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OF
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chapter 15

IRRIGATION FOR HUMID AREAS

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15.1 INTRODUCTION

15.1.1 Definition of Humid Areas

Irrigation in humid areas is, of course, governed by the same principles and technologies as in more arid areas, but differences in climate, soils, and prevalent crop culture combine to alter the design and management of irrigation systems in many areas. Insofar as possible, discussion in this chapter will not repeat that of other chapters in this monograph; rather it will refer the reader to pertinent sections and concentrate on differences between irrigation in humid areas and the general case.

Climate classification schemes differ in their definition of a humid area. For instance, both Köppen (Köppen, 1931; Köppen and Geiger, 1930) and Koeppe (Koeppe and DeLong, 1958) group the area in the U.S. east of the Mississippi River into a single humid temperate category. On the other hand, Thornthwaite (1948) distinguished between the southeastern Coastal Plain and the Ohio and upper Mississippi River basins because of the difference in evaporative demand. More complex schemes might consider growing season conditions rather than annual climate, which might be more useful for irrigation management. (Irrigation water supply must still consider the annual case.) When only growing season conditions are considered, the area of the southeastern U.S. can be compared to, for example, the Sud-Sahel–both are sandy, flat, and depend upon summertime thunderstorms for ongoing water supplies (D.E. Linvill, 1989, personal communication).

It is not the intent here to argue the merits of these systems; climates change spatially in a continuous rather than discrete fashion, and vary temporally to the extent that a wet year in a subhumid zone is often more humid than a dry year in a humid zone. For this chapter, humid regions will be defined generally as those areas with normal annual rainfall approaching or exceeding annual evapotranspiration (E_t).

Climate of the earth according to Köppen (1931) includes several categories that are humid, at least during the growing season. A listing of these categories provides an indication of their geographic extent worldwide. The warmest sub-category of the Marine Humid Mesothermal Climate (Cfa) includes southeastern and south central North America, southeastern South America including Uraguay and parts of Argentina and Brazil, southeastern South Africa, southeastern and central China, southern Japan, and the eastern band of Australia. A slightly cooler category (Cfb) includes most of western Europe, New Zealand, extreme western Canada, and Chile. More information on these climates in Hungary has been compiled by F. Ligetvari (personal communication, 1989). The Short Summer Humid Microthermal Climate (Dfa, Dfb) lies north of Cfa in North America, ranging into Canada, and includes most of eastern Europe, southern USSR, and northern Japan.

The tropical Monsoon Climate (Cw) includes parts of southeastern Asia, some area of south central Africa, and higher elevations of tropical areas of North America and South America. The Savannah Climate (Aw) ranges from 5° to 20° north and south latitude worldwide with significant extents in South America, Africa, southern Asia, and northern Australia. The Tropical Rain Forest Climate (Af, Am) is located in an equatorial band, mostly ±5° latitude in continental areas and ranging up to ±20° latitude in coastal locations. Discussion in this chapter will be directed toward warm, humid areas because the predominant requirement for irrigation exists there.

15.1.2 Description of Humid Areas

Aside from the obvious difference in rainfall, climate in humid regions may be unique in several other ways, many of which are caused by generally higher humidity associated with more available water. Cloudiness reduces total solar irradiance, and the cloud type, typically cumulus, causes high variability in irradiance on a short time scale. Dew forms frequently, and wet leaf conditions may continue for several hours after sunrise. July climatic conditions in the southeastern U.S., an example of a warm humid area, include mean temperatures of 27-30° C, mean daily irradiance of 20-25 MJ/(m^2.d), mean wind of 10-15 km/h, and mean relative humidity of 75-80% (U.S. Dept. of Commerce, 1968). These contrast to conditions at similar latitudes in the Great Plains and Southwest by being slightly cooler, with less wind, and more humidity. One further climatic characteristic of the southeastern U.S. is the mean freeze-free period of >210 days, which allows long-season cultivars and double cropping of several crops. The transition into and out of the growing season is poorly defined. A significant period in both spring and fall has days warm enough to cause considerable crop growth but significant likelihood of nighttime frost or freeze. These combinations of length and vague limits to the growing season complicate water management for both frost/freeze protection and multiple cropping.

These conditions, integrated by the energy balance, may present a picture of the growing crop that is far different from that obtained in arid zones. High humidity and low wind speeds often result in crop temperatures above the air temperature until late in the day. This may affect the interpretation of the crop water stress index (CWSI), which was developed under conditions much more arid. In fact, few summer days in the southeastern U.S. will have entirely clear skies for an hour either side of solar noon, which is precisely the condition in which nearly all published CWSI data were obtained.

Soils in humid regions vary across the total range of textural classes in much the same manner as other regions. Spatial uniformity of soil properties can be very poor, particularly in areas where topography changes within short distances, as in the southeastern U.S. Poor soil spatial uniformity, particularly for soil properties such as water storage capacity, severely complicates irrigation management. In many cases, soil properties change drastically within the area covered by a small center pivot system. The landscape is extremely variable, ranging from wet, low-lying areas with persistent high water tables to relatively high elevations, with steep slopes and little groundwater at shallow depths. These variations result from the combined effects of geology, topography, and climate. Soil variability and small cropped areas bounded by trees combine to cause extremely variable soil water storage and E_t rates within the same field.

Generally, pests such as insects, nematodes, fungal and bacterial pathogens, and weeds are more plentiful in humid regions. Increased rainfall supports more plant biomass, and mild winter temperatures allow a diversity of living vegetation to exist year-round, both on cropped and border areas. In addition to exacerbating weed problems, the living vegetation serves as primary and secondary hosts of insects, nematodes, and diseases. In much of the region, the soil does not freeze significantly, and winter is a time of moist soil conditions. Thus, while freezing or desiccation may reduce pathogen populations in other regions, pathogens are supported over winter in humid areas. Control of selective plant species that serve as host for insect or disease pests may be possible in arid and semi-arid regions. Rapid and abundant vegetative growth and prevalence of non-cropped borders, even in prime agricultural areas, make this difficult in humid regions. Existence of diseases associated with high humidity, wet plant surfaces, and periods of wet soil conditions generally reduce the potential number of crops that can be grown in humid areas as compared to arid areas.

15.1.3 Description of Water Supplies

Water supplies for irrigation in humid areas generally are not different from those in other areas except that surface supplies assume a more dominant role because high annual rainfall increases their extent and reliability. Surface supplies consist primarily of ponds and reservoirs constructed on the farm, streams flowing through the farm (either with or without structures to control the storage volume), and large lakes near the farm that were developed for other purposes, such as flood control or power generation. Some surface supplies are not very reliable, particularly during prolonged periods of low rainfall (1-3 years) or severe drought following low rainfall during a winter season. For this reason, farmers often use groundwater. In some humid areas, such as parts of the southeastern U.S., adequate supplies of water are available from aquifers at multiple depths at a single location. In other cases, low-yielding wells are used to fill small reservoirs and are operated over an extended duty cycle in relation to the irrigation system requirements. A relatively new concept in water supply is the use of structures to control the water level in the stream, thus storing runoff both in the stream and in the soil profile on either side of the stream for several weeks, possibly months (Figure 15.1) (Doty et al., 1987). If the water table is maintained 0.6 to 1.0 m below the soil surface, crops can obtain water directly from the water table. As water is pumped from the stream for irrigation, more water flows through the soil profile and into the stream to replace it. This applies to small streams in relatively flat areas with soils having a high storage capacity and a high hydraulic conductivity at depths of 3 to 8 m. Advantages of this system include increased storage of runoff from periods of excess rainfall, more efficient use of land when water is stored under a growing crop instead of in impoundments, reduction in water delivery costs because the water source is near the point of use, and lower equipment and energy requirements than when pumping from a deep well.

A major difference between irrigation water supplies in humid and arid areas is that humid-area water supplies are more often developed on-site (by the land owner, for a specific purpose) at the time of irrigation system installation, but arid-area supplies are most often developed in large projects, often by a government or a water management district. This can cause problems in humid areas because irrigation systems are often designed to provide irrigation water

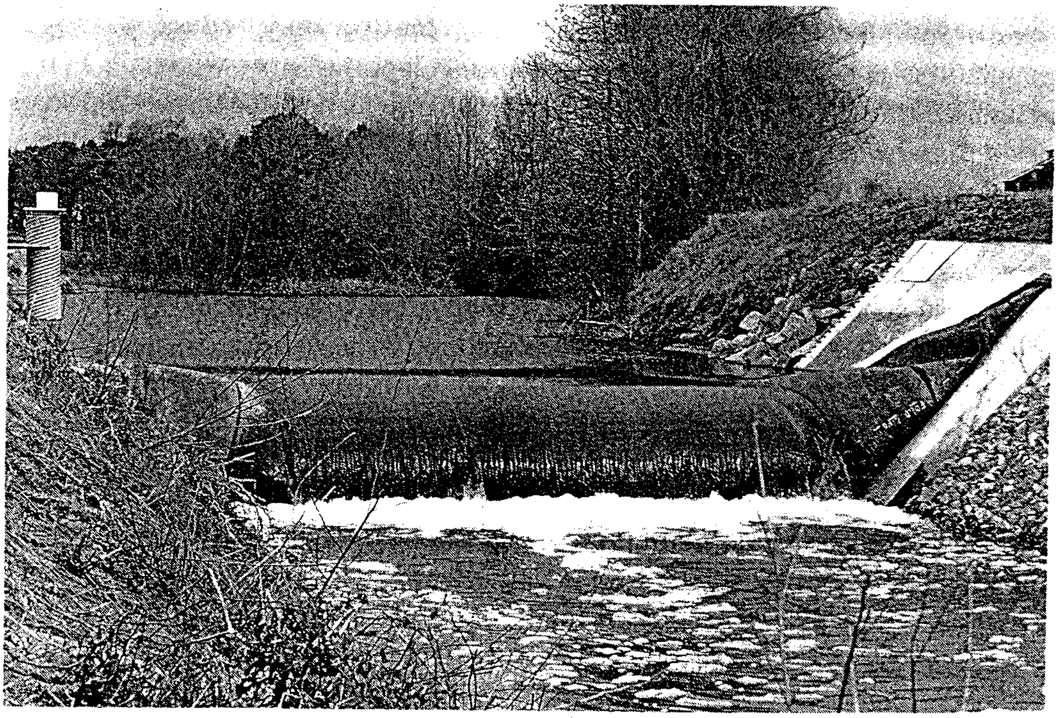

Figure 15.1. Inflatible structure for controlling stream level in Edgecome County, NC. (Photo courtesy of USDA-ARS, Florence, SC.)

to supplement rainfall, not to provide the total crop water requirement. Consequently, during extreme drought, water supplies may be inadequate.

Groundwater supplies in some humid areas are generally reliable for irrigation purposes; however, water levels in some aquifers in the southeastern U.S. are declining rapidly (U.S. Geological Survey, 1985). In most states of the eastern U.S., water laws are not as clearly defined as in arid areas. As competition for groundwater in these high-use areas increases, some users will be either limited or prohibited from using the water supply. Industry, municipalities, and agriculture are the principle competitors for groundwater. With poorly defined water rights, agriculture often is not in a strong competitive position, particularly against municipalities.

Quality of irrigation water supplies in humid areas is usually good to excellent; however, the quality and chemical content of water will vary considerably from site to site (U.S. Geological Survey, 1988). Quality of surface water supplies is dependent upon the source of runoff because most of these supplies are dependent upon rainfall (U.S. Geological Survey, 1986). The cause for deteriorated quality in either surface water or groundwater supplies is usually some form of chemical contamination, which has been caused by both point and non-point sources. There have been a few isolated cases in which groundwater supplies were extremely corrosive to the metal parts in irrigation systems and lime injection was required to raise the water pH. Saline water is a problem in coastal humid areas for groundwater supplies where saltwater intrusion becomes important and for surface water supplies that are in contact with ocean waters. In the latter case, winds can cause saline water conditions for several kilometers inland.

15.1.4 Institutional or Regulatory Incentives or Deterrents

There are a number of rules and regulations that govern the use of water for irrigation and that potentially can affect the growth of irrigation. In much of the eastern U.S., the Doctrine of Riparian Rights covers the use of stream flow for irrigation. This doctrine follows the theory of reasonable use with the fundamental guideline being that a given water use must be compatible with other uses relying on the same source. Under the reasonable use rule, a riparian owner whose use is not adversely affected by a reduction in stream flow has no basis for a legal action.

Some states now interpret the riparian rights doctrine to include diffuse surface water that is flowing across the ground surface prior to reaching a defined channel. Much of this water is the source of recharge for the large number of ponds that are located in the southeastern U.S. Several states in the eastern U.S. do not recognize the Doctrine of Riparian Rights, but instead use a modified form of Prior Appropriation or some other type of priority or permit system to govern the use of irrigation water.

For many years, there were no restrictions on use of groundwater, but in recent years, several states have instituted a well permit system or restrictions on use of groundwater. For example, North Carolina has a capacity use system that covers both groundwater and surface water, including streams, lakes, and ponds. This system, where applicable, requires permits and regular reporting of water use for irrigation. Many states also have a law on dam safety: dams above a certain height and ponds larger than a specified capacity have to be approved by state regulatory agencies and the design and construction supervised by a professional engineer.

As irrigated area increases, there will be increasing competition for water and more regulation and control. During the drought of 1988, low stream flow resulted in restrictions being placed on irrigation from streams in Mississippi. Restrictions will probably be more severe in densely populated, industrialized humid areas than in less-developed humid areas because municipal and industrial water requirements will normally have a higher priority than agricultural water requirements in those areas.

Other concerns related to irrigation include non-point source pollution, downstream effects, and wetland legislation. Some states in the semi-arid areas consider runoff from irrigated fields to be point source pollution. Excess water can move pesticides and nutrients into groundwater by percolation and into surface water by runoff. Concern is increasing about this non-point source pollution, which can occur both during irrigation and rainfall. Pesticide and nutrient application rates are often increased under irrigation. This increases the possibility of non-point source pollution, especially where irrigation application rates exceed soil infiltration rates.

Where these materials reach streams, there can be adverse effects downstream. There is also the concern for water quality degradation where sediments move off the site. Another concern downstream about water withdrawals for irrigation is the effect of reduced flow on aquatic life in the stream and recreational use of the stream.

The 1985 U.S. Farm Bill, which virtually eliminated the clearing of wetlands for the production of annual crops, could have some effect on irrigation development. Most subirrigation and controlled drainage systems that have been installed in the 1980s have been installed on somewhat-poorly to poorly drained soils that, at one time, might have been considered wetlands under present definitions. Growers can probably continue to add subirrigation and controlled drainage systems, but there will be little conversion of wetlands to crop land.

Another concern is the development of water supplies for irrigation. Often, to develop a surface water supply, it is necessary to construct a dam or excavate a pond or ditch in wetlands (and dispense of spoil material), or to install a pipeline across wetlands from a stream. A number of state and federal laws now govern what can legally be done in wetlands. One can only speculate what new environmental legislation might be passed in the future.

15.2 IMPORTANCE OF ENERGY AND WATER CONSERVATION

15.2.1 Implications of Energy and Water Conservation

Within the broad objective of achieving economic sustainability, agricultural managers manipulate costs to obtain maximum profit. In enterprises such as agriculture, many unquantifiable and even unknown costs exist, such as those associated with declining water supplies and quality, future regulatory actions, long-term effects of chemical residues, etc. Given the uncertainties of the costs and benefits of individual decisions, managers concentrate on manipulating controllable costs. For irrigated agriculture, one important such cost is for water, both initial development and continuing delivery. Once the water source has been developed, the primary operating cost is for energy to deliver the water. In contrast to arid areas whose water supplies are generally developed on a large scale and are often subsidized, water supplies in humid areas are developed primarily by individual land owners. Conserving water and energy while maintaining an economic yield is one area that has received considerable attention.

While it is difficult to provide a widely accepted definition of conservation, particularly as it relates to water, in this section conservation is defined as the judicious use of a resource such as energy and water. This is particularly appropriate for humid areas because judicious use most often means reduction in use of either water or energy or both, primarily through better irrigation scheduling and more effective use of rainfall. However, there are cases where other inputs such as capital or labor may be substituted for energy or water, but these choices are made most often in the design rather than management phase.

While water supplies in humid areas have often been considered plentiful relative to arid areas, declining groundwater levels and depleted surface storage during extended drought periods in the past decade have demonstrated the finite extent of these supplies. Consequently, public concern for the adequacy of water supplies in the southeastern U.S. has greatly increased with the droughts of the 1980s. The need to control the use of water by all sectors of society is gradually being recognized, certainly by public officials responsible for protection and utilization of this resource. Conservation of water in the southeastern U.S. varies widely. In Florida, water management districts and state regulations control surface and groundwater usage through permitting and distribution systems. In other states of this region, on-farm surface and groundwater withdrawals for irrigation require neither permits nor measurement. Contrary to states like Florida, where conservation is practiced under several regulatory constraints, conservation of the water resource in these other states is left to the discretion of the individual farm operators.

Generally, both surface water supplies and groundwater aquifers in humid regions are renewable on an annual basis. In areas of concentrated municipal, industrial, and/or agricultural withdrawals, groundwater levels have declined over several years. When annual withdrawals consistently exceed annual replenishment in the aquifer recharge zones, or when aquifer transmissivity is too low to annually replenish these zones, water levels fall. Increased pumping costs gradually become limits to economic use of water for irrigation, or competition between users results in restrictions on use, as seen in the Potomac aquifer in Virginia and North Carolina and the Clayton aquifer in Georgia (U.S. Geological Survey, 1985).

Because of these pumping requirements, energy must be considered in irrigation management. Significant changes in both design and management of irrigation systems resulted from the rapid escalation in unit energy costs beginning in the 1970s. Total energy cost became a major factor in determining the benefit of irrigation. This is important in humid areas because many crops can be produced with rainfall only, although the risk of poor yield may be large some years.

In humid areas, irrigation scheduling is complicated by the higher probability of rainfall. Irrigation scheduling must consider rainfall probability, not only to conserve energy and water, but also to reduce the potential for leaching nutrients and pesticides from the soil profile. The nutrient loss is costly, reduces yield if not replaced, and can cause pollution of surface and groundwater supplies. The potential for leaching chemicals from the soil profile is greatest on coarse-textured soils when high-intensity rainfall follows irrigation that completely refills the soil storage capacity.

15.2.2 Benefits of Improved Management for Energy and Water Conservation

If irrigation is managed properly and without significant resource constraint, then profit should be maximized. In most cases, crop yield and quality, and, consequently, income should improve with good irrigation management. If water or energy are limited below optimum values because of abnormal weather conditions or mechanical problems, yield, income, and profit will most likely be reduced. Conservation of resources through good management will promote improved environmental quality by reducing excess water, which may cause chemical loss to groundwater and streams. Leaching caused by over-irrigation should be eliminated, and leaching caused by rainfall following irrigation could be reduced significantly if accurate rainfall forecasts were available. Soil losses caused by erosion could be reduced for the same reasons. Improved crop quality and storage properties should result from good irrigation management and resource conservation if these attributes were not excluded by the management strategy selected.

15.2.3 Economic and Technical Factors of Energy and Water Conservation

The economical operation of an irrigation system starts with proper design and selection of equipment components, particularly those that affect the energy consumption and efficiency of the system. Energy cost increases during the last two decades have had a significant influence on the design and operation of irrigation systems. Likewise, within humid areas, the cost and availability of water will probably have a similar effect on systems in the future. Major reductions in energy use can normally be realized by using surface water supplies instead of deep groundwater. In humid areas, locally recharged surface supplies are much more feasible than in arid areas because of recharge from rainfall, but the cost of development must be considered for each site. Another choice that must be made is the energy source to be used. Unit costs for various forms of energy (electricity, solar, petroleum, etc.) vary among locations, even within a country or territory; consequently, the choice of energy source must be made based on local conditions. Also, the conditions often change with time, so that once a decision is made there is no assurance that it will be the best choice in the future. Therefore, the manager must continually monitor the system operating costs and carefully evaluate opportunities to reduce these costs.

As new technology becomes available, managers must evaluate the technology, its cost in relation to potential savings or increased income, and make a decision based on increased profit, the solution of a resource constraint, or to satisfy institutional regulations. For example, if new technology that provided irrigation scheduling based on accurate rainfall prediction for field-scale areas became available, it could significantly reduce the irrigation requirement most years in many humid areas. Managers must evaluate technology in view of its cost, the potential savings in irrigation costs, and increased profits from improved crop yield or quality. Water savings may mean increased production area without requiring a new water supply.

Irrigators may face institutional or regulatory restrictions such as environmental concerns, energy costs, water allocation or availability, or competition from other water users. Should this occur, the manager might choose other crops that use less water or that require different pesticides or nutrients. Another alternative might be a change to an irrigation system that uses less water, applies water more precisely and efficiently, and operates at a much lower pressure. In either case, managers must make decisions based upon expected profit while operating within the imposed constraints.

Where water supplies are limited or water is allocated, adequate water might not be available to meet crop requirements and yield and/or quality increases may not cover the cost of irrigation. This is particularly true when growers are irrigating multiple crops, which is likely in humid areas because of the long growing season. The production of multiple crops with different critical moisture periods requires an irrigation system and water supply that is adaptable to a wide range of conditions. The manager must also plan the cropping pattern so that the water supply is adequate to satisfy peak water requirement for each crop.

15.3 IRRIGATION WATER REQUIREMENTS

15.3.1 Evapotranspiration Requirement

The general question of E_t requirements for crops in humid areas is no different from the general case, which is covered in Chapters 3 and 8. Climatic conditions in humid areas, however, cause certain assumptions implicit in some models and measurement techniques to be invalid. Three main topics are to be noted: the distinguishing characteristics of the humid environment that cause one to require locally calibrated methods; how these characteristics affect the models and measurements of E_t; and the availability of information originating within humid areas.

High humidity directly affects E_t in two ways. Associated with higher humidity is an increase in cloud cover, which directly reduces radiant energy available for evaporation. The second effect is more subtle. Higher humidity with constant temperature reduces the atmospheric vapor pressure deficit, which is the driving gradient for transport of vapor away from the evaporating surface. The energy balance is met by elevated leaf temperatures, so that additional heat is driven off by sensible heat exchange. Elevated leaf temperatures also raise leaf vapor pressure, which compensates for the reduction in vapor pressure deficit. The net effect of leaf temperatures being elevated relative to air temperatures is a shift in the partitioning of radiant energy into sensible rather than latent heat. Compounding the effect of reduced vapor pressure deficits is the generally lower wind speed encountered in humid regions for which the authors have experience. Reduced wind speeds, other conditions being equal, reduce E_t because of increased aerodynamic resistance to transport of latent heat, causing locally higher humidities near the evaporating surface. In summary, average E_t in humid regions is generally lower than in arid regions at the same temperature and latitude, because of the shading effect of clouds. However, peak daily E_t approaches that of more arid areas, because peak rates are likely to occur during essentially cloud-free days. A second difference is the partitioning of net radiation, which is shifted from latent heat exchange toward sensible heat exchange because of higher humidities.

Measurement of E_t or the transpiration component has also lagged in the humid regions. For example, weighing lysimeters have only recently been installed in the southeastern U.S. Therefore, direct calibration of E_t models has not been achieved. Mass balance techniques are difficult and inaccurate under most conditions. In the humid climate in particular, change in stored soil water is small compared to the less precisely measured deep percolation and runoff components of the balance. Application of micrometeorological methods is complicated by difficulties in obtaining sufficient fetch in normally small fields and in estimating aerodynamic resistance under low wind speeds and non-neutral conditions.

Humid-area E_t data available from the southeastern U.S. was catalogued by Sadler and Camp (1986) and from Florida by Jones et al. (1984). The quantity and quality do not approach that obtained under more arid conditions. A moderate amount of interest continues, including lysimeter installations in Florida and Tennessee, irrigation scheduling studies (Camp and Campbell, 1988; Cassel et al., 1985; Hammond et al., 1981; Hook et al., 1984; Hook, 1985; Wright et al., 1984), and energy balance studies (Evans and Sadler, 1987). Current interest also includes inputs to environmental quality issues (Dennehy and McMahon, 1987) and effects of global greenhouse warming. Similar interest has been shown in other humid areas, e.g., Mason et al. (1980) in Australia; Ligetvari (1985) in Hungary; and Merva and Fernandez (1985) in north central U.S.

15.3.2 Crop Response to Irrigation

Crop production functions, relating yield loss or relative yield production to water used by the crop during various growth stages or during the entire season, have not been developed as extensively in humid regions as in other areas. For most crops, a linear relationship can be found between biomass accumulation and water transpired (Hammond et al., 1981; Shih, 1986; Singh and Malik, 1983; Calvert and Smajstrla, 1984; Clark and Smajstrla, 1983). In arid regions, each unit of water added can be related to a unit of yield increase. In much of the humid areas, yield loss is related to factors other than water. Coarse-textured soils develop root-restricting pans, which affect both water and nutrient availability. Acidic subsoils have a similar effect. Nutrient imbalances are common. Diseases, nematodes, weeds, and insects can reduce yield without reducing water use.

The impetus for determining production functions for the humid climates did not exist until recently. Until the rapid expansion in irrigated area in the humid area of the U.S. during the mid-seventies, there was little need to be concerned with water use efficiency of crops. Even with irrigation, water management in coarse-textured soils involves day-to-day re-evaluations of soil and crop condition with little luxury for long-range planning because rainfall disrupts it. Because irrigation in the humid eastern U.S. is the individual farmer's responsibility, few of them can afford to collect and analyze the climatological data needed to estimate E_t accurately. They cannot apply production functions and cannot manage checkbook methods closely without E_t values (Merva and Fernandez, 1985).

Methods by which plants can adapt to water stress have been compared for humid climates. Osmotic adjustment was found to be inefficient in maintaining turgor on sandy soils, often found in humid southeastern U.S. conditions, because of the rapid development of stress on these soils (Jones and Zur, 1984). For clay soils and with a moderate 10-day drying cycle, cumulative transpiration, photosynthesis, and growth can be increased by osmotic adjustment. Root growth is a more effective means by which plants can adapt to water stress, which points out the importance of maintaining good rooting conditions in soils. No osmotic adjustment was found in soybean when stress was allowed to develop before irrigation, but root and water extraction depths increased as plants adjusted to avoid drought (Constable and Hearn, 1980). Leaf water potential was found to be dependent upon root pattern, which in turn was affected by water stress during the vegetative development period, with more deep roots developed if stress occurred at that stage (Hearn and Constable, 1981).

15.3.3 Effect of Cultural Practices

Direct runoff in the southeastern U.S. carries an estimated 25% of the annual precipitation to the Atlantic Ocean and Gulf of Mexico (Doty et al., 1987). Much of this occurs during the winter, but a substantial portion occurs during the growing season. For effective utilization of the rainfall, soil surfaces must be adequately mulched. The intercepted rainfall could account for most crop water needs in some years.

Efficient irrigation begins by getting applied water into the soil as uniformly as possible. Undersander et al. (1985) compared the effectiveness of several tillage methods on preventing local runoff during sprinkler irrigation. Compared to conventional plowing and disking, both plowing plus deep ripping and minimum tillage reduced runoff. Furrow diking after conventional tillage prevented all runoff during irrigation. They found no differences between high pressure (380 kPa) and low pressure (170 kPa) spray nozzles on direct evaporative losses.

Where root access to subsoil water is restricted by hard pans, crop water needs can be met by either irrigation, disruption of the pan, or both. In years with moderate rainfall, in-row subsoiling alone can alleviate most of the crop water deficit. For example, maize yields in the Atlantic Coastal Plain were increased 32% over 4 years with subsoiling and no irrigation, 98% with irrigation and no subsoiling, and 110% when both practices were used (Wright et al., 1984).

15.3.4 Miscellaneous Irrigation Requirements.

Chemigation may be especially well suited for humid areas (Threadgill, 1985, and Chapter 20). Frequent low-volume irrigations, often practiced in humid areas, permit chemigation with little change in irrigation schedules. Risk of rainfall following irrigation increases risk of nutrient leaching so that frequent applications of small amounts of chemicals through chemigation should reduce the risk of leaching (Gascho and Hook, 1984; Gascho et al., 1984; Rhoads and Manning, 1986). Reducing leaching is important for efficiency of the enterprise and for maintaining quality of groundwater, both of which are assuming greater significance in humid as well as other areas. The numerous weed, insect, and disease pests prevalent in humid and, particularly, humid thermic regions require postplant control for which chemigation is well suited. Because frequent rainfall reduces the need for irrigation, a system design capable of minimum water applications is required to prevent water logging and leaching. Of the major types of chemigation, fertigation is the most common in humid areas. For this, center pivot, linear move, solid-set sprinkler, and micro-irrigation systems are normally used, because they provide the best uniformity.

Frost/freeze protection is particularly important in humid temperate zones because warm temperatures occur much earlier than the probable last frost or freeze. Warm temperatures induce budding and blossoming, particularly in tree and small fruit crops, and late frost can cause severe economic damage. Most frost/freeze protection in humid areas is accomplished with overhead sprinkler irrigation. Crops on which frost/freeze protection is used include citrus, apple, peach, and other tree fruits; small bush crops such as blueberries and strawberries; some vegetables and nursery crops; and seedling beds. Another crop, cranberries, can be protected by flooding the bogs.

Although humid-area rainfall is often sufficient for crop establishment, irrigation can ensure uniform germination and emergence. For this purpose, most sprinkler systems are well adapted. High-volume (gun) sprinklers, which are common in the southeastern U.S., produce larger droplet sizes and may cause surface sealing and poor germination. Furrow irrigation, subirrigation, and some micro-irrigation systems are not well suited for this purpose because of inadequate moisture movement to the seed location. Micro-irrigation systems can be used effectively for establishing transplanted crops, such as trees and vine crops. Micro-irrigation has also been used to increase quality of crops for which economic yield is highly sensitive to quality, e.g., grapes (Ligetvari, 1984, 1986), tomatoes (Camp et al., 1989b), and other vegetables (Camp et al., 1989a).

Leaf and fruit temperatures that exceed air temperature by 6-7° C are not uncommon in humid areas. Sprinkler irrigation to reduce this heat stress, and also evaporative demand, is commonly referred to as evaporative cooling (EC) irrigation. It can also improve germination of direct-seeded crops and insure survivability of transplants. Evaporative cooling can reduce blossom drop in a number of crops. It has increased yield and quality of crops such as green bean, tomato, cucumber, potato, southern pea, strawberry, apple, and muskmelon. Most EC irrigation has been used for fruit, vegetable, and nursery crops that have a value sufficient to justify the added expense of EC irrigation.

15.4 IRRIGATION SYSTEM TECHNOLOGY

15.4.1 Types of Irrigation Systems

Most of the same types of irrigation systems used in arid and semi-arid regions are used in humid regions. The size and mix of these systems may be somewhat different than in other regions, depending upon soil type, field size and shape, topography, crop, and availability of adequate water supplies. For example, center pivot irrigation systems in humid areas vary in size from 4 ha to more than 120 ha.

In the humid areas of the U.S., the predominant system types are sprinkler, micro-irrigation, and water table management systems. However, in parts of Florida, Louisiana, Arkansas, and Mississippi, large areas are surface-irrigated. In other humid areas throughout the world, surface irrigation remains predominant because of water cost, topography, labor cost, and crop. Furrow or flood irrigation is used in some humid areas for sugar cane, rice, and cranberries.

Because of rainfall in humid areas, irrigation provides a lower marginal return than in arid or semi-arid areas; consequently, growers must consider whether income increase and risk reduction are sufficient to cover capital investment and annual operating cost (Boggess et al., 1983; Swaney et al., 1983). Another concern is whether changing to irrigated agriculture will require major changes in the farming operation, management, and equipment.

One of the most important parameters of irrigation system design is the water supply rate, both gross and net. Required irrigation system capacities for various types of systems used in humid areas based on a net irrigation requirement of 32 mm/week are included in Table 15.1. As noted, some system capacities should be increased for crops and/or applications with higher net irrigation requirements.

In humid areas, the land area of crops being irrigated with micro-irrigation systems, which include various in-line emitters, tapes, discrete emitters, and micro-sprinklers, increases each year. Fruits, vegetables, and, to a lesser extent, nursery and greenhouse crops are the major crops being irrigated with these systems. Line-source, micro-irrigation systems are being used mainly to irrigate vegetable crops, either with or without plastic mulches. Most of these use laterals buried 2-4 cm under the soil surface. Point-source, micro-irrigation systems are being used to irrigate vine, bush, and tree crops and both container and field-grown nursery crops. Micro-sprinkler systems are mainly used to irrigate container, shrubbery, vine, bush, and tree crops. These systems are being very successfully used by citrus, apple, and nursery producers in many parts of the world. Other than for experimental purposes, there has been little use of subsurface micro-irrigation systems on field crops in humid areas.

Water table management or subirrigation systems have been used in somewhat-poorly-drained to poorly-drained soils on flat terrain for more than six decades. However, with the development of better computer models, emphasis on water quality, increased energy cost, and seemingly more variable rainfall, renewed interest in these systems has developed in recent years. These systems vary from controlled drainage to complete subirrigation systems; the soil type, crop, and water supply generally determine which system will be used. These systems are discussed in greater detail in Chapter 21.

Some combination systems using surface-applied irrigation and water table management systems are being used. One example is the Mitchell Creek project in Edgecombe County, NC (Case Study No. 26F). A structure in a main channel controls the stream level, reduces outflow of shallow groundwater, and maintains the field water table about 1 m below the soil surface. Sprinkler irrigation systems are used to apply irrigation to the soil surface instead of using drain lines or field ditches to subirrigate the field. Sprinkler irrigation is necessary because topography and soil type prevent subirrigation from supplying sufficient water in some areas of the watershed. The channel and shallow groundwater provide a source for both irrigation and direct uptake by

TABLE 15.1. REQUIRED IRRIGATION SYSTEM CAPACITY FOR NET IRRIGATION OF 32 MM/WEEK.*

System Type	System Capacity		Operation Time	
	(L/min. per ha)	(mm/d)	(h/week)	(%)
Micro Irrigation	42 - 65	6 - 9	90 - 150	54 - 89
Hand Move				
Small Sprinkler	120 - 140	17 - 20	50 - 60	30 - 36
Gun Sprinkler	120 - 140	17 - 20	50 - 60	30 - 36
Solid Set†	170 - 440	24 - 63	15 - 40	9 - 24
Permanent†	170 - 440	24 - 63	15 - 40	9 - 24
Traveler	65 - 90	9 - 13	80 - 108	48 - 64
Center-Pivot	50 - 56	7 - 8	120 - 132	71 - 78
Linear-Move	50 - 56	7 - 8	120 - 132	71 - 78
Water Table Mgmt.	39 - 56	6 - 8	120 - 168	71 - 100

* Crops such as corn require 40-50 mm/week of net irrigation. Container grown nursery crops require 75-100 mm/week of net irrigation.

† Most of these systems are used for high value fruit and ornamental crops. Normally they are operated for shorter periods of time than other systems. For small fruits and tree fruits, systems are normally designed for frost/freeze protection and water requirements can range from 80-135 mm/d.

crops from the water table, which reduces the irrigation requirement.

15.4.2 Attainable Irrigation Efficiencies.

Flexible schedules were required for efficient irrigation in humid areas when using the Ritchie (1972) model for scheduling the number and timing of irrigations (Smith et al., 1985). Increasing irrigation frequency (by irrigation at a higher soil water content) resulted in increased runoff and increased evaporation, but not necessarily significant increases in yield (Mason et al., 1980). There were larger differences in water use efficiency among years rather than between irrigation scheduling methods within years because of the overriding effect of rainfall distribution. In humid regions, a possible advantage to less frequent irrigation is that more of the rainfall may be stored because the average soil water content will more likely be lower.

Computed soybean irrigation requirements based upon 25 years of weather record showed that the number of irrigations required varied from 2 to 6 (Mason and Smith, 1981). Based on 45 years of weather record, the frequency distribution expected for corn irrigation on southeastern Coastal Plain soils were computed (Chesness et al., 1986). As return frequency changed from 2 to 20 years, annual irrigation water requirements increased from 260 mm to 340 mm because of decrease in rainfall and increase in evaporation. The optimum soil water content (remaining available water) at which to irrigate cotton varied with rainfall patterns, due in part to yield reductions from excessive irrigation with some schedules in some years (Constable and Hearn, 1981).

When overhead irrigation is applied in light, frequent applications, a larger portion of the applied water remains on the plant and at the soil surface than when fewer, larger applications are made. One study found that 2.7 mm of the water applied by a center pivot remained in the canopy of a mature maize crop (Steiner et al., 1983). Part of this water will replace water which would otherwise transpire from the crop, but part probably will not be used productively. However, another study found no significant differences in seasonal water use whether soybeans were irrigated by sprinkler, micro, or subsurface methods (Calvert and Smajstrla, 1984).

15.4.3 Economic and Technical Considerations of New Irrigation Technology

Most irrigation in humid areas is supplemental to reduce crop stress caused by short duration droughts. While there are some large irrigation systems in humid areas, systems tend to be smaller than in arid areas, water supplies are individually owned or controlled, fields that are irrigated are often not contiguous, and soil conditions tend to be highly variable. An individual grower may irrigate several different crops that have different critical moisture periods.

During the last decade in the southeastern U.S., a number of irrigation systems were purchased to irrigate corn, soybean, and peanut. During this same period, the market price of corn and soybean decreased 50%, and a number of growers declared bankruptcy. The added cost of irrigation, which often was not being equalled or exceeded by increased income, was often the reason for failure of the operation. Most of the growth in irrigated area has occurred with center pivot, linear move, traveler, and micro-irrigation systems. Future growth will likely be with these or similar systems with emphasis on water, energy, and labor conservation.

There have been more advances in irrigation technology in the past three decades than in the previous history of irrigation. Included in these advances are water application methods, scheduling methods, flow measurement, system controls, and automation equipment. However, if one examines the adoption of these new technologies in humid areas, it is evident that they are now being and probably will continue to be adopted at a variable rate depending on the technology.

Several researchers have examined irrigation scheduling in humid areas using direct and indirect soil moisture measuring devices, computer models, and computer-assisted water balance methods. Some consultants have offered irrigation scheduling services, but with limited success. Highly variable soils and rainfall, lack of good data on rooting depths with time, and a general reluctance on the part of growers contribute to slow adoption of new technology.

Plant growth simulation models, expert systems, and irrigation system design and management models are being developed and refined by several research groups. DRAINMOD (Skaggs, 1978, 1980), a drainage and subirrigation design and operation model for drainage-subirrigation systems, is probably the best known and most accepted water management model in humid areas. For soybean, SOYGRO (Wilkerson et al., 1983) has been widely studied and has been adapted to irrigation scheduling (Fortson et al., 1989). Similarly the cotton model GOSSYM (Baker et al., 1983) has been widely examined under pilot studies on farmer fields in the southeastern U.S. The CERES models for wheat and maize (Ritchie and Otter, 1985; Jones and Kiniry, 1986) have also been evaluated and used on a limited scale in the eastern U.S. It is likely that improvements in these and related models will lead to increased acceptance of simulation models for estimation of crop water requirements. Expert systems have been devised to simplify data input, model operation, and interpretation of predictions made by the crop models (Jones et al., 1987). These, as well as automated weather stations, should also hasten acceptance of models. Factors hindering use of the models in humid climates include poorly characterized or extremely variable soil, lack of centralized updating of models, and lack of on-site rain gauges needed for this variable rainfall area.

Other technical improvements decrease cost, increase safety, and enhance compliance with various regulations. Most growers have engine or electric motor safety protection and a few systems such as those used for frost and freeze protection have automatic start devices. In some areas, growers utilize interruptible electrical service in order to receive lower rates from power suppliers and reduce operating costs. Most state and territorial governments have passed legislation requiring growers to install proper safety equipment to prevent contamination of water supplies when applying chemicals through irrigation systems.

Most growers have not installed water measuring equipment on irrigation systems unless government regulations require them to report water usage. For most growers, this would be a minor additional expense and is highly recommended to assist in irrigation management. Most growers do not know whether systems are applying water according to design specifications. Water measuring equipment would allow them to evaluate the system with respect to water volume applied and would also assist in system management should water allocation be adopted in the future. Also, a history of water usage could help justify a future allocation request.

In humid areas, as in other areas, some growers readily adopt new technology while others will proceed more slowly. Some new technology is more adapted to arid areas where irrigation is a necessity for crop production. Availability of dealers to install and service some new technology will also affect its rate of adoption.

15.5 IRRIGATION MANAGEMENT

15.5.1 Irrigation Management Objectives and Strategies

In humid areas, it is imperative that the irrigation manager select a management objective before the growing season. An important reason for doing so is that many cultural practices are different for irrigated culture than for rainfed culture in humid areas. For example, if fertilizer and seeding rates, cultivar, and row spacing recommended for irrigated conditions are not used, the maximum benefit of irrigation will probably not be recognized and profit could be reduced. Historically, cultural practices for crops in most humid areas have been selected to produce an acceptable crop yield with below or near "normal" rainfall. Even when irrigation was first used in humid areas, it was used only to supplement rainfall during periods of drought. Because of the high labor costs of those early hand-move systems, a significant threshold had to be overcome before irrigation was initiated each season. There was a great tendency to "wait another day" in anticipation of rainfall. Regardless of the particular objective selected, irrigation must be managed as an integral part of the production system, not as an element to be used only in emergency or unusual situations. Four possible management objectives include maximum profit, maximum yield, minimum risk, and resource optimization.

Maximum profit is probably the most popular objective, primarily because of the realization that, with increased operating costs, maximum yield does not necessarily provide maximum profit. As markets become more competitive, commodity prices tend to decrease, and this objective becomes more important. The maximum yield objective lost favor as energy and other operating costs increased and commodity prices decreased. Also, this management objective is often not compatible with conservation of water and energy resources and with protection of surface and groundwater. The minimum risk objective may be desirable for a variety of situations where the manager is required to reduce exposure or vulnerability in certain areas, e.g., high debt level, low cash flow, marginal system reliability, and commodity delivery contract. Finally, it may be necessary to adopt an objective based on optimization of available resources, specifically water, energy, land, and/or equipment. Some irrigation systems and water supplies in humid areas are designed for normal or average climatic conditions. In those cases where temperatures are abnormally high and rainfall is low (high E_t conditions), irrigation systems may be unable to provide irrigation sufficient for optimum crop growth and yield. In these cases, it is necessary to allocate water to those crops that would benefit most from irrigation. Alternatives, such as less-than-optimum irrigation for several crops or optimum irrigation for some crops and little or none for others, have to be considered.

The type and design of the irrigation system and how it is operated basically determine how much water is applied, but irrigation strategy will also affect this. The system may be operated in a low volume/high frequency mode where it essentially replaces daily crop water use, which is a common operational mode for micro-irrigation systems. Similarly, it may be operated in a medium volume/medium frequency mode, where only a fraction of the depleted soil water storage capacity is refilled, so that rainfall occurring shortly after irrigation may be effectively stored and the cost of additional irrigation is saved. Unless rainfall completely refills the soil profile, which can happen often in humid areas, more frequent irrigation is required with this strategy. Finally, the irrigation system may be operated in a high volume/low frequency mode. In this mode, depleted soil storage is refilled completely with each irrigation; consequently, rainfall that occurs 1-2 days following irrigation cannot be stored in the soil profile and is lost to either runoff or deep seepage. In humid areas, this operational mode is likely to lead to saturated soil conditions, poor aeration, leaching of nutrients, and poor utilization of rainfall.

15.5.2 Applicability of Scheduling Methods

Most available irrigation scheduling methods can be used in humid areas as well as in other climatic areas, although some adaptation and additional interpretation and experience may be required. Although irrigation scheduling technology for humid areas has been available for several years, it is not widely used in the humid areas of the U.S. (Lambert, 1980). Major factors that determine the acceptability of any irrigation scheduling method are ease of use, maintenance requirement, user confidence, and expense.

The major difference in scheduling irrigation for humid areas, in comparison to arid areas, is the increased need to deal with rainfall, either to benefit from it by using rainfall to reduce the irrigation requirement or to minimize adverse crop conditions such as saturated soils caused by rainfall following irrigation. For this reason, irrigation scheduling methods that utilize some type of weather data (forecasts, long-term record, generated, etc.) to project the need for irrigation, normally for a specified probability, for several days ahead will be most effective in humid areas. Various computer-based methods, such as those using a water balance or crop simulation, could be adapted to include this capability, if it is not implemented in current versions.

The major disadvantage in computer-based scheduling programs is the need for accurate input (soil, crop, and climate) data. As discussed elsewhere in this chapter, little reliable data, particularly crop water-use rates of this type exist for humid areas, . The extreme spatial variability of soils also causes problems in applying these techniques because a single set of soil parameters normally must be selected for each irrigation system which may include several different soils. Finally, a computer-based water balance or crop simulation model must accurately represent the field situation under a wide range of conditions. Most currently available water balance methods provide reasonably accurate results for short time periods; therefore, they require periodic correction during the growing season (Camp and Campbell, 1988).

Various forms of computer-based water balance scheduling methods have been developed and evaluated for humid-area conditions. A simple water balance method that was developed for the personal computer and used the modified Jensen-Haise method to estimate daily E_t (Lambert, 1980) was evaluated for corn over a large geographic area within the southeastern U.S. for a three-year period ending in 1982 (Camp and Campbell, 1988). At each of the five locations, the computer-based water balance method was compared to a method using tensiometers. At a sixth location, another computer-based procedure was used (Ritchie, 1972) and evaluated using measured soil water contents. These results showed only small, inconsistent differences between scheduling methods among the various locations, established the usefulness of the computer-based water balance as a scheduling method, and demonstrated the importance of accurate soil and water input parameters as well as the need for periodic corrections during the growing season. At one location in this study, a method using pan evaporation was included in the comparison with other methods. However, no consistent differences were evident during this three-year study, which included soybean as well as corn (Camp et al., 1988). Other computer-based procedures that can be used to schedule irrigation include calculated risk models (Allen and Lambert 1971a,b), and others, which were not developed to schedule irrigation, may be used to effectively assist in analysis of irrigation applications (Baker et al., 1983; Martin et al., 1985; Tew and Boggess, 1984).

Scheduling methods that are based upon soil or plant measurements, basically, are "reactive" management tools in that first, an observation is made, then the value is compared to a preselected threshold value that indicates when irrigation is required, and finally a decision is made either to irrigate or not to irrigate. The procedure can be modified depending upon the knowledge level of the manager, particularly with respect to the probability of receiving rainfall within a specified period of time. This information can then be incorporated with the measured value to influence the decision of whether to irrigate or not. The advantages and disadvantages of various soil and plant measurement instrumentation and their applicability in humid areas will be discussed elsewhere in this monograph.

15.5.3 Sensing Irrigation Needs and System Controls

Sensors and systems to control irrigation application that are available for general use can be used in humid areas although some may require modification and others may require special interpretation or may be limited in their scope of application. Soil-based methods for sensing need for irrigation include many found in more arid areas – tensiometers, gravimetric sampling, neutron probes, moisture blocks, and simple manual estimation. General limitations to these methods may assume greater importance in humid regions, at least in the southeastern U.S. For instance, stratified soils with very distinct horizon-to-horizon texture changes make measurement of soil water content using neutron probes less satisfactory than in uniform soils. The relatively small changes between upper and lower limits of available water in sandy soils also render the neutron probe less satisfactory. The rate of increase of tensiometer readings in sandy soils reduces the usefulness of this method for these conditions, and tensiometers often require frequent servicing. High soil variability requires increased spatial resolution in sampling, with associated increased labor requirement. This is exacerbated by small field size. Whereas the difficulties in estimating runoff and drainage complicate the measurement of E_t in humid regions, use of soil-based methods eliminate the requirement for estimating these components to schedule irrigation. One must develop a certain amount of experience with soil-based techniques, however, to practice predictive irrigation management. By re-initializing the soil water contents in computer-based water balance methods, the benefits of both techniques can be obtained.

Implications of variable irradiance or a shift in T_c-T_a relationships may include re-interpretation of the canopy-temperature-based crop water status indicators, such as the crop water stress index, or CWSI (Idso et al., 1981; Jackson et al., 1981). Irrigation management using a technique that was developed under nearly constant clear-sky conditions would appear to be susceptible to error under humid conditions, although commercial units are being offered and used. It appears that locally calibrated coefficients for the empirical CWSI should be used in humid areas. The theoretical CWSI may allow accounting for differences in irradiance and windspeed (Kustas and Sadler, 1989). Any empirical method, including E_t models, should be used with caution outside the range of validation.

Soybean leaflet angle has been suggested as a technique to schedule irrigation. Good agreement was found between percent of plants whose midrib of the terminal trifoliate of the last fully expanded leaf had drooped more than 45° from the horizontal and the water content of the upper 45 cm of soil (Wright and Berliner, 1986).

Many irrigation managers in humid areas use less quantitative methods for scheduling irrigation. Visible plant wilting is one method that may provide quite different results depending on the crop and experience of the manager. Generally, crop stress sufficient to reduce yield exists before visible wilting occurs. Various rules of thumb also exist for irrigation scheduling and can be fairly effective in humid areas. An example is the weekly application of irrigation to provide a total (including rainfall) amount of water each week, adjusted periodically during the growing season for changing crop requirements. Others sometimes require grower experience to be applied effectively. Soil "feel" is used in all areas to determine the need for irrigation. Generally, based primarily on experience and knowledge of soil properties, the manager estimates soil water content (or soil water depletion) based on the appearance and feel of soil samples collected from the surface or various depths in the profile.

15.5.4 Dealing with Soil Variability

Generally, as uniformity of irrigation system application decreases, response to water applied decreases (Letey, 1985). The optimum crop production from well-timed irrigation will be greater for uniform soils than when the field contains soils coarser- or finer-textured than the soil for which the irrigation was timed. This is true for most climatic areas, particularly where soils are extremely variable within irrigation management units and for soils with low water storage volumes. Rainfall can have an ameliorating effect on this phenomenon in humid areas if it refills the soil profile often enough.

Until irrigation systems are developed that can apply water at different rates within the system, it will not be possible to precisely manage irrigation by soil parameters (e.g., storage volume). Even then, the application pattern of the irrigation system must roughly coincide with the soil variability patterns in order to achieve precise irrigation management.

15.5.5 Effective Use of Precipitation

Irrigation to avoid yield reduction may not be the most rational economic use of irrigation water in a humid climate. Greater overall economic returns were realized even with lower average yields in a study that examined strategies using less water per unit area but irrigating more land to compensate for the lower yields (Constable and Hearn, 1980). However, this may not apply in many cases. Economics indicate that planned water deficit would only be profitable if near maximum yields are obtained, because water savings are small relative to the value of the crop (Ziska and Hall, 1983).

Simulation results for sandy soils under central Florida weather show that either decreasing application amounts per irrigation (deficit irrigation) or waiting until more of the available soil water was depleted before irrigation could save water and make more effective use of rainfall (Smajstrla and Hanson, 1980). Total seasonal E_t was not affected by the decrease in irrigation because of frequent rainfall.

Where irrigation water must be ordered days in advance from water management districts (e.g., Florida), there may be reduced water use efficiency because growers are unable to take advantage of intervening rainfall. Under similar conditions in Australia, increases in water use efficiency of 33 to 47% could be attained with better scheduling (Mason and Smith, 1981b).

Soil water contents within a large, moving irrigation system, such as a center pivot, vary with time since application. In arid areas, the time between last irrigation application is essentially constant because the system normally moves in the same direction and at the same rate. In humid areas, rainfall between irrigation applications essentially re-initializes the system time scale and introduces the soil water variable again. This affects the amount of rainfall that can be stored effectively and the level of crop stress at which irrigation is applied. With this restriction, it will be difficult for any management system to precisely manage irrigation except through the use of variable application rates.

Johnson et al. (1987) related soil conditions to design parameters of center pivots. They noted that in the humid southeastern U.S., center pivot systems differed in annual fixed costs because of the lower annual applications of water. Using cotton as an example, Gohring and Wallender (1987) computed optimum economic irrigation for production with various sprinkler irrigation systems in arid areas. They noted that the amount of applied water required for optimum economic value was 50 mm to 150 mm below the water application for peak yield. This may also hold in the humid region, but the challenge facing the irrigator is to decide which irrigations will be eliminated or decreased when irrigation amounts and application dates are so dependent on rainfall timing.

Irrigation in humid areas will not always be profitable, but it may be used for insurance when high value crops are grown or when the grower uses forward marketing strategies. Irrigation of peanuts in Florida was only marginally profitable over long periods, but in two dry years, peanut yield responses of 1600 kg/ha ($656/ha) with irrigation provided protection against economic failure (Hewitt et al., 1980).

If not properly managed, particularly with respect to timing in relation to expected rainfall, irrigation in humid areas can cause yield reduction. Irrigating cotton when available soil water was 22, 53, and 84% resulted in zero, one, and four days of flooding on a clay soil that had a low percolation rate. The flooding caused reduced soil oxygen, which in turn caused stomatal closure during flooded periods and caused lower cottonseed and lint yields as well as delayed maturity (Hewitt et al., 1980).

15.6 NEEDED RESEARCH AND TECHNOLOGY IMPROVEMENT

15.6.1 Improved Crop and Water Balance Models

Crop and water balance models for humid areas must be more complex than those for arid areas because of rainfall. Most current models do not effectively deal with rainfall, either in utilization of rainfall forecasts to delay irrigation or in partitioning rainfall amounts into infiltrated and runoff components. If more accurate rainfall forecasts become available for smaller areas, such as a watershed, and in a more usable form, such as digitized data, the potential for significant improvement in irrigation management should result in improved models. Similarly, there is need for root growth functions for a wide range of crops to be included in various irrigation management models. Most models currently require that rooting depth data be entered manually on a daily basis. These functions are particularly important for the application of water balance models for layered soils, which are quite common in some humid areas, e.g., southeastern U.S. Some of these soils have compacted layers that severely restrict rooting depth under some conditions, and many of these soils also have low water holding capacities. The combination of these factors makes it very difficult to estimate profile water storage if accurate rooting and water storage data for the various layers are not known. There is also need for overall improvement in input data required by models to characterize climate, crop, and soil. Crop water requirements (E_{tc} curves) will be addressed separately. A major problem exists in selecting a single set of parameters to describe conditions that vary considerably within an irrigation system (e.g., soils). A method to systematically deal with this variance in a manner that will provide effective irrigation management would be very helpful. Finally, as higher-level systems such as knowledge-based expert systems become available to improve the usefulness of models and to disseminate knowledge to more users, models must have links that can be used to connect them to these new systems. Improvement in the user interface of many existing models would expand their use to significantly more managers.

15.6.2 Crop Water Requirements

The need for research in crop water requirements is probably more critical in humid areas than in more arid zones (see Chapter 8), not because of the relative size of irrigated area, but because of the lack of data upon which to base research and management decisions. Sadler and Camp (1986) concluded that there was a critical need for benchmark-quality data on E_t for humid regions. Specifically, there was limited information for most crops, there was less information available to describe the effect of humid-zone cultural and environmental influences, and there was almost no data to test physical models of E_t and related water relationships.

15.6.3 Validation of E_t Models

The need for research to validate E_t models was discussed in general in Chapter 3. Specific needs in humid areas are critical, since no data set exists from humid crop areas upon which to base a validation. Empirical models are, for the most part, clearly outside their range of development. Some humid temperate data has been used to test some models, but no clear case has been made to date. Most researchers in the southeastern U.S. have simply computed E_t using some form of the Penman (1948) equation as a surrogate for lysimeter or other data. A precise lysimeter, capable of discriminating hourly E_t, is needed to test E_t models for at least the major crops produced in warm humid regions. This type data would extend the envelope of geographical and climatic applicability of E_t models, thus increasing the generality of the basic theories involved.

15.6.4 Prediction and Measurement of Meteorological Variables

The general cases for future research needs in prediction and measurement of meteorological variables was made in Chapters 3 and 8. Specific needs for the humid areas include an increased ability to describe probabilities of and to forecast rainfall, temperatures, and radiation. These needs are relatively more significant in humid areas because of the increased variability these parameters have over arid zones. Estimates of spatial dependencies of these parameters would improve extension to individual farms as well.

15.6.5 Automation, Sensors, Remote Sensing, and Feedback

At the present time, the extent of automation in humid areas is minimal. A few frost/freeze protection systems are controlled using refrigeration type thermostats to sense temperature and activate the system, but most are stopped manually. Some greenhouse watering systems and propagation systems are automated using weighing blocks, synthetic weighing leaves, or other similar devices. A few systems use switching tensiometers to automatically start the system based on measured soil water potential. A number of turf and lawn irrigation systems use automatic timers that start and stop the systems, but most of these are based on starting at a preset time and applying a preset amount of water or for a preset time with no evaluation of available soil moisture.

An ideal irrigation system would be one that could apply the correct amount of water in response to soil or crop condition, apply pesticides and fertilizers as needed, and provide environmental modification (crop cooling and/or frost/freeze protection) as needed. Technology probably exists to equip a fixed sprinkler system such as a solid-set or permanent system to accomplish these tasks, but doing so on a large scale with variable soils and crops would be difficult. Such a system would require multiple soil moisture or crop stress sensors where individual readings could be used singly or in combination to control a portion of the entire system. Measurement sensors to determine the need for pesticides and fertilizer generally are not currently available, and automatic application of these chemicals might not be desirable from the safety standpoint.

It is possible to automatically stop some irrigation systems when a rainfall event occurs. Furthermore, it is possible that the system would not be stopped until soil and/or plant water demand is satisfied, based on soil or plant moisture sensors. Automatic control of a continuously moving system would be more difficult because of variation in soil water content caused by the existence of both irrigated and nonirrigated sections at the time rainfall occurs. With the proper logic and control system, irrigation could still be applied to the nonirrigated area, if needed, based on soil or plant sensors. Another problem with adaptation of automatic controls for systems in humid areas is the cost of equipment to control a small number of irrigation systems relative to the number that might be controlled by such a system in arid areas. This coupled with the lower irrigation frequency could make the cost of such control systems prohibitive.

15.6.6 Measurement of Applied Irrigation Water

Irrigation systems in humid areas are normally equipped with flow measuring equipment only where growers are either on public or community water supplies where meters are required or where they must report water usage to state regulatory agencies. Most growers base their water application on specified pump capacity, pressure, nozzle size, and number of sprinklers or on information supplied by the irrigation dealer. For this reason, the volume and uniformity of irrigation water applied is not known by many growers.

Other concerns that affect uniformity in humid areas include lack of adjustment for elevation changes, running fixed laterals up and down slope rather than across the slope, laterals of incorrect size, and lack of adjustment in operation times for night versus day operations. In humid areas, evaporation losses can account for 20-30% of the total water being applied.

Probably the biggest concern in humid areas is that irrigation is considered to be supplemental and rainfall can mask some of the non-uniformity of irrigation application. However, when irrigation is used for an extended period of time, these non-uniformities become noticeable. More effort should be devoted to helping designers and users understand the necessity of good uniformity and to providing methods to evaluate uniformity. The reader is referred to Chapters 6 and 10 and ASAE Standards for additional detail regarding water use and uniformity measurement.

15.7 SUMMARY

In some respects, the need for improved irrigation management may be greater in humid areas than in arid areas although the relative size of irrigated areas and volume of water required are much lower. Because irrigation is not required to produce most crops, the need for a share of available water supplies as perceived by the general public and government regulatory agencies may be extremely low or nonexistent. In contrast, it is widely recognized in arid areas that water is needed for irrigation if crops are to be produced, and the perception of need is much higher. Consequently, as competition for water increases, agriculture may have a relatively more difficult task in obtaining or retaining a share of the water supply in the humid areas than in arid areas.

The existence of irrigation in some humid areas in the future may depend upon improved management of irrigation. It is also possible that economics will override water availability as the controlling factor for humid-area irrigation. Because of the lower marginal return for irrigation in these areas and the increased vulnerability of enterprises to fluctuating market prices and operating costs, better management is required.

Irrigation managers in humid areas must first select an objective based on expected yields, resource availability, and expected market prices. The irrigation management strategy to be used depends upon the type of irrigation system; management effort available; soil, crop, and climate factors; and water supply. Various irrigation scheduling methods are available and applicable to humid areas, but utilization of these techniques is relatively low. Because of the need to include rainfall in the management scheme, computer-based models offer several advantages, including the opportunity to incorporate rainfall forecasts and schedule irrigation applications several days in advance. Utilization of rainfall improves profitability by reducing operating costs and can reduce the adverse effects of wet soils on crop yield. Available technology to assist in irrigation management currently exceeds its general application by growers and managers. Increased technology transfer activities and the increased use of irrigation consultants should significantly improve irrigation management in humid areas. Improved technology in the areas of soil and crop sensors, user interface to computer models, and use of higher-level systems such as knowledge-based expert systems should increase the application of good management practices. Major research needs are improvement in computer-based water balance models and the validation of various E_t models for humid areas. A method is needed for integrating multiple values of soil and crop input parameters for various models to represent a single irrigation system. In the final analysis, the adoption and effective utilization of any technology to improve irrigation management in humid areas will depend upon economic considerations: increased profitability through increased income or reduced cost.

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