Prospects for High-Frequency Irrigation

Uniform, frequent irrigation optimizes the root environment while drastically reducing water use.

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Supplying water artificially to permit farming in arid regions or to offset droughts in humid regions is an age-old art. Practiced on every continent, irrigation is a crucial input to food production for many nations. Areas in which civilization exists solely because of irrigation lie mainly within two arid belts encircling the globe. In other areas, where ample rain falls annually but in only half the year, irrigation is practiced to make double and even triple cropping possible.

Irrigation alone cannot prevent the spread of famine or near famine that now exists in some developing countries. Only about 14 percent of the world's farmland is irrigated, and even if production from it were doubled it would not be enough. Obviously, efforts to bring into production the undeveloped half of the world's arable land must be accelerated beyond the snail's pace of 0.15 percent per year for the past 20 years (*1*). But the best land is already developed. New gains will be difficult and expensive, regardless of the approach taken.

In many instances, irrigation can play a key role in feeding an expanding population. For example, economists and engineers associated with the Asian Development Bank (*2*) concluded that in many parts of Asia intensively developing irrigation would be much easier and more economical than developing new land. Improvement of irrigation systems will also be necessary on parts of the Indo-Pakistan subcontinent, not only to increase food production for an expanding population, but to preserve the production capacity that already exists. Diversion structures placed on the major rivers of the region in the 1880's deliver irrigation water through main distribution systems to outlets serving 40 to 200 hectares. Responsibility for water courses beyond the main outlets and any provision for drainage are left mainly to the individual farmers (*3*). As a consequence, water management has been poor. Deep percolation on the 10 million hectares irrigated in the Indus Plain, for example, has caused a rise in the water table to within 3 meters of the surface in almost half the area. Waterlogging and salinity are severe on nearly 1 million hectares (*4*).

Irrigation was first developed in level areas near streams that could be easily flooded. Later, dams and canals were built and fields were leveled to extend the area, but the basic method for applying water to fields has changed very little. Surface irrigation imposes two fundamental constraints on irrigation management: (i) it depends on flow over the soil surface to distribute water from a turnout to the field, which requires a minimum depth of water simply to achieve coverage, and (ii) a fixed cost is associated with each application. Both of these constraints make it economically advantageous to decrease the number of irrigations by increasing the time between them. As a consequence, the science of irrigation management has focused on decreasing irrigation frequency by storing as much water as possible in the soil profile during an irrigation and using as much of this as practical before the next.

The recent introduction of pressure irrigation systems that distribute water to all parts of the field through pipes essentially reverses the economic picture. The capital cost of such a system depends largely on pipe size. Pipe size, which is governed by maximum required delivery rates, can be minimized by increasing the duration of each irrigation. Because it costs no more to use a system once it is permanently installed, the best use is almost continuous irrigation during the period of peak water use. This changes the irrigation pattern from one dominated by extraction following a brief period of infiltration to one dominated by infiltration. It also minimizes the importance of physical properties such as the water-holding capacity of the soil as the primary basis for determining which soils are irrigable, making efficient irrigation practical where previously it was not possible.

In this article we consider what the consequences to food production might be if the management alternatives made possible by these new irrigation systems were implemented.

Water in the Physiology of Crops

Water is crucial to the physiological processes of crops. Considering that plant life evolved in an aqueous medium, this is not surprising. For most vascular plants, evolution has consisted primarily of adaptations to maintain an aqueous environment within their leaves even though they are bathed in dry air. Although the total potential [partial specific free energy of water relative to that of pure free liquid water at the same temperature and height and at atmospheric pressure (*5*)] in dry air is typically equivalent to − 1000 bars or less, most plant processes are severely inhibited if leaf water potential drops to − 10 bars (Fig. 1). To maintain the water potential of the leaf above this critical level as water moves in the transpiration stream from the soil to the leaf and from the leaf to the atmosphere, the flow resistance impeding water loss from the leaf must be at least 100 times that in the pathway supplying water to it.

Resistance to water loss from the leaf is greatest at the epidermis. Effectively sealed in most plants by a wax-coated cuticle, the epidermis is perforated by stomata whose openings are highly regulated by the plant. Whenever leaf water potential drops into a critical range, stomata begin to close, preventing excessive loss of water even at the expense of decreased carbon dioxide uptake.

Most physiological processes are affected by the time the plant reaches permanent wilting (Fig. 1). At this point, cell expansion has long since ceased and the tightly closed stomata

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severely restrict carbon dioxide entry as well as water loss. Transpiration rate does not decrease appreciably until leaf water potential approaches the wilting point. On the basis of this observation, irrigation researchers in the early 1930's, working mainly with perennial trees, concluded that crop production was unaffected by soil water stress until the water content of the soil fell to a value near the permanent wilting point. The fact that growth decreases at higher water potentials than does transpiration invalidates such a conclusion. It is now generally accepted that in most crops growth proceeds completely unimpaired, and crop yield is maximal, only when water potential remains high throughout the life of the crop (*6, 7*).

For most crops, keeping plant water potential high results in maximum production per unit area, but does it also result in maximum production per unit of water consumed? If the water content is kept high by increasing irrigation frequency without decreasing the depth of water applied at each irrigation, water is wasted through deep percolation. But disregarding this, do well-watered plants use more water per unit of dry matter produced than plants subjected to some water stress? Because stomata offer a proportionately greater resistance to water vapor than to carbon dioxide, several workers (*8*) hypothesized that increasing stomatal diffusion resistance increases water-use efficiency. In tests of this hypothesis in controlled environments, plants sprayed with chemicals to close their stomata generally showed improved water-use efficiency. However, in controlled environments leaf temperature is kept more or less constant, whereas in the field leaf temperature may rise as stomata close and less radiant energy is dissipated by transpiration. This rise in temperature causes an exponential increase in the vapor pressure gradient from the leaf to the atmosphere, tending to offset the increased stomatal resistance. Taking this factor into account, Cowan and Troughton (*9*) concluded from theoretical arguments that increasing stomatal resistance would decrease water-use efficiency of many crops in the field. Sinclair *et al.* (*10*) recently demonstrated in the field that the management program which prevents plant water stress optimizes water-use efficiency as well as yield for corn.

From the standpoint of dry matter production, either per unit of water used or per unit of land occupied, there seems to be no advantage in permitting crops to undergo water stress. However, except for some forage crops, dry matter production is seldom equivalent to marketable yield. For crops that require water stress to initiate differentiation or maturation of the harvested portion of the plant, programming one or more periods of water stress into the growing season may be essential.

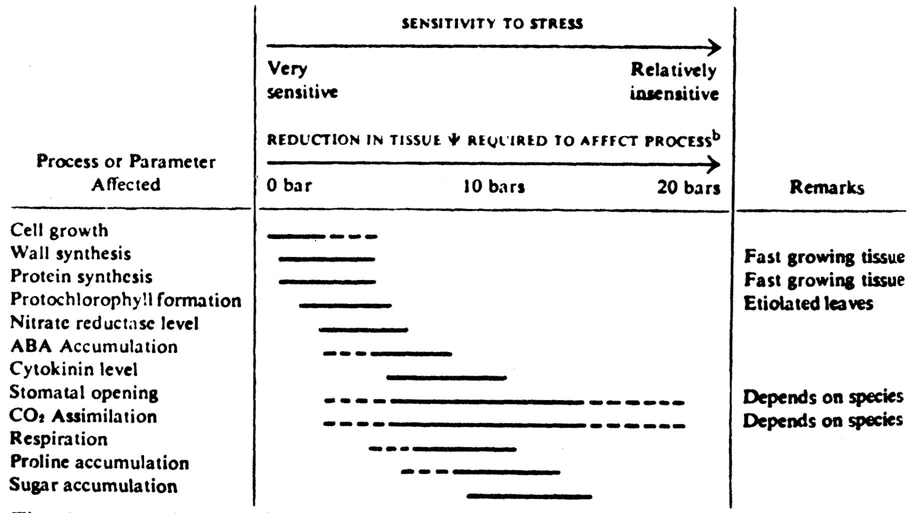

Fig. 1. Generalized sensitivity to water stress of plant processes or parameters. The length of the horizontal lines represents the range of stress levels within which a process first becomes affected. Dashed lines signify deductions based on more tenuous data. The leaf water potential, Ψ, of well-watered plants under mild evaporative demand is used as the reference point. Abbreviation: *ABA*, abscisic acid. [Reproduced with permission from Hsiao (*7*, p. 554)]

It is also important to realize that, regardless of how wet the soil is kept, plants are still subject to water stress during periods of high transpiration as a consequence of increased water potential drop across resistances within them. Leaf water potential normally drops several bars during the daytime, even for plants in a nutrient solution. Midday depression of leaf water potential is greatest where resistance in the pathway supplying water to the leaves is high, for example, as a consequence of a small root system, low soil temperature, or unusually high transpiration. Hoffman and co-workers (*11*) found that plants grown in nutrient solution at low relative humidity had a greater ratio of roots to shoots and a lower average maximum stomatal aperture than plants grown at high relative humidity. Although these morphological adjustments kept the leaf water potential of plants grown at low relative humidity essentially the same as that of plants grown at high relative humidity, total growth was usually considerably less. Others (*12*) have found significant yield responses to mist irrigation in the field.

Results from experiments on the aftereffects of water stress on plant growth (*7*) suggest that periods of decreased leaf water potential during which growth is stopped do not decrease net growth if they are not too long. Assimilates can be stored for several hours before photosynthesis is decreased, and can then be used in accelerated growth when stress is relieved. This is why daily stress that lasts for hours is preferable to less frequent stress that lasts for days.

If yield is to be maximized, irrigation, in addition to keeping the soil wet, must be managed to minimize the osmotic pressure of the soil solution. Although crops differ in salt tolerance (*13*), all grow best near the minimum practical salinities attainable in the field. Some of the principles involved in optimizing irrigation management to minimize soil leaching while keeping the effective soil salinity below levels that significantly reduce yields are discussed in the following sections.

Environment of the Plant Roots

Irrigation should supply water at a sufficient rate to satisfy the evaporative demand and, at the same time, maintain a high matric potential Φ_s and osmotic potential π_s of the soil water (*5*) at the surface of the plant roots. In this section we briefly consider the physical properties of the soil that govern its ability to meet these requirements. At any point in the soil, the balance of mass for the water may be written as

$$d\theta/dt = -\nabla\cdot\mathbf{F} + \lambda \quad (1)$$

where t is the time, θ is the volumetric water content, ∇ is the vector differential operator, **F** is the volumetric flux, and λ is the volumetric rate of uptake by the plant roots. The flux **F** is assumed to be given by Darcy's law

$$\mathbf{F} = -(k/g)\nabla\Phi_s + k\nabla z \quad (2)$$

where k is the hydraulic conductivity, g is the gravitational constant, and z is the vertical coordinate taken positive downward. Nonlinear, hysteretic relationships among the variables describing the flow make the mathematical analysis of movement of water in the root zone interesting but difficult. In general, the potential Φ_s is a function of the history of the water content θ. The plot of Φ_s against θ is called the water retentivity curve (Fig. 2A). The differential water capacity, $d\theta/d\Phi_s$, is a measure of the capacity of the soil to store water at a given potential Φ_s. The conductivity, k, is a function of the water content, θ (Fig. 2B), and hence a function of the history of the potential Φ_s. The relative rate of change of k with respect to the pressure head Φ_s/g, that is, $(1/k)dk/d(\Phi_s/g) = d(\ln k)/d(\Phi_s/g) = \alpha$, which has the units of reciprocal length, is a measure of the relative importance of capillarity and gravity in Eq. 2, and serves as a characteristic length. Values of α range from 0.01 cm^{-1} for fine-textured soils to 0.2 cm^{-1} for coarse-textured soils. Steady matric potential distributions and flow patterns are determined largely by αL, where L is a characteristic length of the flow region such as the rooting depth (*14*) or the spacing between line sources (*15*).

For a particular distribution of the potentials Φ_s and π_s, and a particular evaporative demand, the potentials Φ_p and π_p in the xylem will depend on $d\Phi_s/d\theta$ and k of the soil and on several parameters affecting the transport of water and solutes across the cortex and the endodermis. The convergence of the flow to the roots and the decrease of k with decreasing Φ_s may combine to cause a large decrease of Φ_s between the bulk soil and the root surface, in particular if Φ_s in the bulk soil is low originally (*16*). In fact, the nonlinearity of the problem is such that there is a definite upper limit to the rate at which water can be extracted (*17*).

It is clear, then, that to satisfy the transpirational demand and keep Φ_p sufficiently high, the irrigator should keep the water content high enough that Φ_s and k remain high. A high water content will also reduce the impedance to root penetration (*18*) and enhance the ability of the soil to supply nutrients to the plant roots (*19*). However, the water content should not be too high. The distribution of the gaseous phase in the root zone should allow a sufficiently rapid diffusive supply of oxygen and removal of carbon dioxide by the atmosphere. For adequate aeration, the air-filled pores should form a continuous phase. In most soils the air-filled pores should be at least 10 percent of the total pore space (*20*). Also, if the water content is very high in the lower part of a root zone in a homogeneous soil, then the associated large conductivity, k, may induce excessive drainage of water from the root zone.

Uptake of water by the plant roots is also affected by the osmotic pressure of the soil solution. The flow from the root surface to the xylem can be treated as a reverse osmosis (hyperfiltration) process, if the active uptake of solutes is taken into account. A theory describing the hydraulic and osmotic transport of water and the diffusive, convective, and active transport of solutes across root membranes has been presented in some detail (*21*). The theory predicts the dependence of the ratio of the osmotic potentials of the nutrient and xylem solutions and of the solute flux on the rate of water uptake. It also predicts a nonlinear relationship between the flux of water and the decrease of matric potential across the root membranes. The results are in good qualitative agreement with a variety of observations on simultaneous uptake of water and solutes. In research on uptake of water from saline soils it has often been assumed that, to a first approximation, the roots exclude virtually all salts, so that the osmotic potential of the soil solution is fully effective in reducing the rate of water uptake. This means that the irrigator should not only keep Φ_s high, he should also keep π_s high in a root zone of sufficient extent.

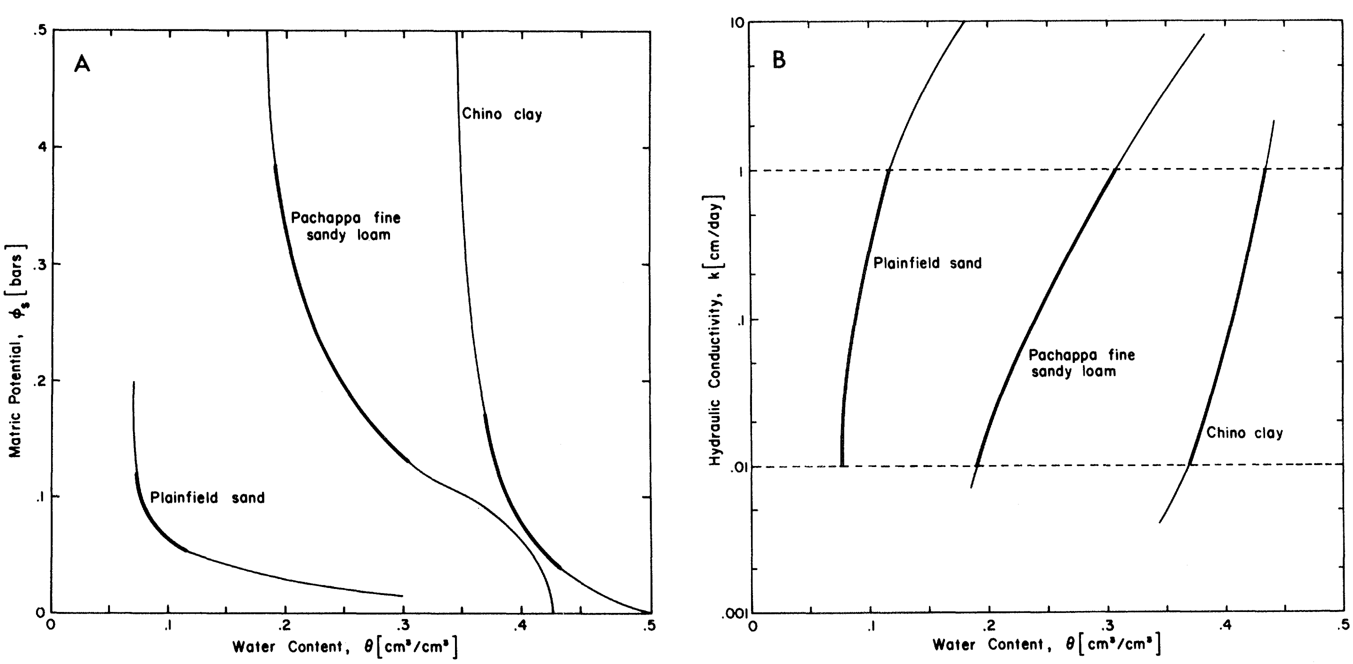

Fig. 2. Water retentivity (A) and hydraulic conductivity (B) curves for three soils, based on data of Gardner and Miklich (*43*) and Black *et al.* (*44*). The heavy portion of each curve corresponds to hydraulic conductivities between 0.01 and 1 cm/day, the range of interest under high-frequency irrigation.

Water and Salt Balances of the Root Zone

For the root zone as a whole, the balance of mass for the water may be written as

$$dS/dt = (R + U + I) - (E + T + D) \quad (3)$$

where S is the total amount of water stored in the root zone at any instant, R is the rate of supply from rainfall, U is the rate of upward flow into the root zone, I is the rate of irrigation, E is the rate of evaporation from the soil surface, T is the rate of transpiration (equal to the integral of λ over the entire root zone), and D is the rate of drainage out of the root zone.

Let us consider first the demands E and T. Figure 3 shows measured evapotranspiration for forage crops as a function of the time of the year for various locations, representing a wide range of climates. Potential evapotranspiration (PET) from a soil surface is primarily a function of the energy supplied to the surface by solar radiation and, usually to lesser extent, advection from the surroundings. Because PET is primarily a function of solar radiation, it varies little from year to year, particularly in arid regions. The actual evapotranspiration, $E + T$, will be a certain fraction of PET, depending on the density and distribution of the roots, the distribution of Φ_s and π_s in the root zone, the aerodynamic properties of the crop canopy, and PET itself. The relative importance of E and T depends on the same factors, in particular on the wetness of the soil surface and on the area and distribution of plant leaves (*22*). As will be seen later, the third demand, D, is dictated by the need to remove salts from the root zone.

The supply R from rainfall, unlike PET, is erratic in most climates. This may put a heavy burden on the capacity of the soil to absorb and store water in the root zone (see Fig. 2A). In particular, sandy soils are at a distinct disadvantage with respect to storage capacity and, as a result, require supplemental irrigation even in humid regions. In such soils high-frequency irrigation systems make it possible to keep Φ_s high and at the same time leave sufficient capacity to store intermittent rain (*23*). Also, irrigation at rates less than the evapotranspiration rate, even when there is still a significant amount of water stored in the profile, may be beneficial. It will keep Φ_s sufficiently high near the soil surface to allow Φ_p to rise into the range for maximum growth each night. The net result may be use of more of the water stored at greater depths in the soil profile. Use of the same fraction of the stored water without supplemental irrigation would seriously reduce yields. In other words, considerably more stored water can be used effectively if it is withdrawn at a controlled rate rather than at a rate necessary to supply total crop needs.

In humid regions with groundwater of good quality, the supply U associated with upward flow from a water table is often important (*24*). However, if the groundwater is saline, such upward flow represents a serious salinity hazard and should be restricted to water stored in the soil profile by extra irrigation or by rainfall.

The irrigation system should deliver water at rates dictated by E, T, and D, insofar as the water is not supplied by R or U. The delivery should be uniform over the field and at all times keep Φ_s high. Flood and furrow irrigation often deliver the water nonuniformly, even if the land is graded carefully. The infiltrability of the soil—that is, the flux through the surface which the soil can maintain with its surface covered with water—is too variable from place to place (*25*) and, except with short furrows, pump back facilities, or small basins, the overland flow cannot be controlled sufficiently to allow equal time intervals for infiltration at all points. Also, with flood and furrow irrigation one cannot simultaneously meet the requirements of keeping D low and Φ_s high.

To get some further insight into the interaction between supplies and demands, let us consider a hypothetical situation with $dS/dt = 0$, $R = 0$, $U = 0$, and I, E, T, and D constant—in other words, a steady flow system without supplies from rainfall and upward flow. Within the root zone, the flux decreases from $I - E$ at the soil surface to $D = LI$ in the region below the root zone, where L is the leaching fraction (*26*). Equations 1 and 2 imply that within the root zone Φ_s, and hence k and θ, will increase toward the soil surface. Assuming that the reciprocal length α is a constant within the range of values of Φ_s of interest and that the uptake distribution can be represented by $\lambda = (T/\delta)\exp(-z/\delta)$, where δ can be interpreted as a rooting depth, one can show that the distribution of k within the root zone is given by (*14*)

$$k = [L + \frac{T}{E+T}(1 - L)\frac{\alpha\delta}{1 + \alpha\delta}\exp(-z/\delta)]I \quad (4)$$

If k is given by an empirical expression of the form $k = a\theta^b$ then

$$\theta = (k/a)^{1/b} \quad (5)$$

Substitution of Eq. 4 into Eq. 5 gives the water content profile. Equation 4 shows that for $\alpha = 0.05$ cm^{-1}, $\delta = 10$ cm, $E = 0$, and $L = 0.1$, k will decrease by a factor of 4 between the soil surface and the bottom of the root zone. The corresponding decrease of Φ_s/g would be 27.8 cm. For $b = 10$, the ratio of the water content at the soil surface to the water content at the bottom of the root zone would be 1.15. During periods of high evapotranspiration the

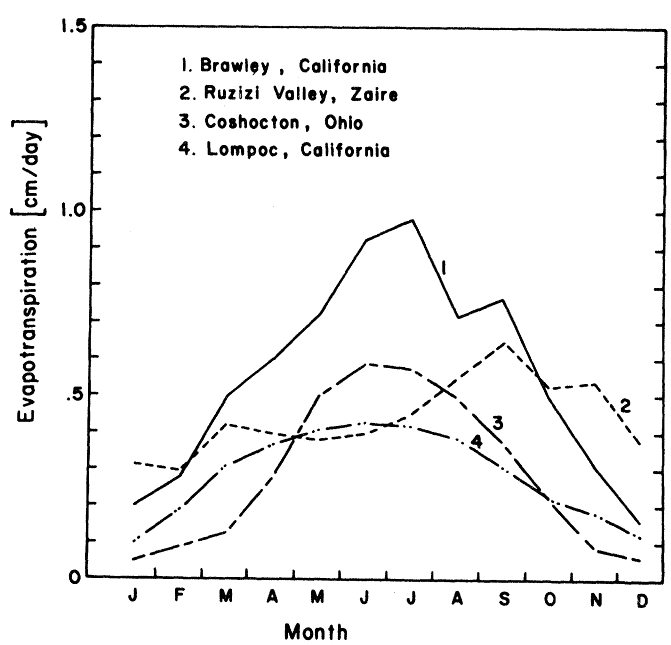

Fig. 3. Evapotranspiration as a function of time of year for four locations. [Modified from Jensen (*45*)]

rate of irrigation will be large and, according to Eq. 4, the conductivity k will everywhere be correspondingly larger. Equation 4 also shows that the larger E/T is, the smaller is the range of values of k between the soil surface and the bottom of the root zone. Under high-frequency irrigation, k in the root zone will always be in the range of 0.01 to 1 cm/day. The corresponding ranges of Φ_s and θ vary widely for different soils (Fig. 2).

The constant rate of drainage in the above example contrasts sharply with the high variability under low-frequency irrigation. Typically, the rate of drainage satisfies (*27*)

$$D = pS^q \qquad (6)$$

where q is about 7 to 9. Calculations based on Eq. 6 show that the rate of drainage may initially be large after an irrigation, but will later decline to very small values. With low-frequency irrigation, one attempts to compensate for the periodically high drainage rates by having the plants dry the soil profile between irrigations. Only with high-frequency irrigation is it possible to maintain a high water content in the root zone and at the same time keep D low.

Assuming that the roots exclude all the salts introduced with the irrigation water, that no salt dissolves or precipitates, and that the salts are transported by convection only, the steady distribution of salts associated with the uptake distribution introduced above will be given by (*14, 28*)

$$c/c_0 = [L + (1 - L - E/I)\exp(-z/\delta)]^{-1} \qquad (7)$$

where c_0 is the concentration of salts in the irrigation water. The values of c/c_0 range from $(1 - E/I)^{-1}$ at the soil surface to L at the bottom of the root zone. When L is small, much of the salt can precipitate in the lower part of the root zone, if irrigation water is high in gypsum and lime. Keeping L as low as possible will minimize both the amount of water and the amount of salt contributed to groundwater and rivers. An important aspect of high-frequency irrigation is that even with a low leaching fraction the osmotic pressure of the soil solution will remain low near the water source. Making the same assumptions that led to Eq. 7, one can show that the uptake weighted mean salinity, σ, for the root zone as a whole is given by

$$\sigma = [\ln(1/L)/(1 - L)]c_0 \qquad (8)$$

independent of the uptake distribution (*28*). According to Eq. 8 σ is proportional to the salinity of the irrigation water. At $L = 0.1$ the value of σ is still only about $2.5c_0$, whereas the salinity of the water leaving the bottom of the root zone is $10c_0$. At low leaching fractions, precipitation of lime and gypsum will reduce σ below the level given by Eq. 8.

With both high- and low-frequency irrigation, plant roots must concentrate the soil solution leaving the root zone to a salinity that is consistent with the leaching fraction. With high-frequency irrigation, as we have seen, Φ_s and π_s decrease with depth, but are relatively constant in time. This means that, although plant water potential must decrease at least to the drainage water potential for periods during high transpiration, it can approach the high water potential near the soil surface for periods when transpiration is low. With low-frequency irrigation, on the other hand, Φ_s and π_s are uniformly high to the depth of water penetration after irrigation, but their sum at all depths tends to be the same at the end of the extraction phase of the irrigation cycle (*29*), reaching the potential of the drainage water at the end of this phase. In other words, for low-frequency irrigation with the same average supplies and demands used in the example considered earlier, σ ranges from c_0 to $10c_0$ during the irrigation cycle, in contrast to the relatively constant value of $2.5c_0$ for high-frequency irrigation. Because the leaf water potential can never rise above the soil water potential with low-frequency irrigation, leaf water potential can be below that permitting growth for an extended period of time both day and night.

Scheduling and Allocation of Water

The physiological, soil physical, and climatological principles outlined above provide a basis for irrigation management. Unfortunately, the irrigator usually must rely on inadequate data. In this section we discuss two studies of scheduling for a specific locality and crop and one study of allocation of water from a desalination plant.

Lewin (*30*) used a water balance for the top 90 cm of the soil profile with inputs from rainfall and irrigation, drainage of any water in excess of field capacity, and a linear relationship between evapotranspiration and storage, S. He accounted for PET and a crop factor by letting the coefficients have different values for each month of the growing season. He further assumed that the decrease in yield of the winter wheat should be related to the number of days when the soil water potential was less than -1.2 bars. Similar "stress day" concepts have been used in many other studies. Lewin found a correlation of -0.864 between calculated number of stress days and percentage of potential yield. Taking 48 years of recorded daily rainfall, he used the model to estimate the yield probability distribution for no irrigation, one irrigation of 150 mm, or two irrigations of 150 mm. The results showed that the first irrigation was more effective, particularly in dry years. This suggests that, if the water supply is limited but land is plentiful, irrigations on a large area may be profitable. Lewin estimated the maximum available soil water in the top 90 cm of the profile to be 140 mm. Therefore, part of the rain falling immediately after an irrigation of 150 mm will be lost as drainage. High-frequency irrigation will allow more effective use of the water present in storage at the beginning of the cropping season and of subsequent rainfall.

Fischbach and co-workers (*31*) developed a method for scheduling irrigations with the primary objective of gradually depleting the available soil water during the growing season. They estimated evapotranspiration on the basis of weather records and crop coefficients, using the Penman equation (*32*) for PET. Using rainfall records, they scheduled irrigations to maintain the storage within limits that were allowed to decrease as the irrigation season progressed. They tried to achieve the maximum value of S early in the growing season, started to irrigate when the deficit exceeded the irrigation application by 2 to 5 cm, and let the deficit gradually increase to about 60 or 80 percent of the capacity. A reconstructed soil water history for sugar beets at Alliance, Nebraska, involved a water budget of 14 cm from the soil, 27 cm from rain, and 25 cm from irrigation. An irrigation system with a daily water capacity of 0.43 cm was required. Together with climatic records, the model could be used to determine the optimum capacity of a center pivot system. High-frequency irrigation goes a long way toward meeting the conflicting requirements of maintaining a high plant water potential and a sufficient capacity to store erratic rainfall.

The scheduling method just discussed attempts, for a given piece of land, to optimize the amount of irrigation water required at any one time during the growing season and to minimize the leaching of nutrients from the profile. Different criteria have to be used if the supply of water is fixed. For example, the supply from a desalination plant would be more or less the same all year. The optimal use of the output of 10^9 gallons ($\sim 4 \times 10^9$ liters) per day from a desalination plant was studied at Oak Ridge National Laboratory under the auspices of the Atomic Energy Commission (*33*). The hypothetical site of the project was El Arish, United Arab Republic, which has a coastal desert climate (10 cm of rainfall during winter) suitable for two to three crops during the year. One important conclusion of the study was that, even if the farming area was reduced from 122,000 ha in the winter to 87,000 ha in the summer, about 20 percent of the total amount of water had to be pumped into and out of storage. Making maximum use of soil storage would reduce the need for storage in aquifers and surface reservoirs.

Irrigation Systems

Systems for high-frequency irrigation must be capable of distributing any desired quantity of water directly and uniformly to each plant. This means that the number of water emitters required per unit crop area varies with plant density.

Water can be distributed by closed conduits or open ditches (as long as they do not leak and flow can be accurately measured), or even carried by hand. The key is that, if a measured quantity of water is supplied to each plant at a rate less than the soil infiltrability, soil variability does not enter as a factor affecting the uniformity of application. By contrast, the quantity of water infiltrating at each plant with systems that permit overland flow always depends on soil infiltrability even if the time available for infiltration is everywhere the same. Systems meeting the essential requirements for high-frequency irrigation range from solid-set or traveling sprinkler, to drip or trickle (applied either at or below the soil surface), to small basins that are periodically filled with a measured quantity of water. Sprinkler and drip systems usually require a sizable capital investment for the pipe or tubing used in the distribution system. However, small basins can be filled by flow through lined ditches or, as in one reported case (*34*), even by hand carrying.

Each irrigation system has specific advantages and disadvantages that are well documented in standard references (*35*). Generally, small basins are practical only for sparsely planted crops, such as in orchards. Drip irrigation is appropriate for orchards and for some widely spaced or valuable row crops, but it is usually too expensive for more densely planted crops. A relatively small number of sprinklers can cover the entire surface area, and they are therefore not limited by the density of the crop. But wind causes serious distortion of the water distribution pattern, and in some cases solutes left on the leaves cause serious damage. For both solid-set sprinkler systems and small basin systems, the flow rates required to achieve uniform distribution are usually greater than the maximum evapotranspiration. As a consequence, such systems are usually operated intermittently. For the same number of distribution lines, therefore, such systems require larger pipes and are initially more expensive than drip irrigation systems, which are usually designed to operate nearly continuously during peak evapotranspiration. However, the small-diameter orifices of drippers, required to control their flow at such low rates, clog easily. Systems that move during application or between irrigations, such as the popular center pivot and side roll sprinkler systems, use the time when solid-set systems would normally not be operating to irrigate other areas. This reduces the number of lateral sprinkler lines required. Subsurface irrigation, a variation of drip irrigation in which the emitters are buried below the soil surface, is designed to decrease water loss by evaporation. Experience so far indicates that the uncertainty about whether the emitters are clogged, the increased flow required to germinate seeds, and the accumulation of salt at the soil surface with use of saline water in arid climates outweigh any advantage of water saving. Before crops reach the closed canopy stage, irrigation methods that wet the least area of soil will tend to be most efficient. After the canopy closes, the difference vanishes. But this difference in water saving between various high-frequency irrigation methods is small compared to the decrease in deep percolation made possible by converting from low- to high-frequency irrigation.

Implications

We do not wish to imply that surface irrigation should immediately be replaced by systems that permit frequent, light applications of water. But we do intend to leave the impression that such systems are more than just another labor-saving gimmick that has merit solely for capital intensive economies. Although nations experiencing food shortages usually lack capital, they also lack other things. Constraints exist in the form of land, water, and fertilizer shortages. Capital is required to supply or develop these resources, or alternatively, to import food. Drainage to arrest the alarming increase of salt-affected soils resulting from inefficient irrigation is also expensive. In short, the inexpensive options have already been exercised.

Langley (*36*) has pointed out that the recent dominance of automatic sprinkler irrigation over surface irrigation in new projects within the United States is primarily a consequence of the substitution of power to pressurize the water for automatic irrigation for labor to distribute it by surface means. The cost of purchasing and maintaining a self-propelled sprinkler system, for example, is approximately the same as the cost of leveling, developing, and maintaining land for surface irrigation. Since the public sector of the economy pays part of the cost of water, the 50 percent saving of water is not the primary economic factor (*4*). If agriculture had to pay the true cost of water, according to Seckler *et al.* (*37*), the reduction in water cost alone would cause a wholesale conversion to pressurized irrigation systems. These authors cite additional benefits accruing from reducing or eliminating the need for drainage, reducing the energy required for land preparation, and increasing yields by an average of 15 percent.

Savings in soluble fertilizers with systems that meter water precisely to plants regardless of topography or soil properties can also be significant. For example, with a mixture of furrow and intermittent sprinkler irrigation, about half of the 140 kg of nitrogen per hectare applied to Valencia oranges at Riverside, California, was collected in drainage from the watershed (*38*). Assuming that the energy required to manufacture nitrogen fertilizer is approximately 9 kilowatt-hours per kilogram (*39*), irrigation that conserved this nitrogen would save 630 kilowatt-hours per hectare, excluding the energy required for transportation and distribution of the fertilizer. Valencia oranges grown on sandy soils near Yuma, Arizona, with flood irrigation require approximately three times more nitrogen than those at Riverside (*40*). Assuming that the extra nitrogen applied is not used, this represents an extra energy expenditure of about 3000 kwh/ha simply to manufacture the wasted nitrogen. By comparison, the energy required to provide 3.5 atmospheres of pressure to distribute a meter depth of water with a pressure system is also approximately 3000 kwh/ha (*41*). The energy used in manufacturing the wasted nitrogen alone is sufficient to pressurize the water needed for irrigation.

Thus, as we face some important decisions on where money and energy will be spent to produce food, we should not overlook the possibilities for conserving and making most effective use of our water, land, and fertilizer resources by using high-frequency irrigation (*42*).

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