
Chapter 3

Crops

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652.0300 Purpose and objective

The purpose of irrigation is to supplement natural precipitation so that moisture requirements of crops being grown are met. Crop response to irrigation varies with soils, fertility, type of plants, stage of growth, and local climate. Where crop stress caused by moisture shortage is prevented by proper and timely irrigation, other factors can become inhibitors to desirable yield and quality.

Knowledge of how plants respond to, and use, soil water throughout their growing season is essential to successfully design and manage an irrigation system. Continuous plant uptake of soil nutrients has a potential for improving ground water quality. Profitable crop production is generally the objective of agriculture. With proper management, soils (or water) affected by salinity or sodicity can sustain plant growth in perpetuity. Irrigation provides the insurance for high quality and desirable quantity crops at reduced risk in semi-arid, subhumid, and humid areas. It is a necessity in arid regions. The effect of irrigation both onsite and offsite on soil, water, air, plant, and animal resources along with human considerations needs to be considered.

(a) Soil condition

For desirable crop growth, good soil condition is key to optimum soil aeration, water infiltration, permeability, and uniform root development. It also helps reduce runoff and potential soil erosion. Good soil condition can be maintained or improved by eliminating excess tillage operations, avoiding field operations while soil-water content is high, using organic material or crop residue, and using grass and legumes in rotation. To reduce opportunity of soil compaction on irrigated pastures, livestock should be excluded during and after irrigation until adequate soil surface dry-out occurs.

(b) Nutrient management

A healthy plant uses water more efficiently than a plant that lacks nutrients and trace elements. Total water use by a healthy plant is greater than that for a plant deprived of nutrients. However, the yield per unit of water is much greater for healthy plants.

Soil fertility is maintained with proper nutrient management by maintaining proper soil reaction (pH level) and by using an appropriate cropping system. Liming may be needed on acid soil. On saline soils, leaching of excess salts is generally needed. On sodic soils, both soil amendments and leaching may be needed. Soil tests, field observations, planned yield and quality, and field experience help determine the type and amount of fertilizers and other elements to use. Using excess fertilizer or poor application timing can result in movement of chemicals below the root zone into the ground water or off the field.

(c) Soil, water, pest, nutrient, and crop residue management

Optimum production requires the operator to control weeds and insects, use high quality seed of adapted varieties, apply fertilizer according to plant needs, and practice good soil and water management during all parts of the growing season. Crops grown should be selected to fit the soil, water, climate, irrigation system, farm equipment, and market availability. Plant population can generally be increased when practicing good soil, water, pesticide, nutrient, and crop residue management.

652.0301 Crop growth characteristics

(a) Response to water, crop yield, and quality

Water is only one component needed to achieve desired crop yield and quality. A practical definition for water *use efficiency* is the amount of yield per unit of area per unit of water, e.g., 6 bushels of wheat per acre per acre-inch of applied water. Such yield water use comparison units can provide a basis for comparison when improvements are made.

Maintaining soil water within a desirable depletion range (preferably less than 5 bars tension) generally provides the expected yield and quality. The effect on yield and quality depends on how severe and during which period of crop growth water deficit occurs. Applying excess irrigation water over and above that necessary to grow a successful crop will not increase yields and generally reduces yields.

Other factors, such as the lack of available nutrients, trace elements, and uncontrolled pest activity, may limit crop yield. Excess irrigation water can leach essential plant nutrients and some pesticides and their metabolites below the root zone. This is especially true with nitrates, which are quite mobile in water. Excess irrigation water percolating below the root zone can pollute ground water.

(b) Critical growth periods

Plants must have ample moisture throughout the growing season for optimum production and the most efficient use of water. This is most important during critical periods of growth and development. Most crops are sensitive to water stress during one or more critical growth periods in their growing season. Moisture stress during a critical period can cause an irreversible loss of yield or product quality. Critical periods must be considered with caution because they depend on plant species as well as variety. Some crops can be moderately stressed during noncritical periods with no adverse effect on yields. Other plants require mild stress to set and develop fruit for optimum harvest time (weather or market).

The need for an irrigation should be determined by an onsite examination of the soil for water content or by any irrigation scheduling method for which basic data have been established. Using only plant appearance as the moisture deficit symptom can lead to misinterpretation, which generally results in reduction of yield and product quality. When the plant appears to be dry, it may already be in a moisture stress condition. Some plants temporarily wilt to conserve moisture during otherwise high evapotranspiration periods of the day. Dry appearance may also be caused by other problems (lack of nutrients, insect activity, disease, lack of essential trace elements). Critical water periods for most crops and other irrigation considerations are displayed in table 3-1. Irrigation scheduling techniques are described in more detail in Chapter 9, Irrigation Water Management.

Table 3-1 Critical periods for plant moisture stress

Crop	Critical period	Comments
Alfalfa hay	At seedling stage for new seedlings, just after cutting for hay, and at start of flowering stage for seed production.	Any moisture stress during growth period reduces yield. Soil moisture is generally reduced immediately before and during cutting, drying, and hay collecting.
Beans, dry	Flowering through pod formation.	Sensitive to over-irrigation.
Beans, green	Blossom through harvest.	
Broccoli	During head formation and enlargement.	
Cabbage	During head formation and enlargement.	
Cauliflower	During entire growing season.	
Cane berries	Blossom through harvest.	
Citrus	During entire growing season.	Blossom and next season fruit set occurs during harvest of the previous crop.
Corn, grain	From tasseling through silk stage and until kernels become firm.	Needs adequate moisture from germination to dent stage for maximum production. Depletion of 80% or more of AWC may be allowed during final ripening period.
Corn, silage	From tasseling through silk stage and until kernels become firm.	Needs adequate moisture from germination to dent stage for maximum production.
Corn, sweet	From tasseling through silk stage until kernels become firm.	
Cotton	First blossom through boll maturing stage.	Any moisture stress, even temporary, ceases blossom formation and boll set for at least 15 days after moisture again becomes available.
Cranberries	Blossom through fruit sizing.	
Fruit trees	During the initiation and early development period of flower buds, the flowering and fruit setting period (maybe the previous year), the fruit growing and enlarging period, and the pre-harvest period.	Stone fruits are especially sensitive to moisture stress during last 2 weeks before harvest.
Grain (small)	During boot, bloom, milk stage, early head development and early ripening stages.	Critical period for malting barley is at soft dough stage to maintain a quality kernel.

Table 3-1 Critical periods for plant moisture stress—Continued

Crop	Critical period	Comments
Grapes	All growth periods especially during fruit filling.	See vine crops.
Peanuts	Full season.	
Lettuce	Head enlargement to harvest.	Water shortage results in a sour and strong lettuce. Crop quality at harvest is controlled by water availability to the plant, MAD 15 – 20% is recommended.
Melons	Blossom through harvest.	
Milo	Secondary rooting and tillering to boot stage, heading, flowering, and grain formation through filling.	
Onions, dry	During bulb formation.	Maintain MAD 30 – 35% of AWC. Let soil dry near harvest.
Onions, green	Blossom through harvest.	Strong and hot onions can result from moisture stress.
Nut trees	During flower initiation period, fruit set, and midseason growth.	Pre-harvest period is not key because nuts form during midseason period.
Pasture	During establishment and boot stage to head formation.	Maintain MAD less than 50%. Moisture stress immediately after grazing encourages fast regrowth.
Peas, dry	At start of flowering and when pods are swelling.	
Peas, green	Blossom through harvest.	
Peppers	At flowering stage and when peppers are in fast enlarging stage.	
Potato	Flowering and tuber formation to harvest.	Sensitive to irrigation scheduling. Restrict MAD to 30 – 35% of AWC. Low quality tubers result if allowed to go into moisture stress during tuber development and growth.
Radish	During period of root enlargement.	Hot radishes can be the result of moisture stress.
Sunflower	Flowering to seed development.	

Table 3-1 Critical periods for plant moisture stress—Continued

Crop	Critical period	Comments
Sorghum grain	Secondary rooting and tillering to boot stage, heading, flowering, and grain formation through filling.	
Soybeans	Flowering and fruiting stage.	
Strawberries	Fruit development through harvest.	
Sugar beets	At time of plant emergence, following thinning, and about 1 month after emergence.	Frequent light applications during early growth period. Temporary leaf wilt on hot days is common even with adequate soil water content. Excessive fall irrigation lowers sugar content, but soil moisture needs to be adequate for easy beet lifting.
Sugarcane	During period of maximum vegetative growth.	
Tobacco	Knee high to blossoming.	
Tomatoes	When flowers are forming, fruit is setting, and fruits are rapidly enlarging.	
Turnips	When size of edible root increases rapidly up to harvest.	Strong tasting turnips can be the result of moisture stress.
Vine crops	Blossom through harvest.	
Watermelon	Blossom to harvest.	

Table 3-2 Adapted irrigation methods

Crop	Management depth (ft)	Adapted irrigation methods					Sprinkler	Micro-	Subirr.
		level		Surface	graded				
		border	furrow	border	furrow	corrug.			
Alfalfa	5	x	x	x	x	x			
Beans, dry	3	x	x	x	x	x			
Beans, green	3				x	x	x		
Cane berries	3	x	x	x	x	x	x		
Citrus	3	x		x		x	x		
Corn, grain	4		x		x	x		x	
Corn, silage	4		x		x	x		x	
Corn, sweet	3		x		x	x		x	
Cotton	3		x		x	x	x		
Grain, small	4	x	x	x	x	x		x	
Cranberries	2	x				x			
Grass, seed	3	x	x	x	x	x			
Grass, silage	3	x	x	x	x	x			
Milo (sorghum)	3	x			x	x		x	
Nursery stock	0-3	x	x	x	x	x	x	x	
Orchard	5	x	x	x	x	x	x	x	
Pasture	3	x		x		x		x	
Peanuts	3		x		x	x		x	
Peas	3	x	x	x	x	x			
Potatoes	3		x		x	x	x		
Safflower	5	x	x	x	x	x			
Sugar beets	5		x		x	x			
Sunflower	5	x	x	x	x	x			
Tobacco	3					x	x		
Tomatoes	2		x		x	x	x	x	
Turf, sod	2	x		x		x			
Turf	2	x		x		x	x		
Vegetables	1/	x	x	x	x	x	x		
Vegetables	2/	x	x	x	x	x	x	x	
Vegetables	3/	x	x	x	x	x	x	x	
Vegetables	4/	x	x	x	x	x	x	x	

1/ 1-foot depth—Lettuce, onions, spinach.

2/ 2-foot depth—Cabbage, brussel sprouts, broccoli, cauliflower.

3/ 3-foot depth—Turnips, parsnips, carrots, beets, green beans.

4/ 4-foot depth—Squash, cucumber, melons.

(c) Irrigation related management

Determining when to irrigate a specific crop requires the selection of a Management Allowable Depletion (MAD) of the available soil water. MAD is defined as the percentage of the available soil water that can be depleted between irrigations without serious plant moisture stress. MAD is expressed as:

- a percentage of the total Available Water Content (AWC) the soil will hold in the root zone,
- a soil-water deficit (SWD) in inches, or
- an allowable soil-water tension level.

Different crops tolerate different soil-water depletion levels at different stages of growth without going into moisture stress. Some crops have critical growth periods during only one stage of growth, while others have critical periods during several stages of growth.

MAD should be evaluated according to crop needs, and, if needed, adjusted during the growing season. Values of MAD, during the growing season are typically 25 to 40 percent for high value, shallow rooted crops; 50 percent for deep rooted crops; and 60 to 65 percent for low value deep rooted crops.

Recommended MAD values by soil texture for deep rooted crops are:

- Fine texture (clayey) soils 40%
- Medium texture (loamy) soils 50%
- Coarse texture (sandy) soils 60%

Table 3-2 displays adapted irrigation methods for various crops, and table 3-3 lists recommended MAD levels by crop development stages for a few crops.

Caution: Medium to fine textured soils can reduce MAD values given in this table.

Table 3-3 Recommended Management Allowable Depletion (MAD) for crop growth stages (% of AWC) growing in loamy soils ^{1/2/}

Crop	Crop growth stage			
	Estab- lishment	Vege- tative	Flowering yield formation	Ripening maturity
Alfalfa hay	50	50	50	50
Alfalfa seed	50	60	50	80
Beans, green	40	40	40	40
Beans, dry	40	40	40	40
Citrus	50	50	50	50
Corn, grain	50	50	50	50
Corn, seed	50	50	50	50
Corn, sweet	50	40	40	40
Cotton	50	50	50	50
Cranberries	40	50	40	40
Garlic	30	30	30	30
Grains, small	50	50	40 ^{3/}	60
Grapes	40	40	40	50
Grass pasture/hay	40	50	50	50
Grass seed	50	50	50	50
Lettuce	40	50	40	20
Milo	50	50	50	50
Mint	40	40	40	50
Nursery stock	50	50	50	50
Onions	40	30	30	30
Orchard, fruit	50	50	50	50
Peas	50	50	50	50
Peanuts	40	50	50	50
Potatoes	35	35	35	50 ^{4/}
Safflower	50	50	50	50
Sorghum, grain	50	50	50	50
Spinach	25	25	25	25
Sugar beets	50	50	50	50
Sunflower	50	50	50	50
Tobacco	40	40	40	50
Vegetables				
1 to 2 ft root depth	35	30	30	35
3 to 4 ft root depth	35	40	40	40

For medium to fine textured soils:

1/ (Most restrictive MAD) Some crops are typically not grown on these soils.

2/ Check soil moisture for crop stress point approximately one-third of the depth of the crop root zone.

3/ From boot stage through flowering.

4/ At vine kill.

(d) Rooting depth and moisture extraction patterns

The soil is a storehouse for plant nutrients, an environment for biological activity, an anchorage for plants, and a reservoir for water to sustain plant growth. The amount of water a soil can hold available for plant use is determined by its physical properties. It also determines the frequency of irrigation and the capacity of the irrigation system needed to ensure continuous crop growth and development.

The type of root system a plant has is fixed by genetic factors. Some plants have tap roots that penetrate deeply into the soil, while others develop many shallow lateral roots. The depth of the soil reservoir that holds water available to a plant is determined by that plant's rooting characteristics and soil characteristics including compaction layers and water management. The distribution of the plant roots determines its moisture extraction pattern. Figure 3-1 shows typical root distribution for several field and vegetable crops. Typical rooting depths for various crops grown on a deep, well drained soil with good water and soil management are listed in table 3-4.

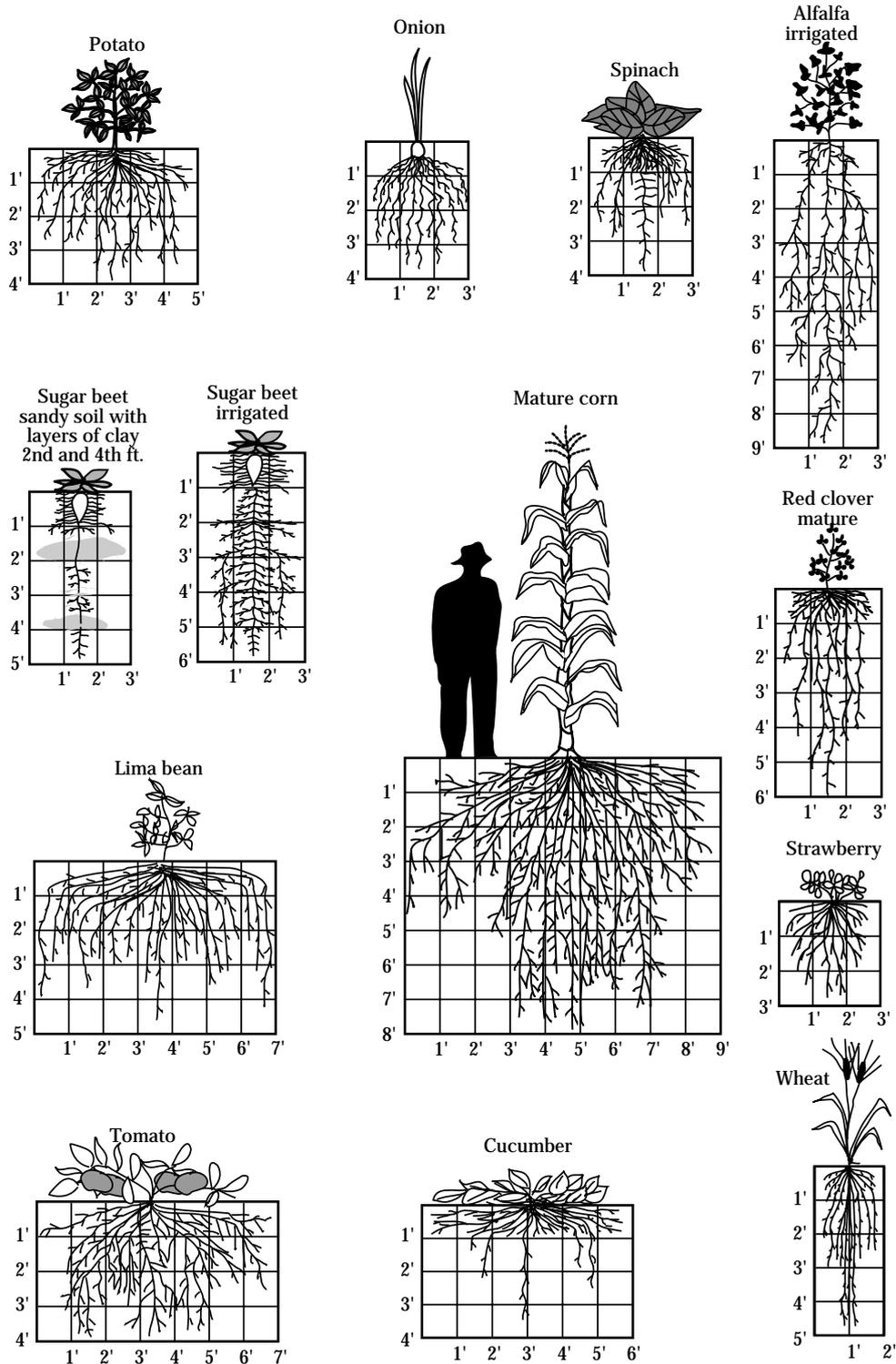
For annual crops, rooting depths vary by stage of growth and should be considered in determining the amount of water to be replaced each irrigation. All plants have very shallow roots early in their development period; therefore, only light and frequent irrigations are needed. Because roots will not grow into a dry soil, soil moisture outside the actual root development area is needed for the plant to develop a full root system in the soil profile. Excess moisture in this area will also limit root development.

For most plants, the concentration of moisture absorbing roots is greatest in the upper part of the root zone (usually in the top quarter). Extraction is most rapid in the zone of greatest root concentration and where the most favorable conditions of aeration, biological activity, temperature, and nutrient availability occur. Water also evaporates from the upper few inches of the soil; therefore, water is diminished most rapidly from the upper part of the soil. This creates a high soil-water potential gradient.

Table 3-4 Depths to which the roots of mature crops will extract available soil water from a deep, uniform, well drained soil under average unrestricted conditions (depths shown are for 80% of the roots)

Crop	Depth (ft)	Crop	Depth (ft)
Alfalfa	5	Peas	2 - 3
Asparagus	5	Peppers	1 - 2
Bananas	5	Potatoes, Irish	2 - 3
Beans, dry	2 - 3	Potatoes, sweet	2 - 3
Beans, green	2 - 3	Pumpkins	3 - 4
Beets, table	2 - 3	Radishes	1
Broccoli	2	Safflower	4
Berries, blue	4 - 5	Sorghum	4
Berries, cane	4 - 5	Spinach	1 - 2
Brussel sprouts	2	Squash	3 - 4
Cabbage	2	Strawberries	1 - 2
Cantaloupes	3	Sudan grass	3 - 4
Carrots	2	Sugar beets	4 - 5
Cauliflower	2	Sugarcane	4 - 5
Celery	1 - 2	Sunflower	4 - 5
Chard	1 - 2	Tobacco	3 - 4
Clover, Ladino	2 - 3	Tomato	3
Cranberries	1	Turnips	2 - 3
Corn, sweet	2 - 3	Watermelon	3 - 4
Corn, grain	3 - 4	Wheat	4
Corn seed	3 - 4		
Corn, silage	3 - 4		
Cotton	4 - 5	Trees	
Cucumber	1 - 2	Fruit	4 - 5
Eggplant	2	Citrus	3 - 4
Garlic	1 - 2	Nut	4 - 5
Grains & flax	3 - 4		
Grapes	5	Shrubs & misc. trees for windbreaks	
Grass pasture/hay	2 - 4	< 10 ft tall	2 - 3+
Grass seed	3 - 4	10 - 25 ft tall	3 - 4+
Lettuce	1 - 2	> 25 ft tall	5+
Melons	2 - 3		
Milo	2 - 4	Other	
Mustard	2	Turf (sod & lawn)	1 - 2
Onions	1 - 2	Nursery stock	1 - 3
Parsnips	2 - 3	Nursery stock	pots
Peanuts	2 - 3		

Figure 3-1 Root distribution systems—deep homogenous soils with good water management and no soil restrictions

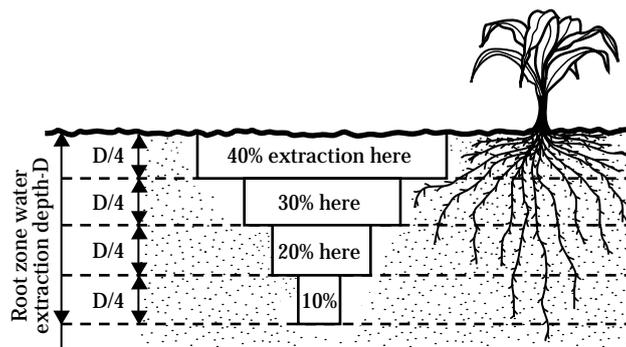


In uniform soils that are at field capacity, plants use water rapidly from the upper part of the root zone and more slowly from the lower parts. Figure 3–2 shows the typical water extraction pattern in a uniform soil. About 70 percent of available soil water comes from the upper half of a uniform soil profile. Any layer or area within the root zone that has a very low AWC or increased bulk density affects root development and may be the controlling factor for frequency of irrigations.

Figure 3–3 illustrates the effect on root development of some limitations in a soil profile. Variations and inclusions are in most soil map units, thus uniformity should not be assumed. Field investigation is required to confirm or determine onsite soil characteristics including surface texture, depth, slope, and potential and actual plant root zone depths.

Soil texture, structure, and condition help determine the available supply of water in the soil for plant use and root development. Unlike texture, structure and condition of the surface soil can be changed with management.

Figure 3–2 Typical water extraction pattern in uniform soil profile



Note: Approximately 70 percent of water used by plants is removed from the upper half of the plant root zone. Optimum crop yields result when soil-water tensions in this area are kept below 5 atmospheres. Very thin tillage pans can restrict root development in an otherwise homogenous soil. **Never assume a plant root zone.** Observe root development of present or former crops.

Numerous soil factors may limit the plant's genetic capabilities for root development. The most important factors are:

- soil density and pore size or configuration,
- depth to restrictive layers and tillage pans,
- soil-water status,
- soil condition,
- soil aeration,
- organic matter,
- nutrient availability,
- textural or structural stratification,
- water table,
- salt concentrations, and
- soil-borne organisms that damage or destroy plant roots.

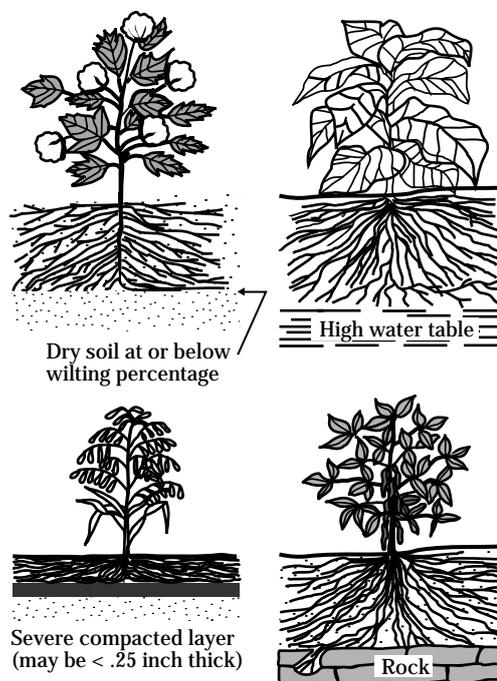
Root penetration can be extremely limited into dry soil, a water table, bedrock, high salt concentration zones, equipment and tillage compaction layers, dense fine texture soils, and hardpans. When root development is restricted, it reduces plant available soil-water storage and greatly alters irrigation practices necessary for the desired crop production and water conservation.

Root penetration is seriously affected by high soil densities that can result from tillage and farm equipment. Severe compacted layers can result from heavy farm equipment, tillage during higher soil moisture level periods, and from the total number of operations during the crop growing season. In many medium to fine textured soils, a compacted layer at a uniform tillage depth causes roots to be confined to the upper 6 to 10 inches. Roots seek the path of least resistance, thus do not penetrate a compacted dense layer except through cracks. Every tillage operation causes some compaction. Even very thin tillage pans restrict root development and can confine roots to a shallow depth, thereby limiting the depth for water extraction. This is probably most common with row crops where many field operations occur and with hayland when soils are at high moisture levels during harvest.

Compaction layers can be fractured by subsoiling when the soil is dry. However, unless the cause of compaction (typically tillage equipment itself), the number of operations, and the method and timing of the equipment's use are changed, compaction layers will again develop. Only those field operations essential to successfully growing a crop should be used. Extra field operations require extra energy (tractor fuel), labor, and cost because of the additional wear and tear on equipment. The lightest equipment with the fewest operations necessary to do the job should be used.

For site specific planning and design, never assume a plant root zone depth. Use a shovel or auger to observe actual root development pattern and depth with cultural practices and management used. The previous crops or even weeds will generally show root development pattern restrictions. See NEH Part 623, (Section 15), Chapter 1, Soil-Plant-Water Relationship, and Chapter 2, Irrigation Water Requirements, for additional information.

Figure 3-3 Effect of root development on soils with depth limitations



652.0302 Crop and irrigation system water requirements

(a) Crop evapotranspiration

Plants need water for growth and cooling. Small apertures (stomata) on the upper and lower surfaces of the leaves allow for the intake of carbon dioxide required for photosynthesis and plant growth. Water vapor is lost to the atmosphere from the plant leaves by a process called transpiration. Direct water evaporation also occurs from the plant leaves and from the soil surface. The total water used by the specific crop, which includes direct evaporation from plant leaves and the soil surface and transpiration, is called crop evapotranspiration (ET_c). Processes to determine local crop evapotranspiration are described in NEH, Part 623, Chapter 2, Irrigation Water Requirements, and in Chapter 4, Water Requirements, of this guide.

(b) Irrigation frequency

How much and how often irrigation water must be applied depends on the soil AWC in the actual plant root zone, the crop grown and stage of growth, the rate of evapotranspiration of the crop, the planned soil Management Allowable Depletion (MAD) level, and effective rainfall. More simply put; it depends on the crop, soil, and climate.

Never assume a plant root zone for management purposes. Check actual root development pattern and depth. See section 652.0301(d).

Once a MAD is selected, determining when to irrigate simply requires estimation or measurement of when the soil moisture reaches that level. Coarse textured and shallow soils must be irrigated more frequently than fine textured deep soils because fine textured deep soils store more available water. The moisture use rate varies with the crop and soil. It increases as the crop area canopy increases, as humidity decreases and as the days become longer and warmer.

Frequency can be estimated by dividing the MAD by the estimated or measured evapotranspiration of the crop as follows:

$$\text{Irrigation frequency (days)} = \frac{\text{MAD (inches)}}{\text{Crop ET rate (in/day)}}$$

A much higher quality product is produced if the MAD level is kept less than 35 percent in some crops, such as potatoes, pecans, vegetables, and melons. This is also true for mint.

Several methods are available for irrigation scheduling (determining when to irrigate and how much to apply). They are described in Chapter 9, Irrigation Water Management.

(c) Net irrigation requirement

The net amount of water to be replaced at each irrigation is the amount the soil can hold between field capacity and the moisture level selected when irrigation is needed (MAD). Maintaining the same soil moisture level throughout the growing season is not practical and probably not desirable. Ideally, an irrigation is started just before the selected MAD level is reached or when the soil will hold the irrigation application plus expected rainfall. The net amount of water required depends on soil AWC in the plant root zone and the ability of a particular crop to tolerate moisture stress. If the MAD level selected is 40 percent of AWC in the root zone (Soil-water Deficit = 40%), it is necessary to add that amount of water to bring the root zone up to field capacity. For example if the total soil AWC in the root zone is 8 inches and MAD = 40%:

$$\begin{aligned} \text{Net irrigation} &= 40\% \times 8 \text{ in} \\ &= 3.2 \text{ in} \end{aligned}$$

In semihumid and humid areas, good water managers do not bring the soil to field capacity with each irrigation, but leave room for storage of expected rainfall. When rainfall does not occur, the irrigation frequency must be shortened to keep the soil moisture within the MAD limit. It is a management decision to let MAD exceed the ability of an irrigation system to apply water. For example, if a center pivot sprinkler system applies a net of 1 inch per cycle, let MAD be equal to 1 inch plus expected rainfall. MAD for a surface irrigation system will be typically greater as heavier applications are required for best uniformity across the field.

(d) Gross irrigation requirement

The gross amount of water to be applied at each irrigation is the amount that must be applied to assure enough water enters the soil and is stored within the plant root zone to meet crop needs. No irrigation system that fully meets the season crop evapotranspiration needs is 100 percent efficient. Not all water applied during the irrigation enters and is held in the plant root zone. Also, all irrigation systems have a distribution uniformity less than 100 percent. Applying too much water too soon (poor irrigation water management) causes the greatest overuse of water. Irrigation systems and management techniques are available that reduce the avoidable losses. They are described in chapters 5, 6, 7, 8, and 9 of this guide.

Unavoidable losses are caused by:

- Unequal distribution of water being applied over the field.
- Deep percolation below the plant root zone in parts of the field.
- Translocation or surface runoff in parts of the field.
- Evaporation from the soil surface; flowing and ponded water.
- Evaporation of water intercepted by the plant canopy under sprinkler systems.
- Evaporation and wind drift from sprinklers or spray heads.
- Nonuniform soils.

For a given irrigation method and system, irrigation efficiency varies with the skill used in planning, designing, installing, and operating the system. Local climatic and physical site conditions (soils, topography) must be assessed. To assure that the net amount of soil water is replaced and retained in the root zone during each irrigation, a larger amount of water must be applied to offset the expected losses. The gross amount to be applied is determined by the equation shown at the bottom of this page.

For more information on irrigation and system requirements, see Chapter 4, Water Requirements; NEH Part 623, Chapter 2, Irrigation Water Requirements; and the West National Technical Center publication, Farm Irrigation Rating Index (FIRI), A method for planning, evaluating and improving irrigation management.

$$\begin{aligned} \text{Gross irrigation amount (in)} &= \frac{\text{Net amount to be replaced (in)}}{\text{Overall irrigation efficiency of system including management (\%)}} \\ &= \frac{\text{Management Allowable Depletion (MAD)}}{\text{Overall irrigation efficiency}} \end{aligned}$$

652.0303 Reduced irrigation and restricted water supply

Several opportunities are available to the irrigator in semiarid, subhumid, and humid areas for reduced irrigation water application:

- Maximizing effective rainfall.
- Deficit or partial season irrigation.
- Selection of crops with low water requirements during normal high water use periods; i.e., small grains, (or accept the risk of drought periods).
- Selection of drought resistant crops and varieties that provide yields based on water availability, i.e., alfalfa hay, grass pasture (accept the reduced yields caused by drought periods).
- Irrigate just before critical growth period(s) of the crop to minimize critical plant moisture stress during those periods.
- Use state-of-art irrigation scheduling techniques that use local area climate and onsite rainfall data, and field-by-field soil moisture status monitoring.
- Use tillage practices that allow maximum surface storage and infiltration of rainfall events, reducing runoff and soil surface evaporation.
- Follow an intensive crop residue management and mulch program and minimize tillage to reduce soil surface evaporation.
- Reduce irrigated acreage to that which can be adequately irrigated with the available water supply.

Risk is less when growing crops on deep, high AWC, loamy soils and in climatic areas that have adequate rainfall for the crop. The risk is greater when growing crops on low AWC soils even in areas that have adequate rainfall during the growing season. When growing high value crops, an irrigation system and adequate water supply are highly desirable for insurance against potential crop loss. A detailed economic analysis should be completed to provide estimates of optimum net benefits. The analysis should include cost of water, pumping costs, reduced yields caused by reduced crop water use, and reduced tillage operation costs. Subsequent management decisions should be based on this analysis. See chapter 11 for additional discussion.

In some areas irrigation water delivery systems, including management, limit on-farm water management improvements. *Rotational* delivery systems have the lowest on-farm water management potential, while *on demand* delivery systems have the highest.

Improving both management and the irrigation system can reduce the amount of water applied and more effectively use existing water supplies. Improving water management, including irrigation scheduling and adequate water measurement, is always the first recommended increment of change. Improving existing irrigation systems is the next. Unless the existing irrigation system is unsuitable for the site, crop grown, or water supply, converting to another irrigation method seldom produces benefits equal to improvements in water management. See Chapter 5, Selecting an Irrigation Method, for additional information on selecting and applying the best method or system for the site.

652.0304 Adapted irrigation systems

All crops can be efficiently irrigated by more than one irrigation method and system. Crops grown and their cultural requirements aid in determining the irrigation method and system used. Crops can be placed in broad categories as follows:

Category 1. Row or bedded crops:

sugar beets, sugarcane, potatoes, pineapple, cotton, soybeans, corn, sorghum, milo, vegetables, vegetable and flower seed, melons, tomatoes, and strawberries.

Category 2. Close-growing crops (sown, drilled, or sodded):

small grain, alfalfa, pasture, and turf.

Category 3. Water flooded crops:

rice and taro.

Category 4. Permanent crops:

orchards of fruit and nuts, citrus groves, grapes, cane berries, blueberries, cranberries, bananas and papaya plantations, hops, and trees and shrubs for windbreaks, wildlife, landscape, and ornamentals.

A comparison of irrigation system versus crops that can be reasonably grown with that system is displayed in table 3-5.

See Chapter 5, Selecting an Irrigation Method, Chapter 6, Irrigation System Design, and chapters 3, 4, 5, 7, and 11 of the National Engineering Handbook, Part 623 (section 15) for more information on adapted irrigation systems.

Table 3-5 Irrigation system vs. crops grown

Irrigation system	--- Crop category ---			
	1	2	3	4
Surface				
Basins, borders		x	x	x
Furrows, corrugations	x	x		x
Contour levee - rice		x	x	
Sprinkler				
Side (wheel) roll lateral	x	x		
Hand move lateral	x	x		x
Fixed (solid) set		x		x
Center pivot, linear move	x	x		
Big guns - traveling, stationary	x	x		
Micro				
Point source				x
Line source	x			x
Basin bubbler				x
Mini sprinklers & spray heads				x
Subirrigation	x	x	x	x

652.0305 Temperature— effects and management

Crop yield and quality can be negatively affected by temperature extremes, both cold and hot. Application of water in a timely manner can provide some degree of protection. Water can also be applied to cool plants to maintain product quality, to delay bud development, and to provide frost protection of buds, flowers, and young fruit.

(a) High temperatures

Extremely high temperatures can

- put plants into a temporary plant moisture stress,
- hasten untimely fruit development and ripening,
- cause moisture stress in ripening fruit,
- sunburn berries and other fruit,
- overheat bare soils during seed germination (i.e., lettuce), and
- overheat standing water in basin irrigation.

Water used for temperature modification as a crop and soil coolant is typically applied with a sprinkler/spray system.

(b) Low temperatures

When temperatures drop below the critical temperature, damage can occur to both annual and perennial plants. If ambient air temperature and humidity are severely low, permanent damage to fruit, citrus, and nut trees can occur. When it drops below freezing, the developing buds and flowers on fruit and berry plants can be damaged. Temporary freeze back of new growth in grasses and legumes can occur, and healthy annual plants can be killed or damaged beyond recovery.

Water can be applied to provide frost protection to about 25 °F. Sprinkler/spray systems that apply water overhead onto the plant canopy are typically used. This allows a protective layer of ice to build up on the leaves, blossoms, and buds. Frost protection involves heat release caused by changing water to ice. The process must be understood to determine the application rate and timing of water for adequate frost protection. Some limited success has been attained with under-tree spray systems and surface flooding systems.

See NEH, Part 623 (Section 15), Chapter 2, Irrigation Water Requirements, for further information.

652.0306 Salinity and sodicity effects

(a) General

In arid areas nearly all irrigation water and soils contain salts, some of which are toxic to plants and animals. When water is removed from the soil profile by plant transpiration and soil surface evaporation, salts remain in the soil profile and on the soil surface. If the soil-water solute is high in sodium, the soil becomes sodic. All other ionic concentrations in solution (i.e., calcium, magnesium, potassium) cause salinity. These conditions are particularly common where most of the crop water requirement comes from irrigation. The problem eventually becomes serious if

- irrigation or natural precipitation is not sufficient to leach the accumulating salts,
- water and soil management are less than adequate,
- soil and water amendments are inadequate, or
- the soil is poorly drained.

Salinity and sodicity problems can also develop as a result of saline seeps, use of poor quality irrigation water including flooding by brackish water near the ocean, or by using drainage water from upslope irrigation. As salt concentrations increase above a threshold level, the growth rate, mature size of crops, and product quality progressively decrease.

Principal objectives of water management are to maintain soil tilth, soil-water content, and salinity and sodicity levels suitable for optimum plant growth. A natural occurring internal drainage or an installed drainage system within the usable soil profile is essential. See Chapter 13, Quality of Water Supply, for additional information.

(b) Measuring salinity and sodicity concentration

A method has been developed to measure and quantify salinity and sodicity levels in soils. Thus, the salinity of a soil can be determined by measuring the electrical conductivity, EC_e , of the soil-water extract expressed in millimhos per centimeter or decisiemens per meter,

corrected to a standard temperature of 77 °F (25 °C).
1 mmho/cm = 1 dS/m.

Salt molecules in solution produce electrically-charged particles called ions. Ions can conduct an electrical current. The greater the concentration of ions in a solution, the greater the electrical conductivity of the solution.

To measure sodicity in soil, the Sodium Adsorption Ratio (SAR) is used. It is a measure of the ratio of sodium to calcium plus magnesium present.

$$SAR = \frac{Na}{\left(\frac{Ca + Mg}{2}\right)^{\frac{1}{2}}}$$

(c) Effects of salinity on yields

Crop yields and quality are reduced when salinity levels exceed a certain threshold. See NEH, Part 623, Irrigation, Chapter 1, Soil-Plant-Water Relationships (table 1–8), and Chapter 2, Irrigation Water Requirements. The information presented provides two essential parameters for expressing salt tolerance:

- The salinity threshold level above which reduced yield will occur
- The percent yield reduction per unit salinity increase beyond the threshold level

(d) Effect of salinity and sodicity on AWC

Plants extract water from the soil by exerting an adsorptive force or tension greater than the attraction of the soil matrix for water. As the soil dries, remaining water in the soil profile is held more tightly by soil particles. Salts also attract water. The combination of drying soils and elevated salt concentrations results in less water at a given tension being available for plant uptake. The reduction in water available to the crop as salinity increases is evident in figure 2–7, chapter 2, which shows the volumetric water content versus soil-water potential for a clay loam soil at various degrees of soil salinity, EC_e . Table 2–4 provides a process to estimate AWC based on texture and EC_e of 0 to 15 mmho/cm.

If the salt content of the soil cannot be maintained or reduced to a point compatible with the optimum yield of a crop, a more salt-tolerant crop should be grown or the operator must accept reduced yields. Most often, salinity or sodicity is not maintained below plant thresholds because less than adequate soil and water management practices are followed.

(e) Management practices for salinity and sodicity control

The major objective of salinity management is to keep soil salinity and sodicity below thresholds for seed germination, seedling establishment, crop growth, and quality while minimizing the salt loading effects of drainage outflow. Procedures that require relatively minor changes in management are:

- Improved irrigation water management
- Improved crop residue management
- Adding soil and water amendments
- Selection of more salt-tolerant crops
- Leaching with additional irrigation water
- Preplant irrigations
- Changing of seed placement on the furrow bed

Maintaining a higher soil-water content decreases soil-water tension; thereby, increasing water available to plants. Alternatives that require significant adjustments are:

- Changing the water supply
- Changing irrigation methods
- Land leveling for improvements to surface drainage and irrigation water distribution
- Modifying the soil profile
- Providing for internal drainage

ASCE Report No. 71, Agricultural Salinity Assessment and Management (1990) gives specific recommendations regarding salinity and sodicity assessment and management.

Irrigated agriculture cannot be sustained without adequate leaching and internal drainage to control buildup of calcium, sodium, and other toxic ions in the soil profile. Where subsurface drainage systems are installed to improve downward water movement and removal of the required leaching volume, soluble salts plus other agricultural chemicals and fertilizers move with the drainage water. They have the potential to move to streams, wetlands, estuaries, and lakes.

Where possible, leaching events should be planned when soil nitrate levels are low. The leaching requirement for salinity control can be minimized with good irrigation water management and with adequately designed, installed, and operated irrigation water delivery and application systems.

Drainage outflow with high salt concentrations can be disposed of through use of evaporation ponds (the salts remain), or often water can be directly reused as an irrigation water supply for applications where saline water is acceptable, such as irrigation of salt-tolerant plants or for industrial uses. In some areas drainage outflow with high salt concentration may not be allowed to be released to public waters without a point-discharge permit, or it must be desalted. In most high salt content water reuse operations, the salt moves and precipitates out at another spot. It does not go away.

When irrigating with high salt content water, internal soil drainage and leaching are required to maintain an acceptable salt balance for the plants being grown. The salt concentration in drainage outflow can be quite high, and concern for safe disposal still exists. Some saline and sodic tolerant crops require high quality water for germination and establishment. Once the crop is established, poorer quality water can be used. Generally, water containing different saline-sodic concentrations should not be mixed.

(f) Toxic elements

Toxicity problems can be the same or different from those of salinity and sodicity because they can occur between the plant and the soil and may not be caused by osmotic potential or water stress. Toxicity normally results when certain ions are present in the soil or absorbed with soil-water, move with the plant transpiration stream, and accumulate in the leaves at concentrations that cause plant damage. It also can result from water sprayed directly on leaf surfaces. The extent of the damage depends on the specific ion concentration, crop sensitivity, crop growth stage, and crop water use rate and time.

The usual toxic ions in irrigation water include chloride, sodium, and boron. Excessive chlorine in domestic water systems and salts from water softeners in home systems can also be a problem. Not all crops are

sensitive to these ions, but some crops are very sensitive. Chemical analysis of plant tissue, soil-water extract, and irrigation water is most commonly used to identify toxicity problems.

The affect of toxic elements (i.e., selenium) on waterfowl from drainage outflow has also been observed in several areas. Toxic elements that occur naturally in the soil (i.e., selenium and boron) in high concentrations or were used as pesticide control in past years (i.e., arsenic and mercury) are of great concern. Irrigation water that deep percolates below the plant root zone can potentially carry these dissolved toxic elements downslope into the ground water and can eventually flow into wetlands, estuaries, streams, and lakes.

See NEH Part 623, Chapter 2, Irrigation Water Requirements, for further information on management of soil salinity and sodicity and on assessment of boron and other toxic elements.

652.0307 Crop data bases

The Field Office Computer System (FOCS) includes a plant data base that is site specific and can be used directly by applications for planning and designing irrigation systems.

652.0308 State supplement