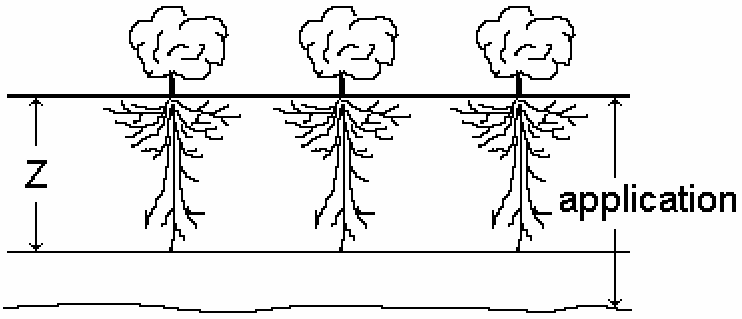
Lecture 4

Set Sprinkler Uniformity & Efficiency

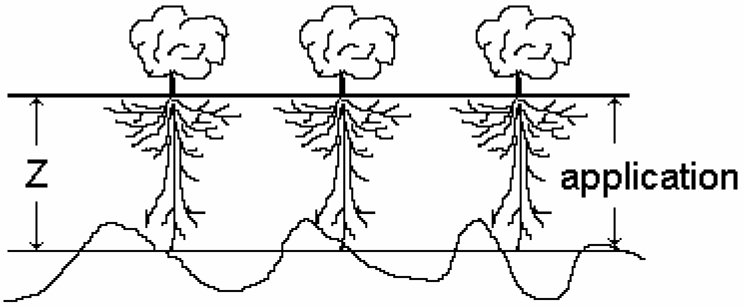
I. Sprinkler Irrigation Efficiency

1. Application uniformity
2. Losses (deep percolation, evaporation, runoff, wind drift, etc.)

- It is not enough to have uniform application if the average depth is not enough to refill the root zone to field capacity
- Similarly, it is not enough to have a correct average application depth if the uniformity is poor
- Consider the following examples:



Uniform, but average depth applied exceeds the soil water deficit (too much deep percolation)



Average depth is correct, but application is highly nonuniform, with underirrigation and DP

- We can design a sprinkler system that is capable of providing good application uniformity, but depth of application is a function of the set time (in periodic-move systems) or "on time" (in fixed systems)
- Thus, uniformity is mainly a function of design and subsequent system maintenance, but application depth is a function of management

II. Quantitative Measures of Uniformity

Distribution uniformity, DU (Eq. 6.1):

$$DU = 100\left(\frac{\text{avg depth of low quarter}}{\text{avg depth}}\right) \tag{46}$$

- The average of the low quarter is obtained by measuring application from a catch-can test, mathematically overlapping the data (if necessary), ranking the values by magnitude, and taking the average of the values from the low ¼ of all values
- For example, if there are 60 values, the low quarter would consist of the 15 values with the lowest “catches”

Christiansen Coefficient of Uniformity, CU (Eq. 6.2):

$$CU = 100\left(1.0 - \frac{\sum_{j=1}^{n} \text{abs}\left(z_j - m\right)}{\sum_{j=1}^{n} z_j}\right) \tag{47}$$

where z are the individual catch-can values (volumes or depths); n is the number of observations; and m is the average of all catch volumes.

- Note that CU can be negative if the distribution is very poor
- There are other, equivalent ways to write the equation
- These two measures of uniformity (CU & DU) date back to the time of slide rules (more than 50 years ago; no electronic calculators), and are designed with computational ease in mind
- More complex statistical analyses can be performed, but these values have remained useful in design and evaluation of sprinkler systems
- For CU > 70% the data usually conform to a normal distribution, symmetrical about the mean value. Then,

$$CU \approx 100\left(\frac{\text{avg depth of low half}}{\text{avg depth}}\right) \tag{48}$$

another way to define CU is through the standard deviation of the values,

$$CU = 100\left(1.0 - \frac{\sigma}{m}\sqrt{\frac{2}{\pi}}\right) \tag{49}$$

where σ is the standard deviation of all values, and a normal distribution is assumed (as previously)

- Note that CU = 100% for $\sigma = 0$
- The above equation assumes a normal distribution of the depth values, whereby:

$$\sum \left| z - m \right| = n\sigma\sqrt{2/\pi} \tag{50}$$

- By the way, the ratio σ/m is known in statistics as the *coefficient of variation*
- Following is the approximate relationship between CU and DU:

$$CU \approx 100 - 0.63(100 - DU) \tag{51}$$

or,

$$DU \approx 100 - 1.59(100 - CU) \tag{52}$$

- These equations are used in evaluations of sprinkler systems for both design and operation
- Typically, 85 to 90% is the practical upper limit on DU for set systems
- DU > 65% and CU > 78% is considered to be the minimum acceptable performance level for an economic system design; so, you would not normally design a system for a CU < 78%, unless the objective is simply to “get rid of water or effluent” (which is sometimes the case)
- For shallow-rooted, high value crops, you may want to use DU > 76% and CU > 85%

III. Alternate Sets (Periodic-Move Systems)

- The effective uniformity (over multiple irrigations) increases if “alternate sets” are used for periodic-move systems ($\frac{1}{2}S_l$)
- This is usually practiced by placing laterals halfway between the positions from the previous irrigation, alternating each time
- The relationship is:

$$\begin{gathered} CU_a \approx 10\sqrt{CU} \\ DU_a \approx 10\sqrt{DU} \end{gathered} \tag{53}$$

- The above are also valid for “double” alternate sets ($S_l/3$)
- Use of alternate sets is a good management practice for periodic-move systems
- The use of alternate sets approaches an S_l of zero, which simulates a continuous-move system

IV. Uniformity Problems

- Of the various causes of non-uniform sprinkler application, some tend to cancel out with time (multiple irrigations) and others tend to concentrate (get worse)
- In other words, the "composite" CU for two or more irrigations may be (but not necessarily) greater than the CU for a single irrigation

1. Factors that tend to Cancel Out

    - Variations in sprinkler rotation speed
    - Variations in sprinkler discharge due to wear
    - Variations in riser angle (especially with hand-move systems)
    - Variations in lateral set time

2. Factors that may both Cancel Out and Concentrate

    - Non-uniform aerial distribution of water between sprinklers

3. Factors that tend to Concentrate

    - Variations in sprinkler discharge due to elevation and head loss
    - Surface ponding and runoff
    - Edge effects at field boundaries

V. System Uniformity

- The uniformity is usually less when the entire sprinkler system is considered, because there tends to be greater pressure variation in the system than at any given lateral position.

$$\text{system CU} \approx \text{CU}\left[\frac{1}{2}\left(1+\sqrt{P_n/P_a}\right)\right] \tag{54}$$

$$\text{system DU} \approx \text{DU}\left[\frac{1}{4}\left(1+3\sqrt{P_n/P_a}\right)\right] \tag{55}$$

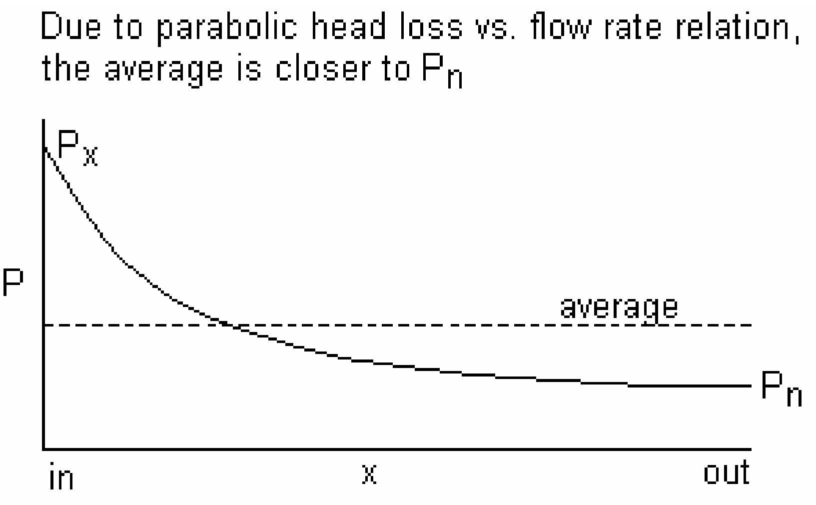
where P_n is the minimum sprinkler pressure in the whole field; and P_a is the average sprinkler pressure in the entire system, over the field area.

- These equations can be used in design and evaluation
- Note that when $P_n = P_a$ (no pressure variation) the system CU equals the CU
- If pressure regulators are used at each sprinkler, the system CU is approximately equal to 0.95CU (same for DU)

- If flexible orifice nozzles are used, calculate system CU as 0.90CU (same for DU)
- The P_a for a system can often be estimated as a weighted average of P_n & P_x:

$$P_a = \frac{2P_n + P_x}{3} \tag{56}$$

where P_x is the maximum nozzle pressure in the system



VI. Computer Software and Standards

- There is a computer program called “Catch-3D” that performs uniformity calculations on sprinkler catch-can data and can show the results graphically
- Jack Keller and John Merriam (1978) published a handbook on the evaluation of irrigation systems, and this includes simple procedures for evaluating the performance of sprinkler systems
- The ASAE S436 (Sep 92) is a detailed standard for determining the application uniformity under center pivots (not a set sprinkler system, but a continuous move system)
- ASAE S398.1 provides a description of various types of information that can be collected during an evaluation of a set sprinkler system

VII. General Sprinkle Application Efficiency

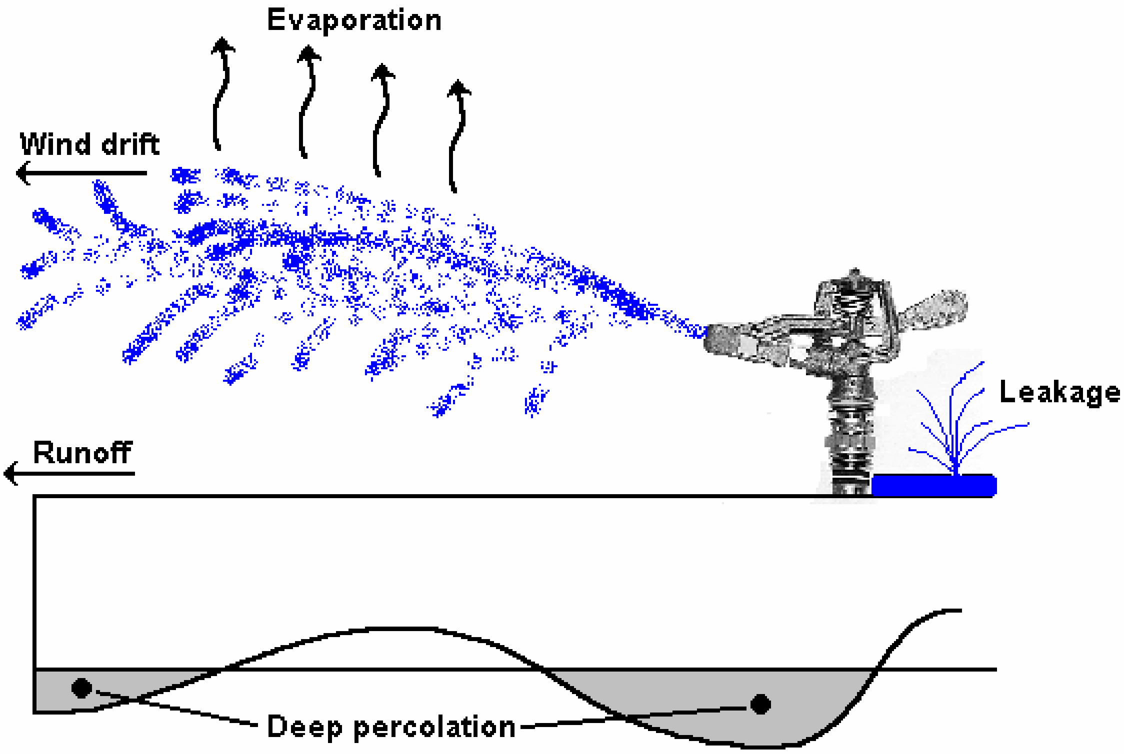
The following material leads up to the development of a general sprinkle application efficiency term (Eq. 6.9) as follows:

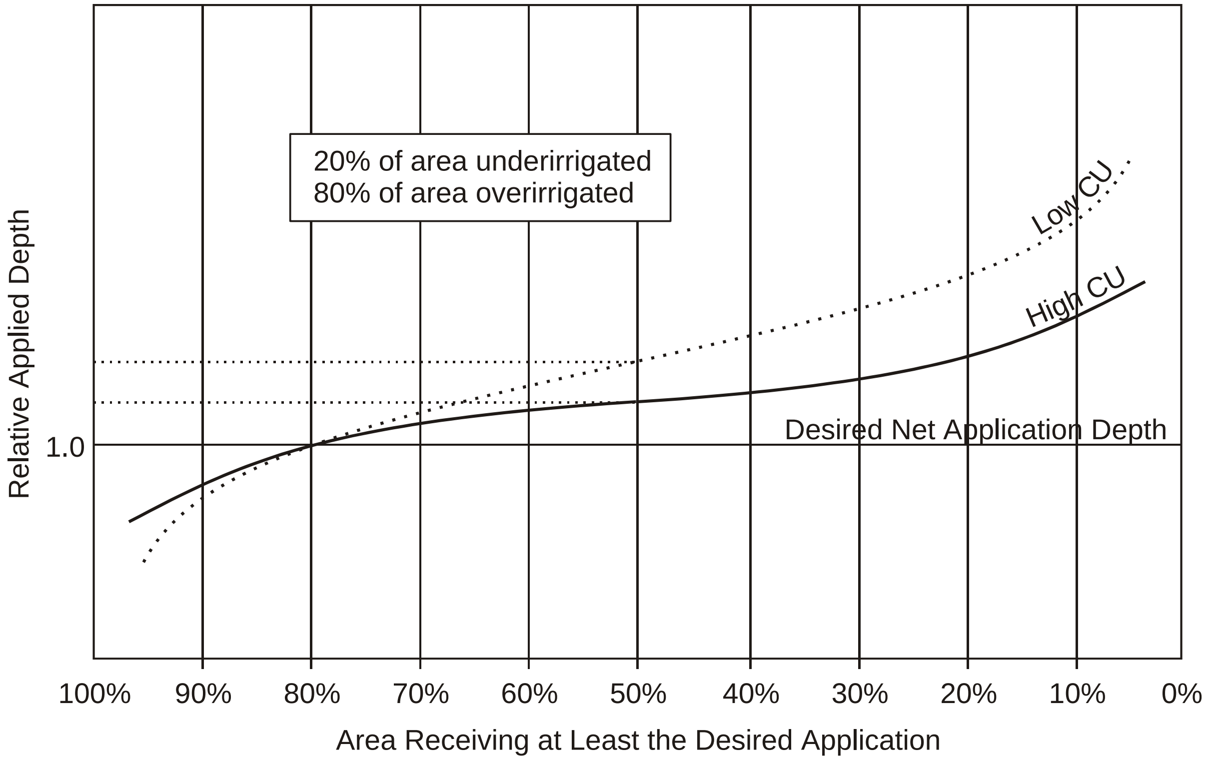
Design Efficiency:

$$E_{pa} = DE_{pa} R_e O_e \tag{57}$$

where DE_{pa} is the distribution efficiency (%); R_e is the fraction of applied water that reaches the soil surface; and O_e is the fraction of water that does not leak from the system pipes.

- The design efficiency, E_{pa}, is used to determine gross application depth (for design purposes), given the net application depth
- In most designs, it is not possible to do a catch-can test and data analysis – you have to install the system in the field first; thus, use the “design efficiency”
- The subscript “pa” represents the “percent area” of the field that is adequately irrigated (to d_n, or greater) – for example, E_{80} and DE_{80} are the application and distribution efficiencies when 80% of the field is adequately irrigated
- Question: can “pa” be less than 50%?





VIII. Distribution Efficiency

- This is used to define the *uniformity* and *adequacy* of irrigation
- DE is based on statistical distributions and application uniformity
- For a given uniformity (CU) and a given percent of land adequately irrigated (equal to or greater than required application depth), Table 6.2 gives values of DE that determine how much water must be applied in excess of the required depth so that the given percent of land really does receive at least the required depth

CU	**Percent area adequately irrigated (pa)**									
	95	**90**	**85**	**80**	**75**	**70**	**65**	**60**	**55**	**50**
94	87.6	90.4	92.2	93.7	94.9	96.1	97.1	98.1	99.1	100.0
92	83.5	87.1	89.6	91.6	93.2	94.7	96.1	97.5	98.7	100.0
90	79.4	83.9	87.0	89.4	91.5	93.4	95.2	96.8	98.4	100.0
88	75.3	80.7	84.4	87.3	89.8	92.1	94.2	96.2	98.1	100.0
86	71.1	77.5	81.8	85.2	88.2	90.8	93.2	95.6	97.8	100.0
84	67.0	74.3	79.2	83.1	86.5	89.5	92.3	94.9	97.5	100.0
82	62.9	71.1	76.6	81.0	84.8	88.2	91.3	94.3	97.2	100.0
80	58.8	67.9	74.0	78.9	83.1	86.8	90.3	93.6	96.8	100.0
78	54.6	64.7	71.4	76.8	81.4	85.5	89.4	93.0	96.5	100.0
76	50.5	61.4	68.8	74.7	79.7	84.2	88.4	92.4	96.2	100.0
74	46.4	58.2	66.2	72.6	78.0	82.9	87.4	91.7	95.9	100.0
72	42.3	55.0	63.6	70.4	76.3	81.6	86.5	91.1	95.6	100.0
70	38.1	51.8	61.0	68.3	74.6	80.3	85.5	90.5	95.3	100.0

- See Fig. 6.7

IX. Wind Drift and Evaporation Losses

- These losses are typically from 5% to 10%, but can be higher when the air is dry, there is a lot of wind, and the water droplets are small
- *Effective portion of the applied water*, R_e. This is defined as the percentage of applied water that actually arrives at the soil surface of the irrigated field.
- This is based on:

  - climatic conditions
  - wind speed
  - spray coarseness

- Figure 6.8 gives the value of R_e for these different factors
- The *Coarseness Index*, CI, is defined as (Eq. 6.7):

$$CI = 0.032\left(\frac{P^{1.3}}{B}\right) \tag{58}$$

where P is the nozzle pressure (kPa) and B is the nozzle diameter (mm)

CI > 17	**17 ≥ CI ≥ 7**	**CI < 7**
fine spray	**between fine and coarse**	**coarse spray**

- When the spray is between fine and coarse, R_e is computed as a weighted average of $(R_e)_{fine}$ and $(R_e)_{coarse}$ (Eq. 6.8):

$$R_e = \frac{(CI-7)}{10}\left(R_e\right)_{fine} + \frac{(17-CI)}{10}\left(R_e\right)_{coarse} \tag{59}$$

- Allen and Fisher (1988) developed a regression equation to fit the curves in Fig. 6.8:

$$\begin{aligned} R_e = 0.976 + 0.005 ET_o - 0.00017 ET_o^2 + 0.0012 W \\ -0.00043(CI)(ET_o) - 0.00018(CI)(W) \\ -0.000016(CI)(ET_o)(W) \end{aligned} \tag{60}$$

where ET_o is the reference ET in mm/day (grass-based); CI is the coarseness index ($7 \le CI \le 17$); and W is the wind speed in km/hr

- For the above equation, if CI < 7 then set it equal to 7; if CI > 17 then set it equal to 17

X. Leaks and Drainage Losses

1. Losses due to drainage of the system after shut-down

    - upon shut-down, most sprinkler systems will partially drain
    - water runs down to the low elevations and or leaves through automatic drain valves that open when pressure drops
    - fixed (solid-set) systems can have anti-drain valves at sprinklers that close when pressure drops (instead of opening, like on wheel lines)

2. Losses due to leaky fittings, valves, and pipes

    - pipes and valves become damaged with handling, especially with hand-move and side-roll systems, but also with orchard sprinklers and end-tow sprinklers
    - gaskets and seals become inflexible and fail

- These losses are quantified in the O_e term
- For systems in good condition these losses may be only 1% or 2%, giving an O_e value of 99% or 98%, respectively
- For system in poor condition these losses can be 10% or higher, giving an O_e value of 90% or less

XI. General Sprinkle Application Efficiency

- As given above, Eq. 6.9 from the textbook, it is:

$$E_{pa} = DE_{pa} R_e O_e \tag{61}$$

where DE_{pa} is in percent; and R_e and O_e are in fraction (0 to 1.0). Thus, E_{pa} is in percent.

XII. Using CU or DU instead of DE_{pa}

1. Application Efficiency of the **Low Quarter**, E_q

    - Given by Eq. 6.9 when DU replaces DE_{pa}
    - Useful for design purposes for medium to high-value crops
    - Only about 10% of the area will be under-irrigated
    - Recall that DU is the average of low quarter divided by average
2. Application Efficiency of the **Low Half**, E_h

    - Given by Eq. 6.9 when CU replaces DE_{pa}
    - Useful for design purposes for low-value and forage crops

  - Only about 20% of the area will be under-irrigated
  - Recall that CU is the average of low half divided by average

XIII. Procedure to Determine CU, Required Pressure, S_e and S_l for a Set System

1. Specify the minimum acceptable E_{pa} and target pa
2. Estimate R_e and O_e (these are often approximately 0.95 and 0.99, respectively)
3. Compute DE_{pa} from E_{pa}, R_e and O_e
4. Using DE_{pa} and pa, determine the CU (Table 6.2) that is required to achieve E_{pa}
5. Compute the set operating time, t_{so}, then adjust f' and d_n so that t_{so} is an appropriate number of hours
6. Compute q_a based on I, S_e and S_l (Eq. 5.5)
7. Search for nozzle size, application rate, S_e and S_l to obtain the CU
8. Repeat steps 5, 6 and 7 as necessary until a workable solution is found

XIV. How to Measure R_e

- The textbook suggests a procedure for estimating R_e
- You can also measure R_e from sprinkler catch-can data:

  1. Compute the average catch depth over the wetted area (if a single sprinkler), or in the area between four adjacent sprinklers (if in a rectangular grid)
  2. Multiply the sprinkler flow rate by the total irrigation time to get the volume applied, then divide by the wetted area to obtain the gross average application depth
  3. Divide the two values to determine the effective portion of the applied water

XV. Line- and Point-Source Sprinklers

- Line-source sprinklers are sometimes used by researches to determine the effects of varying water application on crop growth and yield
- A line-source sprinkler system consists of sprinklers spaced evenly along a straight lateral pipe in which the application rate varies linearly with distance away from the lateral pipe, orthogonally
- Thus, a line-source sprinkler system applies the most water at the lateral pipe, decreasing linearly to zero to either side of the lateral pipe
- A point-source sprinkler is a single sprinkler that gives linearly-varying application rate with radial distance from the sprinkler

- With a point-source sprinkler, the contours of equal application rate are concentric circles, centered at the sprinkler location (assuming the riser is vertical and there is no wind)