

Lecture 3

Sprinkler Characteristics

I. Hardware Design Process

1. Sprinkler selection
2. Design of the system layout
3. Design of the laterals
4. Design of the mainline
5. Pump and power unit selection



II. Classification of Sprinklers and Applicability

(see Table 5.1 from the textbook)

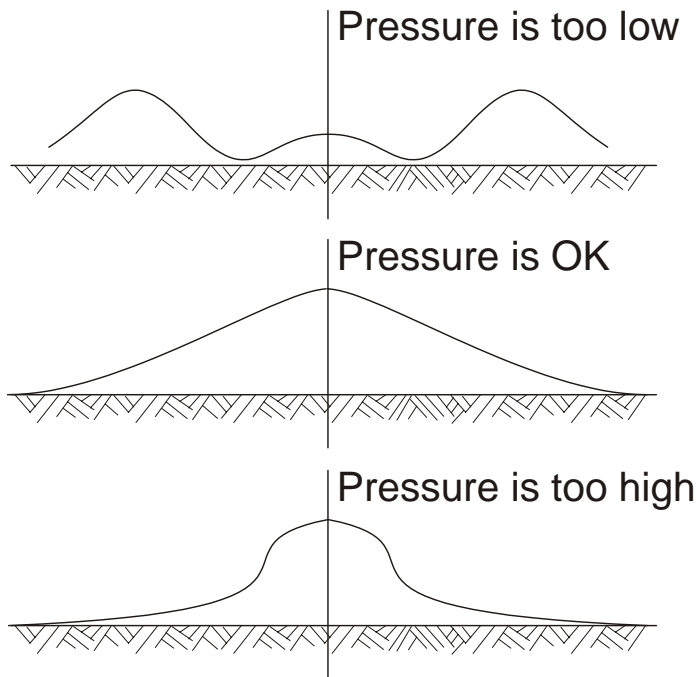
- Agricultural sprinklers typically have flow rates from 4 to 45 lpm (1 to 12 gpm), at nozzle pressures of 135 to 700 kPa (20 to 100 psi)
- “Gun” sprinklers may have flow rates up to 2,000 lpm (500 gpm; 33 lps) or more, at pressures up to 750 kPa (110 psi) or more
- Sprinklers with higher manufacturer *design pressures* tend to have larger wetted diameters
- But, deviations from manufacturer’s recommended pressure may have the opposite effect (increase in pressure, decrease in diameter), and uniformity will probably be compromised

- Sprinklers are usually made of plastic, brass, and or steel
- Low pressure nozzles save pumping costs, but tend to have large drop sizes and high application rates
- Medium pressure sprinklers (210 - 410 kPa, or 30 to 60 psi) tend to have the best application uniformity
- Medium pressure sprinklers also tend to have the lowest minimum application rates
- High pressure sprinklers have high pumping costs, but when used in periodic-move systems can cover a large area at each set
- High pressure sprinklers have high application rates

- Rotating sprinklers have lower application rates because the water is only wetting a “sector” (not a full circle) at any given instance...
- For the same pressure and discharge, rotating sprinklers have larger wetted diameters
- Impact sprinklers always rotate; the “impact” action on the stream of water is designed to provide acceptable uniformity, given that much of the water would otherwise fall far from the sprinkler (the arm breaks up part of the stream)
- Check out Web sites such as www.rainbird.com

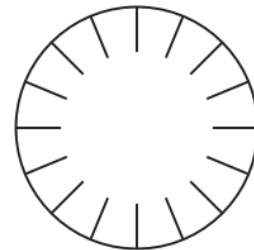
III. Precipitation Profiles

- Typical examples of low, correct, and high sprinkler pressures (see Fig 5.5).

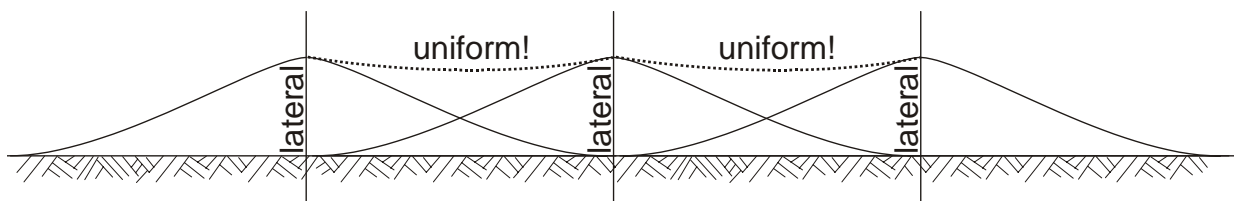


- The precipitation profile (and uniformity) is a function of many factors:

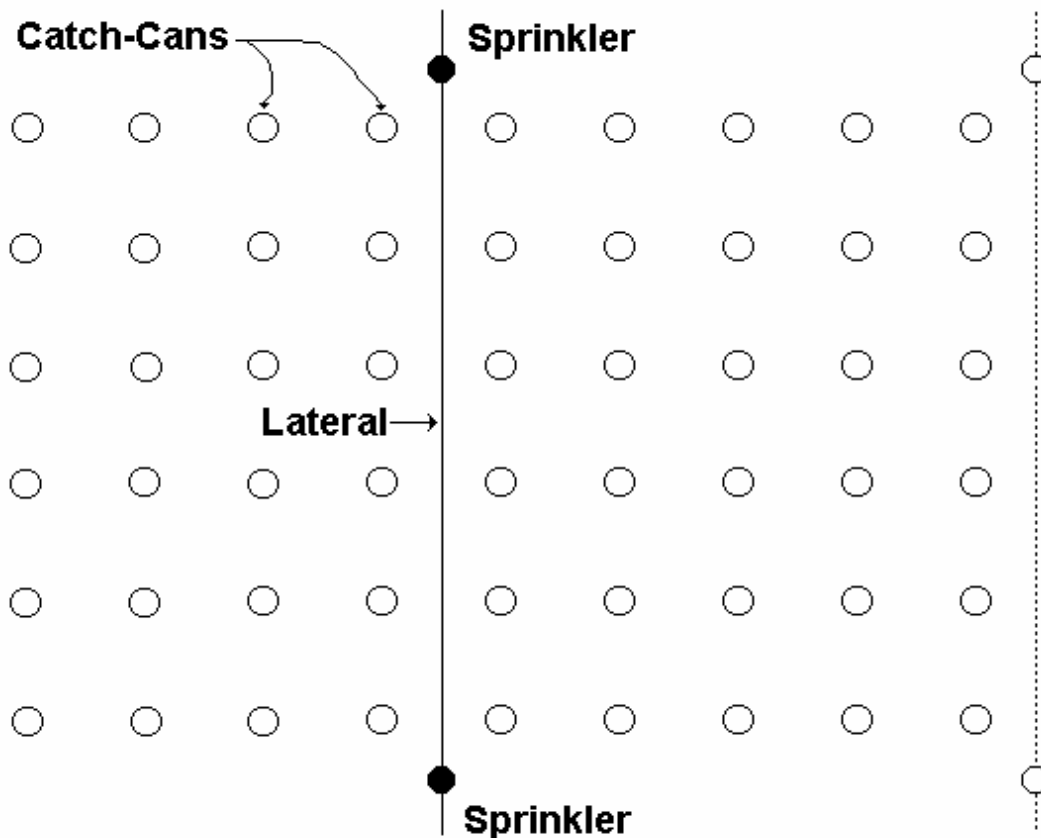
1. nozzle pressure
2. nozzle shape & size
3. sprinkler head design
4. presence of straightening vanes
5. sprinkler rotation speed
6. trajectory angle
7. riser height
8. wind



- Straightening vanes can be used to compensate for consistently windy conditions
- Overlapping sprinkler profiles (see Fig. 5.7)



- Simulate different lateral spacings by “overlapping” catch-can data in the direction of lateral movement (overlapping along the lateral is automatically included in the catch-can data, unless it’s just one sprinkler)



IV. Field Evaluation of Sprinklers

- Catch-can tests are typically conducted to evaluate the uniformities of installed sprinkler systems and manufacturers’ products
- Catch-can data is often overlapped for various sprinkler and lateral spacings to evaluate uniformities for design and management purposes
- A computer program developed at USU does the overlapping: **CATCH3D**; you can also use a spreadsheet program to simulate overlapping (e.g. *Ctrl-C, Edit | Paste Special, Operation: Add*)
- Note that catch-can tests represent a specific wind and pressure situation and must be repeated to obtain information for other pressures or wind conditions
- Typical catch-can spacings are 2 or 3 m on a square grid, or 1 to 2 m spacings along one or more “radial legs”, with the sprinkler in the center
- Set up cans with half spacing from sprinklers (in both axes) to facilitate overlap calculations
- See Merriam & Keller (1978); also see ASAE S398.1 and ASAE S436

V. Choosing a Sprinkler

- the system designer doesn't "design" a sprinkler, but "selects" a sprinkler
- there are hundreds of sprinkler designs and variations from several manufacturers, and new sprinklers appear on the market often
- the system designer often must choose between different nozzle sizes and nozzle designs for a given sprinkler head design
- the objective is to combine sprinkler selection with S_e and S_l to provide acceptable application uniformity, acceptable pumping costs, and acceptable hardware costs
- manufacturers provide recommended spacings and pressures
- there are special sprinklers designed for use in frost control

VI. Windy Conditions

- When winds are consistently recurring at some specific hour, the system can be shut down during this period (T in Eq. 5.4 is reduced)
- For center pivots, rotation should not be a multiple of 24 hours, even if there is no appreciable wind (evaporation during day, much less at night)
- If winds consistently occur, special straightening vanes can be used upstream of the sprinkler nozzles to reduce turbulence; wind is responsible for breaking up the stream, so under calm conditions the uniformity could decrease
- For periodic-move systems, laterals should be moved in same direction as prevailing winds to achieve greater uniformity (because $S_e < S_l$)
- Laterals should also move in the direction of wind to mitigate problems of salt accumulating on plant leaves
- Wind can be a major factor on the application uniformity on soils with low infiltration rates (i.e. low application rates and small drop sizes)
- In windy areas with periodic-move sprinkler systems, the use of offset laterals ($\frac{1}{2}S_l$) may significantly increase application uniformity
- Alternating the time of day of lateral operation in each place in the field may also improve uniformity under windy conditions
- Occasionally, wind can help increase uniformity, as the randomness of wind turbulence and gusts helps to smooth out the precipitation profile

Wind effects on the diameter of throw:

0-3 mph wind: reduce manufacturer's listed diameter of throw by 10% for an effective value (i.e. the diameter where the application of water is significant)

over 3 mph wind: reduce manufacturer's listed diameter of throw by an additional 2.5% for every 1 mph above 3 mph (5.6% for every 1 m/s over 1.34 m/s)

In equation form:

For 0-3 mph (0-1.34 m/s):

$$\text{diam} = 0.9 \text{diam}_{\text{manuf}} \quad (20)$$

For > 3 mph (> 1.34 m/s):

$$\text{diam} = \text{diam}_{\text{manuf}} \left[0.9 - 0.025(\text{wind}_{\text{mph}} - 3) \right] \quad (21)$$

or,

$$\text{diam} = \text{diam}_{\text{manuf}} \left[0.9 - 0.056(\text{wind}_{\text{m/s}} - 1.34) \right] \quad (22)$$

Example: a manufacturer gives an 80-ft diameter of throw for a certain sprinkler and operating pressure. For a 5 mph wind, what is the effective diameter?

$$80 \text{ ft} - (0.10)(0.80) = 72 \text{ ft} \quad (23)$$

$$72 \text{ ft} - (5 \text{ mph} - 3 \text{ mph})(0.025)(72 \text{ ft}) = 68 \text{ ft} \quad (24)$$

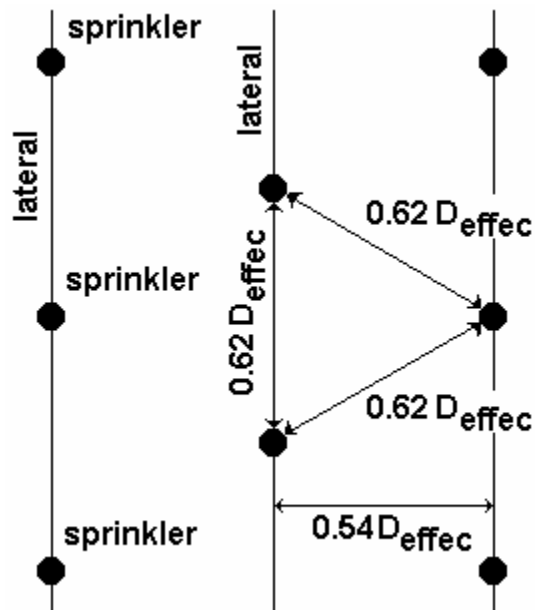
or,

$$\text{diam} = 80(0.9 - 0.025(5 - 3)) = 68 \text{ ft} \quad (25)$$

VII. General Spacing Recommendations

- Sprinkler spacing is usually rectangular or triangular
- Triangular spacing is more common under fixed-system sprinklers
- Sprinkler spacings based on average (moderate) wind speeds:

1. **Rectangular** spacing is 40% (S_e) by 67% (S_l) of the effective diameter
2. **Square** spacing is 50% of the effective diameter
3. Equilateral **triangle** spacing is 62% of the effective diameter [lateral spacing is $0.62 \cos(60^\circ/2) = 0.54$, or 54% of the effective diameter, D_{effec}]



- See Fig. 5.8 about profiles and spacings

VIII. Pressure-Discharge Relationship

- Equation 5.1:

$$q = K_d \sqrt{P} \quad (26)$$

where q is the sprinkler flow rate; K_d is an empirical coefficient; and P is the nozzle pressure

- The above equation is for a simple round orifice nozzle
- Eq. 5.1 can be derived from Bernoulli's equation like this:

$$\frac{P}{\gamma} = \frac{V^2}{2g} = \frac{q^2}{2gA^2} \quad (27)$$

$$\sqrt{\frac{2gA^2P}{\rho g}} = K_d \sqrt{P} = q \quad (28)$$

where the elevations are the same ($z_1 = z_2$) and the conversion through the nozzle is assumed to be *all pressure to all velocity*

- P can be replaced by H (head), but the value of K_d will be different
- Eq. 5.1 is accurate within a certain range of pressures
- See Table 5.2 for P , q , and K_d relationships
- K_d can be separated into an orifice coefficient, K_o , and nozzle bore area, A :

$$q = K_o A \sqrt{P} \quad (29)$$

whereby,

$$K_o = \sqrt{2/\rho} \quad (30)$$

where the value of K_o is fairly consistent across nozzle sizes for a specific model and manufacturer

- From Table 5.2 in the textbook, the values of K_o are as follows:

Flow Rate q	Head or Pressure H or P	Nozzle Bore d	K_o
lps	m	mm	0.00443
lps	kPa	mm	0.00137
lpm	m	mm	0.258
lpm	kPa	mm	0.0824
gpm	ft	inch	24.2
gpm	psi	inch	36.8

- Similar values can be determined from manufacturer's technical information
- Note also that nozzle diameter (bore) can be determined by rearranging the above equation as follows:

$$d = \sqrt{\frac{4q}{\pi K_o \sqrt{P}}} \quad (31)$$

- The value of d can then be rounded up to the nearest available diameter (64ths of an inch, or mm)
- Then, either P or q are adjusted as necessary in the irrigation system design
- Below is a sample *pressure versus discharge* table for a RainBird[®] sprinkler

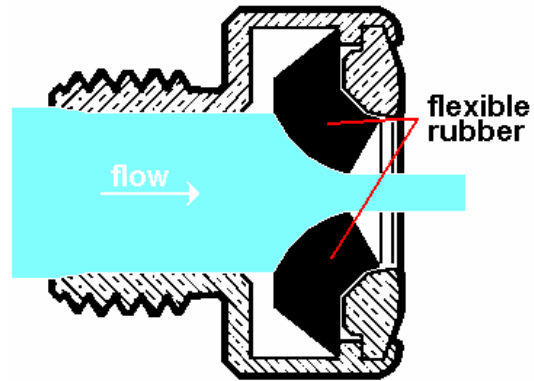
Straight Bore Nozzle (SBN-4) with Plug (Stream Height: 8 ft.)

PSI @ Nozzle	NOZZLE SIZE													
	7/32"		1/4"		9/32"		15/16"		11/32"		3/8"		13/32"	
	Rad.	GPM	Rad.	GPM	Rad.	GPM	Rad.	GPM	Rad.	GPM	Rad.	GPM	Rad.	GPM
40	57	8.80	60	11.50	62	14.60	65	17.70	66	21.10	68	24.40	70	28.50
45	58	9.40	61	12.20	64	15.50	66	18.90	68	22.50	70	26.00	72	30.40
50	59	9.90	62	12.90	65	16.30	68	20.00	70	23.80	71	27.50	73	32.30
55	60	10.40	63	13.60	66	17.20	70	21.00	71	25.00	73	29.10	75	34.00
60	61	10.90	64	14.20	67	18.00	71	22.00	73	26.20	74	30.60	77	35.70
65	62	11.40	65	14.80	68	18.80	72	23.00	74	27.40	76	32.00	78	37.30
70	63	11.80	66	15.40	70	19.50	73	23.90	76	28.50	77	33.20	79	38.90
75	64	12.20	67	16.00	71	20.30	74	24.80	77	29.60	78	34.50	81	40.40
80	65	12.60	68	16.50	72	20.90	75	25.70	78	30.60	80	35.70	82	41.80

Application Rates

I. Flow Control Nozzles

- More expensive than regular nozzles (compare \$0.60 for a brass nozzle to about \$2.70 for a flow control nozzle)
- May require more frequent maintenance
- The orifice has a flexible ring that decreases the opening with higher pressures, whereby the value of $A\sqrt{P}$ in the equation remains approximately constant
- It can be less expensive to design laterals and mainline so that these types of nozzles are not required, but this is not always the case
- FCNs are specified for nominal discharges (4, 4.5, 4.8, 5.0 gpm, etc.)
- The *manufacturer's coefficient of variation* is about $\pm 5\%$ of q ; don't use FCNs unless pressure variation is greater than about 10% (along lateral and for different lateral positions)



Flow Control Nozzle

$$\sqrt{1.10P} \approx 1.05\sqrt{P} \quad (32)$$

II. Low-Pressure Sprinklers

1. Pressure alone is not sufficient to break up the stream in a standard nozzle design for acceptable application uniformity
2. Need some mechanical method to reduce drop sizes from the sprinkler:
 - pins that partially obstruct the stream of water
 - sharp-edged orifices
 - triangular, rectangular, oval nozzle shapes
3. Some sprinkler companies have invested much into the design of such devices for low-pressure sprinkler nozzles
4. Low-pressure nozzles can be more expensive, possibly with reduced uniformity and increased application rate, but the trade-off is in operating cost

III. Gross Application Depth

$$d = \frac{d_n}{E_{pa}}, \quad \text{for } LR \leq 0.1 \quad (33)$$

where E_{pa} is the “designer” application efficiency (decimal; Eq. 6.9). And,

$$d = \frac{0.9d_n}{(1-LR)E_{pa}}, \quad \text{for } LR > 0.1 \quad (34)$$

- The gross application depth is the total equivalent depth of water which must be delivered to the field to replace (all or part of) the soil moisture deficit in the root zone of the soil, plus any seepage, evaporation, spray drift, runoff and deep percolation losses
- The above equations for d presume that the first 10% of the leaching requirement will be satisfied by the E_{pa} (deep percolation losses due to application variability). This presumes that areas which are under-irrigated during one irrigation will also be over-irrigated in the following irrigation, or that sufficient leaching will occur during non-growing season (winter) months.
- When the LR value is small ($EC_w \leq \frac{1}{2}EC_e$), leaching may be accomplished both before and after the peak ET period, and the first equation (for $LR \leq 0.1$) can be used for design and sizing of system components. This will reduce the required pipe and pump sizes because the “extra” system capacity during the non-peak ET periods is used to provide water for leaching.

IV. System Capacity

- Application volume can be expressed as either Qt or Ad , where Q is flow rate, t is time, A is irrigated area and d is gross application depth
- Both terms are in units of volume
- Thus, the system capacity is defined as (Eq. 5.4):

$$Q_s = K \frac{Ad}{fT} \quad (35)$$

where,

- Q_s = system capacity;
- T = hours of system operation per day (obviously, $T \leq 24$; also, $t = fT$)
- K = coefficient for conversion of units (see below)
- d = gross application depth (equals U_d/Eff during f' period)
- f = time to complete one irrigation (days); equal to f' minus the days

off

- A = net irrigated area supplied by the discharge Q_s

Value of K:

- **Metric:** for d in mm, A in ha, and Q_s in lps: **K = 2.78**
- **English:** for d in inches, A in acres, and Q_s in gpm: **K = 453**

Notes about system capacity:

- Eq. 5.4 is normally used for periodic-move and linear-move sprinkler systems
- The equation can also be used for center pivots if f is decimal days to complete one revolution and d is the gross application depth per revolution
- For center pivot and solid-set systems, irrigations can be light and frequent ($d_{\text{applied}} < d$): soil water is maintained somewhat below field capacity at all times (assuming no leaching requirement), and there is very little deep percolation loss
- Also, there is a margin of safety in the event that the pump fails (or the system is temporarily out of operation for whatever reason) just when MAD is reached (time to irrigate), because the soil water deficit is never allowed to reach MAD
- However, light and frequent irrigations are associated with higher evaporative losses, and probably higher ET too (due to more optimal soil moisture conditions). This corresponds to a higher basal crop coefficient ($K_{cb} + K_s$), where K_s is increased, and possibly K_{cb} too.
- When a solid-set (fixed) system is used for frost control, all sprinklers must operate simultaneously and the value of Q_s is equal to the number of sprinklers multiplied by q_a . This tends to give a higher Q_s than that calculated from Eq. 5.4.

V. Set Sprinkler Application Rate

- The average application rate is calculated as (after Eq. 5.5):

$$I = \frac{3600qR_e}{S_e S_l} \quad (36)$$

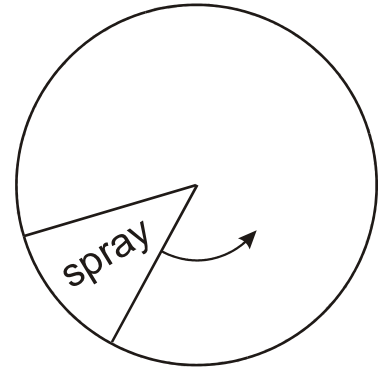
where I is the application rate (mm/hr); q is the flow rate (lps); S_e is the sprinkler spacing (m); S_l is the lateral spacing (m); and R_e is the fraction of water emitted by the nozzle that reaches the soil (takes into account the evaporative/wind loss)

- R_e is defined in Chapter 6 of the textbook
- The instantaneous application rate for a rotating sprinkler (after Eq. 5.6):

$$I_i = \frac{3600 q R_e}{\pi R_j^2 \left(\frac{S_a}{360} \right)} \quad (37)$$

where I_i is the application rate (mm/hr); R_j is the radius of throw, or wetted radius (m); and S_a is the segment wetted by the sprinkler when the sprinkler is not allowed to rotate (degrees)

- Note that due to sprinkler overlap, the instantaneous application rate may actually be higher than that given by I_i above
- For a non-rotating sprinkler, the instantaneous application rate is equal to the average application rate
- For a rotating sprinkler, the instantaneous application rate may be allowed to exceed the basic intake rate of the soil because excess (ponded) water has a chance to infiltrate while the sprinkler completes each rotation
- See sample calculation 5.3 in the textbook
- Higher pressures can give lower instantaneous application rates, but if the wetted radius does not increase significantly with an increase in pressure, the instantaneous rate may increase
- The minimum tangential rotation speed at the periphery of the wetted area should normally be about 1.5 m/s. For example, for 1 rpm:



$$\frac{(1.5 \text{ m/s})(60 \text{ s/min})}{(1 \text{ rev/min})(2\pi \text{ rad/rev})} = 14.3 \text{ m (radius)} \quad (38)$$

- Thus, a sprinkler with a wetted radius of 14.3 m should rotate at least 1 rpm
- “Big gun” sprinklers can rotate slower than 1 rpm and still meet this criterion

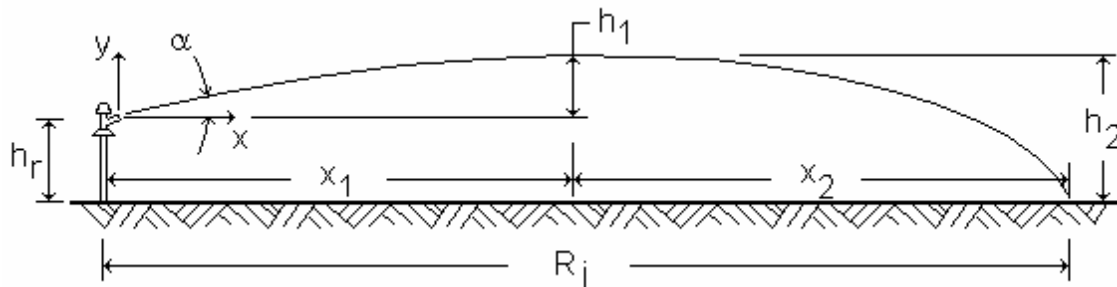
VI. Intake & Optimum Application Rates

- Factors influencing the rate at which water should be applied:
 1. Soil intake characteristics, field slope, and crop cover
 2. Minimum application rate that will give acceptable uniformity
 3. Practicalities regarding lateral movement in periodic-move systems

- Impact of water drops on bare soil can cause “surface sealing” effects, especially on heavy-textured (clayey) soils
- The result is a reduction in infiltration rate due to the formation of a semi-impermeable soil layer
- Sprinklers typically produce drops from ½ to 5 mm
- Terminal velocity of falling drops is from 2 to 22 m/s
- Water drops from sprinklers typically reach their terminal velocity before arriving at the soil surface (especially sprinklers with high risers)
- See Tables 5.3 and 5.4 in the textbook

V. Approximate Sprinkler Trajectory

- The trajectory of water from a sprinkler can be estimated according to physics equations
- The following analysis does not consider aerodynamic resistance nor wind effects, and is applicable to the largest drops issuing from a sprinkler operating under a recommended pressure
- Of course, smaller water drops tend to fall nearer to the sprinkler
- In the figure below, R_j refers to the approximate wetted radius of the sprinkler



- If the velocity in the vertical direction at the nozzle, V_y , is taken as zero at time t_1 , then,

$$(V_y)_{t_1} = V_0 \sin \alpha - gt_1 = 0 \quad (39)$$

where V_0 is the velocity of the stream leaving the nozzle (m/s); α is the angle of the nozzle; t_1 is the time for a drop to travel from the nozzle to the highest point in the trajectory (s); and g is the ratio of weight to mass (9.81 m/s^2)

- Note that the term $V_0 \sin \alpha$ in Eq. 37 is the initial velocity component in the vertical direction, and the term gt_1 is the downward acceleration over time t_1
- The above equation can be solved for t_1
- The initial velocity, V_0 , can be calculated based on the sprinkler discharge and the nozzle diameter
- Values of α can be found from manufacturers' information

- Now, what is the highest point in the trajectory?
- First, solve for t_1 in the previous equation:

$$t_1 = \frac{V_0 \sin \alpha}{g} \quad (40)$$

then,

$$h_1 = V_0 \sin \alpha t_1 - \frac{gt_1^2}{2} = \frac{V_0^2 \sin^2 \alpha}{2g} \quad (41)$$

- Assuming no acceleration in the horizontal direction,

$$x_1 = V_0 \cos \alpha t_1 \quad (42)$$

solving for h_2 ,

$$h_2 = h_r + h_1 = V_y t_2 + \frac{gt_2^2}{2} \quad (43)$$

where h_r is the riser height (m); t_2 is the time for a drop of water to travel from the highest point in the trajectory to impact on the ground; and $V_y = 0$

- Then, x_2 is defined as:

$$x_2 = V_0 \cos \alpha t_2 = V_0 \cos \alpha \sqrt{\frac{2(h_r + h_1)}{g}} \quad (44)$$

And, the approximate wetted radius of the sprinkler is:

$$R_j = x_1 + x_2 \quad (45)$$

- In summary, if air resistance is ignored and the sprinkler riser is truly vertical, the theoretical value of R_j is a function of:

1. Angle, α
2. Nozzle velocity (q_a/A)
3. Riser height, h_r

- And, q_a is a function of P

