangular area. Thus, the total water applied into the rectangular area is the sum of one-fourth of the flow from four sprinklers equaling the discharge from one sprinkler. Water from a sprinkler may be applied beyond the representative area; however, an adjacent sprinkler applies water into the area which offsets the overthrow from the original sprinkler. Therefore, the effective water discharge into the area is the discharge from one sprinkler. Thus, the application rate—volume per unit area per unit time—for sprinklers positioned in a rectangular spacing is given by:

$$A_r = \frac{96.3 \; q_s}{S_L \; S_m}$$

(11.2)

### Table 11.3: Maximum spacing of sprinklers.

<table>
<thead>
<tr>
<th>Average Wind Speed (mph)</th>
<th>Maximum Spacing Between Sprinklers on the Lateral</th>
<th>Maximum Spacing Between Laterals Along the Mainline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectangular Spacing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0–3</td>
<td>50% of diameter</td>
<td>60% of diameter</td>
</tr>
<tr>
<td>4–7</td>
<td>45% of diameter</td>
<td>60% of diameter</td>
</tr>
<tr>
<td>8–12</td>
<td>40% of diameter</td>
<td>60% of diameter</td>
</tr>
<tr>
<td>Square Spacing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0–3</td>
<td>55% of diameter</td>
<td>-</td>
</tr>
<tr>
<td>4–7</td>
<td>50% of diameter</td>
<td>-</td>
</tr>
<tr>
<td>8–12</td>
<td>45% of diameter</td>
<td>-</td>
</tr>
<tr>
<td>Equilateral Triangle Spacing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0–3</td>
<td>60% of diameter</td>
<td>[a]</td>
</tr>
<tr>
<td>4–7</td>
<td>55% of diameter</td>
<td>[a]</td>
</tr>
<tr>
<td>8–12</td>
<td>50% of diameter</td>
<td>[a]</td>
</tr>
</tbody>
</table>

[a] For an equilateral triangle pattern, the spacing between laterals is $0.866 \times$ sprinkler spacing.

### Example 11.2

Adequate overlap is necessary with sprinkler systems to ensure that the water application is reasonably uniform. Will the layout described below provide acceptable uniformity?

**Given:** Impact sprinklers with two nozzles (23° exit angle for range nozzle) are spaced 40 ft apart along a lateral. Laterals are spaced at intervals of 60 ft along the mainline.

- The nozzle sizes are 11/64 in $\times$ 3/32 in and the operating pressure is 50 psi.
- Wind in the area usually averages 5 mph.

**Solution:**

1. The diameter of coverage for the range nozzle (11/64 in) is 95 ft, from Table 11.2.
2. From Table 11.3 the maximum sprinkler spacing along the lateral is 45% of the diameter of coverage.

   $$\text{Maximum spacing along lateral} = 0.45 \times 95 = 43 \text{ ft}$$

   The maximum spacing between laterals is 60% of the diameter of coverage.

   $$\text{Maximum spacing between laterals} = 0.60 \times 95 = 57 \text{ ft}$$

   So, this layout just fails the criteria for the spacing between laterals in Table 11.3 and uniformity may be less than desired.

   A straightening vane for the nozzle would probably provide adequate coverage.
where: $A_r =$ the rate of water application (in/hr),
$q_s =$ the sprinkler discharge rate (gpm),
$S_L =$ spacing of sprinklers along the lateral (ft),
$S_m =$ spacing of laterals along the mainline (ft), and
96.3 is for unit conversion.

For a square spacing $S_L$ and $S_m$ are equal so that the denominator becomes $S_L^2$.

The effective water supply into a triangular space is half of the discharge from a sprinkler, i.e., a sprinkler applies water into six triangles surrounding the sprinkler. This yields the application rate of a system with sprinklers oriented in an *equilateral triangle* spacing as:

$$A_r = \frac{111.2 \cdot q_s}{S^2}$$  \hspace{1cm} \text{(11.3)}$$

where $S =$ the spacing of sprinklers in the triangular orientation and all other parameters are as previously defined.

The application rate of the sprinkler system is important for two reasons. First, the depth of water applied for a given time is proportional to the application rate:

$$d_g = A_r \cdot T_o$$  \hspace{1cm} \text{(11.4)}$$

where: $d_g =$ the gross depth of water applied per irrigation (in) and
$T_o =$ the actual time of operation (hr).

For example, if the application rate was 0.4 in/hr, then an irrigation that lasted 10 hours would apply 4 in of water. The time of operation ($T_o$) is the time that water is applied. The quantity of water determined from Equation 11.4 is a gross application and must be reduced by the application efficiency to determine the amount of water provided to the crop.

Second, when the application rate of the sprinkler system exceeds the infiltration rate of the soil, water will accumulate on the soil surface. If enough water accumulates, runoff will begin. The maximum application rate that is acceptable for different soils and slopes is summarized in Table 11.4. These are general recommendations and should be adjusted upward for production practices that enhance infiltration, especially where adequate crop residue protects the soil, and downward for practices that reduce infiltration.

**Table 11.4. Maximum recommended water application rates for soils (inches/hr).[a]**

<table>
<thead>
<tr>
<th>Slope (%)</th>
<th>Coarse Textured Soils (sands, fine sands, and loamy fine sands)</th>
<th>Medium Textured Soils (sandy loams, fine sandy loams, and silt loam soils)</th>
<th>Fine Textured Soils (silty clay loams, clay loams, and clayey soils)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil Surface Not Protected</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0–5</td>
<td>0.50–0.75</td>
<td>0.25–0.50</td>
<td>0.10–0.25</td>
</tr>
<tr>
<td>6–8</td>
<td>0.40–0.60</td>
<td>0.20–0.40</td>
<td>0.08–0.20</td>
</tr>
<tr>
<td>9–12</td>
<td>0.30–0.45</td>
<td>0.15–0.30</td>
<td>0.06–0.15</td>
</tr>
<tr>
<td>13–20</td>
<td>0.20–0.30</td>
<td>0.10–0.20</td>
<td>0.04–0.10</td>
</tr>
<tr>
<td>&gt; 20</td>
<td>0.10–0.20</td>
<td>0.05–0.10</td>
<td>0.02–0.05</td>
</tr>
<tr>
<td>Turfgrass or Heavy Residue Cover</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0–5</td>
<td>0.85–1.30</td>
<td>0.50–0.95</td>
<td>0.15–0.35</td>
</tr>
<tr>
<td>6–8</td>
<td>0.70–1.00</td>
<td>0.40–0.75</td>
<td>0.10–0.25</td>
</tr>
<tr>
<td>9–12</td>
<td>0.50–0.75</td>
<td>0.30–0.55</td>
<td>0.10–0.20</td>
</tr>
<tr>
<td>13–20</td>
<td>0.35–0.50</td>
<td>0.20–0.40</td>
<td>0.05–0.15</td>
</tr>
<tr>
<td>&gt; 20</td>
<td>0.15–0.35</td>
<td>0.10–0.20</td>
<td>0.03–0.05</td>
</tr>
</tbody>
</table>

[a] Based on recommendations of the Rain Bird Corporation and Pair et al., 1983.
### Example 11.3

A sprinkler irrigation system is used to irrigate a young row crop with an unprotected soil surface. The sprinkler spacing is 40 ft between sprinklers and 60 ft between the laterals. A pressure of 50 psi is available at the design location along the lateral. Wind in the region averages 5 mph during the irrigation season. The soil texture is silt loam. The sprinklers are brass impact sprinklers with straight bore nozzles and the range nozzle has an exit angle of 23° above horizontal.

Determine the smallest nozzle size that is acceptable and the application rate of the system.

Is this system acceptable for a silt loam soils with a slope of 2%?

**Given:**  
Sprinkler spacing 40 ft x 60 ft  
Soil is silt loam  
$P_a = 50$ psi  
Wind = 5 mph  
Brass impact sprinklers with straight bore and range nozzles at 23° angle

**Solution:**

a. The maximum spacing of sprinklers along the lateral is 45% of the diameter of coverage for a wind speed of 5 mph in Table 11.3. The maximum spacing between laterals is 60% of the diameter of coverage for that wind speed.

Since we know the actual spacing of the sprinklers and the lateral spacing, we need to determine the diameter of coverage ($d_c$) needed for this system:

$$d_c \text{ needed} = \text{maximum of } S_l/0.45 \text{ and } S_m/0.60 \text{ or }$$

$$d_c \text{ needed} = \text{maximum of } 40/0.45 = 89 \text{ ft and } 60/0.60 = 100 \text{ ft}.$$ 

The spacing of laterals along the mainline is the most limiting based on the criteria in Table 11.3.

Thus, a diameter of coverage of 100 feet is needed for sprinklers in this system.

From Table 11.2, a nozzle size of 3/16 inch will provide a diameter of coverage of 100 feet when operated at a pressure of 50 psi, so the nozzle should provide adequate overlap.

b. From Table 11.1, a 3/16-inch nozzle operated at 50 psi produces a discharge of 7.2 gpm.

Using Equation 11.2 the application rate would be:

$$A_r = \frac{96.3 \times q_s}{S_s \times S_m} = \frac{96.3 \times 7.2 \text{ gpm}}{40 \text{ ft} \times 60 \text{ ft}} = 0.29 \text{ in/hr}$$

The maximum recommended application rate for silty loam soil with little cover is between 0.25 and 0.5 in/hr (Table 11.4).

Therefore, the 3/16-inch nozzle meets the overlap and application rate limitations.

### 11.4 Lateral Design

Sizing laterals is fundamental to sprinkler irrigation. Laterals must be large enough to carry the needed flow without excessive pressure loss. The general criteria constraints the variation of sprinkler discharge along the lateral. The difference between discharge from the sprinkler with the largest flow to the sprinkler with the smallest flow should be less than 10% of the average discharge. Since discharge from a sprinkler is related to the square root of pressure, 10% discharge variation is equivalent to a maximum permissible pressure variation of 20% (i.e., since $q_0 \propto \sqrt{P}$ if the maximum discharge ratio is 1.1, then the maximum ratio for pressure variation would be $1.1^2 = 1.21$ or about 1.2).

Pressure varies along a lateral due to elevation changes and friction loss in the pipe and fittings. The pressure distribution along a lateral placed on level ground is illustrated in Figure 11.9. The pressure at the inlet of the lateral is determined by the pressure available from the mainline. The pressure loss in the first several lengths of the lateral is nearly the same as for a conveyance pipe without outlets along the pipe. However, as water is discharged from sprinklers the flow in the lateral decreases with distance. Ultimately, the flow in the last section of the lateral is that discharged from the last sprinkler. Of course, there is very little loss in the lateral for such a small flow.
The example in Figure 11.9 represents a 3-inch aluminum pipe lateral with sprinklers spaced 40 feet apart. The lateral is 800 feet long with 20 sprinklers averaging 8 gpm discharge per sprinkler. The friction loss in a 3-inch conveyance pipe 800-ft long with an inflow of 160 gpm is approximately 35 psi. Since the inlet pressure is 60 psi, the pressure at the end of the pipe is about 25 psi. The pressure loss in a lateral with the same pipe is only about 13 psi. The friction loss for this lateral is about 37% of the loss encountered in a conveyance pipe of the same diameter and inflow (the same as listed in Table 8.3 for 20 sprinklers). The average pressure along the lateral is about 50 psi and the average pressure occurs about 38% of the way along the lateral from the inlet. About 75% of the total head loss along the lateral occurs between the inlet and the point where the average pressure occurs.

Sprinkler systems are usually designed by selecting the nozzle size for the average pressure along the lateral. Then the pressures at the ends of the lateral are computed. The pressures for a lateral on level ground can be computed by:

\[
P_i = P_a + 0.75 P_l
\]

\[
P_d = P_a - 0.25 P_l
\]

where:
- \(P_i\) = pressure at the inlet into the lateral (psi),
- \(P_a\) = average pressure along the lateral (psi),
- \(P_d\) = pressure at the distal end of the lateral (psi), and
- \(P_l\) = pressure loss along the lateral (psi).

The maximum pressure loss along a lateral on the level is 20% of the average, or design, pressure of the lateral:

\[
\text{Max } P_l = 0.20 P_a
\]

When a lateral runs up or down hill, the change in elevation causes changes in pressure. An elevation change of 10 ft is equal to a pressure change of 4.3 psi. Thus, when laterals run downhill there is less pressure variation from the inlet to the distal end than for laterals on
level ground because the downslope provides some pressure increase. When laterals run up-hill, the pressure in the lateral drops because of friction and because of the change in elevation. Equations 11.5 and 11.6 can be adjusted to account for changes in elevation:

\[ P_i = P_a + 0.75 P_t - 0.5 \left( \frac{E_i - E_d}{2.31} \right) \] (11.8)

\[ P_d = P_a - 0.25 P_t + 0.5 \left( \frac{E_i - E_d}{2.31} \right) \] (11.9)

where: \( E_i \) = the elevation of the inlet to the lateral (ft) and \( E_d \) = the elevation of the distal end of the lateral (ft).

**Example 11.4**

Given: A sprinkler lateral designed for an average pressure of 50 psi has sprinkler heads with one 5/32-inch nozzle.

The sprinkler lateral is 4-inch diameter aluminum pipe (3.90 in inside diameter) with sections 30 feet long. The lateral is 1,320 feet long.

Find: The pressure at the inlet and distal ends of the lateral when the lateral is:

- On level ground
- Runs down a uniform 2% grade
- Runs up a uniform 2% grade

Which of these systems meet the criteria for pressure variation along laterals?

Solution:

There are 44 sprinklers on the lateral (i.e., 1,320 feet with 30 feet between sprinklers).

The average sprinkler discharge is 5 gpm for 5/32-inch nozzles at 50 psi (Table 11.1)

The inflow to the lateral is 220 gpm (5 gpm/sprinkler \( \times \) 44 sprinklers).

The friction loss in 4-inch diameter aluminum pipe for a flow of 220 gpm is 1.87 psi/100 ft from Table 8.2a. The loss for a conveyance pipe is then 1.87 \( \times \) 1320/100 = 24.7 psi.

The multiple outlet friction factor (F) for a lateral with 44 sprinklers is about 0.36 (Table 8.3) so the friction loss for the lateral is:

\[ P_f = F P_m = 0.36 \times 24.7 \text{ psi} = 8.9 \text{ psi} \]

The pressure at the inlet to the lateral for level ground is:

\[ P_i = P_a + 0.75 P_t = 50 + 0.75 \times 8.9 = 56.7 \text{ psi} \]

The pressure at the distal end of the lateral for level ground is:

\[ P_d = P_a - 0.25 P_t = 50 - 0.25 \times 8.9 = 47.8 \text{ psi} \]

a. The pressure variation along the lateral is 8.9 psi compared to the average pressure of 50 psi. The variation is 17.8% of the average pressure and is less than the permissible variation so the lateral meets the standard.

b. When the lateral runs down a 2% grade, the elevation change along the lateral is:

\[ E_i - E_d = 0.02 \times 1320 = 26.4 \text{ ft} \]

The inlet is 26.4 feet above the distal end. The pressures at the inlet and distal ends are:

\[ P_i = P_a + 0.75 P_t - 0.5 \left( \frac{E_i - E_d}{2.31} \right) = 50 + 0.75 \times 8.9 - 0.5 \left( \frac{26.4}{2.31} \right) = 51 \text{ psi} \] (Eq. 11.8)

\[ P_d = P_a - 0.25 P_t + 0.5 \left( \frac{E_i - E_d}{2.31} \right) = 50 - 0.25 (7.7) + 0.5 (26.4 / 2.31) = 53.8 \text{ psi} \] (Eq. 11.9)

Here the pressure variation is only 2.8 psi, well within the allowable variation.

b. When the lateral runs uphill the elevation of the inlet is below the distal end so the value of \( E_i - E_d \) = -26.4 feet. Using this value the pressures at the ends of the lateral are \( P_i = 62.4 \text{ psi} \) and \( P_d = 42.1 \text{ psi} \).

The pressure variation is 20.3 psi or 41% of the average pressure, which exceeds the criteria.
It is not always possible to satisfy the allowable pressure variation limitation for laterals. In such cases pressure regulators or pressure compensating nozzles (flow control) can be used to control sprinkler discharge. A regulator can provide nearly constant outlet pressure for a range of inlet pressures (Figure 11.10). This provides the same pressure to sprinklers along the lateral and produces high uniformity; however, a higher inlet pressure is required so that all sprinklers receive the design pressure. Regulators may not be required along the entire lateral if the same end of the lateral is always next to the mainline. Some pressure is lost as water flows through the regulator so inlet pressure must be increased to overcome this loss. The regulators also increase the operating and the initial cost of the system. Pressure compensating nozzles serve the same purpose and may reduce both the operating and installation costs compared to pressure regulators. Some designs of pressure compensating nozzles include flexible orifices that contract at high pressure and expand under low pressure. The change of the orifice size regulates the flow as shown in Figure 11.10. Compensating nozzles generally have a smaller operating range than regulators.

### 11.5 Maximum Lateral Inflow

The maximum inflow to a sprinkler lateral is limited by two conditions: the maximum permissible pressure variation and the maximum acceptable water velocity in the lateral pipe. The maximum permissible pressure variation along the lateral limits the maximum inflow as described in the previous section (Section 11.4). The maximum pressure variation along the lateral is 20% of the average operating pressure, therefore:

\[
\text{Max } P_l = 0.20 \times P_a
\]  

(11.10)
Using the Hazen-Williams equation for pressure loss the maximum inflow for the lateral can be determined:

$$\text{Max } P_l = 4.56 \left( \frac{Q_{\text{max}}}{C} \right)^{1.852} \frac{L}{D^{4.866}}$$

(11.11)

where $F$ is the multiple outlet factor from Table 8.3 and all other terms are as previously defined. The above equations can be combined to yield an expression for the maximum inflow that is permissible for a lateral of given length and size (i.e., fixed diameter and $C$ value):

$$Q_{\text{max}} = \left( \frac{0.2}{0.456} \frac{P_a D^{4.866}}{4.56} \frac{C^{1.852}}{F L} \right)^{1/1.852}$$

(11.12)

where $Q_{\text{max}}$ is the maximum inflow to the lateral to maintain pressure variation less than 20% of the average pressure.

The second factor that can limit the inflow rate to the lateral is the maximum allowable velocity in the pipeline. The danger of damage to the pipeline and its components due to pressure surges increases when the velocity of water in the pipeline increases. Sprinkler laterals can withstand higher velocities than mainlines because the sprinklers on the lateral allow water and air under high pressure to escape before damaging the pipe. However, there is still an upper limit to the velocity of water flow in sprinkler laterals. Commonly the upper limit is 7 feet per second, while 10 feet per second can be used if the valve closes gradually and the pipe is filled slowly. The maximum velocity can also determine the maximum inflow for the pipeline:

$$Q_{\text{max}} = 2.445 \, v_{\text{max}} D^2$$

(11.13)

where $v_{\text{max}}$ = the maximum water velocity in the lateral and all other terms are as previously defined.

Equations 11.12 and 11.13 can be combined to provide limits for the maximum inflow to the sprinkler lateral so that the velocity is below the maximum permissible and the pressure variation along the lateral is less than 20% of the average pressure. The smallest value from the two equations defines the maximum inflow. These equations were used to develop charts for the maximum inflow for aluminum pipe with couplers forty feet apart as shown in Figure 11.11. Similar relationships can be developed for other types of pipe material to use as general guidelines for laterals.

Solution of equation 11.13 for the maximum inflow at a velocity of seven feet per second gives flows of 410, 260, and 145 gpm for 5-inch, 4-inch, and 3-inch pipe respectively as shown in Figure 11.11.

Results in Figure 11.11 show that the velocity limit (7 ft/sec) determines the maximum inflow for the initial lengths of the lateral. As the lateral length increases, the friction loss limitation determines the maximum inflow rate. Results in Figure 11.11 can be used for laterals with different sprinkler outlet spacings because the velocity limits the inflow for short laterals. By the time friction loss becomes determinant a significant number of sprinklers will be included and the friction factor ($F$) for laterals will be nearly the same for either sprinkler spacing. Thus, the friction loss will be comparable since all other factors are the same for friction loss calculations.

**Example 11.5**

Determine the maximum sprinkler discharge for a 5-inch aluminum pipe lateral that is 1,000 feet long where the average pressure is 50 psi. Sprinklers are spaced 40 feet apart along the lateral.

Given:

- $P_a = 50 \, \text{psi}$
- $D = 5 \, \text{in}$
- $L = 1,000 \, \text{ft}$
- $S_L = 40 \, \text{ft}$
- $C = 120$ (aluminum pipe with couplers, Table 8.1)
- $q_s = \text{discharge of individual sprinklers}$

Solution:

From Figure 11.11 the maximum lateral inflow is about 410 gpm.

For a lateral 1,000 ft long, 25 sprinklers would be needed if spaced at 40 ft.

Thus, each sprinkler could average up to 16.4 gpm, which is a high flow for most applications.
Figure 11.11. Maximum inflow for three diameters of aluminum sprinkler lateral pipe with outlets 40 feet apart (C value = 120), and three average pressures along the lateral. A maximum velocity of 7 feet per second is used for this chart.
11.6 Sprinkler System Design

Detailed design of sprinkler lateral systems is beyond the scope here; however, some general relationships are needed to manage systems properly. We have considered the hydraulics of sprinkler laterals and the pressure variation along the lateral. Two important considerations that are still needed are: how to select sprinkler nozzles to satisfy capacity requirements of the system, and how many laterals are required for the field in a moved lateral system.

Sprinkler systems must apply enough water to satisfy crop water requirements and to account for inefficiencies and nonuniformities in the irrigation system and the field. From Chapter 5, the net system capacity requirement and the application efficiency for the system can be estimated. These quantities are used to compute the gross capacity, $Q_c$ (gallons per minute per acre, gpm/ac). The problem is to determine how that capacity is used to arrange sprinkler laterals, and to select the appropriate nozzles and pressure for the sprinkler system. For a moved lateral system with multiple laterals each having the same length, the minimum discharge required from each sprinkler on the lateral can be determined from:

$$ q_s = \left( \frac{Q_c S_L S_m}{43560} \right) \left( \frac{N_s}{N_l} \right) \left( \frac{T_o}{T_s} \right) \left( \frac{I_i}{I_i - T_d} \right) \quad (11.14) $$

where:
- $Q_c$ = gross system capacity requirement (gpm/ac),
- $N_s$ = number of sets required to irrigate the field,
- $N_l$ = number of laterals used to irrigate the field,
- $T_o$ = time of actual operation per set (hr),
- $T_s$ = set time (hr),
- $I_i$ = irrigation interval (days), and
- $T_d$ = downtime for system (days); other parameters are as already defined.

The time of operation is the actual time that water is applied during the total set time. For example, a lateral may only operate 10 hours out of a 12-hour set. This provides time to drain and move the lateral. The irrigation interval is the amount of time between successive irrigations of the field. The downtime is the time required to maintain the engine, system, etc., to prepare the laterals for the next irrigation, and for any harvesting, farming, or other operations.

The number of sets in the field is determined by:

$$ N_s = \frac{W_f}{S_m} \quad (11.15) $$

where $W_f$ is the width of the field as shown in Figure 11.12. It is often the case that more than one lateral is needed to irrigate a field.

The nozzle size(s) needed for the sprinklers on the lateral can now be determined using Tables 11.1 and 11.2. The spacing criteria must be considered as the nozzle size(s) is determined. The total flow required for the lateral is the product of the number of sprinklers on the lateral and the required discharge for each sprinkler:

$$ Q_i = \frac{q_s L}{S_L} \quad (11.16) $$

where:
- $Q_i$ = inflow to lateral (gpm) and
- $L$ = length of lateral.

The inflow to the lateral must be less than the maximum allowable inflow determined in the Section 11.5. If the inflow is excessive, more laterals are generally required with longer set times or shorter lengths.

Considering the operation of the lateral system requires a balance of management factors including the time of operation, the sprinkler and lateral spacing, the number of laterals required, and the application efficiency. Pressure and flow limitations must also be considered for proper operation. Often, a trial-and-error procedure is needed to balance all factors, and
tradeoffs frequently are required. The landowner’s and/or irrigation manager’s preferences for operation should be incorporated into a management plan for the system.

The layout of laterals on sloping fields can be crucial. It is generally best to run the mainline up and down the hillslope while positioning the lateral so that it is relatively level. If the lateral must run up and down the hill, it is best to run the lateral downslope if possible. The prevailing wind direction and speed during the irrigation season should also be considered.
11.7 Frost Protection

Agricultural and horticultural plants are produced in regions where cold temperatures may damage crops. If the plant temperature drops below a critical value, production may be lost on annual crops and perennial species may be damaged. Damage can result from two types of cooling. An **advective freeze** occurs when the ambient air temperature drops below a critical level and wind increases the convective heat transfer from the cold air to plants. There is little that irrigation can do to protect plants from an advective freeze. In fact, wetting the foliage can cool plants substantially causing increased damage. In addition, the buildup of ice on plants and irrigation systems can cause structural damage.

**Radiant frost** occurs in a clear, calm, and dry environment where energy is radiated from plants into the atmosphere. The ambient air temperature is generally above critical temperatures that causes damage, but outgoing radiation cools plants 1° to 4°F below the air temperature. In addition, crops draw energy from the air immediately surrounding the plants, thus, air in contact with plants is cooler than above the canopy. Light winds reduce the turbulence above plants allowing the plant surfaces to cool further. Frost begins to form on plants when the canopy temperature drops below the dew point temperature of the air. The dew point may be lower than critical temperature in dry environments.

Leaves, blossoms, and young fruit are usually the most sensitive to frost damage and are frequently killed at temperatures between 26° to 30°F. Lethal temperatures for more hardy plant parts are related to the stage of development; thus, protection may be more important at one time than another.

Managing for frost protection requires an understanding of the processes involved when water changes phases. Water can exist as a vapor, liquid, or solid. Changing phases involves energy exchange. Evaporation requires about 585 calories of energy per gram of water. The example of the minimum sprinkler discharge required for the system described below:

**Example 11.6**

Compute the minimum sprinkler discharge required for the system described below.

Given: A square field (1,200 feet × 1,200 feet) is irrigated with a portable set-move (moved lateral) sprinkler system. The gross system capacity has been determined to be 6.0 gpm/ac. The spacing of sprinklers is 40 feet along the lateral and 50 feet between lateral sets. The system operates for 10 hours out of a 12-hour set. The field must be irrigated at least once every 10 days and 2 days are needed to move laterals to the beginning side and for equipment maintenance.

Find: Compute the minimum sprinkler discharge required for the system.

Solution:

The number of sets in the field are $N_s = W_l/S_m = 1,200 \text{ ft}/50 \text{ ft} = 24 \text{ sets}$. (Eq. 11.15)

With 12-hour set times, 2 sets can be irrigated daily so 12 days of continual irrigation would be required with one lateral.

We only have 8 days available to irrigate since 2 out of 10 days are used for downtime. Therefore, 2 laterals will be needed ($N_l = 2$).

Each lateral must irrigate 12 sets taking 6 days. Thus, the irrigation interval could be 8 days rather than 10.

Then using Equation 11.14:

$$q_s = \left(\frac{Q_s S_l S_m}{43,560}\right) \times \left(\frac{N_s}{N_l}\right) \times \left(\frac{T_s}{T_d}\right) \times \left(\frac{1}{I_i - T_d}\right)$$

$$q_s = \left(\frac{60 \text{ gpm/ac}}{43,560 \text{ ft}^2/\text{ac}}\right) \times 24 \text{ sets} \times \left(\frac{12 \text{ hr}}{10 \text{ hr}}\right) \times \frac{8 \text{ days}}{8-2 \text{ days}}$$

$$q_s = 6.0 \text{ gpm/ac} \times 0.55 \text{ ac/sprinkler} \times 1.2 \times 1.33 = 5.3 \text{ gpm/sprinkler}$$
reverse process, condensation, releases energy. Melting ice requires energy, and freezing water releases an equal amount of energy. Sublimation is where ice is transformed directly into water vapor without going through the liquid state. Sublimation requires a great deal of energy.

What happens during sprinkling to provide frost protection? Consider an irrigation sprinkler operating while the air temperature is 33°F. Irrigation water is usually much warmer than critical temperatures, for example groundwater in northern climates where frost protection is needed averages about 50 to 55°F. After water leaves the nozzle, the droplets begin to cool and evaporate. Cooling the droplets adds energy to the air providing some frost protection. However, large amounts of water are needed since only 1 calorie is released per gram for each °C of temperature change of the water. With time, the droplets cool to the wet bulb temperature of the air, which can be below 33°F. If droplets reach plants before reaching the wet bulb temperature, water will evaporate from the plant surface, drawing energy from plants—further cooling plants. If sprinkling only wets the crop canopy so that evaporation occurs, the plants will be cooled below the ambient air temperature, and sprinkling could damage the crop rather than protect it.

What must happen to provide protection? The processes that release energy, thereby warming plants and the air, include condensation and freezing. These processes must occur at a faster rate than the inverse processes of evaporation, melting, and sublimation. The irrigation system should be operated to provide that environment.

Coating plants with a water film can maintain temperatures above the critical damage temperature. Energy is lost from the outer surface of the water film by radiation, convection, and evaporation. The heat of fusion is released from the thin film as the water freezes. If the film is maintained, the temperature will remain near 32°F as freezing supplies the energy lost from the outer surface of the water film. The ice coating on the plant must be continually in contact with unfrozen water until the air warms so that the wet bulb temperature of the air is above the critical temperature. Usually sprinkling is required until the ice formed on the plants completely melts the next morning. Sprinkling above the crop has provided frost protection; however, results have been mixed and protection is not a certainty.

The appropriate application rate for frost protection depends on several factors and general recommendations are risky as evidenced by the failures of overcrop sprinkling. Yet, results from Gerber and Harrison (1964) provide an initial estimate of the required application rate for frost protection (Table 11.5). The most practical rates range from 0.1 to 0.3 inches per hour. Repeat frequency of leaf or foliage wetting must be once each minute. Sprinkling must begin by the time the wet bulb temperature reaches 4°F above the lethal temperature of the plant parts to be protected. Sprinkling must continue until the wet bulb temperature is back above the lethal temperature by about 4°F. Systems are usually operated until the plant is free of ice, due to rising air temperature. Recommended minimum temperature for turning the irrigation system on or off for frost control of apple trees in Washington is given in Table 11.6.

Research has shown that overcrop sprinklers can be operated intermittently to provide frost protection while minimizing the amount of water applied. The cycling frequency affects the water application rate and frost protection. The foliage configuration of the plants, especially the

<table>
<thead>
<tr>
<th>Temperature of a Dry Leaf (°F)</th>
<th>0–1</th>
<th>2–4</th>
<th>5–8</th>
<th>10–14</th>
<th>18–22</th>
</tr>
</thead>
<tbody>
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<td>0.1</td>
<td>0.1</td>
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</table>

[a] The temperature of a dry leaf is the expected minimum leaf temperature on an unprotected leaf. This will range from 1°F below air temperature on nights with light wind to 3° to 4°F below air temperature on very calm nights.

[b] Note: These rates assume that relative humidity does not affect frost protection. Thus, the rates should be used as a first approximation in determining the application rate for design and planning. The rates should not be used to manage an actual sprinkler irrigation system.
amount of foliage overlap, has a significant effect on success. The portion of the wetted area that receives water is also important for selecting an application rate and cycle frequency.

Undertree sprinkling can provide frost protection. Undertree sprinklers often produce small water droplets below the canopy, an area Barfield et al. (1990) termed the misting zone. Water droplets cool and evaporate, transferring energy from the water into the air surrounding the plants. If the humidification of the air causes ice formation on the plants, energy will be released that can increase frost protection. Evaporation from the soil increases the humidity, increasing the efficiency of undertree sprinkling. As the relative humidity increases the emissivity of the air decreases, reducing the outgoing long-wave radiation, and the degree of frost damage. The level of protection is dependent on the amount of water applied and the aerial extent of the freezing surface. Part of the heat from freezing and cooling of water is carried into the ground by infiltrating water, part goes into warming the air, and part into evaporation. Heat is transferred from the frosty buds by radiation, convection, and by condensation which occurs on the coldest plant tissues. Ambient air temperature increases of about 2°F are common, although increases up to 4°F have been found. Most of the systems use small (5/64 to 3/32 in), low-trajectory (< 7°) sprinkler heads at 40 to 50 psi. Application rates range from 0.08 to 0.12 inches per hour or slightly more than half of typical overtree requirements.

Undertree sprinkling appears to be promising; however, the process is not fully understood, and has not been tested as extensively as overtree sprinkling. Additional testing is needed before recommendations can be developed.

Sprinkler systems can provide frost protection in addition to evapotranspiration and salinity management requirements. Frost protection can pay high dividends during short periods. The rate and timing of water application is often more important than the volume of water applied. In some cases, one sprinkler system can accommodate both the primary uses and frost protection. In other cases, frost protection requires performance that the system cannot satisfy, and a second irrigation system may be required. The design of the secondary system is much different than for the primary system and additional information from specific references must be consulted. In any case, careful management is required for frost protection. The air temperature and ice formation should be carefully monitored.

This discussion on frost protection highlights the processes and provides some very general management practices. However, the process is sensitive to local meteorological conditions that change rapidly. Success requires monitoring of ambient conditions and reliable information for crop susceptibility during sensitive growth stages. Local management guides must be used for each plant species. Care must be taken to minimize runoff, deep percolation, and depletion of scarce water supplies. Snyder and Melo-Abreu (2005) provide a thorough treatise of frost protection and this or similar references as well as local information should be consulted for successful frost protection.

<table>
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<tr>
<th>Critical Temperature (°F)</th>
<th>Dewpoint Temperature Range (°F)</th>
<th>Minimum Turn-On or Turn-Off Air Temperature[^a] (°F)</th>
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[^a] Absolute minimum temperature for turning the irrigation system on or off. It is recommended that the system be turned on or off 2°F or 3°F higher than the indicated minimum.
11.8 Summary

Sprinkler irrigation is the most broadly used method of irrigation in the United States. Sprinkler systems consist of the sprinkler device, the lateral pipe that delivers water to a series of sprinklers along the pipe, a mainline that provides water to the inlet of each lateral, and a source of water provided under pressure—usually by pumping. Efficient irrigation depends on understanding the performance characteristics of sprinkler systems. Key parameters are the water flow rate from the nozzle and the diameter wetted by the sprinkler. These factors depend on the pressure provided to the sprinkler and the diameter of the sprinkler nozzle. Uniformity of application is achieved by limiting the variation of pressure along laterals and mainlines. Pressure variation is controlled by selecting pipe sizes that limit pressure loss and maintain flow velocities below limits that may cause pressure surges or water hammer. Simultaneously, the application rate of water depends on the discharge from nozzle(s) and the representative area for an individual sprinkler. The representative area is determined by the spacing between sprinklers on the lateral and the distance between laterals. The uniformity of application is also controlled by the spacing of sprinklers along laterals and between laterals, relative to the diameter of coverage of a sprinkler. Finally, the depth of water applied depends on how long water is applied and the rate of application. The depth of water applied must be adequate to meet crop needs over the time between irrigations. These relationships are described in this chapter, which lays the foundation for subsequent chapters on specific types of sprinkler irrigation systems.

Questions

1. What wetting pattern and distribution would be expected if the operating pressures is higher than recommended for a sprinkler? What role does water drop size play?

2. Should laterals be positioned perpendicular or parallel to the predominant wind? Explain.

3. How is sprinkler spacing important to uniformity, investment cost, and application rate?

4. If the limits of pressure variation along the lateral cannot be met, what options are available to resolve the problem?

5. Define and explain the two conditions limiting the maximum inflow rate into a sprinkler lateral.

6. Determine the discharge from a 1/4-inch nozzle operated at 30 psi. What size nozzle (in 128ths of an inch) would you select to increase the flow (gpm) by 25% at the same pressure?

7. What is the application rate for an irrigation system that has a triangular spacing of 30 ft and the discharge from each sprinkler is 4.2 gpm? Is this acceptable for a silt loam soil with 8% slope?

8. How long would a sprinkler system need to operate to apply 3 in of water if the sprinkler discharge was 10 gpm and the sprinkler spacing was 40 ft × 60 ft? If the application efficiency was 75%, how long would it take to apply a net depth of 3 in?

9. A 4-inch sprinkler lateral of aluminum pipe is 1,320 ft long with sprinklers spaced at 40 ft along the lateral. The average pressure along the lateral is 45 psi and the average discharge is 8 gpm per sprinkler. The lateral lays on level land. Does this lateral conform to the criteria for pressure variation?

10. Sprinklers are placed in a rectangular orientation with a spacing of 30 ft × 40 ft. The gross system capacity is 5 gpm/ac. There are 14 laterals in the field. The field is irrigated every
other day and can only be irrigated at night from 11 p.m. till 6 a.m. The laterals are connected to a controller that automatically cycles from one lateral to another. What discharge is needed for each sprinkler?

11. A grower wants to protect an orchard from frost by sprinkling. The solid-set system was designed to meet ET requirements. The following information is available:

- Sprinkler discharge = 12 gpm
- Sprinkler spacing = 40 ft × 60 ft
- An automatic controller is available to control set times
- Number of laterals in the field = 25

How could this system be used for frost protection if the dry leaf temperature is 24°F and the wind speed is 6 mph? What dangers might exist?

References


