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# Methods and technologies to improve efficiency of water use

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[1] The competition for existing freshwater supplies will require a paradigmatic shift from maximizing productivity per unit of land area to maximizing productivity per unit of water consumed. This shift will, in turn, demand broad systems approaches that physically and biologically optimize irrigation relative to water delivery and application schemes, rainfall, critical growth stages, soil fertility, location, and weather. Water can be conserved at a watershed or regional level for other uses only if evaporation, transpiration, or both are reduced and unrecoverable losses to unusable sinks are minimized (e.g., salty groundwater or oceans). Agricultural advances will include implementation of crop location strategies, conversion to crops with higher economic value or productivity per unit of water consumed, and adoption of alternate drought-tolerant crops. Emerging computerized GPS-based precision irrigation technologies for self-propelled sprinklers and microirrigation systems will enable growers to apply water and agrochemicals more precisely and site specifically to match soil and plant status and needs as provided by wireless sensor networks. Agriculturalists will need to exercise flexibility in managing the rate, frequency, and duration of water supplies to successfully allocate limited water and other inputs to crops. The most effective means to conserve water appears to be through carefully managed deficit irrigation strategies that are supported by advanced irrigation system and flexible, state-of-the-art water delivery systems. Nonagricultural water users will need to exercise patience as tools reflecting the paradigmatic shift are actualized. Both groups will need to cooperate and compromise as they practice more conservative approaches to freshwater consumption.

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## 1. Introduction

[2] The supply of freshwater that supports human health and enterprise is basically constant, representing only about 1% of the water available worldwide. Good quality, nonsaline water is the global asset most important in satisfying the increasing demand for basic food, fiber, feed and fuels.

[3] As the major consumer of this global asset, irrigation accounts for about four fifths of the total freshwater consumed and about two thirds of the total diverted for human uses. Irrigation has shaped the economies of many semiarid and arid areas, permanently coloring the social fabric of numerous regions around the world. It has stabilized rural communities, increasing income and providing many new opportunities for economic advancement. Irrigation permits human habitation, at times quite dense populations, where it otherwise could not exist. Nevertheless, it is estimated that 60% of the global population may suffer from waster scarcity by 2025 [*Qadir et al.*, 2007].

[4] An estimated 260 million hectares (ha) worldwide are irrigated compared to fewer than 100 million ha in 1950. These lands constitute approximately 17% of the world's total cultivated farmland but produce 40% of its food and fiber. Irrigated agricultural activities also provide considerable food source and foraging areas for migratory and local birds as well as other wildlife. In short, irrigation underpins current society and lifestyle.

[5] Yet irrigation is not without its problems and critics. Water's uneven geographical distribution has made its acquisition a matter of great contention. The picture is further complicated by the fact that the productivity of the currently irrigated land base around the world is actually declining because of soil salination, waterlogging, and soil erosion. As the water resource-hungry competition swells in the form of increasing population, urbanization, environmental consciousness, recreation and tourism, and related concerns, agriculture's access to a critical resource is no longer guaranteed. This scarcity is especially evident in the prime agricultural areas of the arid and semiarid areas, but it is also being felt in the humid regions of the world.

[6] The United Nations [*U.N. Educational, Scientific, and Cultural Organization*, 2006] recently estimated that increased cropping intensity to meet world demands will require an increase of 40% in the area of harvest crops by 2030, and that the amount of water allocated to irrigation must increase correspondingly by 14%. However, it unlikely that the needed water will be available. This is creating a major paradox and a looming crisis. At the same time that both irrigated agriculture's land base and water supplies are

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being depleted and reallocated, it is being asked to produce even more.

[7] Total irrigated agricultural cropland in the U.S. exceeds 21.3 million hectares [*National Agricultural Statistics Service* (*NASS*), 2002], plus an estimated 16 million hectares in managed, irrigated urban turf grass [*Milesi et al.*, 2005] excluded from the U.S. Census of Agriculture [*NASS*, 2002] and USGS irrigation estimates [*Hutson et al.*, 2004]. The impact of urban turf grass is significant because urban and agrarian users often compete for the same water supplies, especially in the water-short 17 western states (not including Hawaii and Alaska), which contain about 30% of the total U.S. turf area. Fortunately, urban and agrarian irrigators are positioned to realize comparable potentials for water and energy savings.

[8] Irrigated agricultural crops in the U.S. have a farm gate value exceeding $40 billion per year. This represents 40% of the market value of all crops, produced on only 18% of all harvested U.S. croplands. Nationally, the higher yields and higher-value crop choices characteristic of harvested irrigated lands result in more than 4.5 times the average sales per hectare of nonirrigated land (N. Gollehon and W. Quimby, Water and wetland resources: Irrigation resources and water costs, chapter 2.1: Agricultural resources and environmental indicators, USDA Economic Research Service, 2006, available at http://www.ers.usda.gov/publications/arei/eib16/chapter2/). The economic value of irrigated urban lands for aesthetics, recreation and tourism, and related concerns is not known but it likely compares with or perhaps exceeds that of irrigated production. The expected rapid expansion of urban turf grass areas and the consequent increase in water usage will further intensify the pressure for irrigated croplands to do more with less.

[9] Global climate change is a source of uncertainty through its potential impacts on temperatures, annual precipitation levels, and regional rainfall distribution patterns and increased water demand. Some of these changes may already be occurring, although predictions of regional impacts are problematic at best. Producers facing greater climatic variability are likely to experience a decrease in the quantity and temporal availability of water supplies. Locally, high daily temperatures could effectively shorten growing seasons for crops that develop at rates proportional to accumulated heat units. Timing of precipitation and runoff from mountain snowmelt would differ from historical norms, leading to more frequent and sustained intense weather events such as droughts in some areas and floods in others. Hydrologic uncertainties would be compounded because modifications in precipitation and temperature can have disproportionately larger effects on crop evapotranspiration (ET) as well as the volume and timing of snowmelt, especially in arid and semiarid areas. The combination of these factors would force changes in the distribution of where and which crops are grown.

[10] The trend to harvest "energy crops" as part of the push for energy independence will also heighten demand for water, specifically because of higher ET demands of corn and high-biomass crops for cellulosic ethanol compared to more traditional farming systems in many areas. This will also compel increased development of less productive lands for crop production. Such lands are characterized by poor soils, low and unstable rainfall, steep slopes, and short growing seasons, but their use will be critical to meeting increased demands for food, fiber, feed and renewable energy crops, and stimulating economic growth.

[11] Urban areas will also have to revise their water supply expectations. Unconventional water sources will have to be developed [*Qadir et al.*, 2007]. Cities may have to build up alternative sources of water such as desalination of seawater to satisfy many of their needs (this is already common in the Middle East). Municipal water districts in Southern California are paying for improvements to irrigation delivery and application systems so that the saved water can be used to satisfy urban needs. Municipal wastewater is currently being used to irrigate golf courses and parks as well as some agricultural crops, and its use will undoubtedly increase.

[12] These trends do not portend well for increased crop production using current strategies and management. The formidable pressures on water resources ensure that water will be the primary natural resource issue of the 21st century [*Seckler and Amarasinghe*, 2000]. Already there are economic and social pressures on all water users to reduce irrigation water amounts, and the major expectations will continue to focus on agriculture's ability to supply needed water by conservation and technology [*Clemmens and Allen*, 2005].

[13] Obviously, novel approaches to water management and systems will be needed to address the declining land base and water allocations to balance production needs. As a society, we must identify measures through which agricultural users can economically adopt advanced irrigation schemes and implement practices to improve irrigation efficiency and water productivity in sustainable agriculture while remaining sensitive to societal needs.

[14] This paper will examine strategies for improving the productivity of water, enhancing management, and advancing irrigation technologies at the farm or field level. The equally important and parallel larger-scale and institutional considerations of this exceedingly complex issue are being addressed by others.

## 2. Basic Concepts and Definitions

[15] This discussion focuses only on ways to use less water for crops while maintaining or even increasing total crop productivity (unrelated to economic value of water) by enhancing the efficient use of water through improved management and advanced irrigation technologies. Strategies to be considered as a part of these activities include redesigning total irrigation systems for higher efficiency, successfully treating and reusing degraded waters, reducing evaporation losses, introducing site-specific applications, implementing managed-deficit irrigations, and employing engineering techniques to minimize leaching and water losses to unrecoverable sinks. There are no one-size-fits-all remedies nor any silver bullets; each area and mix of cropping systems will have unique solutions.

[16] To set the stage we have made the assumptions that the four following premises are necessarily true. (1) Irrigation must be economically and environmentally sustainable on the basis of the argument that society cannot afford to lose the huge contributions to food, fiber, feed and fuel production from irrigated lands. (2) Reducing agricultural water use while at the same time increasing the needed production

requires the evolution and integration of cultural, engineering, and management systems with institutional alternatives [*Howell*, 2006]. (3) There will be an attitude shift and a lowering of expectations by both agricultural and nonagricultural water users on why, when, where and how water is used, starting in arid areas but moving to more humid regions. (4) The necessary institutional and policy changes will be accomplished to facilitate more efficient and effective water use. The underlying principle is that any applied water that is not consumed by the field crops or weeds, evaporated or used by riparian vegetation will eventually be available for other uses in the hydrologic system unless it lost to unrecoverable sinks or becomes severely degraded.

### 2.1. Efficiency Terms

[17] *Burt et al.* [1997] presents a comprehensive discussion on the definitions of various efficiencies and uniformity measures related to irrigation. Several authors [e.g., *Allen et al.*, 1997; *Jensen*, 2007] have noted that use of the "efficiency" term often leads to misconceptions and misunderstandings, especially when increasing efficiencies is equated with creating more available water.

[18] *Wolters* [1992] described efficiencies in terms of the irrigation subsystem: storage, conveyance, distribution off- and on-farm, and on-farm application subsystems. He defines them as the ratio between the water depth delivered by the particular subsystem and the water depth supplied to that subsystem, usually being expressed in percentage. Therefore, a "total" system efficiency is the product of the various efficiencies of the respective subsystems [*Hsiao et al.*, 2007]. Three efficiency terms discussed in this paper are often misused and misapplied–application efficiency, irrigation efficiency, and water use efficiency. These terms and many other water related efficiency terms are often used interchangeably by regulators and many others; however, these are very different concepts, and their use often greatly confuses the issues because of differing perceptions of their meanings.

[19] Application efficiencies are defined in terms of percent water used by the plant divided by the water added or stored in the soil that is available for crop use. *Jensen* [2007] asserts that application efficiency is not really efficiency because it incorrectly implies that nonconsumed water is lost to the hydrologic system. Because the water stored in the soil for crop use is usually different (with a few exceptions such as well-managed buried drip irrigation) from the amount of water applied, irrigation efficiency is defined as the amount of water used by the plant divided by the total amount of water applied (or water delivered to the field) and is also expressed as a percentage. Irrigation efficiency includes any losses during the application process from factors such as wind drift, runoff and deep percolation.

[20] Another term commonly used, mainly in reference to irrigation, is water use efficiency (WUE). Adding to the confusion is that there are also many definitions of WUE. This will be discussed in more detail later.

[21] Uniformity of water application is a measure of the spatial distribution of the depth of water applied to a field, and is primarily a function of the field irrigation system design. It may be enhanced by management with surface irrigation systems, but is basically fixed with pressurized systems (e.g., trickle and sprinklers).

### 2.2. Crop Water Use

[22] Over the past several decades, much research has focused on quantifying crop water use under nonstressed conditions, commonly referred to as potential evapotranspiration (ET), which is the combination of the evaporation (E) and transpiration (T). This body of research generally defines ET as a measure of water usage (depth on the land area in mm, inches, etc.) by plants growing in controlled conditions under relatively low stress levels. This potential ET or $ET_p$ is one of the most accurate estimates available to managers of irrigation delivery and on-farm systems. Nevertheless, much additional information is required about the actual crop ET ($ET_a$) levels when plants experience different levels of stress during different growth stages of both major and minor annual crops in managed soil water deficits underirrigation. This has not been done because of the expense as well as the complexity of the interactions with other factors that also affect $ET_a$. For example, it may be necessary to determine these values by considering both increased soil salinity levels and the timing of water stresses with the end result focused on yields and crop quality. The long-term effect of managed and unmanaged deficit irrigations on many perennial crops also needs more research to ensure sustainability.

[23] Errors in estimating ET can result in reduced yields, wasted water, increased soil salination, undesirable physiological responses in plants, or a combination of these and other factors. These uncertainties in turn require that soil water or plant water potentials be monitored under all irrigation methods for proper irrigation scheduling and implementation of advanced technologies and management to reduce crop water use.

[24] Critical information is lacking on actual $ET_a$ in irrigation systems used for environmental modification to protect crops from both cold and hot temperatures, conditions that may become more common under many global climate change models. In addition, investigations of irrigation management and water use requirements for intercropping production systems would be useful. More study of how to address spatial variability in $ET_a$ across large fields as a result of pests or soil types is also warranted. Such information would be critical to future determinations of both agricultural and urban water rights, water banking, and government allocations. Some general strategies to reduce crop water use are briefly presented below.

#### 2.2.1. Antitransiprants

[25] The use of various antitranspirants received much attention in the 1960s and 1970s. However, results were highly variable, and many researchers concluded they were economically and practically infeasible. Daily ET could be reduced (e.g., 5% to 10%) after the application of antitranspirant materials (e.g., stomata closing type chemicals such as phenyl mercuric acetate or Atrazine, or reflecting materials such as finely powdered white clays like Kaolin), but efficacy was limited to about two weeks under rainless weather conditions [*Gale and Hagan*, 1966; *Davenport*, 1967; *Agarwal and De*, 1979; *Yadov and Singh*, 1981]. The purpose of film-type antitranspirants (i.e., various long-chain alcohols) was to block water loss, but they tended to block photosynthesis more than they blocked transpiration because $CO_2$ molecules are 1.6 times larger than water molecules.

### 2.2.2. Crop Genetics

[26] Genetic approaches to raising water use efficiencies focus on the selection of varieties with growth characteristics and tolerances (i.e., heat, cold, salinity, pests, drought, shorter growing seasons, earlier flowering, and more efficient nutrient use) matched to relatively location-specific conditions. Crop breeding will have greatest impact on increasing water use efficiency by selecting for optimal growing season lengths and harvest dates that take maximum advantage of rainfall timing at critical growth stages for each region.

[27] There is little biotechnological work thus far on introducing complex traits aimed at reducing the transpiration requirements of individual plants although efforts are underway. The selection process also keys on reducing the base water requirements needed to achieve the first unit of production, particularly for dryland species. Depending on genetic and environmental interactions, genetic improvements may play a major role, but are unlikely to create major shifts in WUE [*Sinclair et al.*, 2004; *Passioura*, 2006]. Improved cultural and management practices to optimize water conservation benefits will probably offer greater potential to reduce water use and a more immediate return on research.

## 3. Options for Improving the Productivity of Water

[28] There are several approaches for improving the crop productivity (yields) of water including replacing high water consuming crops with lower-consuming ones and adopting management and systems improvements to increase productivity per unit of water consumed. Reallocation of water from low-value crops to higher-value crops can increase the economic productivity of water; however this conserves water only if the high-value crop has a shorter growing season, and the land is not recropped the same year. Thus, the most significant sources of "new" water will be through improvements in productivity per unit of water with the adoption of appropriate management and water application systems. Each basin and watershed may have different solutions depending on specific socioeconomic, soils, water supply and climatic characteristics.

[29] Efficiencies must be considered in terms of both the diverted water that is consumed and the proportion that is not consumptively used that is available for reuse or becomes degraded or otherwise unusable. Efficiencies are increased when the total amount of water consumed by crops, evaporation and other users can be reduced. The available water resource within a basin or subbasin can also be effectively conserved for other uses by improving efficiencies to reduce the unusable water losses.

[30] There may be no water savings at the watershed or regional scale if the volume of evaporation and transpiration consumed by the crops and nonbeneficial uses (e.g., weeds) stays the same (assuming no unrecoverable losses). We know that improving only on-farm irrigation efficiencies will usually not save water, and may, in fact, increase total water use because both higher irrigation uniformities and increased inputs (e.g., fertilizer) can increase total yields. Growers may also shift to higher value, higher water-using crops because the improved irrigation system renders it more feasible. However, improved irrigation systems do make the farmers more efficient in their overall operations and more competitive, and they are certainly a huge advantage in drought or other deficit irrigation conditions when limited water can be applied more uniformly and create better yields. Nevertheless, under drought conditions, application efficiencies may reach 100% and return flows will be low, potentially affecting riparian ecosystems.

[31] Water is a critical productive resource, and conservation efforts at the local level even when total ET is not reduced can have large, positive basin-wide impacts. Regional net economic returns may be increased by improvements to water delivery systems as well as off-farm and on-farm irrigation systems that change the timing of water deliveries. For example, reducing irrigation diversions may make more water available for time-critical intermediate uses such as hydropower, municipal and industrial uses, and recreation and tourism. Using the technologies and methods described in this article, water quality may be enhanced, which benefits fisheries, water sports, endangered species programs, recreation and other water users. Reducing early season releases from reservoirs can enhance the effectiveness of scientific irrigation scheduling to achieve optimal yields due to sufficient and timely water availability later in the year. In addition, minimizing irrigation diversions can have the added benefit of reducing energy demand for on-farm pumping and fertilizers. In short, there are many very good reasons to improve irrigation systems and their management, but, depending on the balance of priorities, actually reducing annual agricultural water use may not be the desired outcome. *Cai et al.* [2003] presents an excellent discussion of the economic implications of the improvement of water productivity at multiple scales including irrigation districts and the whole basin.

[32] In an urban setting, appropriate selection of drought tolerant grasses and other plants can save substantial amount of water when combined with reduced fertilizer use and other strategies to maximize use of rainfall and optimization of where and when water is applied to spatially diverse landscapes such as highway medians. This could also reduce mowing and maintenance costs while still providing an acceptable appearance. Xeroscapes and minimal irrigation of golf course roughs will likewise have a large impact on reducing urban water use.

[33] Cultural practices such as conservation tillage, planting densities, and improved varieties and pest control will affect crop productivity and water use. Cropping strategies such as double-cropping, intercropping, relay cropping, crop specific rotations and sequences can take advantage of the lower water demand of certain crops and times or periods with higher rainfall to increase productivity.

[34] In addition to general water conservation and reuse practices, three complementary and overlapping options can be exercised to save water at the farm and field level. These options comprise (1) increasing crop productivity per unit of water, (2) improving management capacity of growers, and (3) spatially optimizing water applications and use. The first option considers alternatives that include planting drought-tolerant cultivars or reducing inputs such as fertilizers or water to decrease vegetative vigor. Option 2 can be realized by increasing grower ability to optimize irrigation amounts in time and space utilizing site-specific irrigation techni-

ques, enhanced water delivery systems, decision support tools, and other advanced methodologies. Option 3 can be exercised through various scientific irrigation scheduling scenarios including deficit irrigation, geographically relocating specific crops to areas of maximum adaptation and productivity, and fully or partially retiring lands from irrigation so water can be moved to more productive areas or uses.

### 3.1. Increasing Crop Productivity Per Unit of Water

#### 3.1.1. Water Use Efficiencies

[35] Crop productivity has often been increased by adding inputs, including water, fertilizers and pest control. However, these activities usually increase rather than reduce water use. It is therefore more logical to consider increasing crop productivity per unit water, which is generally termed water use efficiency (WUE) or crop water productivity.

[36] WUE is basically defined at an input/output ratio as a measure of productivity. However, many different definitions of WUE have been offered, which add a high level of confusion and misunderstanding to the concept. Mathematically, it is the average slope of the yield:ET curve evaluated at the yield of interest. However, because most agronomic studies are not designed to generate these curves, WUE is the generally considered the ratio of the harvested biomass to the water consumed to achieve that yield [*Steduto*, 1996].

[37] According to *Viets* [1962], WUE is the yield of interest (e.g., grain, biomass) divided by the water used to produce that yield. *Howell* [2001] pointed out that the denominator is difficult to measure and suggested that water used be estimated from effective rainfall plus irrigation plus change in soil water content. Another measure sometimes used is the yield benefit from irrigation divided by the irrigation water applied [*Bos*, 1980]; in this case, the expected or measured rain-fed yield is subtracted from the irrigated yield to obtain the numerator. WUE has also been defined in terms of the dry matter harvest index (ratio of yield biomass to the total cumulative biomass at harvest) as the yield of interest divided by water use [*Howell et al.*, 1990; *Howell*, 2001, 2006]. *Steduto et al.* [2007] and others have shown that WUE tends to be relatively constant when normalized for climate.

[38] However, the concept of water use efficiency has a number of drawbacks when being applied to broad area water conservation issues. Primarily, it is a biological response ratio rather than an efficiency term, which is why many people are now referring to this concept as crop water production [*Howell*, 2006; *Steduto et al.*, 2007]. WUE is not expressed as a percentage. *Monteith* [1984, 1993] criticized the WUE term and pointed out that no theoretical limits exist as reference, as should be the case for efficiency in an engineering sense. Second, many manuscripts and reports present information on water use efficiencies, but these are often referring to irrigation efficiencies, application efficiencies, conveyance efficiencies or some other measure of overall irrigation system performance and not the water use efficiencies as defined above [*Jensen*, 2007].

[39] WUE is also complicated by the presence of a base amount of soil available water or "overhead" from any source that is required to achieve the first unit of production. This is the water required for germination and initial growth to the stage where yield first becomes possible. This can be a major part of dryland WUE calculations, and adjustments are often made to account for this water. WUE can vary within the same species depending on whether the particular cultivar was selected for dryland or irrigated production. To complicate this topic further, WUE may also be greatly influenced by the timing of water applications as is evident in supplemental irrigations in humid areas. Irrigation at just the right time to avoid short-term drought can have very large increase in WUE (also depending on the WUE definition being used). Practically, maximizing WUE is seldom of interest except under rain-fed conditions (water not managed) or when available irrigation water is reduced (e.g., deficit irrigation) in time and amount by an irrigation district delivery policy.

[40] The term WUE is often mentioned in discussions on agricultural water conservation, but it is usually not being used in the same context as discussed above. In these cases, the intention behind the use of the term "water use efficiency" is that growers basically need to do more with less. Growers still need to maintain crop yields at the same or improved levels to satisfy world production needs while actually consuming less total water over the season. Thus, to avoid misunderstandings, the term "water use efficiency" or, more appropriately, crop water productivity, should only be used to measure the performance of plants and crops, and not be used in the context of water conservation at all.

[41] Thus, it is our contention that maximizing or improving WUE as defined above is not a concept that should be used in designing and executing water conservation programs for irrigated lands. WUE is a measure of productivity and is not appropriate in this context. Rather, the discussion really needs to be defined in terms of the economic optimum and maximizing economic productivity per unit of water applied to that area.

[42] In principle, the objective of water conservation is to reduce the amount of water used for crop production, which often results in a net reduction in ET. However, reductions in crop ET usually translate to reduced yields as well with a few exceptions (e.g., some tree and vine crops), which may not be economically desirable.

[43] Water conservation and the need to meet the anticipated future demands for food, fiber, livestock feed, and biological fuel alternatives are creating a paradox. On one hand, demands to increase crop production imply greater water use by agriculture. On the other hand, competition for this limited resource will cause a general decrease in the agricultural use of water well below current values over large areas. The later represents a paradigmatic shift from the current emphasis on maximizing yield per unit area, and it will require a significant rethinking of how, where, and why irrigation is practiced by both urban and agricultural water users.

#### 3.1.2. Improving Management Capacity

[44] The next option for raising the productivity of water is to manage soil water through improved irrigation timing to minimize negative effects of water deficits on yields and quality. This will require changes to the physical and managerial aspects of the water delivery and farm irrigation system designs that will enable growers to apply the right amount of water at the right place for all irrigations. Optimal use of available precipitation will obviously be required.

[45] Our contention is that the largest potential for basin-wide water savings will likely come from carefully scheduled, reduced irrigation levels on broad-area agro-

nomic crops such as wheat, corn, alfalfa and cotton. These crops tend to have more linear yield responses to water consumed than many high-value crops (i.e., vegetables) and quality is not as critical (or as sensitive to water stress).

[46] Thus, future irrigators will often be operating under a range of managed crop water deficit scenarios. Deficit irrigation is currently being used in large areas in the Texas High Plains and in the Columbia Basin in Oregon and Washington on annual crops [*Musick et al.*, 1988; *English*, 1990] and on perennial crops [*Drake and Evans*, 1997; *Evans*, 1999]. In addition to water shortages, the need for deficit irrigation management strategies may be induced by increased costs of inputs such as electricity, labor or combinations of external factors, which may be economically substituted for water [*Nieswiadomy*, 1988; *Edwards et al.*, 1996]. Increasing crop productivity while reducing the amount of applied water implies that producers will often be managing irrigations under severe to moderate soil water deficit conditions (drought) during at least part of the growing season. While the intention is to economically optimize production for each unit of water, different crops will have different allowable deficit levels. Improperly managed deficits may also impact the harvestable quality of some crops.

[47] Managed deficit irrigation strategies can potentially reduce agricultural and urban water use and conserve water, but they require excellent control of the timing and amounts of the applied water. Deficit irrigation strategies will result in high field application efficiencies because crop water use can be substantially less than potential ET (similar to dryland production), but the "irrigation system" efficiencies and uniformities are minimally affected because they are a function of the system design. However, producers in many arid and semiarid areas still need to manage irrigations seasonally to satisfy leaching requirements that minimize soil salt accumulations.

[48] Different crops will respond much differently to managed deficits. For example, some potato varieties can withstand very little drought without significant quality problems, whereas wine grapes (*Vitis vinifera*) can produce high-quality grapes with only about 50% of that of a fully irrigated vine as long as the water applications are properly managed in time and amount over the season [*Evans*, 1999].

[49] More detailed knowledge is needed of the physiological effects of environmental conditions on crop production. There is some indication that biochemical signals reflecting water and nutrient conditions in the soil are transmitted from the root to the shoot to regulate plant water use, and this information will be critical to any genetic manipulation via genomics or breeding [*Radin and Mauney*, 1986; *Clarkson et al.*, 2000; *Sobeih et al.*, 2004]. Knowledge of these response mechanisms may also be critical for optimized deficit irrigation management. Research to determine deficit management strategies in the absence of physiological understanding will be very resource intensive.

[50] Optimal deficit irrigation strategies still must be developed for most crops with the most pressing need being strategies for low-value field crops (including bioenergy crops). Some deficit irrigation strategies are now being developed for high-value vegetable and fruit crops. The research must include ways to match crop/plant needs with inputs over time, adjusting plant populations for various drought levels, figuring out when stress is most easily tolerated with the least yield loss, and developing means to minimize pest issues to below economic thresholds. Advanced irrigation scheduling techniques to better manage in both time and space will be required with these deficit strategies.

#### 3.1.2.1. Scientific Irrigation Scheduling

[51] Optimization of irrigation amounts in time and space requires scientific irrigation scheduling practices. Scientific irrigation scheduling is a systematic procedure that calculates an estimated future water requirement over relatively short periods of time to meet all crop needs and avoid water overapplication or underapplication. There are many variations, but these scheduling approaches generally use immediate past short-term climate data (e.g., last 5 days) to predict future short-term water use (e.g., next 10 days) to forecast the date of the next irrigation event.

[52] Traditionally, irrigation scheduling is designed to meet full irrigation conditions, but the concepts apply equally well to deficit irrigation. Schedules can also be based on plant responses to stress such as plant temperature, stem water potentials, growth rates or fluctuations in stem diameters, internode lengths, measured soil water levels, or calculated on the basis of energy balances and known crop response functions, or various combinations of these methods with climate-based approaches.

[53] Irrigation scheduling often improves the ratio of yield to consumptive use (water productivity), primarily because of improved timing of water applications. However, it is usually not possible to separate the effects of scheduling from other improved farming practices that typically accompany an on-farm irrigation scheduling program. Improving irrigation practices such as by converting from gravity surface irrigation systems to pressurized drip or sprinkler systems can facilitate irrigation scheduling, especially when the system is automated and controlled on the basis of in situ soil water sensors, but it is difficult to assign or quantify specific benefits of scheduling practices.

#### 3.1.2.2. Managed Deficit Irrigations

[54] There are three general scenarios for reducing water supplies to agriculture; each has specific management considerations and all require some form of scientific irrigation scheduling. In the first scenario, under full season drought management a given volume is available for distribution within a fixed land area over the course of the growing season as the grower sees fit (often requiring water storage in surface or subsurface reservoirs). In the second, under partial season drought management, a limited volume of water may be available over a fixed land area for only for a specific time period (e.g., first half the growing season) over a fixed land area. In the third, spatial optimization strategies are discussed such as moving production of specific crops to areas with greatest yield potential because of water availability or climatic and soil conditions. Full or intermittent retirement of land may be part of each of the above water supply scenarios. These situations provide quite different challenges and will vary greatly depending on whether the crop is annual or perennial.

[55] These three scenarios involve integrated practices that stress crops at various growth stages, allocate limited water through the full season, or manage limited water that is available only part of the growing season. Perennial crops such as apples, pears, peaches, olives, citrus and wine grapes

may have less yield reduction than annual crops to managed deficit irrigation techniques under full season reduced water supplies. Annual and biannual crops may be more adaptable than perennials to partial season drought management techniques, but long-season annuals such as potatoes may not be adaptable to full season deficit irrigation strategies. However, we know very little about deficit irrigation management strategies for most field and horticultural crops. Full season drought management and partial season drought management strategies are discussed below.

### 3.1.3. Full Season Drought Management

[56] Because of the vagaries in weather, spatial variability in soils, irrigation system breakdowns and external factors, crop yields may drop sharply under deficit conditions. In addition, the ability to manage deficit irrigations may also be limited by water delivery and regulatory constraints. Thus, deficit irrigation strategies will demand a rethinking of the total system from delivery systems to crop insurance and other farm safety net programs.

[57] There are three basic variations of controlled root zone strategies when limited water is available for the entire season, including regulated deficit irrigation, controlled late season deficit irrigation, and fallowing land. The first technique has become more and more common on tree and vine crops, but has also been used on as many annual crops [*Chalmers et al.*, 1986; *Fereres et al.*, 2003; *Fereres and Soriano*, 2006].

#### 3.1.3.1. Regulated Deficit Irrigation

[58] Regulated deficit irrigation (RDI) is limited to relatively arid areas with limited summer rainfall and is mostly a strategy for high-value perennial crops using conventional irrigation systems. A variant of RDI called partial root zone drying alternates water applications from one side of the plant to the other, basically requiring two irrigation systems. This technique deliberately imposes specific plant water stresses during specific growth stages (usually early in the season) using daily sprinkler or microirrigation techniques, but only replaces 10–30% of the plant's daily water use. The wetted soil volume contracts from the sides and bottom of the root zone. At the end of the stress period, as may be indicated by various physiological markers, water application amounts are increased (e.g., up to 85–100% daily plant potential ET); but soil water profiles are not totally refilled, and the size of the small wetted soil volume remains constant and relatively small. Water productivity for RDI of many perennial pome, stone and vine crops may be misleading because the plants are managed (pruned, thinned, etc.) to meet certain size and quality standards at levels considerably below maximum yield.

[59] RDI usually requires that adequate allocations of late season water be available to maintain quality and size at harvest and that the system be designed to apply at least peak crop water use on a daily basis throughout the entire growing season. Automated microirrigation is often used for maximum control of RDI.

[60] To date, RDI has been investigated mainly on perennial crops, but some annual crops should also benefit. RDI has been tested in many tree crops and grapes with generally good results [*Fereres and Soriano*, 2006], particularly with respect to product quality [*Drake and Evans*, 1997]. These management strategies are taking advantage of physiological responses of certain crops to drought stresses that result in a reduction in vegetative production in favor of fruit yield. Research has shown beneficial responses in Australia on peaches [*Chalmers et al.*, 1981] and pears [*Mitchell et al.*, 1984]; and in Washington on apples [*Proebsting et al.*, 1977; *Middleton et al.*, 1981; *Peretz et al.*, 1984; *Evans et al.*, 1993, *Ebel et al.*, 1995; *Drake and Evans*, 1997], citrus [*Goldhamer and Salinas*, 2000], grapes [*Evans et al.*, 1990; *Dry and Loveys*, 1998; *McCarthy et al.*, 2000], and other crops. These results have shown that carefully managing the severity and duration of a uniform, constant level of water stress on vigorous perennial crops can be advantageous to crop quality, depending somewhat on rootstocks and varieties. RDI has been found to control vegetative growth, increase fruiting, advance fruit maturity, and increase precocity and soluble solids in fruits. The key to successful RDI is good control of all water (irrigation or rain) to limit soil water volumes, which in turn limit vegetative growth, but water must be available for the entire growing season. Soil water volume control is made possible by two factors, the practical ability to achieve high-frequency irrigation regimes and the capacity to restrict soil water carefully by controlling the application amount and size of the wetted volume of soil available to roots. It can be a difficult practice to implement in many areas because all the water savings are typically early in the season when water is usually most abundant.

[61] *Fereres and Soriano* [2006] estimate that annual water diversions can be reduced by as much as 40% from full ET under RDI techniques, depending on the particular crop and crop quality requirements. Many varieties of wine grapes (*Vitis vinifera*) can tolerate a 50% reduction in seasonal water use while improving juice quality; however, the targeted yields are relatively low compared to the maximum [*Evans*, 1999]. On the other hand, under the right conditions RDI of apples, peaches and pears have been found to reduce season water use ranging from 10% to 30% with increased yields and soluble solids over fully irrigated trees, depending on the rootstock and variety. But, the total areas planted to high-value perennial crops suitable for RDI is relatively low compared to annual and perennial field crops. For example, a 40% decrease on only 1% of the total irrigated area will only have a relatively small impact on water conservation in a watershed.

#### 3.1.3.2. Controlled Deficit Irrigation

[62] Controlled or late season deficit irrigation (CDI) generally describes irrigation strategies whereby water supplies are relatively adequate early in the growing season but are later limited. This is a common scenario in many areas where late season water applications are in deficit. Irrigations are managed to minimize negative physiological responses on annual or perennial crops at critical growth stages because of the late season drought stresses. CDI is often used as a water conservation technique with perennial crops in arid areas, such as peaches, plums, or cherries, which are harvested in early to midsummer, but careful management of postharvest stresses are needed to avoid negative yield effects on the following year's crop. Annual water savings will be on the order of 10% to 25% or more.

#### 3.1.3.3. Fallowing Irrigated Lands

[63] Selected fields may be intermittently "fallowed" (not irrigated) for one or more years as part of multiyear rotations using the water savings to irrigate the reduced

acreage. The semi-"fallowed" land may be planted in dryland crops, converted to dryland pasture or managed to conserve as much precipitation as possible for subsequent irrigated crops.

#### 3.1.4. Partial Season Drought Management

[64] One of the most common reduced water scenarios consists of making a fixed quantity of water available for only the early part of the growing season. Over the longer term, this will likely lead to a shift in crops as well as reduced fertilizer, water and chemical inputs. Irrigation strategies are implemented to supply water at critical times and growth stages to minimize drought-related yield reductions. Short-season high-value crops such as vegetables may be substituted for longer-season crops on less area.

##### 3.1.4.1. Crop Selection

[65] In arid and semiarid areas where cutbacks in time and amount of irrigation water delivered to farms results in frequent partial season droughts, there will likely be a shift to crops that mature more quickly, such as small grains, cool season oil seeds (e.g., mustards, camelina), or various pulse crops such as peas and lentils. Shifts to deep rooted, drought-resistant crops such as sunflower and safflower may also occur to maximize use of precipitation stored in the soil. Depending on climatic conditions during the season, longer-season crops such as maize (corn) will have reduced yields and quality.

##### 3.1.4.2. Supplemental Irrigation

[66] By definition, all irrigation is supplemental to natural precipitation. In some humid and temperate areas, such as the Mississippi River Delta and the southeast United States, supplemental irrigation is a tactical measure to complement reasonably sufficient rainfall and stabilize production despite short-term droughts. However, this discussion is directed primarily toward arid and semiarid areas where it may be possible to apply only one or two irrigations per season. This is a form of managed deficit irrigation where the impact of the timing and applications of limited water supplies relative to only rain-fed agriculture can be very positive [*Sojka et al.*, 1981; *Zhang and Oweis*, 1999; *Oweis et al.*, 2000; *Solomon and Labuschagne*, 2003]. These techniques work to apply water during critical growth stages. For example, in situations where rainfall is insufficient at planting time, even limited irrigation just before or after planting will help ensure adequate germination for good stand establishment and greatly increased harvest potential. Likewise, a second irrigation at pollination of many crops could help ensure a better harvest.

### 3.2. Spatially Optimizing Production

[67] The third option for improving the productivity of water delivery is its spatial optimization. Spatially optimal land use includes geographically relocating certain crops to their most productive areas and soils, thereby minimizing irrigation amounts and maximizing overall efficiencies; and potentially retiring lands from irrigation in other areas.

#### 3.2.1. Geographic Optimization of Crop Production

[68] Relocating specified crops to climatic regions and soil types best suited to maximal output would be the most economically efficient use of resources. For each field, farm, irrigation district, watershed, or region, relocation concerns what is produced, what could be produced, and what should be produced.

[69] For example, the Palouse area in eastern Washington State and western Idaho is probably one of the best wheat-growing areas in the world as evidenced by long-term production records. Other similar areas exist in the central United States, Ukraine, and other central Eurasian countries; but even together they cannot supply all the world's wheat needs. On the other hand, the Palouse area is not suitable for dryland maize production, despite irrigated maize yields in that region being among the highest in the world. Thus, choices are complex, and decisions must be based on perhaps more information than historically used or even currently available. Improved crop genetics can certainly play an important role.

[70] Such land use options can have major economic and environmental implications ranging from individual fields to entire regions. Lands that are vacated by the geographic relocations would either be converted to dryland (nonirrigated) crops or pastures, shifted to more "suitable" irrigated crops, or totally retired from production.

#### 3.2.2. Total or Partial Retirement of Lands

[71] Total or partial permanent retirement of lands from irrigation is an option for both full season and partial season drought management. Most commonly, a portion of the irrigated land may be "retired": from irrigation to fully irrigate the remainder. Usually, the retired lands are converted back to dryland crop or animal grazing. The available water supplies are then applied to smaller areas to achieve maximum production (lower total yield). Land retirements may also be temporary in response to short-term drought.

[72] Land may be permanently retired voluntarily though purchases by urban areas for the water or other government programs. This can work well locally by abandoning salty or shallow soil areas as well as eroded and highly erodible areas. For example, the Westland Irrigation District in California purchased about 40,000 ha of highly saline, poorly producing lands and transferred the water to more productive lands. Several cities along the Front Range in Colorado have purchased thousands of hectares of land to obtain their water rights for urban uses. Another example is the City of Tucson, Arizona which has also had a similar land purchase program to the point where only about 25% of the historically farmed lands are still in agricultural production. Land may also be involuntarily retired in response to changes in climatic or economic conditions.

## 4. Advanced Irrigation Technologies

[73] Worldwide, irrigation has been practiced for more than 6000 years [*Postel*, 1999], but more innovation has occurred in this arena in the last 100 years than in all of the preceding centuries combined. Almost every aspect of irrigation has seen significant innovation, including diversion works, pumping, filtration, conveyance, distribution, application methods, drainage, power sources, scheduling, fertigation, chemigation, erosion control, land grading, soil water measurement, and water conservation.

[74] From early diversions of water from streams in ditches dug by hand, irrigation technology has developed to include massive reservoirs and networks of canals to satisfy gravity irrigation systems, manually and mechanically moved sprinkler systems, and a variety of low-flow systems referred to as microirrigation. Originally, irrigation was accomplished by methods utilizing gravity to distribute and apply water.

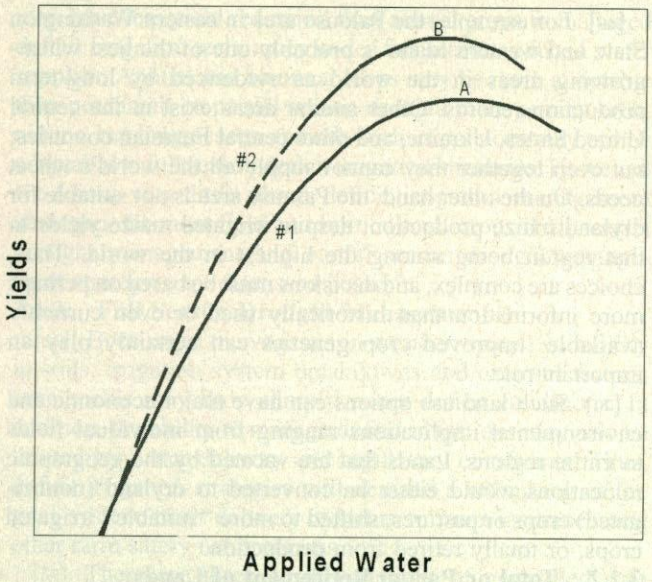


**Figure 1.** Hypothetical diagram of the crop production functions for two different irrigation systems for the same crop and variety on a field scale showing the potential shift in yields and applied water.

Sprinkler technology was enhanced by the development of low-cost aluminum and later PVC pipe, and currently more land is irrigated in the United States by sprinklers than by gravity methods.

[75] Irrigation management Irrigation management and systems that utilize soil water more efficiently have been shown to reduce not only cost and energy use but also water quality impacts. High-frequency drip irrigation and other microirrigation methods have been shown to increase the yield and quality of fruit and vegetable crops through reduced water and nutrient stresses. Tied to an effective soil water monitoring program, good design, and appropriate management practices, microirrigation can have an application efficiency of 95% or better without drought stress, and is now used on about 5% of the irrigated area in the United States [*NASS*, 2002], although on less than 1% worldwide. Another example of an efficient scheme is combining already highly efficient microirrigation systems with biodegradable plastic mulches to reduce soil evaporation and further increase potential water savings. Similarly, a modification of self-propelled sprinkler irrigation systems termed low-energy precision applications (LEPA) has been found to be more than 95% efficient in field situations, although it is being used on less than 1% of U.S. lands and even less worldwide. The potential difficulties for these systems to conserve water are discussed below.

### 4.1. Water Conservation Potential

[76] One of the major points of this paper is that only improving an on-farm irrigation system may not necessarily result in water savings at the irrigation district or basin scales. To illustrate this concept at the field level, Figure 1 shows a hypothetical representation of the average yield versus all applied water for two different irrigation systems (including irrigation and precipitation) at the field level (not individual plants) with its inherent spatial variability of soils, salinity, pests, fertility and water application uniformity. This curve is commonly referred to as the maximum field production function for a given crop because all measured yields lie on or below this curve. This envelope curve generally applies to a given irrigation (water application) system and location (soils, climate, etc.). Curve 1 represents an "old," less efficient irrigation system that is replaced with an "improved" irrigation system, shown in curve 2. The offset in the X intercept represents the amount of water necessary to achieve the first unit of yield.

[77] It should be noted that production function curves presented in the literature are often a compilation of results achieved for several different crop varieties under many different irrigation systems and locations, each with its inherent uniformity and efficiencies. In these cases, the summary production function actually consists of a series of the above curves representing each water application system and location. An increase in irrigation efficiencies by improved irrigation systems tends to move the potential field production function upward. Improved genetics (increases in physiological water productivity that improve yields) may also move the curve upward.

[78] The differences between the two curves basically represent the benefits of improved uniformity and application efficiencies across a field. Maximum potential yield of curve 1 is represented by the point A. Similarly, point B is the maximum potential yield of the improved system. The point of maximum production (points A or B depending on the irrigation system) is where most growers prefer to operate because it has the lowest risk and uncertainty when water is not limiting. When water is limiting, growers strive to operate as high on this curve as possible.

[79] Many government programs assume reductions in applied water as growers move from A to B to be the water savings attributed to irrigation system improvements. In reality, this line is often shifted upward by the more efficient, more uniform irrigation system that leads to increased yields over the entire field and likely higher total ET (higher seasonal water consumption).

[80] Note that a graph of yield:ET is basically a straight line with a slope about the same as the slope of the lower-left portions of two curves in Figure 1 up to a genetic maximum where it plateaus. In this context, Figure 1 illustrates that the shift to the improved irrigation system (system 2) reduces applied water but yields are increased, which implies increased ET. If "WUE" is calculated as the ratio of yield to ET, the shift from A to B may show a calculated increase in WUE (water productivity), but it actually results in a net water use increase and not in any water savings.

[81] The production increases (moving from point A to B) are mostly due to improved uniformity increasing crop production in previously water-short areas in the field and the capacity for improved irrigation schedules that minimize short-term drought stresses. There are economic incentives to increase inputs such as fertilizer to the crop, which can further increase ET. Growers may shift to higher water use crops that may have higher net returns, further reducing net water savings.

[82] Confusion often arises because improving only on-farm irrigation efficiencies with more efficient systems may not actually save water for the overall hydrologic system (e.g., river) unless total seasonal diversions to the farm are correspondingly reduced. This is not often done because

most delivery systems were designed for the older technologies and because on-farm improvements are rarely accomplished at the same pace across the entire delivery system area. Most particularly in the western United States, irrigation water delivery systems are not designed to operate at the substantially reduced flow rates needed to fully realize the benefits of improved irrigation systems. Many improvements to water delivery systems are needed before such strategies can become effective at the farm level.

[83] Figure 1 also provides an illustration of deficit irrigation management. As growers attempt to manage irrigations under deficit conditions (reduce applied water), they move back (to the left) along the curve for the corresponding irrigation system. This results in less water being applied and usually a slight yield reduction, depending somewhat on management and timing. It also carries a high level of economic and agronomic risk to producers. As they operate to the left of maximum yield, application efficiency, as defined previously, approaches its maximum because all the stored soil water is utilized. Irrigation efficiency increases to a maximum, but less than 100% because the uniformity of the water applications is minimally or not affected, and there are still some inherent system losses to the total applied water.

[84] Depending on the slope of the crop water production curve, a 30% to 40% decrease in water applied may result in only a 5% to 10% yield reduction. A 10% decrease in water use on broad acreages can be highly significant for low-value crops whereas, a 10% decrease on only 10% of the land that is in high-value crops may have marginal water conservation benefits although economic benefits can be high.

[85] Inherent in efforts to reduce seasonal crop water use is the need to optimize effective rainfall, improve application timing, employ deficit irrigation, and maximize crop production or income per unit of water. Integrating these allows one to target inputs as part of a compromise on yield goals at less than maximum yields near the economic optimum rather than the point of maximum production.

### 4.2. Improved Irrigation Systems

[86] Under certain conditions, surface irrigation techniques such as level basins can also be very efficient. These methods require precise grading of the topography, high instantaneous flow rates and relatively high levels of automation and management.

[87] Microirrigation is the slow rate of water application at discrete locations at low pressures, and includes trickle or surface drip, subsurface drip, microsprinklers and bubblers. It has made tremendous strides over the past three decades, and has become the modern standard for efficient irrigation practices for water conservation and optimal plant responses. These systems have small diameter tubing laid in the field, either on the surface or underground, with small water application devices that apply water (usually a drip or very small stream of water) directly to a plant at low pressures. These systems are particularly advantageous on widely spaced tree and vine crops as well as high-value vegetable crops (e.g., under plastic mulches that control weeds, minimize foliar diseases and eliminate soil evaporation). Carefully managed subsurface (buried) drip will probably provide the greatest potential for water conservation because of the potential for reduced losses.

[88] Self-propelled irrigation systems include center pivots that use long, single-pipe laterals moving in a circle around a central point, and linear move sprinkler irrigation systems that move in straight lines. As they travel across a field, these systems apply water just above or in the plant canopy using small sprinklers, sprayers or bubblers. Nominally, water is applied uniformly regardless of topographic, soil type or plant differences over the entire field. These systems are most suited for low-growing crops such as vegetables, alfalfa, small grains, rice, soybeans and sugar beet as well as taller crops such as corn and sugarcane.

[89] One highly efficient variation of water application by self-propelled irrigation systems is referred to as low-energy precision applications or LEPA. Water is actually applied at ground level between plant rows (e.g., every other row). Water bubbles out of the application device into the furrow, and some people have referred to this technique as "traveling drip." The term precision here is a little misleading as it is not precision in exactly meeting plant needs, but it applies the water more precisely in space than a sprinkler. LEPA is commonly used on large fields located in water-short areas such as the Ogallala aquifer in the Central High Plains.

[90] A major reason for growers to make system improvements to any of these irrigation schemes is to reduce labor by automation, minimizing water costs by conservation (higher irrigation efficiencies). Another reason is to enable them to expand their irrigated area with the same diverted water volume (irrigation capacity), which is allowed in some states as "water spreading." (This practice will probably disappear in the near future in most western states.)

[91] There are several management options for reducing water losses. Making small pits or basins (minireservoirs), commonly called furrow diking, in sprinkler irrigated fields to hold water where it falls from both irrigation or precipitation can be beneficial (this may be required under LEPA systems). Reducing areas of irrigated and fertilized crops, but unharvested for whatever reason will likewise reduce nonbeneficial uses. Irrigation at night can reduce evaporation losses. Weeds are a major nonbeneficial use of water and their control is critical, but chemical control is costly and may have unwanted environmental consequences. The use of mulches for weed control may reduce nonbeneficial ET and soil evaporation. Reduced tillage techniques can reduce soil evaporation losses. Drip irrigation technologies can conserve water by greatly reducing soil evaporation and maximizing crop water productivity. These strategies could also incorporate alternative cropping systems including winter crops and deep rooted cultivars that maximize use of stored soil water and some nutrients.

[92] Improving irrigation efficiencies through the above means will require substantial investments by farmers in infrastructure and new equipment; and such investments are often accompanied by higher operating and more energy costs and requires greater management skills. Growers will need the flexibility to manage rate, frequency, and duration of water supplies to optimize allocation of limited water and other inputs among crops, minimize evaporation and seepage losses, reduce soil erosion, and capture dissolved nutrients. Changes in water policies and institutional structures will be needed to enable and foster emerging irrigation technologies.

[93] Nevertheless, the deficit irrigation strategies discussed above will not be possible without advanced irriga-

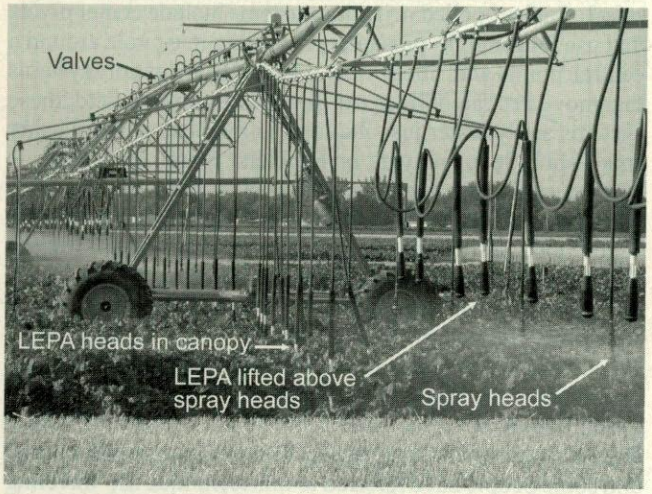


**Figure 2.** Photograph of site-specific sprinkler irrigation system used in water management research. See color version of this figure in the HTML.

tion methods, and the potential to save water depends on the capabilities of the irrigation system and the operator to implement water-saving practices and technologies. Self-propelled center pivot or linear move sprinkler and various microirrigation systems are good alternatives to improve efficiencies through site-specific and accurate applications at various points across a field. These technologies will also benefit from other precision agriculture tools such as site-specific nutrient applications.

#### 4.2.1. Site-Specific Irrigation

[94] One of the greatest constraints to managing for enhanced productivity as well as water quality is the inability of agricultural producers to control inputs in ways that accommodate variable growing conditions across a field. Infiltration rates have long been known to vary between irrigation events, but they also vary among locations within the field. Wide variations in soil types, soil chemical properties, subsurface conditions, topography, drainage, insect/weed/disease problems, soil compaction, weather patterns, and wind distortion of sprinkler patterns, as well as external factors such as herbicide drift, can cause yields and crop water use to vary across a field and among fields. These may also be impacted by tillage practices and crop rotations. Thus, it may be more advantageous to vary water applications across a field to accommodate potential production differences and environmental consequences from the variability of these numerous factors than to manage the entire field as one unit. Or, in other words, the objective is to apply water nonuniformly over nonuniform soils and field conditions to provide optimal growing conditions. The challenges and opportunities for irrigation equipment manufacturers, designers, researchers, managers, and growers will be considerable, but may ultimately be quite profitable [*Sadler et al.*, 2007].

[95] Self-propelled center pivot and linear move irrigation systems are particularly amenable to site-specific approaches because of their current level of automation and large area coverage with a single lateral pipe. These technologies make it potentially possible to vary water and agrochemicals (e.g., labeled water-soluble compounds and wettable powders) to meet the specific needs of a crop in each unique zone within a field to optimize crop yield and quality goals while improving environmental health (reduced water, agrochemical use, and leaching). Microprocessor-controlled center pivot and linear move irrigation systems also provide a unique control and sensor platform to provide the real-time data that is necessary to achieve the maximum potential for economical and effective precision-irrigated crop management. Potential water savings under nonstress conditions (maximum yield) using site-specific technologies are probably on the order of about 5% or less, but may be in the range of 15% to 30% [*Sadler et al.*, 2005].

[96] The ability to vary water application along the main lateral of the center pivot on the basis of position in the field would allow the field manager to address specific soil and/or slope conditions. By aligning irrigation water application with variable water requirements in the field, total water diversions may be reduced and, almost certainly, deep percolation and surface run off will be reduced. Energy use and other production costs may also be lowered. However, installing the variable rate water application technology on these machines adds about $U.S. 250 to $300 per hectare to the initial cost [*Evans and Harting*, 1999; *Evans and Iversen*, 2005]. Reducing excess water applications will decrease the potential to move nutrients past the plant root zone [*King et al.*, 1995], and the fungal disease pressure should also decrease [*Neibling and Gallian*, 1997]. Position in the field can be determined by differential GPS, electronic compasses, or electronic angle resolvers. It may also be economically feasible to use low-cost, passive radio tag markers placed in specific locations across a field to provide acceptable precision for site specific management.

[97] The development of control and management technologies that can spatially and temporally direct the amount and frequency of water (and appropriate agrochemical) applications by "precision" self-propelled irrigation systems would be a very powerful tool, increasing productivity and minimizing adverse water quality impacts. There is also a need to develop more efficient methods of applying crop amendments (e.g., nutrients, pesticides, and growth regulators) to reduce usage, improve profit margins, and decrease environmental impacts.

[98] Research on variations in site-specific irrigation using self-propelled center pivot and linear move irrigation machines has been undertaken at Ft. Collins, Colorado [*Duke et al.*, 1992; *Fraisse et al.*, 1992]; Aberdeen, Idaho [*McCann and Stark*, 1993; *King et al.*, 1995; *McCann et al.*, 1997]; Prosser, Washington [*Evans et al.*, 1996]; Florence, South Carolina [*Camp and Sadler*, 1994; 1997; *Sadler et al.*, 1996; *Omary et al.*, 1997; *Camp et al.*, 1998, 2002; *Sadler et al.*, 2002a, 2002b]; and Sidney, Montana [*Evans and Iversen*, 2005]. The equipment and methods developed in Prosser were installed on a three-pivot cluster in commercial farms in south central Washington State and in north central Oregon [*Harting*, 1999; *Evans and Harting*, 1999]. A large farm in north central Oregon is currently using site-specific technologies on several center pivots to conserve energy as well as enhance productivity on shallow soils. Figure 2 is a photograph of a research installation with the capacity for site-specific water application on a self-propelled sprinkler irrigation system. These projects demonstrate it is possible to economically install and operate precision site-specific irrigation on self-propelled linear move and center pivot systems.

#### 4.2.2. Microirrigation

[99] Microirrigation offers the potential for high levels of water savings because of precise, high-level management and is an extremely flexible irrigation method. Generally, their high cost and intensive management requirement currently restricts its use to relatively small field sizes. Microirrigation can be adapted to almost any cropping situation and climatic zone. Microirrigation can be used over a wide range of terrain, and it has allowed expansion of irrigated crop production into areas with problem soils (either very low or very high infiltration rates), salt affected soils, and poor water quality that could not be utilized with other irrigation methods. It can be installed as either a surface [*Schwankl and Hanson*, 2007] or subsurface [*Camp*, 1998; *Lamm and Camp*, 2007] water application system. As noted earlier, microirrigation is used on less than 1% of lands worldwide, primarily because of its recent development and high initial capital cost.

[100] Microirrigation can be used on most agricultural crops, although it is most often used with high-value specialty crops such as vegetables, ornamentals, vines, berries, olives, avocados, nuts, fruit crops, and greenhouse plants because of its relatively high cost and management requirements. In many cases, it can also be economically used for field crops, golf greens, fairways, cotton, and sugarcane. However, the requirements for appropriate designs and management in humid areas can be considerably different from those in arid areas, so the technology and techniques suitable in one area may not work in another. Such an irrigation method will not be the most appropriate or economical in all situations, but changing the economic viability because of water shortages could dramatically change this picture.

[101] The use of microirrigation is increasing around the world, and it is expected to continue to be a viable irrigation method for agricultural production in the foreseeable future. With increasing demands on limited water resources and the need to minimize environmental consequences of irrigation, this technology will undoubtedly play an even more important role in the future. Microirrigation provides many unique agronomic as well as water and energy conservation benefits that address many of the challenges facing irrigated agriculture.

[102] Farmers and other microirrigation users are continually seeking new applications, such as wastewater reuse, that will continue to challenge designers and irrigation managers. Even with its many variations, however, substantial benefits are possible if microirrigation can be made less expensive to allow growers to adopt and utilize these technologies, especially in developing countries.

#### 4.2.3. Supporting Technologies

[103] Ensuring the success of irrigated farming enterprises will require the development of reliable, more timely information on field and plant status to support decision making. Current plant models capable of predicting the physiological needs of a crop over space and time tend to be complex and only work on one set of accurately defined input conditions based on one point in a field, and are generally impractical for real-time on-farm management. However, simple models might be accurate enough, but still need to be developed. These models would likely rely on frequent updating via automated, field-based sensor systems to readjust model variables, thereby ensuring reasonable tracking and spatial predictions of field conditions for model corrections.

[104] Remote sensing of plant and soil status using integrated satellite, aerial, and field-level plant- and soil-based sensor systems can provide information on plant and soil nutrient and water status. Nevertheless, this technology needs further development to improve spatial-temporal modeling and hands-on use for on-farm management as well as irrigation district operations. Better systems and methods capable of measuring specific plant parameters (e.g., nutrient status, water status, disease, competing weeds) on a timely basis are becoming available, and are expected to provide information required to enhance crop modeling use and thus improve within-season management.

[105] Real-time, on-the-go irrigation scheduling could be very effective in improving water management when based on distributed networks of farm-level microclimate and soil water sensor stations that feed into a microprocessor control system to manage irrigations according to rules preestablished by the producer. This effort must be supported by expanded agricultural weather networks that incorporate greater spatial density as well as by grower-friendly information delivery systems that schedule irrigations in terms of pest management and marketing information. Input from distributed weather networks must be integrated with other information from remotely sensed and ground-based sources to effectively contribute to on-farm and irrigation district decision support processes.

#### 4.2.4. Decision Support

[106] Improved irrigation technologies, while usually requiring less field labor, often demand more intensive management. Thus, support aids must also be developed that improve the producer's ability to implement decisions quickly and easily; however, this also requires control and monitoring systems. Decision support systems are needed to help make timely decisions based on complex inputs. Climatic variations and pest outbreaks require precisely timed and placed water and chemical applications on a daily and seasonal basis. The decision support process must also provide accurate predictions of crop water use, application efficiencies, and uniformities to improve management flexibility.

## 5. Integration of Components Into Whole Systems

[107] System-level optimization with appropriate feedback mechanisms will be required on a regional or irrigation district level to enable growers to conserve water. In terms of the hydrologic balance equations (presented elsewhere), one would expect maximum production if all terms that do not produce yield were eliminated, leaving all water for productive use. This has been the incentive for reducing conveyance systems leaks and spills, to reduce field runoff or leaching, and to use subsurface drip irrigation to reduce soil evaporation. However, in the systems perspective, some of these uses that do not produce immediate yield increases can contribute to long-term yield. A leaching requirement in arid and some semiarid areas is a good example as irrigation without some leaching can eventually lead to soil salination. There may be some short-term benefit from evaporation in that it helps meet the energy balance. And, at the watershed or basin level, loss from one system may be the water supply to

the next system downstream. Thus, any manipulation of the system must consider the whole system; compartmental optimization is not likely to provide the global optimum.

[108] The cultural, engineering, management and institutional systems are interdependent, and it is necessary to custom design a synergistic mix of strategies that fit the delivery systems, farming culture, crop water use patterns, soils, regional hydrology, and other environmental characteristics unique to an area.

[109] Inherent in the evolution of on-farm management is the integration of irrigation, fertilizer, and pest management strategies into systems that optimize total management practices for temporal and spatial variability using precision agriculture tools. This integration will require broad systems approaches that physically and biologically optimize irrigations with respect to water delivery and application schemes, rainfall, critical growth stages, soil fertility, location, and weather. Spatial and temporal management strategies will need to address site-specific crop requirements for water, nutrition, pest management, and irrigation scheduling in both agrarian and urban settings. There will be a mix of strategies and systems that will be integrated differently in every watershed for every cropping system choice.

## 6. Conclusions

[110] Irrigation is globally critical to quality of life, providing at least 40% of the total worldwide food and fiber supply. Despite current problems and negative perceptions in many sectors of society, irrigation continues to be a necessary and important component of the world's well being and growth.

[111] The paradox is that agriculture needs to increase production to meet societal needs; but the productive irrigated land base and available water is declining. This will probably lead to targeting inputs to meet yield goals somewhere near the economic optimum; however, increasing the efficiency of water use usually means reduced yields at some level. Such production will necessitate a major paradigm shift in water use within the next 25 years in many areas in the world. Both urban and rural users will need to lower and adjust their expectations on how and where water will be used; and they may have to accept much higher water and food prices as a result.

[112] Genetic approaches will be a necessary part of more efficient irrigated production (both typical and supplemental). However, there is a much greater possibility of reducing water consumption with improved management of water than with biotechnology and breeding, at least in the short term.

[113] Major water-saving improvements from irrigation in the future will be realized largely through the management and innovative design of integrated water delivery and field irrigation systems for both agrarian and urban settings. Rural and urban irrigators will have to improve productivity per unit of water consumed. However, doing so will require major systematic cultural, managerial, engineering and institutional changes. This must be supported by system-wide enhancement of water delivery systems, advanced site-specific irrigation technologies that include self-propelled sprinklers and microirrigation systems, and other supporting monitoring, modeling and control technologies. Decision support tools will be needed to assist growers and managers in optimizing the allocation of limited water among crops, selection of crops by regions, and adoption of appropriate alternative crops in drought years.

[114] Carefully managed deficit irrigation on agronomic crops would provide the greatest potential for substantially reducing agricultural water use because of the larger land areas that are involved. High-value crops may also produce some water savings through various deficit irrigation strategies, but their impact will be much lower because they generally occupy less than 10% of irrigated area (location specific). However, deficit irrigation strategies still must be developed for most crops. Advanced irrigation technologies and state-of-the-art delivery systems, will be needed to be able to be able to fully implement successful deficit irrigation strategies. Precision agriculture tools such as site-specific water and nutrient applications will play an important role.

[115] Managing and developing infrastructure and policies for water security to equitably satisfy the demands of all users of this limited resource will be a challenging and lengthy task. Changes in policy and incentives will clearly become necessary. However, water and land resources and their many complex and competing uses must be considered in a comprehensive regional and international framework. Improvements should be systematic, not concentrated on only one or two components of the hydrologic system.

[116] Irrigated agriculture can reduce its water use while maintaining reasonable production levels. However, the challenges are substantial. In this era of declining field research on cropping systems, we must determine the specific knowledge and technologies required to accomplish this sustainability. To function as a society, we have to trust enough water will be available to satisfy all the needs for food, fiber, feed, and fuels in addition to environmental, recreation and municipal requirements. Nevertheless, major questions on water's allocation in each river basin and watershed remain to be resolved.

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