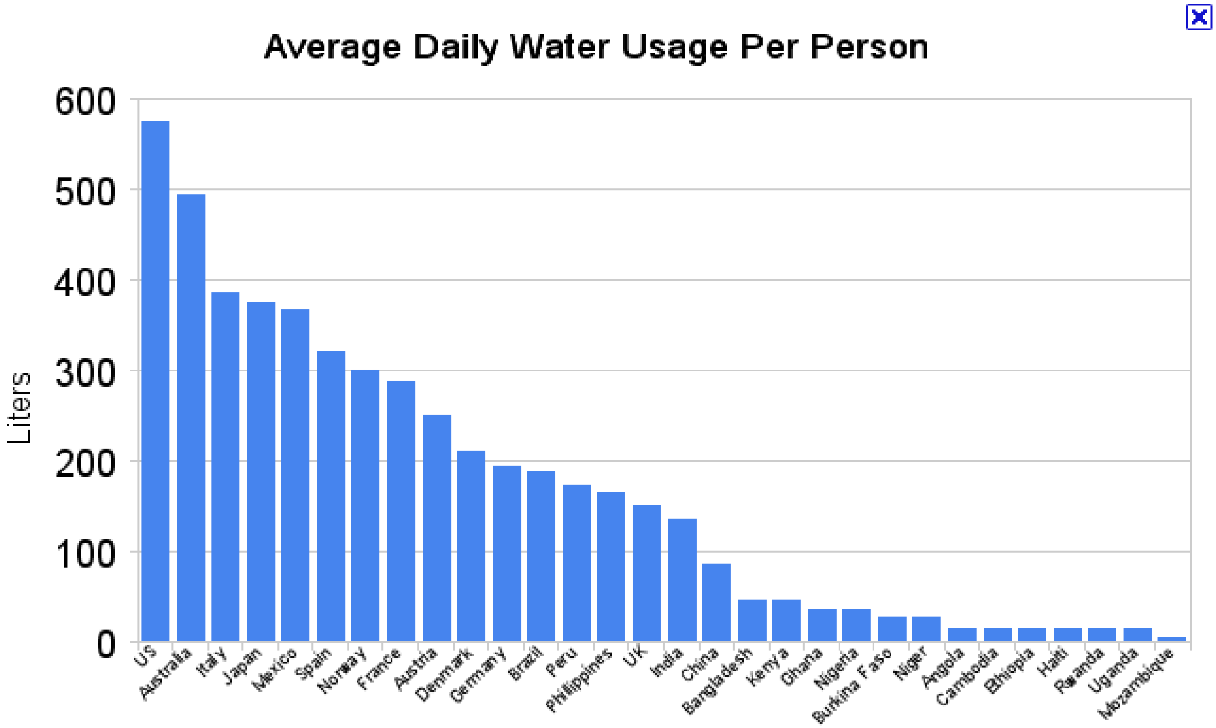
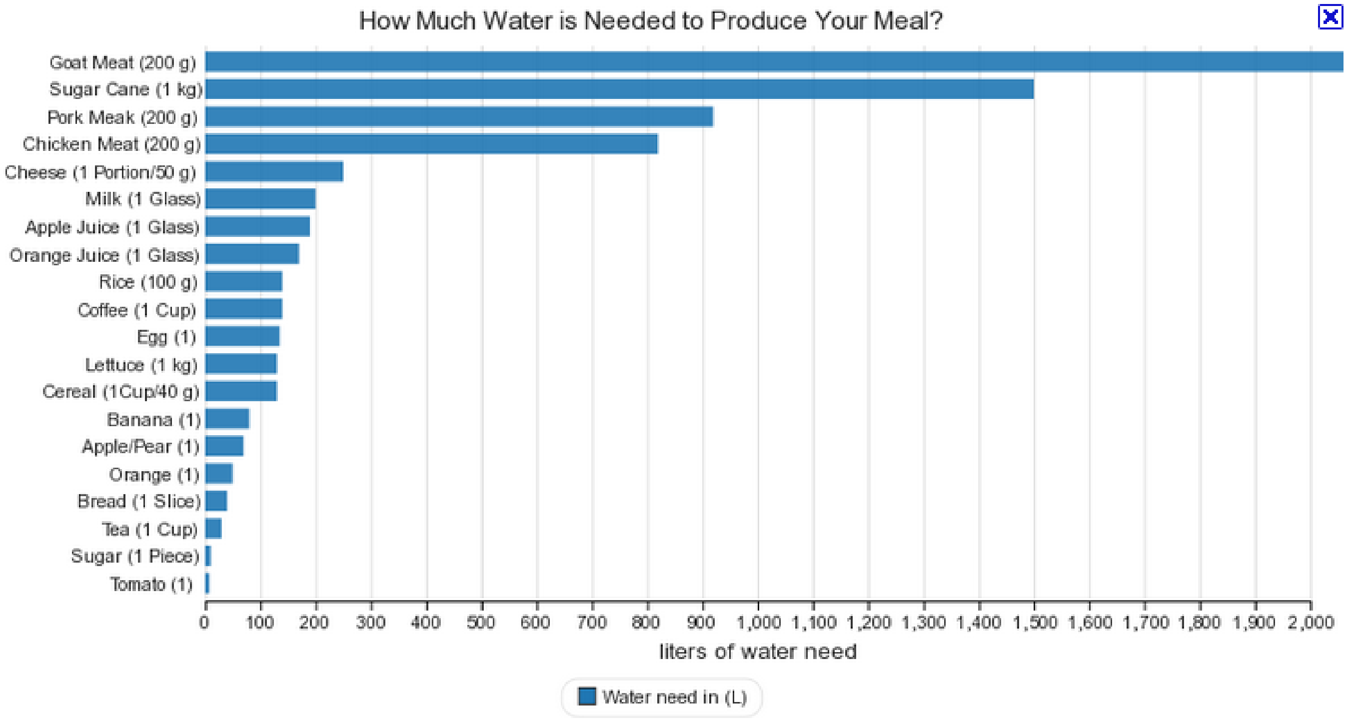
TMAG 4019
Irrigation Principles – Part 1

- Increasing demands for water, limited available, and concerns about water quality, make effective use of water essential.

- Because irrigation is a major water user, is essential that irrigation systems be planned, designed, and operated efficiently.

- How much water does irrigation use?
  - **Agriculture is responsible for 87 % of the total water used globally.**
  - **It is estimated that 69% of worldwide water use is for irrigation, with 15-35% of irrigation withdrawals being unsustainable. (Wikipedia)**




How Much Water is Needed to Produce Your Meal?
Goat Meat (200 g)
Sugar Cane (1 kg)
Pork Meak (200 g)
Chicken Meat (200 g)
Cheese (1 Portion/50 g)
Milk (1 Glass)
Apple Juice (1 Glass)
Orange Juice (1 Glass)
Rice (100 g)
Coffee (1 Cup)
Egg (1)
Lettuce (1 kg)
Cereal (1Cup/40 g)
Banana (1)
Apple/Pear (1)
Orange (1)
Bread (1 Slice)
Tea (1 Cup)
Sugar (1 Piece)
Tomato (1)
0 100 200 300 400 500 600 700 800 900 1,000 1,100 1,200 1,300 1,400 1,500 1,600 1,700 1,800 1,900 2,000
liters of water need
Water need in (L)

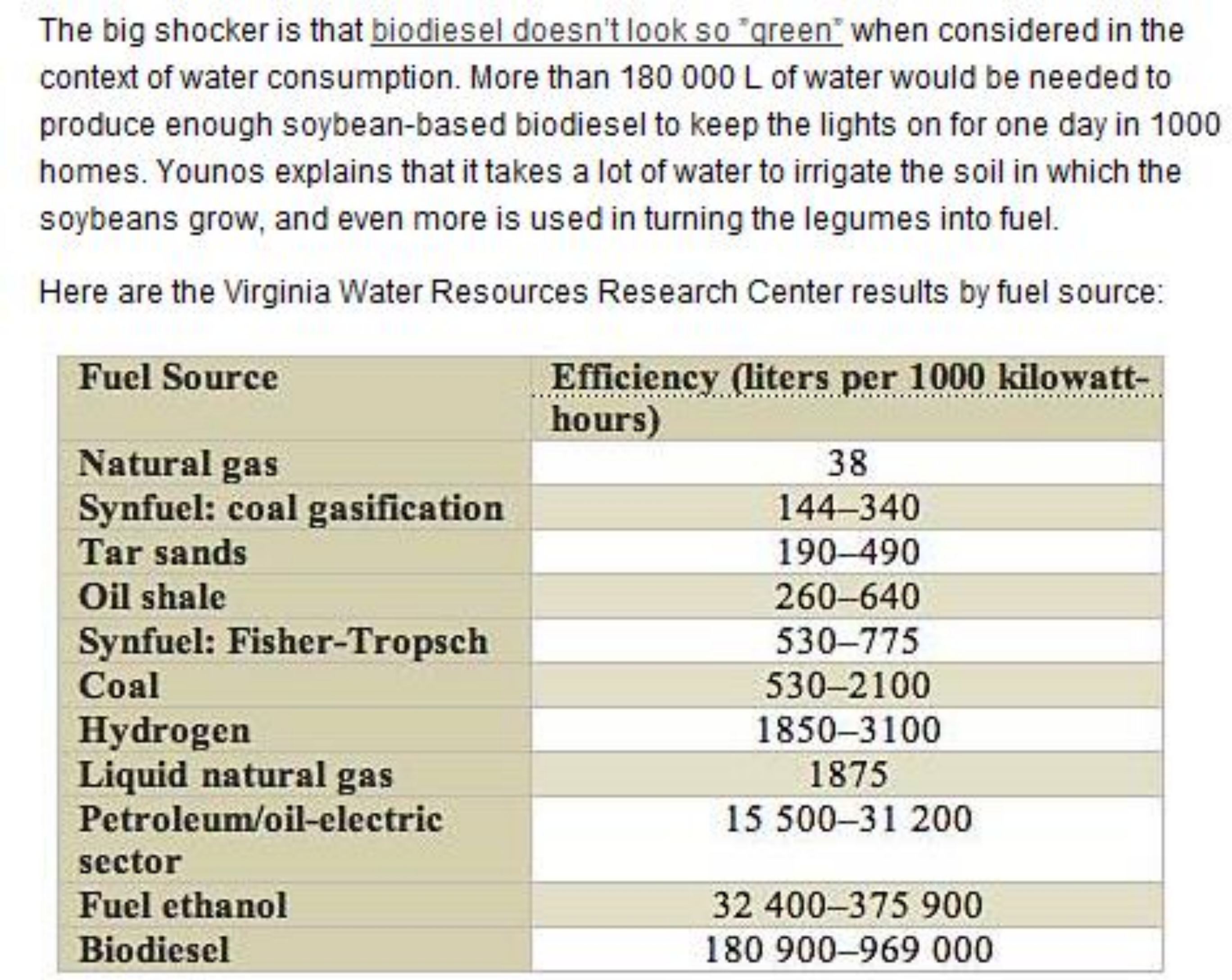

HOW MUCH WATER IS
NEEDED TO PRODUCE
1 hamburger?
2400
litres

How much water is required for the hamberger bun?

- Assume 1 sq. ft of wheat is required to produce the bun.
- Assume typical wheat season is 135 days
- Assume average evapotranspiration is 2.5 mm/day
- Consider irrigation only (i.e., no post harvest processing)

$$\frac{2.5\,mm\cdot 1\,ft^{2}}{day}\cdot 135\,day = 31.35\,liter$$

Water use for alternative fuel sources



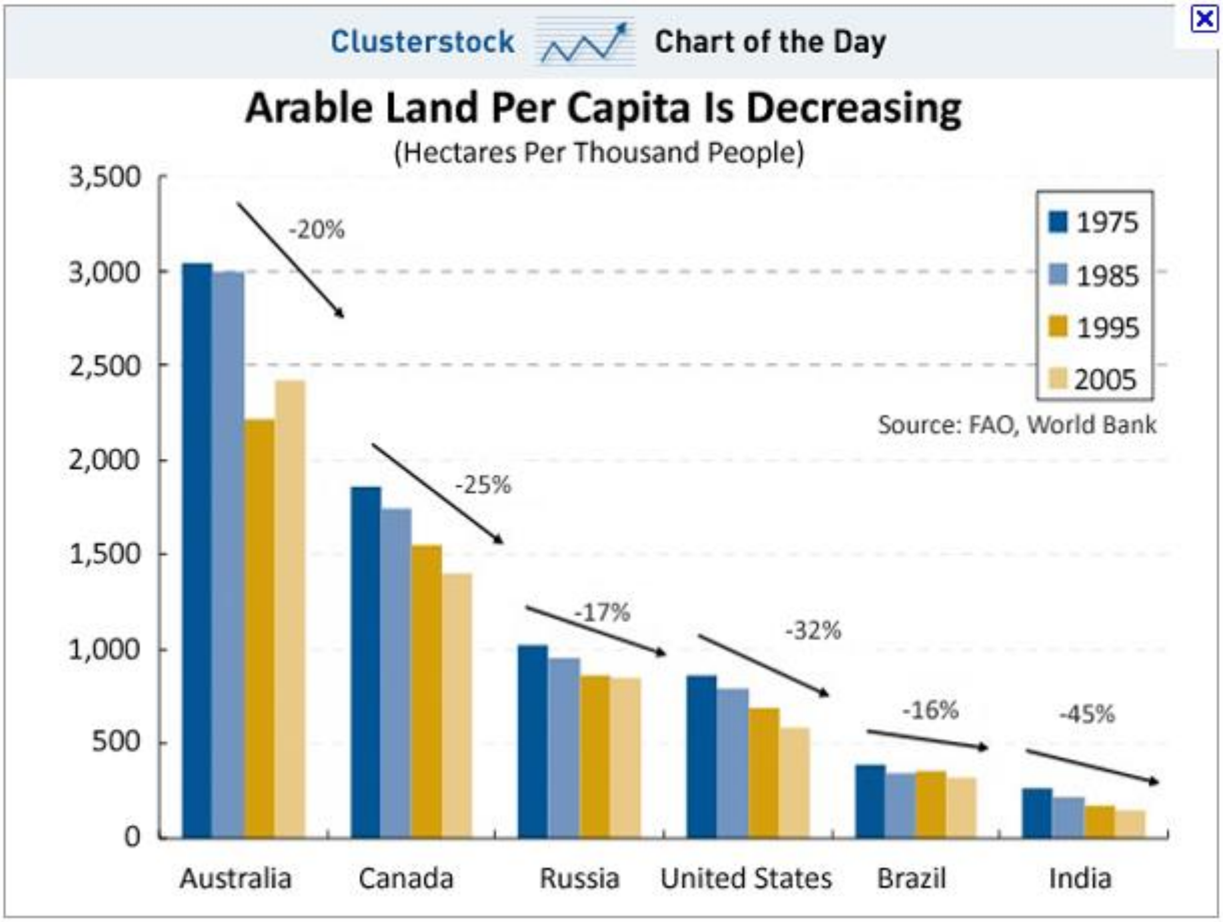
The big shocker is that biodiesel doesn't look so "green" when considered in the context of water consumption. More than 180 000 L of water would be needed to produce enough soybean-based biodiesel to keep the lights on for one day in 1000 homes. Younos explains that it takes a lot of water to irrigate the soil in which the soybeans grow, and even more is used in turning the legumes into fuel.

Here are the Virginia Water Resources Research Center results by fuel source:

Fuel Source	Efficiency (liters per 1000 kilowatt-hours)
Natural gas	38
Synfuel: coal gasification	144–340
Tar sands	190–490
Oil shale	260–640
Synfuel: Fisher-Tropsch	530–775
Coal	530–2100
Hydrogen	1850–3100
Liquid natural gas	1875
Petroleum/oil-electric sector	15 500–31 200
Fuel ethanol	32 400–375 900
Biodiesel	180 900–969 000

http://spectrum.ieee.org/energy/environment/how-much-water-does-it-take-to-make-electricity

We are loosing arable land to produce food.



Arable Land Per Capita Is Decreasing

(Hectares Per Thousand People)

Source: FAO, World Bank

In Puerto Rico, "…..in 1964 the agricultural land area was estimated at 1,595,866 acres and in 2018 at 474,332 acres (USDA-NASS, 2018). This dramatic reduction amounts to an agricultural land-area loss of about 70% of that in 1964. In the last five years Puerto Rico lost 94,534 acres, part of which was associated with inventory loss due to Hurricanes Irma and María."

From:
The case for preserving agricultural land area in Puerto Rico and green-energy projects, by David Sotomayor-Ramírez, Ph.D, Professor of Soil Science

Crop Water Requirements

- Water requirements and time of maximum water demand vary by crop.
- The irrigator should have knowledge of the seasonal water requirements of crops at all growth stages.
- Seasonal water required to select the crop to meet the water supply.

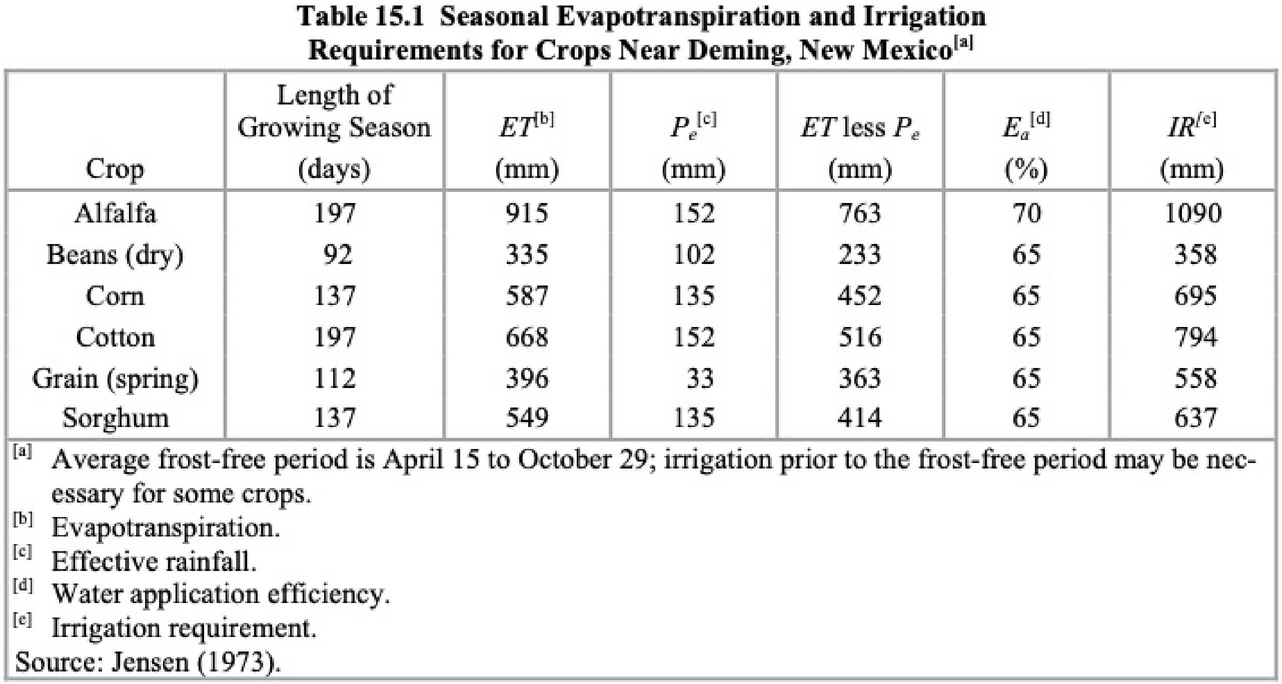


Table 15.1 Seasonal Evapotranspiration and Irrigation Requirements for Crops Near Deming, New Mexico[a]

Crop	Length of Growing Season (days)	ET[b] (mm)	P_e[c] (mm)	ET less P_e (mm)	E_a[d] (%)	IR[e] (mm)
Alfalfa	197	915	152	763	70	1090
Beans (dry)	92	335	102	233	65	358
Corn	137	587	135	452	65	695
Cotton	197	668	152	516	65	794
Grain (spring)	112	396	33	363	65	558
Sorghum	137	549	135	414	65	637

[a] Average frost-free period is April 15 to October 29; irrigation prior to the frost-free period may be necessary for some crops.

[b] Evapotranspiration.

[c] Effective rainfall.

[d] Water application efficiency.

[e] Irrigation requirement.

Source: Jensen (1973).

- Estimates of evapotranspiration must be know when planning and managing an irrigation system (Chapter 4 of text)

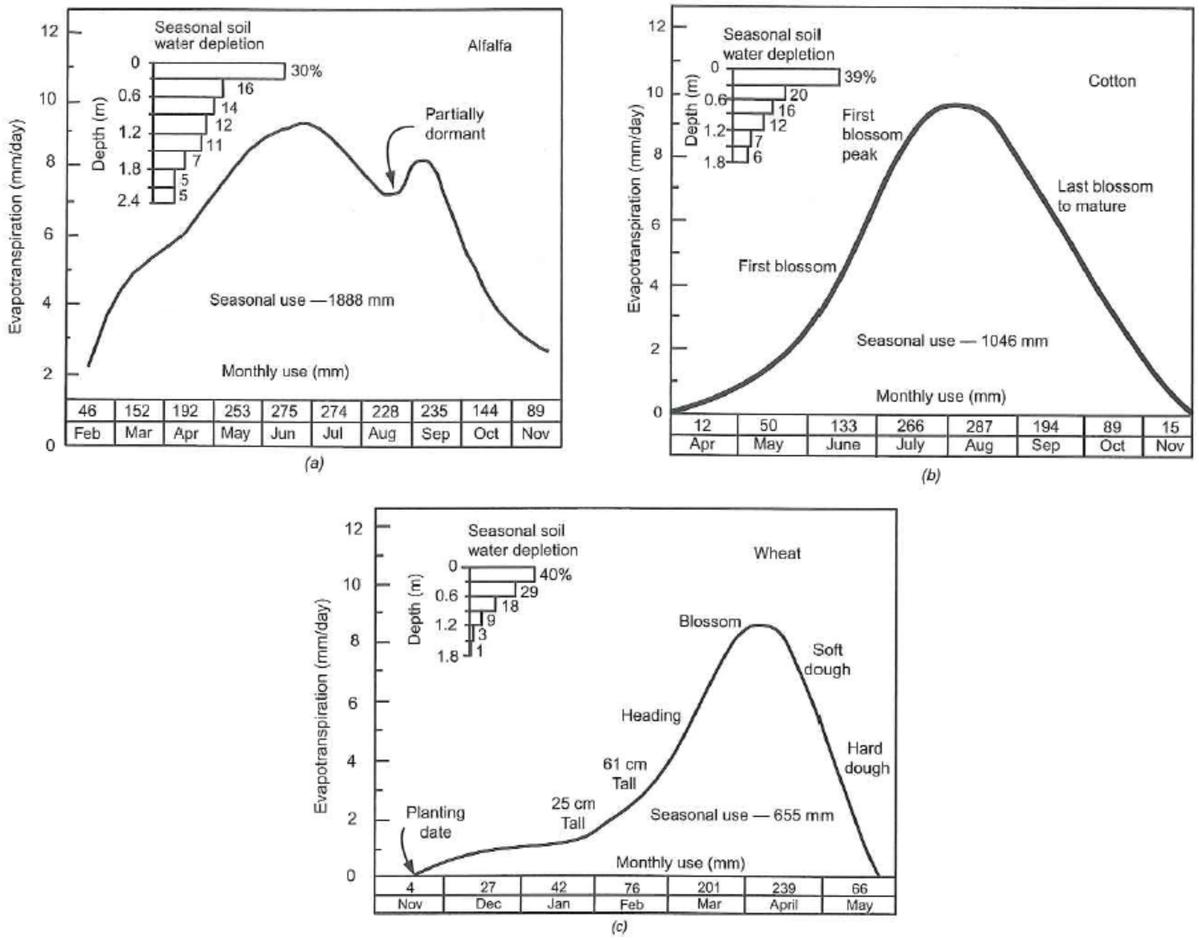


Figure 15–1 Average evapotranspiration and seasonal water depletion with depth for (a) alfalfa, (b) cotton, and (c) wheat at Mesa and Tempe, Arizona. (Redrawn and adapted from Erie et al., 1982)

Effective Rainfall

Not all rainfall is effective, **only the portion that contributes to evapotranspiration.**

$$P_e = f(D)\cdot\left(1.25\cdot P_m^{0.824} - 2.93\right)\cdot\left(10^{0.000955\cdot ET}\right) \tag{15.1}$$

$$f(D) = 0.53 + 0.0116\cdot D - 8.94\cdot 10^{-5}\cdot D^2 + 2.32\cdot 10^{-7}\cdot D^3 \tag{15.2}$$

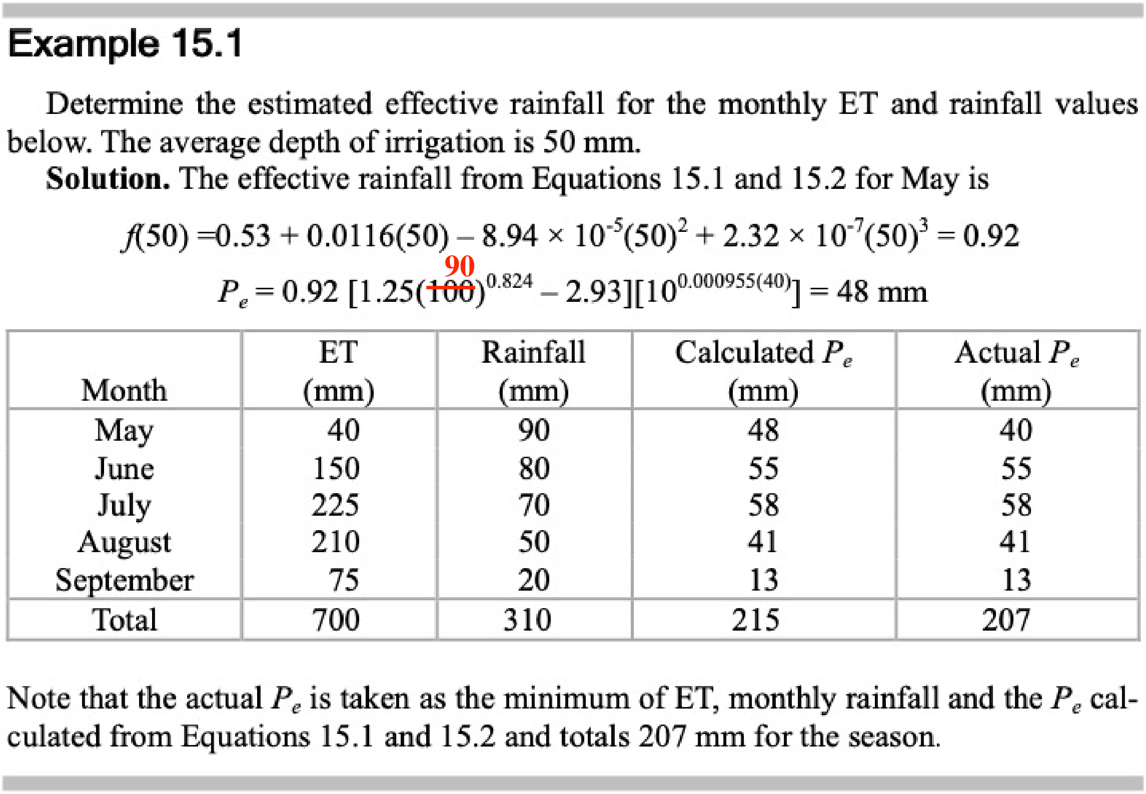
P_e = estimated effective rainfall (mm)
f(D) = adjustment factor for soil water deficits or net irrigation depths
P_m = mean monthly rainfall (mm)
ET = average monthly evapotranspiration (mm)
D = soil water deficit or net irrigation depth (mm)

Note that P_e is taken as the lowest of P_m, ET or P_e from equations 15.1 and 15.2 because effective precipitation cannot exceed the monthly rainfall or evapotranspiration.

Example Problem

Determine the effective rainfall for the monthly ET and rainfall values below. The average depth of irrigation is 50 mm.

Solution. The effective rainfall from equations 15.1 and 15.2 are given below.



Example 15.1

Determine the estimated effective rainfall for the monthly ET and rainfall values below. The average depth of irrigation is 50 mm.

Solution. The effective rainfall from Equations 15.1 and 15.2 for May is

$$f(50) = 0.53 + 0.0116(50) - 8.94 \times 10^{-5}(50)^2 + 2.32 \times 10^{-7}(50)^3 = 0.92$$

$$P_e = 0.92\,[1.25(\overset{90}{\cancel{100}})^{0.824} - 2.93][10^{0.000955(40)}] = 48 \text{ mm}$$

Month	ET (mm)	Rainfall (mm)	Calculated P_e (mm)	Actual P_e (mm)
May	40	90	48	40
June	150	80	55	55
July	225	70	58	58
August	210	50	41	41
September	75	20	13	13
Total	700	310	215	207

Note that the actual P_e is taken as the minimum of ET, monthly rainfall and the P_e calculated from Equations 15.1 and 15.2 and totals 207 mm for the season.

- The soil characteristics are very important for crop production.
- The soil is a reservoir for water and chemicals including plant nutrients, plus provides a medieum to support the plants
- For irrigation, the water-holding capacity and salt content of the soil must be considered.

The Soil Water Reservoir

- The soil can be considered as a container which is periodically filled with water by rainfall or irrigation. The water entering the soil profile may contain salts and other chemicals.
- The soil water is slowly depleted by evapotranspiration.
- Water applied in access of the ***field capacity*** of the soil is wasted, unless it is used to leach the soil of salts.
- Irrigation is scheduled in order to prevent the soil profile from becoming too depleted of water, which will cause plant stress.
- Water can be applied to the soil profile via sprinkler, surface or drip irrigation.
- The infiltration capacity and permeability will determine how fast water can enter the soil. Water applied in excess of the infiltration capacity will cause surface runoff.
- The field capacity or the soil water holding capacity of the soil must be known. Table 15-2 provides representative values along with some other important soil properties.

Table 15-2.

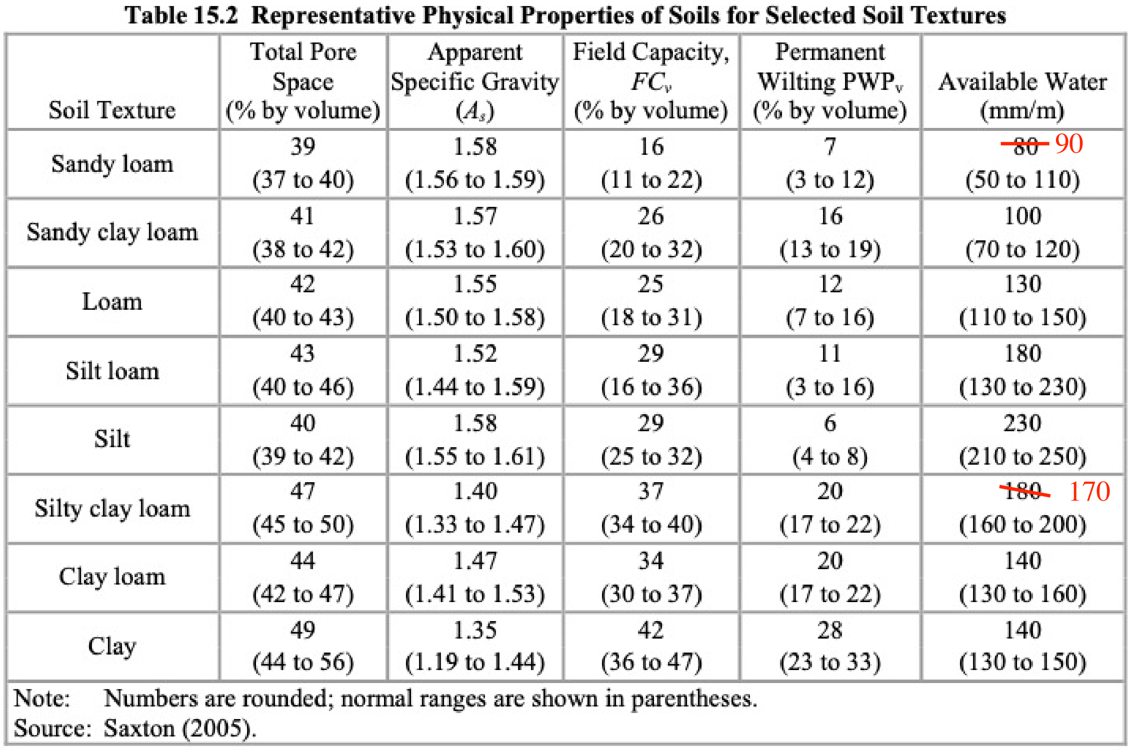


Table 15.2 Representative Physical Properties of Soils for Selected Soil Textures

Soil Texture	Total Pore Space (% by volume)	Apparent Specific Gravity (A_s)	Field Capacity, FC_v (% by volume)	Permanent Wilting PWP_v (% by volume)	Available Water (mm/m)
Sandy loam	39 (37 to 40)	1.58 (1.56 to 1.59)	16 (11 to 22)	7 (3 to 12)	~~80~~ 90 (50 to 110)
Sandy clay loam	41 (38 to 42)	1.57 (1.53 to 1.60)	26 (20 to 32)	16 (13 to 19)	100 (70 to 120)
Loam	42 (40 to 43)	1.55 (1.50 to 1.58)	25 (18 to 31)	12 (7 to 16)	130 (110 to 150)
Silt loam	43 (40 to 46)	1.52 (1.44 to 1.59)	29 (16 to 36)	11 (3 to 16)	180 (130 to 230)
Silt	40 (39 to 42)	1.58 (1.55 to 1.61)	29 (25 to 32)	6 (4 to 8)	230 (210 to 250)
Silty clay loam	47 (45 to 50)	1.40 (1.33 to 1.47)	37 (34 to 40)	20 (17 to 22)	~~180~~ 170 (160 to 200)
Clay loam	44 (42 to 47)	1.47 (1.41 to 1.53)	34 (30 to 37)	20 (17 to 22)	140 (130 to 160)
Clay	49 (44 to 56)	1.35 (1.19 to 1.44)	42 (36 to 47)	28 (23 to 33)	140 (130 to 150)

Note: Numbers are rounded; normal ranges are shown in parentheses.
Source: Saxton (2005).

- Total porosity is the percentage of the bulk soil that is pores.
- Apparent specific gravity (A_s) is the density of the dry bulk density divided by the density of water.
- Field Capacity (FC) is the water content after a soil is well wetted and allowed to drain for 1 to 2 days, and represents the upper limit of the water available to plants.
- Permanent wilting point (PWP) represents the lower limit of water available to plants.
- The difference between FC and PWP is the Available Water (AW):

$$AW = (FC_v - PWP_v)*D_r$$

where
AW = depth of water available to plants (L)
FC_v = volumentric field capacity (L^3/L^3)

PWP_v = volumentric permant wilting point (L_3/L_3)
D_r = depth of the root zone or depth of a layer of soil with the root zone (L)

- ***Volumetric water content*** or volumetric moisture content

θ_v = volume of water in soil / volume of soil sample

= (wet weight – dry weight) / (volume of sample x ρ_w)

= (wet weight – dry weight)* A_s / dry weight of soil sample

Note that

(wet weight – dry weight) / dry weight of soil sample

is referred to as the ***soil water content – dry weight basis***

- Range of rooting depths are given in Table 15-3.

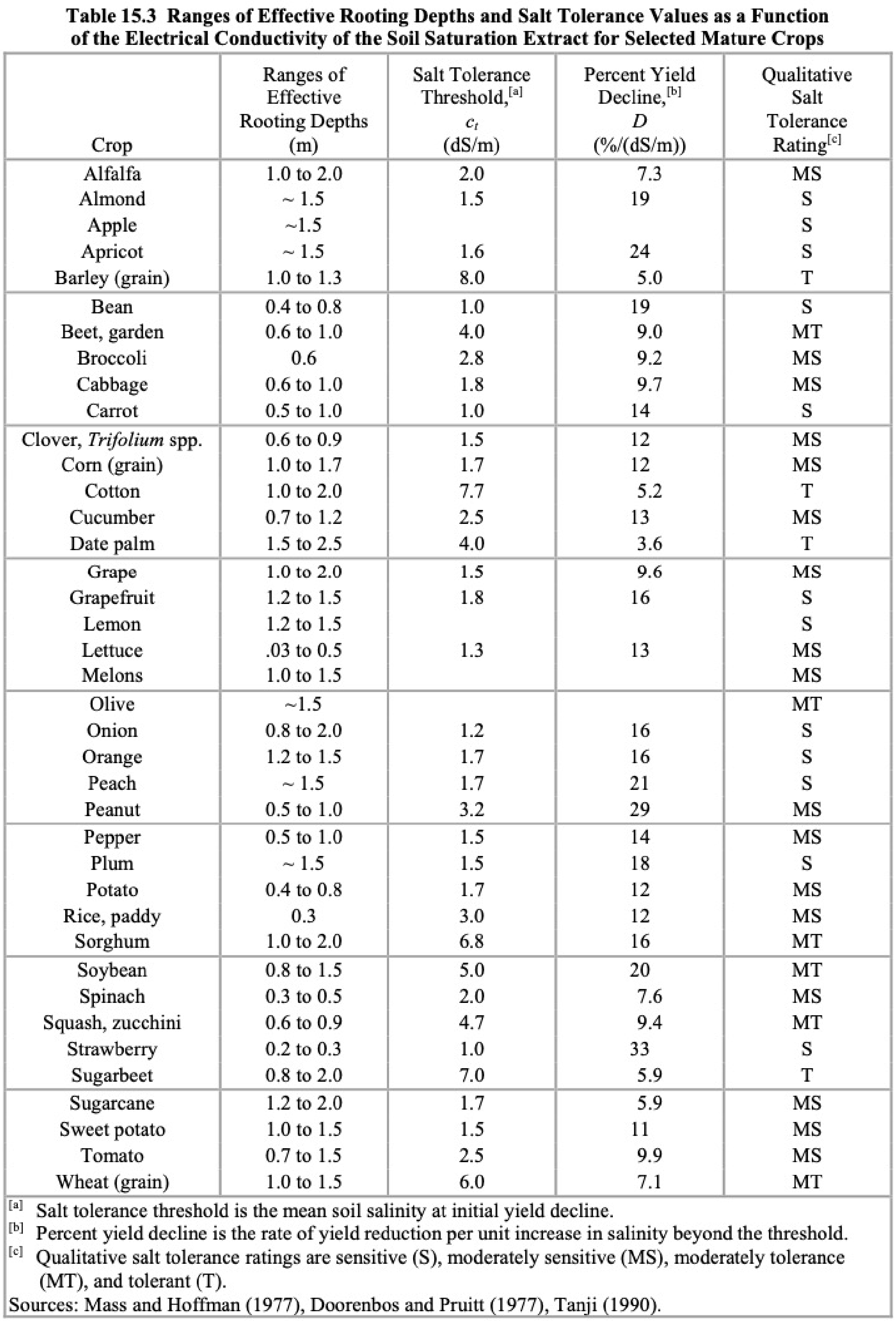


Table 15.3 Ranges of Effective Rooting Depths and Salt Tolerance Values as a Function of the Electrical Conductivity of the Soil Saturation Extract for Selected Mature Crops

Crop	Ranges of Effective Rooting Depths (m)	Salt Tolerance Threshold,[a] c_t (dS/m)	Percent Yield Decline,[b] D (%/(dS/m))	Qualitative Salt Tolerance Rating[c]
Alfalfa	1.0 to 2.0	2.0	7.3	MS
Almond	~ 1.5	1.5	19	S
Apple	~1.5			S
Apricot	~ 1.5	1.6	24	S
Barley (grain)	1.0 to 1.3	8.0	5.0	T
Bean	0.4 to 0.8	1.0	19	S
Beet, garden	0.6 to 1.0	4.0	9.0	MT
Broccoli	0.6	2.8	9.2	MS
Cabbage	0.6 to 1.0	1.8	9.7	MS
Carrot	0.5 to 1.0	1.0	14	S
Clover, *Trifolium* spp.	0.6 to 0.9	1.5	12	MS
Corn (grain)	1.0 to 1.7	1.7	12	MS
Cotton	1.0 to 2.0	7.7	5.2	T
Cucumber	0.7 to 1.2	2.5	13	MS
Date palm	1.5 to 2.5	4.0	3.6	T
Grape	1.0 to 2.0	1.5	9.6	MS
Grapefruit	1.2 to 1.5	1.8	16	S
Lemon	1.2 to 1.5			S
Lettuce	.03 to 0.5	1.3	13	MS
Melons	1.0 to 1.5			MS
Olive	~1.5			MT
Onion	0.8 to 2.0	1.2	16	S
Orange	1.2 to 1.5	1.7	16	S
Peach	~ 1.5	1.7	21	S
Peanut	0.5 to 1.0	3.2	29	MS
Pepper	0.5 to 1.0	1.5	14	MS
Plum	~ 1.5	1.5	18	S
Potato	0.4 to 0.8	1.7	12	MS
Rice, paddy	0.3	3.0	12	MS
Sorghum	1.0 to 2.0	6.8	16	MT
Soybean	0.8 to 1.5	5.0	20	MT
Spinach	0.3 to 0.5	2.0	7.6	MS
Squash, zucchini	0.6 to 0.9	4.7	9.4	MT
Strawberry	0.2 to 0.3	1.0	33	S
Sugarbeet	0.8 to 2.0	7.0	5.9	T
Sugarcane	1.2 to 2.0	1.7	5.9	MS
Sweet potato	1.0 to 1.5	1.5	11	MS
Tomato	0.7 to 1.5	2.5	9.9	MS
Wheat (grain)	1.0 to 1.5	6.0	7.1	MT

[a] Salt tolerance threshold is the mean soil salinity at initial yield decline.

[b] Percent yield decline is the rate of yield reduction per unit increase in salinity beyond the threshold.

[c] Qualitative salt tolerance ratings are sensitive (S), moderately sensitive (MS), moderately tolerance (MT), and tolerant (T).

Sources: Mass and Hoffman (1977), Doorenbos and Pruitt (1977), Tanji (1990).

Plants can only remove a portion of the available water before they go into stress. This portion is called the Readily Available Water (RAW). RAW is estimated as follows:

RAW = MAD x AW

Values of the MAD can be found in Table 15-4.

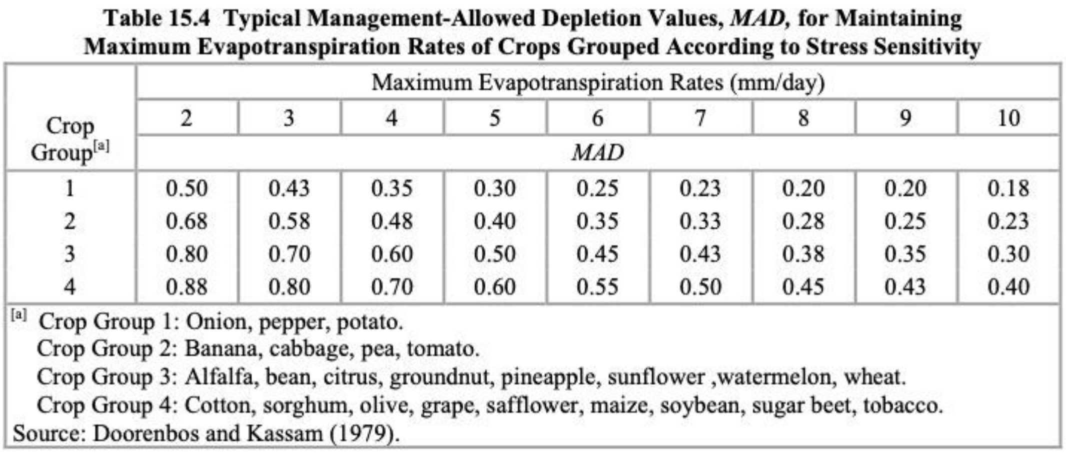


Table 15.4 Typical Management-Allowed Depletion Values, *MAD,* for Maintaining Maximum Evapotranspiration Rates of Crops Grouped According to Stress Sensitivity

Crop Group[a]	Maximum Evapotranspiration Rates (mm/day)								
	2	3	4	5	6	7	8	9	10
	MAD								
1	0.50	0.43	0.35	0.30	0.25	0.23	0.20	0.20	0.18
2	0.68	0.58	0.48	0.40	0.35	0.33	0.28	0.25	0.23
3	0.80	0.70	0.60	0.50	0.45	0.43	0.38	0.35	0.30
4	0.88	0.80	0.70	0.60	0.55	0.50	0.45	0.43	0.40

[a] Crop Group 1: Onion, pepper, potato.
Crop Group 2: Banana, cabbage, pea, tomato.
Crop Group 3: Alfalfa, bean, citrus, groundnut, pineapple, sunflower ,watermelon, wheat.
Crop Group 4: Cotton, sorghum, olive, grape, safflower, maize, soybean, sugar beet, tobacco.
Source: Doorenbos and Kassam (1979).

Example 15.2
Determine the readily available water for corn having a 1.5-m rooting depth in a fine sandy loam soil and a maximum ET of 7 mm/day. From physical sampling of the soil, the apparent specific gravity is 1.45, FC and PWP are 0.18 and 0.10 dry weight basis, respectively.

Solution. From the equation for AW, determine the available water.

AW=(.18 x 1.45 – 0.1 x 1.45) x 1.5 m = 0.174 ~~mm~~ or 174 mm

From Table 15-4 read MAD = 0.5, and determine RAW using the above equation.

RAW = 0.5 x 174 mm = 87 mm.

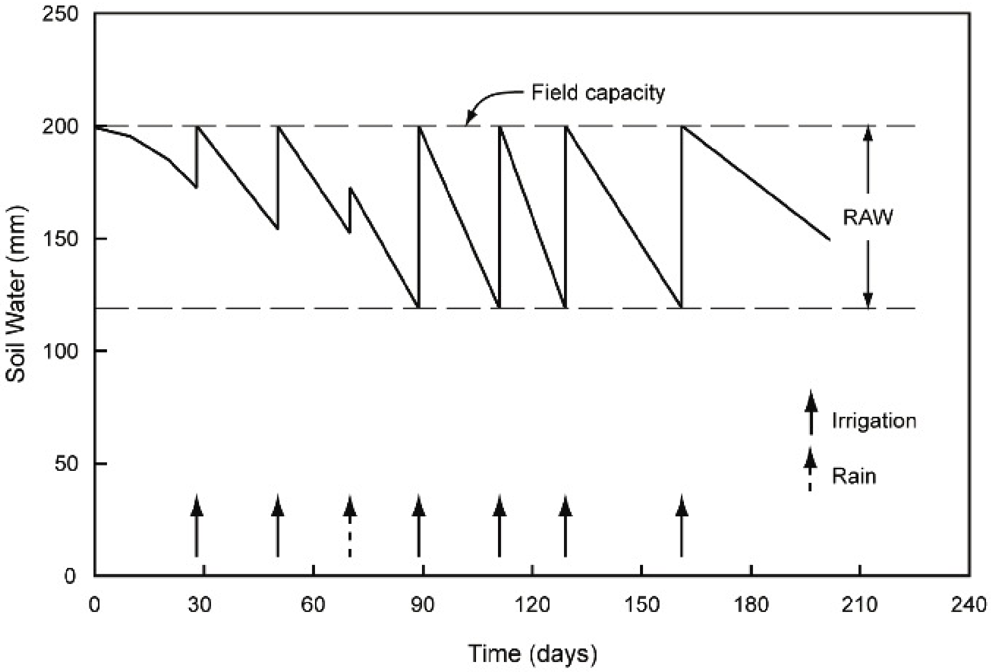


Figure 15.2–Illustration of the changes in soil water during a growing season.

Soil Salinity

- The presence of soluble salts in the root zone can be a serious problem, especially in arid regions.
- In subhumid regions, were irrigation is provided on a supplemental basis, salinity is usually of little concern, because rainfall is sufficient to leach out any accumulated salts.
- The salt content of soils is determined by measuring its electrical conductivity, EC in units of dS/m.
- **Saline Soils**. These soils contain sufficient soluble salts (calcium and magnesium) to affect the growth of most plants.
  - White crust on surface
  - Spotty stands
  - Stunted and irregular plant growth
  - Curling and yellowing of leaves

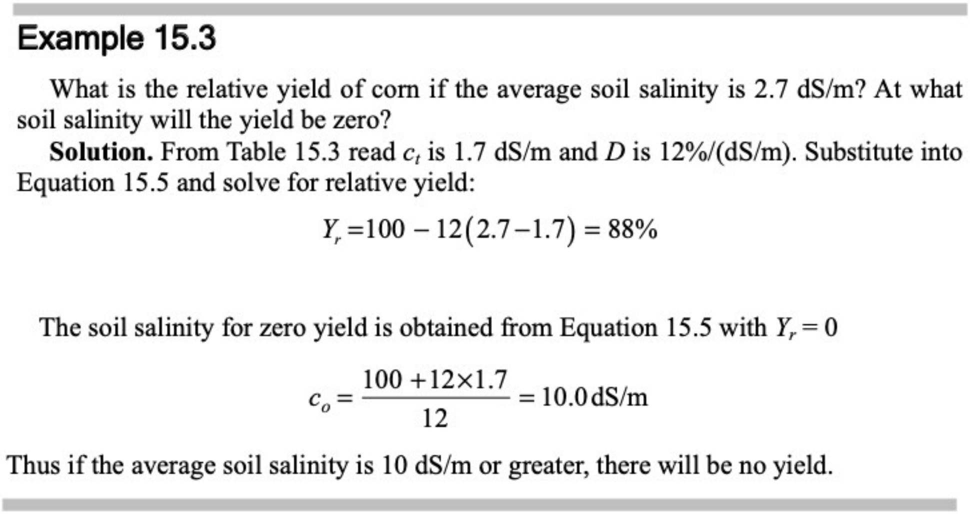
- **Sodic Soils**. These soils are relatively low in soluble salts, but contain sufficient exchangeable (adsorbed) sodium to interfere with the growth of most plants.
    - Sodium is not readily leached until displaced by other cations, such as calcium and magnesium.
    - Sodic soils tend to become dispersed, less permeable to water, and poorer tilth.
- **Saline-Sodic Soils**. These soils contain sufficient quantities of both total soluble salts and adsorbed sodium to reduce the yields of most plants.

Relative crop yield can be estimate from the following equations:

$$Y_r = \left\{ \begin{array}{ll} 100 & 0 \leq c \leq c_t \\ 100 - D(c - c_t) & c_t \leq c \leq c_0 \\ 0 & c \geq c_0 \end{array} \right\} \tag{15.5}$$

where Y_r = relative yield,
D = yield decline from Table 15-3, percent/(dS/m),
c = average root zone salinity (dS/m),
c_t = salt tolerance threshold from Table 15-3 (dS/m),
c_o = soil salinity above which the yield is zero (dS/m).

Table 15.5



Example 15.3

What is the relative yield of corn if the average soil salinity is 2.7 dS/m? At what soil salinity will the yield be zero?

Solution. From Table 15.3 read c_t is 1.7 dS/m and D is 12%/(dS/m). Substitute into Equation 15.5 and solve for relative yield:

$$Y_r = 100 - 12(2.7 - 1.7) = 88\%$$

The soil salinity for zero yield is obtained from Equation 15.5 with $Y_r = 0$

$$c_o = \frac{100 + 12 \times 1.7}{12} = 10.0\,\text{dS/m}$$

Thus if the average soil salinity is 10 dS/m or greater, there will be no yield.

Leaching Requirement

The salinity leaching requirement can be determined using the following graph. The crop salt-tolerance threshold value can be obtained from the above table (c_t). The value of L_r represents the fraction of water over and above the water requirement of the crop needed to leach the soil of soluble salts.

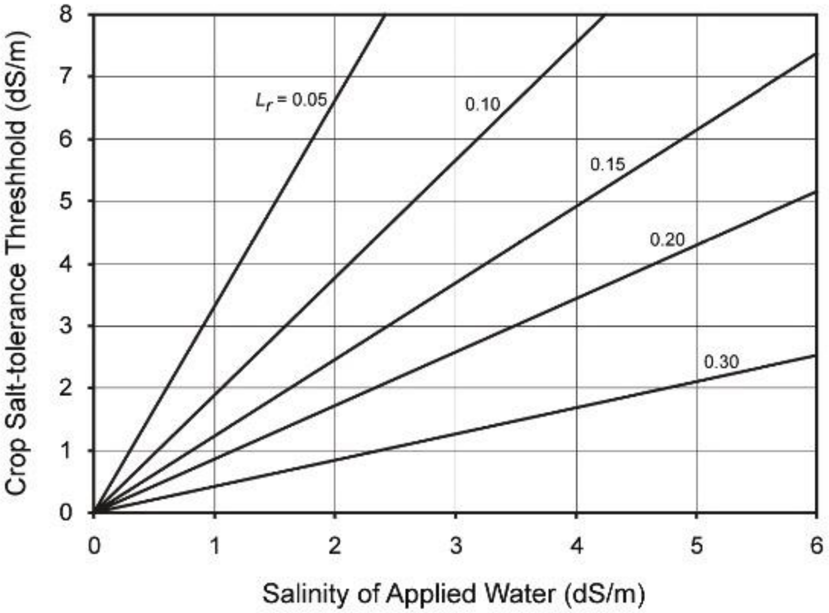


Figure 15.3–Leaching requirement L_r as a function of the salinity of the applied water and the salt tolerant threshold value for a crop. The dashed lines are from Example 15.7. (Source: Hoffman and van Genuchten, 1983.)

Fig. 15.3

Then the irrigation requirement (IR), accounting for leaching is given by:

$$IR = \frac{(ET - P_e)(1 + L_r)}{E_a} \tag{15.11}$$

where IR = seasonal irrigation requirement (L),
ET = seasonal evapotranspiration (L),
P_e = effective rainfall from Equations 15.1 and 15.2 (L),
L_r = leaching requirement as defined by Equation 15.5 and Figure 15.3,
E_a = application efficiency (decimal).

Equation 15.11 assumes that the soil water contents at the beginning and end of the season are similar.

Example 15.8

Corn is sprinkler irrigated with water having an electrical conductivity of 1.2 dS/m; the depth of irrigation is 50 mm; and the application efficiency is 70%. Use the rainfall, ET, and effective rainfall data from Example 15.1. Compute the seasonal irrigation requirement.

Solution. Assume no yield reduction is preferred and from Table 15.3 the threshold salinity value is 1.7 dS/m, then from Figure 15.3 read L_r = 0.13. Now solve Equation 15.11 for the irrigation requirement:

$$IR = \frac{(700 - 207)(1 + 0.13)}{0.70} = 796 \text{ mm}$$

–

Irrigation Efficiency and Uniformity

- Irrigation efficiency:
  - Water conveyance efficiency, E_c
  - Water-application efficiency, E_a
  - Water-use efficiency, E_u

$E_c = 100 * W_d/W_i$ equ. 15.6

where
W_d = water delivered by a distribution system
W_i = water introduced into the distribution system
E_c can be applied along any reach of a distribution system.

$E_a = 100\ W_s/W_d$ equ. 15.7

where
W_s = water stored in the soil root zone by irrigation,
W_d= water delivered to the area being irrigation.
E_a can be calculate for an individual furrow or border strip, for an entire field, or an entire farm or project.

$$E_u = \frac{\text{Irrigation Water Beneficially Used}}{\text{Irrigation Water Applied}} \times 100$$

$$= W_u \times 100\ /W_d \qquad \text{equ. 15.8}$$

where
W_u is water beneficially used
W_d = water delivered to the area being irrigation

- Applicable for field, farm, or larger area.
- Maximum value is 100%.
- Beneficial uses include: Crop ET, Salt Removal, Climate Control, Soil Preparation, etc.
- Non-Beneficial uses include: Excess Deep Percolation, Spray Evaporation Losses, Surface Runoff, Water Spillage, Seepage from Unlined Ditches, Etc.
- Irrigation Efficiency does not provide information about distribution uniformity (DU). It is possible to have a high DU and a very low E_u.

Example 15.4

If 42 m^3/s is pumped into a distribution system and 38 m^3/s is delivered to a turnout 3 km from the pumps, what is the conveyance efficiency of the portion of the distribution system used for conveying this water?

$E_c = 100 \times 38/42 = 90\%$

Example 15.5

Delivery of 0.5 m^3/s to a 30-ha field is continue for 40 hr. Soil water measuremnts before and after the irrigation indicate that 0.16 m of water was stored in the root zone. Computer the application efficiency.

$W_d = (0.5\ m^3/s)(3600\ s/hr)(40\ hr) = 72000\ m^3$
$W_s = (0.16\ m)(30\ ha)(10000 m^2/ha)= 48000\ m^3$
$E_a = 100(48000/72000) = 67\%$

The difference between 72000 – 48000 = 24000 m^3 is deep percolation or runoff.

Example:
Delivery of 6 ft^3/sec (cfs) to an 80 acre field is continued for 3 days. Ten percent of this flow volume (~~0.3 cfs~~) is for salt removal. Soil water measurements indicate 4.1 inches of water was stored in the root zone. There was no runoff from the field or other losses. Compute the water use efficiency E_u.

Water delivered to the field

$$W_d \equiv 6 \cdot \frac{ft^3}{sec} \cdot 3600 \frac{sec}{hr} \cdot 24 \cdot \frac{hr}{day} \cdot 3 \cdot day \cdot \frac{acre}{43560 \cdot ft^2}$$

$$W_d = 35.7\, acre \cdot ft$$

Amount of this water for salt control (10% of W_d)

$$W_{salt} \equiv 35.7 \cdot acre \cdot ft \cdot 0.1$$

$$W_{salt} = 3.6\, acre \cdot ft$$

Soil water measurements indicate 4.1 inches of water were stored in the root zone. Therefore, water being beneficially used

Water Use Efficiency:

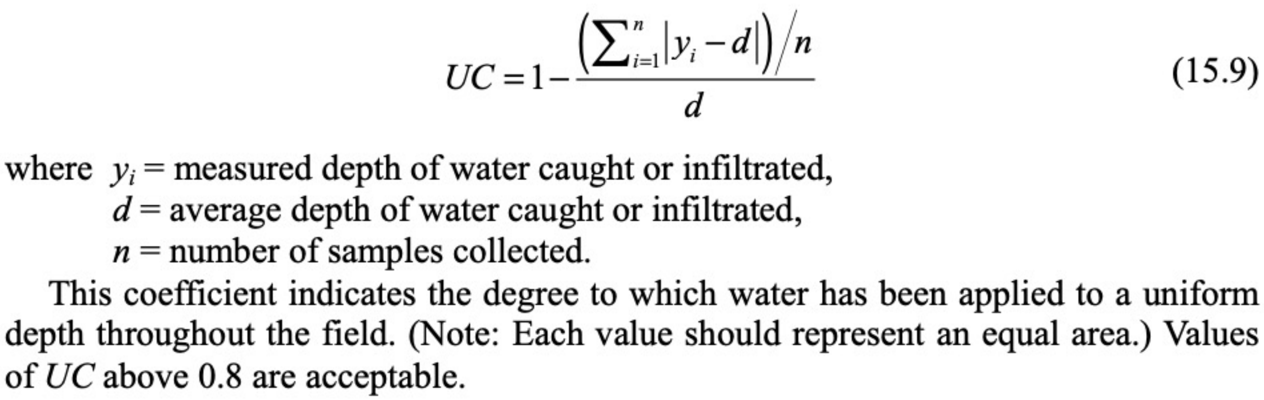
$$W_u \equiv \left(80 \cdot acre \cdot 4.1 \cdot in \cdot \frac{ft}{12 \cdot in}\right) + 3.6 \cdot acre \cdot ft$$

$$W_u = 30.9\,acre \cdot ft$$

$$\frac{W_u \cdot 100}{W_d} = 86.6 \qquad \%$$

Distribution Uniformity (DU or UC)

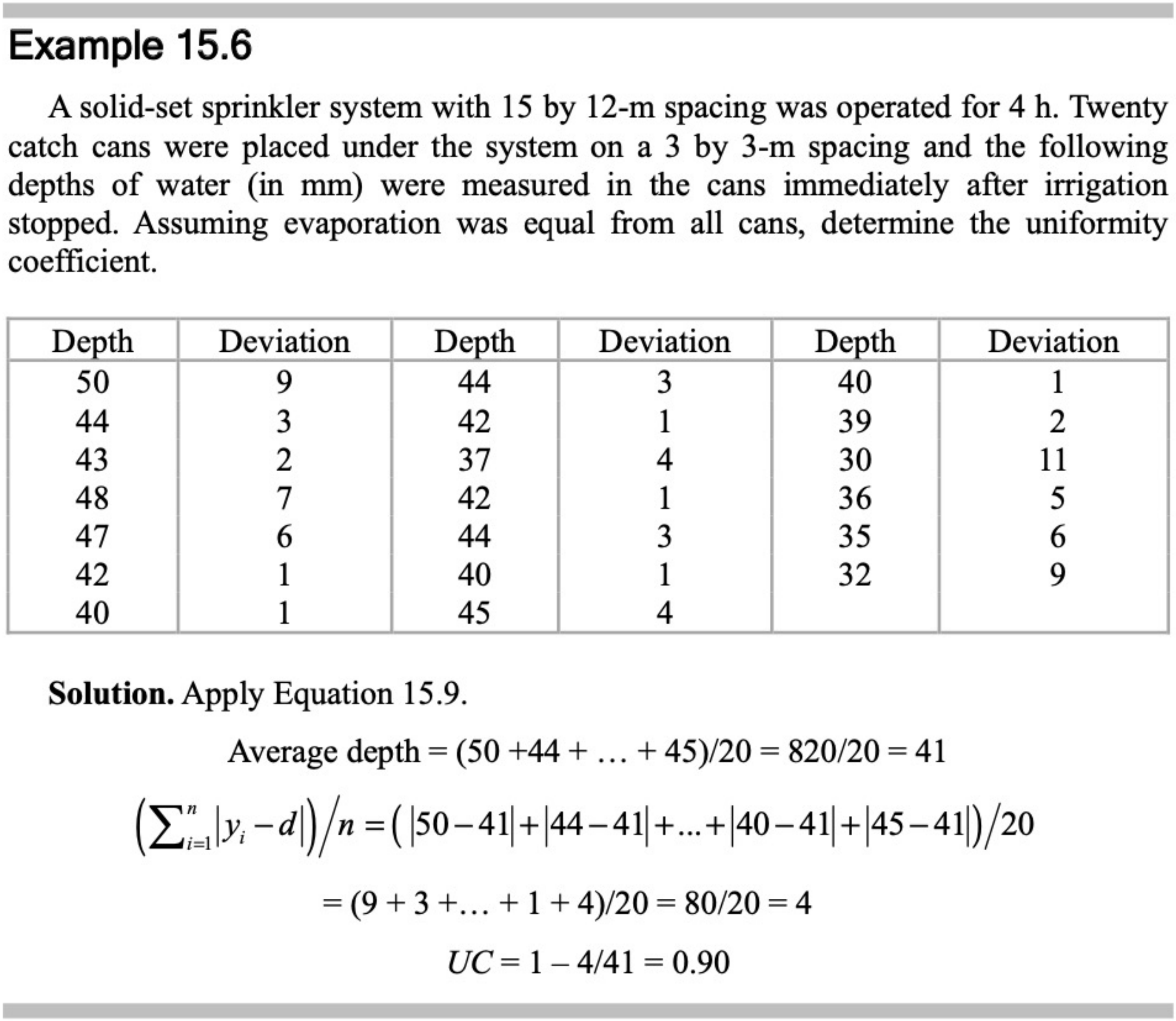
- Indicates the degree to which water has been applied to a uniform depth throughout the field.
- DU is one of the most important concepts in drip irrigation because if the uniformity is low a percentage of the plants (or trees) may not receive any irrigation at all!
- Values above 0.8 are acceptable.



$$UC = 1 - \frac{\left(\sum_{i=1}^{n} \left| y_i - d \right|\right) \big/ n}{d} \qquad (15.9)$$

where y_i = measured depth of water caught or infiltrated,
d = average depth of water caught or infiltrated,
n = number of samples collected.

This coefficient indicates the degree to which water has been applied to a uniform depth throughout the field. (Note: Each value should represent an equal area.) Values of UC above 0.8 are acceptable.



Example 15.6

A solid-set sprinkler system with 15 by 12-m spacing was operated for 4 h. Twenty catch cans were placed under the system on a 3 by 3-m spacing and the following depths of water (in mm) were measured in the cans immediately after irrigation stopped. Assuming evaporation was equal from all cans, determine the uniformity coefficient.

Depth	Deviation	Depth	Deviation	Depth	Deviation
50	9	44	3	40	1
44	3	42	1	39	2
43	2	37	4	30	11
48	7	42	1	36	5
47	6	44	3	35	6
42	1	40	1	32	9
40	1	45	4		

Solution. Apply Equation 15.9.

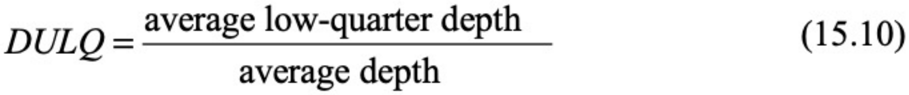
$$\text{Average depth} = (50 + 44 + \ldots + 45)/20 = 820/20 = 41$$

$$\left(\sum_{i=1}^{n}|y_i - d|\right)\Big/n = \left(|50-41|+|44-41|+\ldots+|40-41|+|45-41|\right)\Big/20$$

$$= (9 + 3 + \ldots + 1 + 4)/20 = 80/20 = 4$$

$$UC = 1 - 4/41 = 0.90$$

Distribution Uniformity using the Low-Quarter (DULQ) Method



$$DULQ = \frac{\text{average low-quarter depth}}{\text{average depth}} \qquad (15.10)$$

Average low-quarter depth is the average of the lowest ONE on-fourth of all values caught or infiltrated where each value represents an equal area. Averaed depth is the average of all values caught or infiltrated. Values of DULQ above 0.7 are considered acceptable.

Example 15.7

A uniformity check was taken by probing for water penetration depth at 16 equally spaced stations down one border strip. The depths of penetration (m) were recorded as follows:

0.95	0.98	0.98	0.92
0.89	0.89	0.83	0.79
0.74	0.68	0.77	0.83
0.78	0.72	0.84	0.88

Solution. Apply Equation 15.10 using the four lowest depths.

$$\text{Average low-quarter depth} = (0.74 + 0.68 + 0.77 + 0.72)/4 = 0.73$$

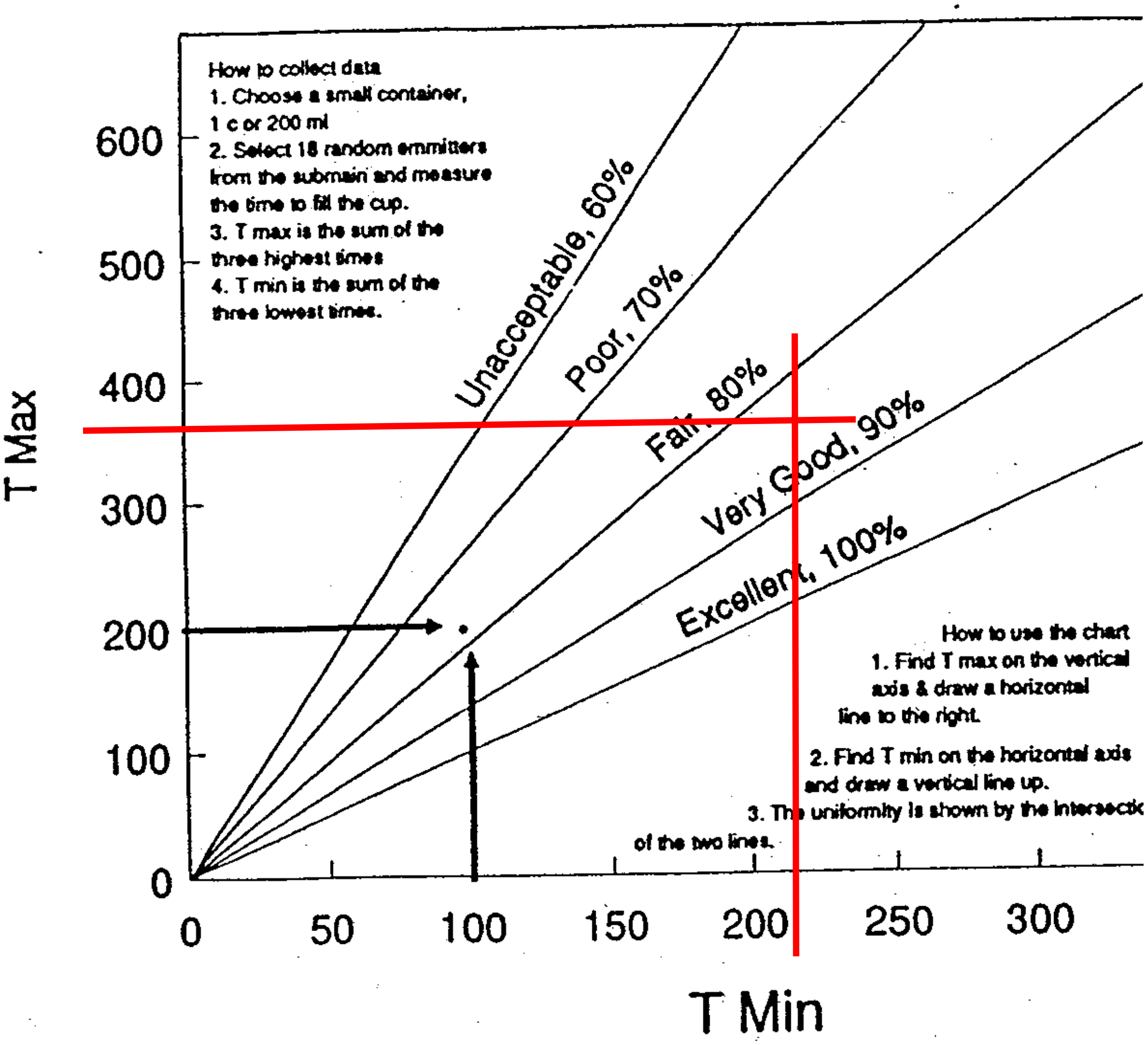
$$\text{Average depth} = (0.95 + 0.98 + \ldots + 84 + 0.88)/16 = 0.84$$

$$DULQ = 0.73/0.84 = 0.87$$

(Note: Depths of penetration are not as reliable as measured depths of infiltrated water, but are often easier to obtain.)

Field Method for Determining Distribution Coefficient

- Use instruction in the following graph to determine the DU in the field.



How to collect data
1. Choose a small container, 1 c or 200 ml
2. Select 18 random emmitters from the submain and measure the time to fill the cup.
3. T max is the sum of the three highest times
4. T min is the sum of the three lowest times.

How to use the chart
1. Find T max on the vertical axis & draw a horizontal line to the right.
2. Find T min on the horizontal axis and draw a vertical line up.
3. The uniformity is shown by the intersectio of the two lines.

Figure 3. Field method for calculating system uniformity.

Example

The following random samples were obtained from 18 drip emitters. The samples represent the number of seconds it took to fill up a bottle cap.

81	76	93	115	75	121
125	105	99	100	83	72
62	111	82	92	110	91

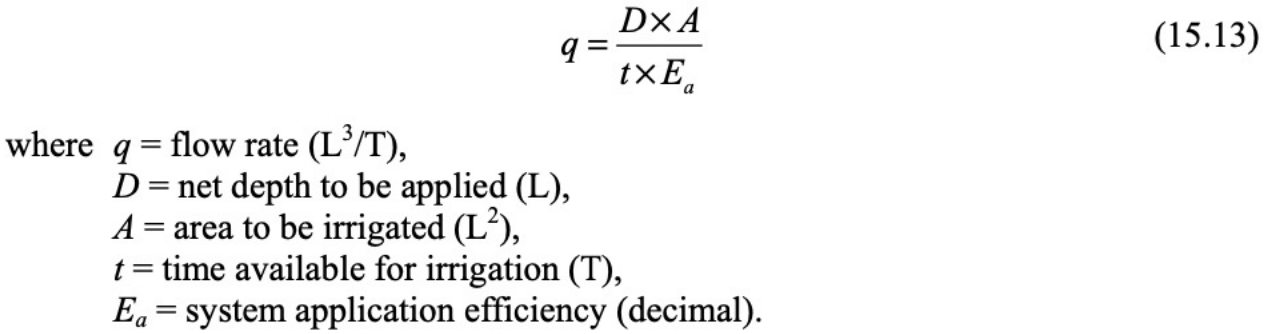
From the instructions in the graph:

Sum of the three highest = 125 + 121+115 = 361

Sum of the three lowest = 62 + 72 + 75 = 209

From the figure, the DU is very good (intersection point).

Irrigation Equation

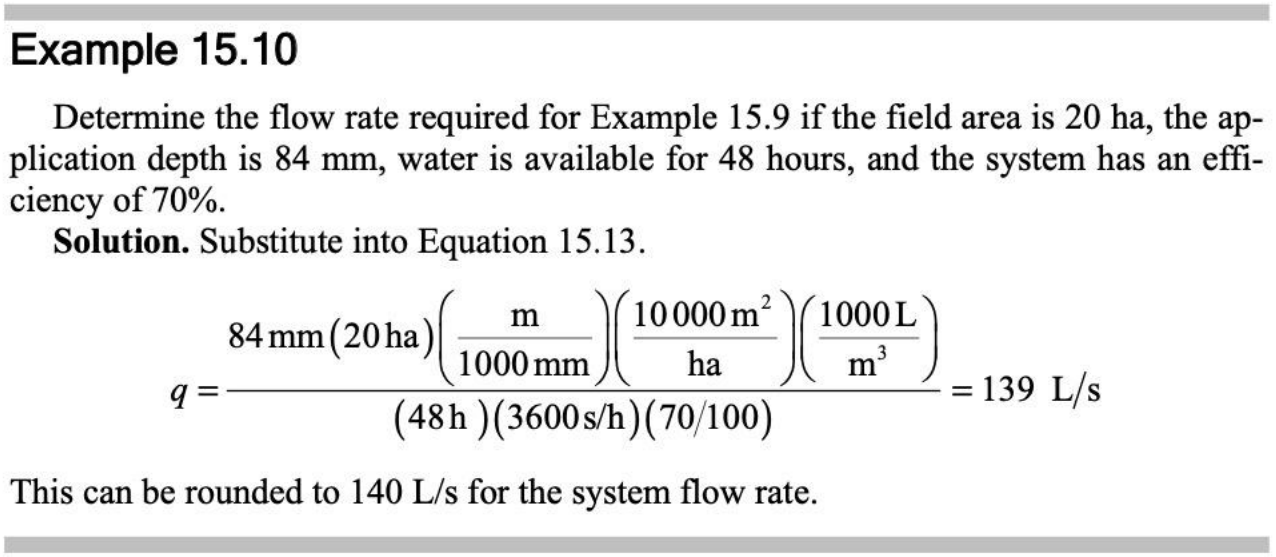


$$q = \frac{D \times A}{t \times E_a} \tag{15.13}$$

where q = flow rate (L^3/T),
D = net depth to be applied (L),
A = area to be irrigated (L^2),
t = time available for irrigation (T),
E_a = system application efficiency (decimal).

Different forms of the Irrigation Equation

$q = D*A/(t*E_a)$
$D=q*t*E_a/A$
$t=D*A/(q*E_a)$
$A=q*t*E_a/D$
$E_a=*D*A/(q*t)$



Example 15.10

Determine the flow rate required for Example 15.9 if the field area is 20 ha, the application depth is 84 mm, water is available for 48 hours, and the system has an efficiency of 70%.

Solution. Substitute into Equation 15.13.

$$q = \frac{84\,\text{mm}\,(20\,\text{ha})\left(\frac{\text{m}}{1000\,\text{mm}}\right)\left(\frac{10\,000\,\text{m}^2}{\text{ha}}\right)\left(\frac{1000\,\text{L}}{\text{m}^3}\right)}{(48\,\text{h})(3600\,\text{s/h})(70/100)} = 139\ \text{L/s}$$

This can be rounded to 140 L/s for the system flow rate.

Irrigation Methods

Subirrigation
Surface Irrigation
Sprinkler Irrigation
Microirrigation

Table 15.5 Comparison of Irrigation Systems in Relation to Site and Situation Factors

	Improved Surface Irrigation Systems		Sprinkler Irrigation Systems			Microirrigation Systems
Site and Situation Factors	Redesigned Surface Systems	Level Basins	Intermittent Mechanical-Move	Continuous Mechanical-Move	Solid-Set and Permanent	Emitters and Porous Tubes
Infiltration rate	Moderate to low	Moderate	All	Medium to high	All	All
Topography	Moderate slopes	Small slopes	Level to rolling	Level to rolling	Level to rolling	All
Crops	All	All	Generally shorter crops	All but trees and vineyards	All	High value required
Water supply	Large streams	Very large streams	Small streams nearly continuous	Small streams nearly continuous	Small streams	Small streams, continuous and clean
Water quality	All but very high salts	All	Salty water may harm plants	Salty water may harm plants	Salty water may harm plants	All; can potentially use high salt waters
Efficiency	Average 60-70%	Average 80%	Average 70-80%	Average 80%	Average 70-80%	Average 80-90%
Labor requirement	High training required	Low, some training	Moderate, some training	Low, some training	Low to seasonal high, little training	Low to high, training required
Capital requirement	Low to moderate	Moderate	Moderate	Moderate	High	High
Energy requirement	Low	Low	Moderate to high	Moderate to high	Moderate	Low to moderate
Management skill	Moderate	Moderate	Moderate	Moderate to high	Moderate	High
Machinery operations	Medium to long fields	Short fields	Medium field length, small interference	Some interference circular fields	Some interference	May have considerable interference
Duration of use	Short to long	Long	Short to medium	Short to medium	Long term	Variable
Weather	All	All	Poor in windy conditions	Better in windy conditions than other sprinklers	Windy conditions reduce performance, good for cooling	All
Chemical application	Fair	Good	Good	Good	Good	Very good

Source: Fangmeier and Biggs (1986).