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Article on Water Conservation

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Here is the article I discussed last week. This was an early draft that I reviewed. The final copy should be available the next several months. There is suppose to be an issue of this journal devoted to such ~~topics~~ topics. I'll keep an eye open for this.

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February 10, 1999

Dr. Darrell Martin
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Dear Dr. Martin:

Thanks for your willingness to review this manuscript on 'Agricultural Water Conservation --- A Global Perspective.' Please return it by February 22, 1999, if at all possible. An Abstract of 100 words or less and a short summary will be added, but, because of time constraints (due March 1), I wanted to get this to you as soon as possible to give you adequate time for reviewing it.

Please document your review on the enclosed form.

Again, thanks.

Sincerely,

Paul W. Unger

PAUL W. UNGER
Soil Scientist

Enclosures

AGRICULTURAL WATER CONSERVATION — A GLOBAL PERSPECTIVE

Paul W. Unger and Terry A. Howell

INTRODUCTION

All plants depend on an adequate and steady water supply for optimum growth and development. For terrestrial plants, water stored in soil from precipitation or irrigation sustains plants until the next precipitation or irrigation event. In humid regions, precipitation usually is frequent and reliable enough so that plants seldom experience a water deficiency, and removal of excess water is required for successful crop production under some conditions. As a result, water conservation for agricultural crops often receives little attention in humid regions. Short-term and periodic droughts, however, occur and water conservation can be beneficial for crop production, even in humid regions. Water conservation in humid regions may be especially beneficial on soils with low water holding capacity. Under such conditions, 7 to 14 days without rain can cause severe plant water deficiencies and, hence, major reductions in crop yields. Water conservation can be beneficial also in humid regions, and we will give some examples for such conditions; however, we will emphasize agricultural water conservation in the drier regions, namely, subhumid and semiarid regions for dryland agriculture and semiarid and arid regions for irrigated agriculture.

In contrast to humid regions, precipitation in subhumid and semiarid regions often is limited and erratic, with periods of various duration without precipitation occurring during the growing season of most crops. During such periods, the amount of plant available soil water has a major effect on plant growth and yield of dryland crops. For example, winter wheat (*Triticum aestivum* L.), grain sorghum [*Sorghum bicolor* (L.) Moench], and sunflower (*Helianthus annuus* L.) grain yields increased 7.2, 17.0, and 7.0 kg ha^{-1}, respectively, for each additional millimeter of plant-available water in Pullman clay loam (fine, mixed, thermic Torrertic Paleustoll) at planting time (Johnson, 1964; Jones and Hauser, 1975). Obviously, water conservation is highly important for dryland crop production in subhumid and semiarid regions, and water conservation has received much attention in those regions.

Irrigation often is used for crop production where precipitation is limited and erratic, as in semiarid regions, and to extend crop production into arid regions where it is a high risk without irrigation. Sometimes, irrigation also is used in subhumid and humid regions to supplement water from precipitation, especially during short-term droughts.

Successful irrigated agriculture depends on a plentiful and reliable water supply, which may be diverted from streams, impounded in reservoirs, or naturally occurring in underground aquifers. Development of irrigated agriculture in a region usually is based on the availability of adequate water. Subsequently, however, competition for water may develop to serve needs of urban, industrial, environmental, and recreational users, which results in less water being available for irrigation. The water resource also may be limited, as in some aquifers. As a result, water removed for irrigation is not being replenished, thus resulting in a decline in water available for future irrigation. The increasing competition for and declining supplies of water clearly show that less water will be available for irrigation in the future and that irrigated agriculture must participate in water conservation efforts so that the needs of all groups can be met.

? Rainfed vs DRYLAND.

DRYLAND AGRICULTURE REGIONS

First, a definition of `dryland agriculture' is in order. Dryland agriculture, also called dry farming (Cannell and Dregne, 1983), has received a range of definitions. According to the SSSA (1996), dryland farming is "crop production without irrigation (rainfed agriculture)." This definition in the strictest sense would include farming in humid regions where precipitation may be excessive for successful crop production, at least for some crops. Although dryland agriculture is rainfed agriculture, others (Cannell and Dregne, 1983; SCSA, 1982; Clarke, 1988; Stewart, 1988) defined dryland agriculture (farming) as agriculture without irrigation where precipitation is low and erratic in amount and distribution, and generally less than potential evapotranspiration during a major part of the year. Use of special water-conserving practices usually is required for successful crop production under such conditions.

Dryland agriculture is practiced on all continents, except Antarctica. Worldwide, about 600 million ha of land, representing about 40% of the world's land surface, are devoted to dryland agriculture (Brady, 1988). Dryland agriculture long has been a major provider of food and fiber products, and increased production of these products will be required under dryland conditions because of the ever-increasing world population. To achieve this, improved water conservation and use will be required because the total amount of water available annually is relatively constant.

IRRIGATED AGRICULTURE REGIONS

As of 1996, about 263 million ha of land were irrigated in the world, with irrigation being done in 166 countries (FAO, 1998). The three countries reporting the most irrigation were India with 57.0 million ha, People's Republic of China (PRC) with 49.9 million ha, and United States of America (USA) with 21.4 million ha. The total for the remaining countries was ~135 million ha. The irrigated area in the USA is relatively constant, but increases were shown for India and the PRC, as well as the total for the remaining countries (FAO, 1998). The amount of water available annually for irrigation and other users (competitors for water) is relatively constant. Therefore, water that is available for irrigation needs to be used more efficiently to achieve the increased production of agricultural products needed for the ever-increasing world population. As for dryland agriculture, improved water conservation under irrigated conditions will play a major role ? in assuring that adequate water will be available to produce the required agricultural products.

FACTORS INVOLVED IN (PRINCIPLES OF) WATER CONSERVATION

On a global basis, individual tracts of land devoted to crop production range from fractions of hectares for subsistence farmers to thousands of hectares for large private or commercial farms. The technologies involved may range from use of human or animal power to large tractors. Because of these size and technology differences, all practices suitable for agricultural water conservation are not equally applicable or adaptable for all conditions. The factors involved in (or principles of) water conservation, however, are applicable for all conditions, regardless of tract or equipment size.

Under all conditions, water conservation for agricultural crops depends first on water infiltration into soil and then on water retention in that portion of the soil where it subsequently can be extracted by crop roots. Effective infiltration depends on conditions being favorable for adequate water flow into soil and on sufficiently low runoff rates so there is adequate time for water to enter soil. To retain water for later use by crops, evaporation, deep percolation, and use by weeds must be prevented or minimized. Water transport characteristics of a soil strongly influence water infiltration, evaporation, and deep percolation rates (van Bavel and Hanks, 1983).

Runoff water is of no direct value to a crop unless it is captured and used for irrigation or it enters a stream from which it can be used for irrigation at another site. To achieve maximum infiltration at a given site, runoff should be minimized or avoided. Runoff is avoided or at a minimum when the application rate (precipitation or irrigation) is at or below the soil's infiltration rate. Matching the water application rate to the infiltration rate is possible for many irrigation systems, but runoff can and often occurs with many surface irrigation methods and with mechanical move sprinkler systems. With precipitation, however, the application rate is not controllable and management practices are needed to reduce or prevent runoff, thus providing adequate time for infiltration. Soil surface and profile conditions, including the antecedent water content, influence the rate at which water infiltrates a soil.

Although runoff may be minimized or avoided, a soil often is not filled to capacity with water during one or even several precipitation events under dryland conditions in a semiarid region. Under such conditions, water harvesting may be used to supply additional water to a site or fallowing may be used to provide more time to store adequate water for the next crop.

The amount of water that can be stored in a soil depends on such factors as its texture, organic matter content, profile depth, and horizon characteristics. Infiltrated water in excess to that needed to fill a soil to capacity is lost to deep percolation unless an impermeable layer is present. Water-logging may occur when deep percolation is hindered. Also, runoff most likely will be greater.

Water retained in a soil is subject to evaporative loss from the surface, which occurs in three stages. Loss is greatest during the first stage when the rate depends on the net effect of water transmission rate to the surface and aboveground conditions such as wind speed, temperature, relative humidity, and radiant energy. Evaporation decreases rapidly during the second stage as the soil water supply decreases and when it depends on the rate of water movement to the surface. Third stage evaporation is low and controlled by adsorptive forces at the solid-liquid interface. The potential for decreasing soil water evaporation is greatest during the first two stages (Lemon, 1956). Methods for decreasing evaporation include decreasing turbulent water vapor transfer to the atmosphere (e.g., crop residues as a mulch), decreasing capillary continuity in the soil or capillary water flow to the surface (shallow tillage), and decreasing water-holding capacity of surface soil layers.

Water retained in a soil is subject to loss through transpiration by weeds. Weeds present before crop establishment decrease the amount of water available for crop use. Those present during the growing season directly compete with crops for water stored in soil; also for light and space. In most cases, crop yields are reduced. Weed control is especially important for dryland crop production and for efficient use of irrigation water.

The above factors also affect water conservation under irrigated conditions. In addition, irrigation involves water conveyance from the supply point to the application site. Unless conveyed in a closed system, water losses due seepage, use by non-crop vegetation, and evaporation are possible. Seepage may be especially large from non-lined conveyance ditches.

Evaporative losses can be large when using high-pressure sprinkler irrigation systems. Also, deep percolation losses can be large when the amount applied exceeds the water storage capacity in the soil's root zone. Deep percolation losses often occur with furrow or flood irrigation.

WATER CONSERVATION PRACTICES

Agricultural water conservation involves water storage in soil, except for that captured and stored in reservoirs for later irrigation of crops. Water storage in soil has been widely researched and numerous practices have been developed. Some are widely applicable whereas others generally are applicable to highly specific conditions. Water storage in reservoirs also is generally applicable to highly specific conditions. The emphasis will be on the more widely applicable practices, but information regarding some other practices will be presented also.

In addition to practices based on research, numerous indigenous and relatively simple practices that provide some water conservation benefits are used by farmers in developing countries (Critchley et al., 1994; Gallacher, 1990). Evaluation and improvement of these practices with the farmers' participation could lead to improved water conservation in countries where more elaborate conservation practices would not be adaptable or acceptable.

Relationships among those factors important for improving water storage in soil, namely, increasing infiltration (reducing runoff), reducing evaporation, eliminating or reducing water use by undesirable plants, and eliminating or reducing deep percolation are highly complex. In many irrigation situations, deep percolation for salinity control and management is required and desired for sustainable crop production. In some cases water is also applied for germination and/or harvesting of crops such as potatoes or sugar beets. ~~[illegible]~~ Evaporation losses of these uses are usually very high!

Infiltration and runoff

Although water runoff and infiltration are closely related (water lost as runoff cannot infiltrate) and reducing runoff is essential for increasing infiltration, all water retained on land does not necessarily infiltrate the soil. Rather, some potential runoff retained in surface depressions evaporates before infiltration occurs, especially when a surface seal or other restrictive layer is present. Also, water retained in surface soil often evaporates before it can be used by plants because it does not move deeply enough to add to the soil water supply. In some isolated instances, infiltrated water may move laterally due to an impeding horizon and enter a stream, thereby contributing to runoff.

A soil must be receptive to applied water and sufficient time must be available for satisfactory infiltration to occur. Development of a soil surface seal (or crust) is a major deterrent to water infiltration. When raindrops strike bare soil, their energy may disperse soil aggregates, thus resulting in seal development and runoff. In contrast, surface residues, as those resulting from use of conservation tillage, dissipate raindrop energy, thus preventing or reducing aggregate dispersion and seal development, and resulting in greater infiltration. Surface residues also retard the rate of water flow across the surface, thus providing more time for infiltration.

Numerous studies involving no-tillage, a type of conservation tillage for which most crop residues remain on the surface, have shown the value of residues for increasing infiltration and, therefore, the potential for greater soil water storage (e.g., Cogle et al., 1996; Gilley et al., 1986; Harrold and Edwards, 1972; O'Leary and Connor, 1997; Opoku and Vyn, 1997; Rockwood and Lal, 1974). In general, runoff increases with increases in soil surface slope, especially under bare soil conditions. With no-tillage, however, surface slope has less effect on runoff, as shown in Tables 1 and 2. Although water contents were not given, reducing runoff provided the opportunity to replenish the soil water supply, which is the goal for water conservation efforts under all conditions. Besides reducing runoff, use of no-tillage also greatly reduced erosion.

Use of tillage may reduce runoff and increase infiltration when residue amounts are low because of low production (as by dryland crops), use for other purposes, or incorporation by previous tillage. Under such conditions, tillage can disrupt the surface seal (or crust), provide ridges on the contour, and increase surface roughness and plow-layer pore space, thus retaining more water on the surface and providing more time for infiltration (Hien et al., 1997; Jones et al., 1994; Muchiri and Gichuki, 1983; Rawitz et al., 1983; Stroosnijder and Hoogmoed, 1984; Willcocks, 1984). Greater infiltration and, hence, greater soil water storage also can be achieved by disrupting slowly permeable or compact layers in the profile (Eck and Taylor, 1969; McConkey et al., 1997; Schneider and Mathers, 1970) or loosening soils subject to freezing (Pikul et al., 1996). These practices increase soil depth at which water is stored and thus enlarge the zone in which plant roots proliferate. Tillage contributes to increased evaporation through

Other practices for increasing infiltration and soil water storage include graded furrowing (Krantz et al., 1978; Pathak et al., 1985; Richardson, 1973), terracing (ASAE, 1982; Beach and Dunning, 1995; Gallacher, 1990; Jones, 1981), furrow diking (tied ridging) (Gallacher, 1990; Jones and Clark, 1987; Vogel et al., 1994), strip cropping and growing vegetative barriers (Alegre and Rao, 1996; Gallacher, 1990; Sharma et al., 1997; Wischmeier and Smith, 1978), and using LEPA (low energy precision application) irrigation. Use of LEPA irrigation resulted in water application efficiencies >95% (Howell et al., 1995; Lyle and Bordovsky, 1983; Schneider and Howell, 1990). With LEPA irrigation, water often is applied at low energy to alternate diked furrows that temporarily detain water on the surface. Diked furrows can be used with most sprinkler method to temporarily impound "excess" water to enhance infiltration by avoiding runoff.

Snow provides much of the water used by crops in the northern U.S. Great Plains, Canadian Prairie Provinces, northern Europe, and northern Asia. A special case involving crop residues or vegetative barriers is their use to trap snow, thus achieving greater and more uniform water storage in soil when the snow melts (Black and Aase, 1988; Campbell et al., 1992; Cutforth and McConkey, 1997; Steppuhn and Waddington, 1996). Under some conditions, snow from early storms is `plowed' into ridges, thus creating barriers for greater trapping of snow from subsequent storms (De Jong and Steppuhn, 1983). Soil water storage from snow melt is highly variable, but up to 50 mm greater storage occurred with than without residues or barriers in place. Vegetative factors that influence snow trapping include stubble height, barrier spacing, and barrier orientation relative to wind direction. Greater soil water contents resulting from trapped snow permitted more intensive cropping and greater crop yields. The barriers also provided microclimate benefits for the next crop. Unfortunately, the greater water contents contributed to development of saline seeps under some conditions (Black and Siddoway, 1976), thus adversely affecting crop yields. Carefully matching crops to the available water supply helps avoid the saline seep problem (Brown et al., 1982).

Some soils are highly unstable at the surface and high runoff of precipitation or irrigation water is common when the soil is not protected by residues or other runoff control practices. Some materials applied to the soil surface or with irrigation water have resulted in major increases in water infiltration as compared to that where the materials were not applied. Runoff was reduced sixfold as compared with that from untreated soil when phosphogypsum (PG) was applied at 10 Mg ha^{-1} to a ridged sandy soil in Israel under field conditions (Agassi et al., 1989). When PG was applied to a clay loam at 3.0 Mg ha^{-1}, runoff was less than from bare soil, but still greater than where wheat straw was applied at 2.2 Mg ha^{-1} (Benyamini and Unger, 1984).

Anionic polymers [polyacrylamide (PAM) or starch copolymer solutions] injected into water used for furrow irrigating a silt loam in Idaho (USA) reduced soil loss in runoff water by 70 to 97%, depending on polymer concentration. The treatments also increased net infiltration and lateral infiltration, probably because of less surface sealing and sediment movement (Lentz et al., 1992; Trout et al., 1995).

Evaporation

Precipitation storage as soil water during the interval between crops in a semiarid region such as the U.S. Great Plains usually is <50%, with amounts much below that occurring in many cases (Jones and Popham, 1997; Unger, 1978, 1994). While runoff accounts for some of the water loss, Bertrand (1966) indicated about 60% of average annual precipitation may be lost directly from soil by evaporation. Evaporative losses can be especially large when most precipitation occurs in relatively small storms. For example, 1522 storms occurred at Bushland, Texas (USA), in the southern Great Plains from 1960 through 1979. Precipitation occurred at ~100 mm $hour^{-1}$ for up to 10 minutes in some storms, but only 11 storms resulted in >50 mm total precipitation and only 73 resulted in >25 mm total precipitation (unpublished precipitation data, Conservation and Production Research Laboratory, Bushland, TX). Small storms result in limited soil wetting and significant evaporative losses. Consequently, water storage efficiencies at Bushland (Jones and Popham, 1997; Unger, 1978, 1994) generally low because most storms occur during the warm season (between late spring and early fall) when the potential for evaporation is greatest. Evaporation from fully wetted soils, however, also results in major water losses (Plauborg, 1995).

Evaporation involves water vapor transfer to the atmosphere, capillary continuity in soil, capillary water flow to the surface, and water-holding capacity of surface soil layers. These factors involve or affect water movement as liquid or vapor in response to soil water potentials, soil temperature gradients, and atmospheric conditions. In addition, deep percolation of water may occur while evaporation occurs from the surface. As a result, soil water evaporation is a highly complex process. In addition, determining evaporation under field conditions is difficult because of the interacting effects of water infiltration, distribution in soil, deep percolation, and subsequent evaporation.

Effects of many types of surface mulch treatments on soil water evaporation have been studied (Unger, 1995), with crop residues used as the mulch in many cases. Residue characteristics affecting evaporation are orientation (flat, matted, or standing), which affects layer porosity and thickness; layer uniformity; rainfall interception; reflectivity, which affects surface radiant energy balance; and aerodynamic roughness resulting from the residues (Van Doren and Allmaras, 1978).

Although difficult to measure under field conditions, results of some studies have shown clearly that retaining crop residues on soil surfaces reduces evaporation. During a 5-week period without precipitation, water loss was 23.1 mm from bare soil, but only 19.6 mm with flat, 18.6 mm with 0.75 flat-0.25 standing, and 15.1 mm with 0.50 flat-0.50 standing wheat residue on the surface (Smika, 1983). Standing residue was 0.46 m tall and the amount present was 4600 kg ha^{-1} in all cases. Greater wind speed was needed to initiate water loss as the amount of standing residue increased and the water loss rate decreased with increasing amounts of standing straw at a given wind speed. Residue orientation also affected average soil temperature (47.8, 41.7, 39.6, and 32.2°C for the respective conditions), which, in turn, affected evaporation through its effect on vapor pressure of soil water (Smika, 1983). Standing residue resulted in the greatest evaporation reduction. Nielsen et al. (1997) showed that potential evaporation decreased as residue height increased, with the height effect being especially important when stem density was <215 m^{-2}. The residue height effect decreased with increasing stem densities.

One day after a 13.5-mm rain, soil water contents were similar to a 15-cm depth where conventional-, minimum-, and no-tillage treatments were imposed after winter wheat harvest at Akron, Colorado (USA). Surface residue amounts were 1200, 2200, and 2700 kg ha^{-1} with the respective treatments. After 34 days without additional rain, soil had dried to a <0.1 m^3 m^{-3} water content to the 12-cm depth with conventional tillage and the 9-cm depth with minimum tillage. Blade tillage had been performed to those depths 8 days before the rain. With no-tillage, soil had dried to that water content only to a 5-cm depth. Some water loss occurred at greater depths with each treatment, but the water content was greatest with no-tillage for which the surface residue amount was greatest (Smika, 1976).

Evaporation reduction in the above studies involving crop residues resulted primarily from reducing the turbulent transfer of water vapor to the atmosphere. Another means of reducing evaporation is to reduce capillary water flow to the surface. Therefore, there long has been an interest in using dust mulching (also called soil mulching) to control evaporation. Dust mulching is essentially a clean-tillage (residue-free) system that involves producing a loose, fine granular or powdery soil layer at the surface by shallow tillage or cultivation. Dust mulching, in general, is effective for reducing evaporation of water already present in soil (Abdullah et al., 1985; Jalota, 1993; Jalota and Prihar, 1990; Papendick, 1987; Singh et al., 1997). Therefore, dust mulching to reduce evaporation is applicable mainly to regions where a distinct wet (rainy) season, which results in water storage in soil, is followed by a distinct dry season. In contrast, dust mulching usually is not effective where precipitation occurs mainly during the summer when the potential for evaporation as greatest, as in the U.S. Great Plains, because much of the water evaporates before the soil dries enough for tillage to be performed (Jacks et al., 1955). Dust mulching also is not suitable for such regions because the frequent tillage needed to maintain the mulch results in bare soil that is highly susceptible to both wind and water erosion. Another reason for poor results with dust mulching in a summer precipitation region is that tillage brings moist soil to the surface, which increases evaporation. Less water storage in soil with stubble mulch tillage than with no-tillage also resulted from the greater evaporation of water from the tilled soil (Jones and Popham, 1997).

Water Retention

The amount of water retained in a soil is influenced mainly by its texture, structure (aggregation and porosity), depth, and organic matter content. A soil's texture is an inherent characteristic resulting from the conditions and location where the soil developed. Sandy soils generally have lower water holding capacities than finer-textured soils (higher silt and clay contents). Deep plowing to mix profile layers or to bring finer materials to the surface increased the water holding capacity of soils initially having a surface horizon with a high sand content (Harper and Brensing, 1950; Miller and Aarstad, 1972). Besides increasing water retention in a given volume of soil, deep plowing and profile mixing also increase the volume of soil in which plant roots can proliferate and extract water (Eck and Taylor, 1969; McConkey et al., 1997; Schneider and Mathers, 1970). These operations, however, require special equipment and are energy-intensive, costly, and time consuming. As a result, they are not widely used, except where major benefits can be achieved. A less intensive operation is chiseling often used to disrupt restrictive zones at relatively shallow depths, especially in irrigated soils.

Organic matter influences water retention in soil through its direct affinity for water and through its effect on aggregation, both of which increase with greater organic matter content. Returning all or most crop residues to a soil helps maintain or, under some conditions, increase the soil's organic matter content. Maintaining or increasing a soil's organic matter content under dryland conditions in a semiarid region such as the southern U.S. Great Plains, however, is difficult because residue production generally is low. Rather, soil organic matter contents generally decreased with continued cropping with clean or stubble mulch (sweep) tillage and tended to be maintained under no-tillage conditions (Potter, 1998; Unger, 1997).

Whereas increasing a soil's organic matter content to increase water retention is difficult, there long has been an interest in adding organic substances to soils to improve water conservation (Unger and Stewart, 1983). Although applying organic substances to soil resulted in less runoff (Weakly, 1960) and evaporation (Olsen et al., 1964), the potential under field conditions was limited because the substances had limited stability in soil and little effect on crop yields. Some recent reports, however, indicated that adding coal-derived humic substances (Piccolo et al., 1996) and synthetic polymers (Choudhary et al., 1995) to soils significantly increased water retention.

In a laboratory study, adding humic substances to soil at a 0.05 g kg^{-1} rate increased the available water content by up to 5.2% as compared with untreated soil, with no further increases when applied at rates up to 1.00 g kg^{-1}. The 0.05 and 0.10 g kg^{-1} rates of application improved soil aggregate stability 40 and 120%, respectively, which contributed to the greater water retention. Further studies were needed to evaluate the potential of the substances under field conditions (Piccolo et al., 1996).

Also under laboratory conditions, Choudhary et al. (1995) added synthetic polymers to two soils at rates of 0.2, 0.4, and 0.6% on a dry weight basis. Increases in amount of polymer applied increased water conservation by increasing the soils' water holding capacity and by decreasing evaporation as compared with that of untreated soil. Water retention benefits from polymer application are attributable to the hydrophilic groups in their molecules (Piccolo et al., 1996).

Weed Control

Where water conservation for crop production is critical, it is imperative that water use by weeds (including volunteer crop plants) be avoided or minimized. This is especially important under dryland conditions in semiarid regions because water used by weeds reduces the amount available for the crop, which then results in lower crop yields. Weed control to avoid direct competition between weeds and crops for water is important not only during a crops' growing season, but also before crop planting when the goal is to store as much water as possible for the crop to be grown. In addition to competition for water, weeds compete with crops for light, nutrients, and space; therefore, their control is important under all cropping conditions.

Land under dryland conditions generally must be kept free of weeds to obtain maximum soil water storage at planting time. Until herbicides became available, a major reason for tillage was to control weeds. Now, tillage or herbicides, or a combination of the two, are available for weed control. Under some conditions, hand weeding may be practiced. Also, use of crop rotations reduces the severity of some weed problems (Wiese, 1983).

Regardless of the method, timeliness of weed control is important because uncontrolled weeds may use about 5 mm of water per day from a soil (Wicks and Smika, 1973). When using tillage, it usually can be delayed until weeds use more water than that lost by evaporation, thus avoiding frequent tillage operations and, thereby, resulting in production cost and energy savings (Lavake and Wiese, 1979). Another consideration is that each tillage operation exposes moist soil to the atmosphere, thus also contributing to soil water losses by evaporation. Good and Smika (1978), for example, showed that each tillage operation resulted in losing 5 to 8 mm of water from the exposed moist soil. An advantage of using tillage for weed control is that it kills weeds almost immediately, thus preventing continued water loss due to transpiration, which may occur with the use of herbicides. Several tillage operations to may be needed to maintain weed control and to obtain optimum water conservation and crop yields (Pressland and Batianoff, 1976).

As with tillage, weed control by hand, which is the common practice of small-scale growers in many countries such as those in sub-Saharan Africa (Twomlow et al., 1997), repeated weeding may be required to achieve optimum crop production. In Zimbabwe, for example, weeding at 2, 4, and 6 weeks after corn (*Zea mays* L.) emergence resulted in greater water use efficiency and grain yield than a single weeding at 2 weeks. The unweeded control treatment resulted in the driest soil and lowest yields.

Herbicides can be applied to prevent weed seed germination or to control existing weeds. Preventing germination would be ideal for preventing soil water loss due to transpiration by weeds. However, use of such herbicides may not prevent germination of all weed seeds in a given crop because some weeds are not controlled by the herbicide. Use of 'safener-treated' crop seed (seed treated to prevent action of a herbicide) has extended the use of some herbicides to prevent weed seed germination (Jones and Popham, 1997).

For established weeds, timeliness of control is highly important for minimizing their competition with crops for water. In general, small weeds are easier to control than large weeds (Wiese et al., 1966). Weeds not killed immediately continue to use soil water. Weed control with herbicides often becomes especially difficult when the plants are stressed for water. The development of herbicide-tolerant crops through genetic engineering has greatly expanded the opportunity for using highly-effective, quick-acting herbicides to control problem weeds in some crops.

Cover crops maintain a cover on the soil surface, thereby "preventing soil erosion, improving water infiltration, maintaining and increasing organic carbon levels, and possibly improving soil productivity" (Tyler, 1998). Although cover crops are not generally considered to be weeds, they influence the water supply for subsequent crops in a manner similar to that of weeds. Use of cover crops generally had little or no effect on the soil water supply for the next crop in humid or subhumid regions because of generally adequate and reliable precipitation before planting the next crop. However, where the goal is to increase soil water storage for the next crop, as under dryland conditions in a semiarid region such as the U.S. southern Great Plains, growing cover crops usually is not recommended (Unger and Vigil, 1998). Growing cover crops generally reduced the amount of soil water available at planting time, thus reducing yields of subsequent economic crops.

Multiple-Factor Water Conservation Practices

For studies under field conditions, the causative factors resulting in soil water contents usually are not clearly differentiated. Rather, at any given time, prevailing water contents reflect the combined effects of water infiltration, runoff, evaporation, retention, and weed control, which were discussed separately in foregoing sections. The literature pertaining to soil water conservation is vast. In this section, some selected examples of the combined effects of the different factors are given and discussed.

Fallowing

Fallowing is the practice of allowing cropland to remain idle during all or part of the growing season when a crop normally would be grown. The land may be tilled or remain untilled during the fallow period. Objectives often are to control weeds, accumulate soil water, and/or accumulate plant nutrients. Fallowing often is used under dryland conditions in semiarid regions, primarily to provide more time to increase soil water storage for the next crop, thus increasing the yield potential and reducing the probability of a crop failure.

Use of fallowing generally increases the soil water content at planting of the next crop, but precipitation storage as soil water (known as fallow efficiency or water storage efficiency) often is low. This is especially the case where long fallow periods are used such as those involving winter and spring wheat in the U.S. Great Plains and Canadian Prairies.

The winter wheat-fallow and spring wheat-fallow systems result in one crop in 2 years; they involve 14 to 17 and about 21 months of fallow between crops, respectively. Use of these systems improved and stabilized crop productions in the Great Plains starting early in the 20th century, but water storage efficiencies generally were <20%. Through the introduction of improved equipment, crop residue management techniques, and weed control practices (including the use of herbicides), water storage efficiencies of ~50% have been achieved under some conditions (Smika, 1986). Data in Table 3 (Greb, 1979) illustrate increases in water storage efficiencies and crop yields that resulted from use of improved practices in the U.S. central Great Plains.

Storage efficiencies are highly variable among years and generally are greater in northern regions (U.S. northern Great Plains and Canadian Prairies) than in southern regions (U.S. southern and central Great Plains). In the northern Great Plains, average storage efficiency was 28%, but ranged from 16 to 44% from 1957 to 1970 (Black and Bauer, 1986). A comparison of water storage efficiencies for various cropping systems and tillage methods is given in Table 4. With improved storage efficiencies, more intensive cropping is possible and some well-adapted systems have been developed.

Crop Selection and Cropping Systems

Crops (also crop varieties or cultivars) vary in length of growing season and usually have peak growth periods at different times of the year. Therefore, for optimum production, especially on dryland, major water requirement periods of selected crops should closely match periods of greatest potential water availability (stored soil water or precipitation). For example, winter wheat in the southern and central Great Plains is maintained during the fall and winter months mainly by water contained in soil at planting time. Although some soil water may remain for the peak demand period in spring (April till June), best yields are obtained when favorable precipitation occurs during that period, which includes the period of greatest precipitation probability in the region. Therefore, winter wheat is well adapted for that region.

Summer crops also are well adapted for the southern and central Great Plains because their growing season roughly corresponds to the time when precipitation (rain) is most likely to occur. Summer crops, however, differ in length of growing season and, therefore, vary in adaptability. For example, sugar beet (*Beta vulgaris* L.) has a long growing season, requires a large amount of water, and generally yields poorly on dryland. Grain sorghum has a shorter growing season, requires less water than beet, and generally yields well unless timely rain does not occur during the critical grain filling period. Grain sorghum is strongly influenced by the soil water content at planting (Jones and Hauser, 1975; Unger and Baumhardt, 1999). Short season crops such as millet (*Pennisetum* spp.) and some hay crops require less water and, therefore, generally produce more with a given amount of water than wheat or sorghum (Greb, 1983).

For greatest water storage after crop harvest, a crop should use most plant-available water by the time it is harvested, thus providing a soil receptive to storing water. Of course, water remaining in soil at harvest may also be available for the next crop, especially when shallow- and deep-rooted crops are grown in rotation.

The foregoing pertained mainly to crops grown annually on the same tract of land (continuous or annual cropping). The crops mentioned, along with others [corn, sunflower (*Helianthus annuus* L.), etc.], generally are well adapted for use also in crops rotations. Use of crop rotations may provide more time for soil water storage (for example, winter wheat-grain sorghum-fallow rotation; two crops in 3 years with 10 to 11 months of fallow between crops); greater extraction of soil water (use of shallow- and deep-rooted crops, mentioned above); and better weed, insect, and disease control (use of different pesticides, tillage methods, and other management practices). All of these have water conservation ramifications and successful dryland crop production frequently involves the use of crop rotations.

As previously mentioned, the introduction of improved equipment, crop residue management techniques, and weed control practices has resulted in greater water storage efficiencies, thus providing an opportunity for more intensive cropping. Because of the generally low water storage efficiency with the wheat-fallow system, it has been replaced by more intensive cropping systems under dryland conditions in many cases. Well-adapted systems include winter wheat-fallow-grain sorghum-fallow (two crops in 3 years) in the southern and central Great Plains (Jones and Popham, 1997; Norwood, 1992; Unger, 1994) and winter wheat-corn (or grain sorghum)-millet-fallow (three crops in 4 years) in the central Great Plains (Wood et al., 1991). In the northern Great Plains, systems of spring wheat-winter wheat-fallow (two crops in 3 years); safflower (*Carthamus tinctorius)*-barley (*Hordeum vulgare* L.)-winter wheat; spring wheat-corn-peas (*Pisum sativum*); spring wheat-winter wheat-sunflower; and spring wheat in rotation with soybean (*Glycine max* L.), peas, safflower, sunflower, buckwheat (*Fagopyrum esculentum* Moench), or canola (*Brassica spp.)* are being used (Black, 1986; Black and Tanaka, 1996; Unger and Vigil, 1998). Under some conditions, use of improved management practices for continuous (annual) cropping systems has increased soil water storage, thus resulting in greater total yields than for crops grown in rotation systems (Campbell et al., 1998; Jones and Popham, 1997). More intensive cropping was reported also by Amir and Sinclair (1996), Carroll et al. (1997), and Sandal and Acharya (1997).

Mulching

Although many mulch materials are available, crop residues usually are used as the mulch under field conditions. In essence, conservation tillage is a mulch tillage (including no-tillage) system. According to the definition of conservation tillage, 30% of the soil surface must be covered by residues after crop planting to control water erosion. For wind erosion control, residues equivalent to 1000 kg ha^{-1} of small grain residues should be present. Besides controlling erosion, crop residues also provide water conservation benefits with water conservation increasing with increased amounts of residues retained on the soil surface (Table 5). Greatest water conservation resulted from the high residue treatments, but dryland crops usually produce much lower amounts of residue. Therefore, water storage usually is lower but still greater than where some or most crop residues are incorporated by tillage, as reported extensively in the literature. Conservation tillage, especially no-tillage, is an effective water conservation practice, even under dryland conditions.

A specialized type of mulching is vertical or slot mulching, which involves opening a slot in the soil with a chisel or other suitable implement and filling the slot with crop residues or other materials (Ramig et al., 1983; Raper et al., 1998). The mulch-filled slot provides for rapid water infiltration, provided the opening to the surface is not closed by subsequent tillage. On a soil subject to freezing near Pullman, Washington (USA), runoff from land planted to wheat was 10 mm with slot mulching compared with 114 mm with no-tillage. The water saved by using slot mulching had potential to increase wheat yields between 1300 to 2000 kg ha^{-1} (Ramig et al., 1983).

Water Harvesting

Ancient stone mounds and water conduits in some countries indicate water harvesting has long been used to capture or divert storm runoff for application to land where crops are grown (Abu-Awwad and Shatanawi, 1997; Greb, 1979; Lavee et al., 1997). The water may be applied directly to cropland or retained in reservoirs for irrigating a crop at a later time. The runoff may be from natural land surfaces or from surfaces treated to enhance runoff.

Direct application of harvested water to crops generally is practiced where precipitation is limited, as in semiarid to arid regions. The goal is to capture water falling on a given area and supplementing it with runoff from a contributing area. The receiving area should be capable of retaining the initial and runoff water without adversely influencing the crop being grown. Types of systems used for direct application of the harvested water include level pans that receive water diverted from natural waterways (Greb, 1979); conservation bench terraces for which runoff from the natural upslope area is captured on the leveled downslope area between terraces (Zingg and Hauser, 1959); level, intermittent, fish scale, and discontinuous parallel terraces for which runoff from part of the land is captured by the terraces (Unger, 1996); and various types of microbasins. Land preparation for receiving harvested water directly generally involves limited modification of the soil surface.

Where runoff is not needed when it occurs and not directly applied to the land, the water storage reservoir should hold adequate water to meet that needed for irrigation, with normal frequency of runoff events and reservoir `leakage' (deep percolation and evaporative losses) influencing its capacity. Water storage in a reservoir is most frequently used in subhumid and humid regions or where distinct rainy seasons are followed by distinct dry seasons, as in parts of India (Krantz et al., 1978) and other countries.

Water conserved and crop yields resulting from water harvesting are highly variable because runoff amount and timing relative to crop requirements are highly variable (Greb, 1979; Kaushik and Gautam, 1994), especially where runoff is directly used on the land. More reliable crop yields are possible when adequate runoff is stored in reservoirs and used as needed for irrigation.

Crop Termination Time

When grain crops such as corn, wheat, and grain sorghum reach physiological maturity, subsequent water use does not increase their yield. Subsequent water use, however, could influence their harvested yield by delaying plant lodging until harvest is possible. Because yield potential is not increased, terminating the crop at physiological maturity would halt soil water extraction and, thereby, conserve some water for the next crop. An alternative would be to terminate plant growth immediately after harvest for crops such as grain sorghum and cotton that have an indeterminate growing season where their growth is not terminated by cold weather. Of course, second or rattoon crops are possible for crops such as grain sorghum, sugarcane (*Saccharum* sp.), and rice (*Oryza sativa*) under some conditions. The rattoon crop most likely would require less water than the first crop because it would require limited additional plant development.

Irrigation Water Delivery Systems and Irrigation Methods

Ideally, all irrigation water would be delivered to crops without loss and at the precise time to provide the greatest benefit. Irrigation delivery may involve transporting water from a sole supply like a dedicated reservoir or a single well where one person (or company) may be in complete control. Most often, however, it involves off-site sources of water and its transportation from pipelines under various pressures (low for gravity surface flows to higher ones for sprinklers) to canals with small head differences above the field surface itself. Supplies might be streams, reservoirs, or groundwater aquifers. Irrigation water supplies often involve many institutions and legal and/or social organizations that can have a myriad of rules, regulations, and/or laws as well as varying purposes for operation.

Irrigation water conservation involves achieving the greatest economic benefit (perhaps even a social or political benefit) from the water and providing for the long-term sustained agricultural system. Irrigation water often will be a shared resource and some application and operational losses (i.e., canal operational spillage, groundwater return flows into streams, surface runoff, required leaching for salinity control, etc.) are regained and subsequently recovered by downstream irrigation users. Therefore, it remains difficult to characterize irrigation water conservation without seeking to define it more globally on a hydrologic and/or irrigation district scale (Burt et al., 1997). Even if defined precisely, it remains quite challenging to characterize all possible components and pathways for water losses and water movements. For further purposes of this chapter, we will discuss water conservation from a field-level perspective, but recognizing the critical importance of the off-farm delivery network to achieve any water conservation goal.

Each previously described water conservation principle for dryland agriculture is equally important for irrigated agriculture. The goal of irrigation is to achieve the greatest fraction of the applied and/or water used to meet the crop transpiration need. Losses to runoff (from both rain or irrigation), evaporation (from plant and soil surfaces), and excess deep percolation beneath the crop root zone (except that required to maintain root zone salinity at a level not harmful to the crop) remain the central components for field-level inefficient irrigation and offer the pathways for achieving enhanced irrigation water conservation. Spatial distribution of rainfall cannot be controlled, but spatial uniformity of irrigation application remains important to successful irrigation water conservation. Spatial and temporal distribution of irrigation are controlled exclusively by management and by the particular irrigation method used. "Irrigation management consists of determining when to irrigate, the amount to apply at each irrigation and during each stage of plant growth, and the operation and maintenance of the irrigation system" (Hoffman et al., 1990; p. 9). Irrigation timing depends largely on the crop and soil water status. But the delivery schedule may be dictated or fixed by the water supplier, and this can impede water conservation goals of the producer. The desired application amount also remains intertwined with the delivery schedule, crop need, and irrigation application technology. Likewise, operation and maintenance needs are directly impacted by the irrigation application method and technologies. In some cases, the crop being grown may dictate that a certain application technology be used (i.e., to keep irrigation water off the fruit or plant).

Irrigation Technology for Conserving Water

The most of the world, various forms of surface irrigation technology are still used mainly because capital to invest in newer technology may be limited, advanced skills for the technology may be unavailable, or institutions desire to use manual labor (and thereby maintain and support an agrarian populous). Improving farm application irrigation efficiency may not improve the larger-scale hydrologic or district irrigation efficiency unless that change provides a smaller non-recoverable loss (i.e., losses to non-reusable saline waters, losses to the vadose zone beneath the crop root zone that will not move to recoverable groundwater, etc.).

Surface irrigation often is classified as "inefficient" because it can have large deep percolation and/or runoff losses that result from relying on the soil as its transport and distribution medium for the water. Musick et al. (1983) greatly reduced infiltration that would lead to undesirable deep percolation by using tractor traffic and wide furrow spacings (alternate furrows), and the practices did not reduce corn yields on a permeable soil. Surface irrigation technology can be efficient (on a farm or field basis) when runoff water is captured and reused, and when managed to avoid or minimize deep percolation losses. Surface irrigation is often regarded as "low tech" because it mainly involves manual labor for water control, but it also can involve a high technological level for such things as automated controls on canals and pipelines that might even use radio, satellite, or cellular telephone communications. Advanced surface irrigation technologies can range from moderately "high tech" [e.g., automated surge flow irrigation (Bishop et al., 1981; Kemper et al., 1988) that can use micro-computer controlled valves to reduce field runoff while achieving a more even irrigation] to precise laser leveling of the ground for dead-level irrigated basins (Dedrick et al., 1982). Kruse et al. (1990) reviewed other automation devices to improve surface irrigation from simple valves to cablegation (Kemper et al., 1981, 1985). As previously mentioned water amendments like PAM can enhance surface irrigation infiltration and reduce erosion. Because infiltration is highly important for achieving high efficiency with surface irrigation, keen management and knowledge of irrigation hydraulics, on-site soil processes (e.g., infiltration), and field soil variability are required regardless of irrigation system sophistication.

The main limitations and challenges for surface irrigation remain avoiding excessive deep percolation and reducing and/or eliminating runoff. Stewart et al. (1983) developed and evaluated a scheme with intentional nonuniform surface applications that avoided deep percolation on the upper furrow ends while not irrigating the lower field end that was diked to impound water from rain. Their system called LID (limited irrigation-dryland) could be used in continental climates where some growing season rain occurs, but where there is not an abundant irrigation water supply (like many semi-arid regions). Improved water use efficiency resulted from making better use of rainfall and maximizing the benefit from irrigation.

Canal linings (cement or flexible membranes) and underground pipelines [cement or polyvinyl chloride (PVC)] remain some of the more basic surface irrigation improvements to reduce losses from surface unlined canals. Gated pipes (aluminum, PVC, or flexible materials) can further reduce surface ditch seepage and spillage losses. Tailwater (surface irrigation runoff) reuse can further reduce net surface irrigation water losses. Because most surface irrigation involves low pressures, energy required for pumping water is low, except when the water source is a deep well.

Sprinkler irrigation technology can be quite varied also. Goals for using sprinklers are to "remove" the soil from its conveyance role in irrigation by using pressurized pipelines and then to use the kinetic force of the pressurized water for distribution in droplet form (like rain) directly to the crop and/or soil surface. System pressure and nozzle diameter affect droplet diameter and, hence, the kinetic energy that drops impart on the soil surface. Large droplets can break down the surface soil aggregates, cause surface sealing, and impede water infiltration rate. Small drops can evaporate more quickly in the air and drift away from the target, thus reducing the amount of water reaching the crop.

Solid set and mechanical types (e.g., center pivots) can be automatically and/or remotely controlled without much difficulty. Sprinkler irrigation should eliminate or allow better control of deep percolation losses and practically eliminate field runoff from irrigation, but it can result in uneven water distribution due to system hydraulics or wind effects on spray patterns. Lower angle and more closely spaced sprinklers or spray heads can reduce pattern interferences from wind.

Center pivots can be equipped with spray heads that cover a smaller wetted diameter, are at a lower elevation above the ground or crop to reduce wind effects and aerial evaporation, and operate at lower pressures (Gilley and Mielke, 1980). Use of these devices, however, results in high instantaneous water application rates that can exceed the soil's infiltration rate and result in surface water redistribution and/or runoff. Lyle and Bordovsky (1981, 1983) developed the LEPA (low energy precision application) application technology for center pivots and lateral-move machines to eliminate aerial evaporative losses, surface redistribution, and runoff. LEPA is intended to be used in conjunction with furrow dikes that impound both irrigation and rain water. Applicators using LEPA usually apply water to alternate furrows through furrow bubbles or drag socks (Fangmeier et al., 1990). Grain crop yields differed little when adequate water was applied using LEPA and spray irrigation at a semiarid site like Bushland (Schneider and Howell, 1990, 1999). Schneider (1999) reviewed much of the literature on LEPA and spray irrigations and concluded, based on efficiency and uniformity, that neither method "could be considered inherently superior to the other." However, when irrigation capacity (flow rate per unit area) becomes low with intentional deficit irrigation, like that practiced for cotton in the Southern High Plains of the USA, then LEPA would be preferable.

Microirrigation (MI) is now the more widely used terminology for drip and trickle irrigation (Kruse et al., 1990). With MI, objectives are to "remove" soil and air as distribution mediums, as occurs with surface and sprinkler irrigation, and to irrigate only the minimum root zone volume that is necessary for each plant. A broad range of technologies encompass both surface and subsurface MI, with many types of applicators being available [drippers, line-source pipes, bubblers, small spray heads, and even small sprinklers (or rotators)].

Subsurface MI systems are called SDI (subsurface drip irrigation), and are installed at soil depths ranging from a few centimeters (these may be laid out on the surface, then cultivators used to cover the lines) to deeper depths (e.g., 30 cm; installed with chisel shanks having reversed bends so the pipe feeds out behind the shank as it plows). The deeper placement makes seed germination difficult, and water either from rain or portable sprinklers may be needed for crop establishment. Lateral line spacing for SDI systems can vary, depending on the crop grown and its culture. For field crops, one line often is midway between two rows to reduce system capital cost.

The main intent of using MI is to apply precisely the amount of water each plant needs at exactly the time when it needs it (Nakayama and Bucks, 1986). MI may not result in wetting the whole soil surface as with most surface irrigation and sprinkler systems, but the area (or root volume) is irrigated more frequently. Typically, MI may involve irrigation intervals from one day to a few days, but can even involve multiple "pulses" in a single day if needed.

MI involves a massive pipe network compared to that with surface or sprinkler irrigation, but the pipes are usually much smaller because the flow rate is less. Also, material (polyethylene, PE; PVC; etc.) costs are lower because a lower pressure (70 to 140 kPa) can be used. Because

MI involves an extensive pipe network, it was first applied more successfully to orchard and vineyard crops with a lower plant density. Now, MI is used for many row crops, but more often for higher valued vegetable crops. For higher valued vegetable row crops, it often is used under a plastic mulch. SDI is now commonly used for many field row crops like cotton and corn as well as for vegetables. MI is easily automated and controlled with various devices from simple timers to microcomputers, and it can be easily used to apply nutrients to the crop.

Runoff should not occur with MI because water applications are small (range from 2-20 mm, but typical values are 5-10 mm). Unwanted deep percolation can be more easily controlled with the small applications and a lesser dependence on the soil for water storage in the root zone because water can be applied more frequently than with the larger amounts required with surface irrigation methods to achieve uniform coverage. Use of SDI can even reduce the evaporation component because the soil surface usually is not wetted. In practice, with many SDI systems, except those installed deeper than 30 cm, some soil surface wetting occurs due to capillary water flow and total elimination of soil water evaporation should not be expected. Also, significant evaporative losses may occur because the area is irrigated more frequently. Many times, however, the wetted area is beneath the crop canopy and the evaporation loss might still be small.

Use of MI requires water filtration and/or chemical water treatment to avoid plugging the small water passageways by sand or other inorganic materials, bicarbonate (lime) and iron (ochre) deposits, and bacterial slime-forming organisms. Plugging can result in poor system performance (uniformity) to complete failures in some cases. Although many of the water filtration and water treatment functions can be automated, careful operator attention is required.

Irrigation Management for Conserving Water

As defined previously, irrigation management encompasses more than just decisions on when and how much to irrigate. Operation and maintenance are critical elements, but they depend on the specific irrigation hardware being used. Maintenance may vary from installing or maintaining a simple surface ditch to intricate mechanical maintenance of a center pivot tower drive mechanism. It can involve almost daily attention to details or those requiring less frequent or possibly only annual checking. Proper maintenance and operation of equipment can avoid breakdowns at critical times when missing an irrigation would be highly detrimental for a crop.

Irrigation management is broadly related to irrigation scheduling. Although simple in concept – when do you irrigate and how much water do you apply – it becomes far more involved in actuality and is an integral part of the "whole" farm decision making process involving both strategic (before the season) and tactical (on the spot day-to-day) planning. The goal of irrigation management then is to make the needed decisions to achieve the greatest net return (profit) from the fixed and variable costs and the value of the crop produced, subject to all constraints (land, labor, water, environment, salinity, legal, etc.).

Preplant irrigation is one strategic decision that can greatly affect subsequent decisions about irrigating. Preplant irrigation may be used for weed seed germination, profile water replenishment, leaching, seed bed preparation, etc. Significant profile replenishment is difficult with small applications typical for MI or most sprinkler systems. Sometimes, excessive infiltration rates can lead to high deep percolation losses for the first surface-applied irrigation, especially if applied after primary tillage. Generally, when rainfall is near or above normal, preplant irrigations do not increase crop yields (Musick,1987). In some cases, early spring soil water loss rates and low rainfall may dictate that a preplant irrigation be made for a summer crop (Musick et al., 1971). When necessary, it should be the carefully planned and executed to minimize deep percolation (unless leaching is desired) and applied shortly before planting.

Irrigation scheduling can involve using a wide range of tools, depending on several circumstances, including the type of irrigation method used. For each type, an "optimum" application range may be most appropriate. With surface methods, for example, water typically is applied more efficiently and evenly when the amount approaches 70 to 120 mm depending on the particular soil, slope, and field geometry (length of run, furrow spacing, border width, etc.). Traditional sprinkler methods may be more suited for applications of ~10 to 50 mm. For MI, amounts in the 5 to 25 mm range might be better, depending on the soil. These "optimum application ranges" will be site and system specific, but a few field trials and routine evaluations

(Merriam and Keller, 1978) can be used to determine the operational parameters needed to achieve the desired irrigation uniformity and efficiency.

The desired irrigation frequency (F, days) is a direct function of application depth and irrigation capacity (flow rate per unit area), and can by computed as

$$F = D_o/(Q*86{,}400) \quad [1]$$

where D_o is "optimum application depth" (mm) and Q is irrigation capacity (L s^{-1} m^{-2}). The 86,400 (a constant) is seconds in a day. Irrigation capacity is determined by the supply rate and the area being irrigated. It is closely aligned with a crop's "peak" irrigation requirement rate (usually expressed in mm d^{-1}, which is equal to Q*86,400). This rate is largely determined by the "peak" ET rate, and is influenced by crop type, the environment, "effective" rainfall, soil type (water holding capacity and depletion permissible without reducing crop yield potential), and irrigation system efficiency.

The peak requirement rate is an irrigation system design parameter, but it influences many aspects of irrigation, including scheduling. It affects irrigation system fixed costs because it determines the pipe sizes needed for that flow rate and variable costs because it affects pumping costs that are a function of the flow rate. Therefore, it is desirable to keep the irrigation capacity (Q) as small as practical and maintain an acceptable level of risk of not being able to meet the desired crop ET rate, but as large as possible to provide the greatest flexibility in irrigation scheduling.

Irrigation timing affects water conservation in two important ways (Martin et al., 1990). One is the earliest date to apply the desired amount without having appreciable application losses (typically runoff and deep percolation). The second is the date for the last irrigation to apply the desired amount without inflicting a significant crop water deficit and "potential" yield loss on the crop. The latter depends on the soil, crop, crop growth stage, and expected or projected ET rate. In this case, the soil profile likely will not be filled to its capacity, thus providing for potential water storage from any rain that might occur. The first depends more directly on the irrigation system and the soil's water content and water holding capacity. The scheduling decision will be subject to weather forecasts (rain and other parameters that affect ET rates).

Irrigation timing decisions can be based on simple pre-season calendars (based on expected or "normal" ET and rainfall rates), checkbook type approaches (manually adding water additions and estimating consumptive use), tracking daily crop water use with computer models of crop ET or growth, or direct sampling of soil or crop water status. The decision needs to incorporate the crop's growth stage and its sensitivity to water deficits at that particular stage. Phene et al. (1990) reviewed many techniques for sensing the crop need for irrigation. Besides determining the need for irrigations, field sampling is critical in evaluating system performance (spotting areas of poor coverage or where system errors and/or malfunctions may have occurred) whether it may be soil or crop water status sensing.

Remote sensing (aerial photography or satellite imagery) is an additional useful irrigation management tool. Good crop or soil sensing along with remote sensing can guide irrigation scheduling models as well. As such, ET modeling and sensing (remote and ground based) should be regarded as complementary management tools and not as individual or mutually exclusive methods for irrigation scheduling.

Conserving water through irrigation management largely rests on the irrigation supply capacity (either the irrigation capacity and/or any legal water use constraints), crop response (yield and/or quality) to irrigation water, and irrigation economics (fixed and variable irrigation costs) (English et al., 1990). Certainly, excessive irrigations that do not contribute to efficient use of water in meeting crop requirements (including any required salinity leaching) should be the first targets for water conservation. Increasing irrigation system efficiency and enhancing irrigation system uniformity should be considered next. All irrigations involve some nonuniformity. Therefore, some areas will receive more water than the mean and others will receive less. Small under irrigations (5 to10%) may not be detectable in most situations and have not affected crop yields in most studies (in some, crop quality concerns occurred).

In many parts of the world, water for irrigation is limited. Crop water needs can be fully met on few irrigated farms in the western part of the Southern High Plains (Musick et al., 1987).

In India, the National Water Commission has based irrigation planning on "50% dependable" water supply (Chitale, 1987). Deficit irrigation practices will often result in crop yields less than the maximum attainable, but it will reduce irrigation water use and enhance crop water use efficiency and improve the capture and use of rainfall. However, soil salinity increases must be carefully monitored and appropriate leaching and reclamation measures must be implemented to protect the soil from salinization in many cases.

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Table 1. Tillage effects on runoff and sediment yield from watersheds planted to corn at Coshocton, Ohio, U.S.A., during a severe storm in July 1969[a].

Tillage	Slope (%)	Rainfall (mm)	Runoff (mm)	Sediment yield (Mg ha^{-1})
Plowed, clean tilled, sloping rows	6.6	140	112	50.7
Plowed, clean tilled, contour rows	5.8	140	58	7.2
No-tillage, contour rows	20.7	129	64	0.07

[a] Adapted from Harrold and Edwards (1972).

Table 2. Effect of soil surface condition (fallow and tillage) on runoff and soil losses from land cropped to corn in Nigeria[a,b].

	Bare fallow		Plowed		No-tillage	
Slope (%)	Runoff (%)	Soil loss (Mg ha^{-1})	Runoff (%)	Soil loss (Mg ha^{-1})	Runoff (%)	Soil loss (Mg ha^{-1})
1	18.8	0.2	8.3	0.04	1.2	0.0007
5	20.2	3.6	8.8	2.16	1.8	0.0007
10	17.5	12.5	8.2	0.39[sic][c]	2.1	0.0047
15	21.5	16.0	13.3	3.92	2.2	0.0015

[a] Adapted from Rockwood and Lal (1974)

[b] Rainfall was 44.2 mm.

[c] Probably an error in original document.

Table 3. Improvements in fallow systems with respect to soil water storage and wheat grain yields at Akron, Colorado, U.S.A.[a].

Years	Tillage during fallow	Fallow water storage (mm)	Fallow water storage (% of precip.)	Wheat yield (Mg ha^{-1})
1916-30	Maximum; plow, harrow (dust mulch)	102	19	1.07
1931-45	Conventional; shallow disk, rod weeder	118	24	1.16
1946-60	Improved conventional; begin stubble mulch in 1957	137	27	1.73
1961-75	Stubble mulch; begin minimum with herbicides in 1969	157	33	2.16
1976-90	Projected estimate; minimum, begin no-tillage in 1983	183	40	2.69

[a] Adapted from Greb (1979).

[b] Based on 14-month fallow, from mid-July to second mid-September.

Table 4. Cropping system and tillage method effects on average water storage efficiency during fallow before grain sorghum and winter wheat crops at Bushland, Texas, U.S.A., 1984-1993[a]

Cropping system and tillage method	Storage efficiency (%)[b]
Fallow before sorghum	
Continuous sorghum — stubble mulch	27.3 (4.1)
Continuous sorghum — no-tillage	32.0 (4.5)
Wheat-sorghum-fallow — stubble mulch	16.5 (2.1)
Wheat-sorghum-fallow — no-tillage	21.0 (2.3)
Fallow before wheat	
Continuous wheat — stubble mulch	13.9 (4.0)
Continuous wheat — no-tillage	19.8 (4.1)
Wheat-fallow — stubble mulch	10.6 (1.8)
Wheat-fallow — no-tillage	11.1 (2.1)
Wheat-sorghum-fallow — stubble mulch	17.0 (2.0)
Wheat-sorghum-fallow — no-tillage	16.8 (2.0)

[a] Adapted from Jones and Popham (1997).

[b] Storage efficiency = soil water storage during fallow as a percentage of fallow-season precipitation. Values in parentheses are the standard error of the mean.

Table 5. Straw mulch effects on average soil water storage during fallow, storage efficiency, dryland grain sorghum yield, and water use efficiency for grain production, Bushland, Texas, U.S.A., 1973-1976[a]

Mulch rate ($Mg\ ha^{-1}$)	Water storage (mm)[b]	Storage effic. (%)[b]	Grain yield ($kg\ ha^{-1}$)	Water use effic. ($kg\ m^{-3}$)[c]
0	72 c[d]	22.6 c	1.78 c	0.56
1	99 b	31.1 b	2.41 b	0.73
2	100 b	31.4 b	2.60 b	0.74
4	116 b	35.6 b	2.98 b	0.84
8	139 a	43.7 a	3.68 a	1.01
12	147 a	46.2 a	3.99 a	1.15

[a] Adapted from Unger (1978).

[b] Water storage determined to 1.8-m depth; precipitation during fallow averaged 318 mm; fallow was 10 to 11 months.

[c] Water use efficiency based on grain produced, growing season rainfall, and soil water content changes during growing season.

[d] Column values followed by the same letter are not significantly different at the 0.05 level (Duncan's multiple range test).