A review of evolving critical priorities for irrigated agriculture

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Abstract

The evolving roles and critical priorities of irrigated agriculture, as perceived by practitioners, researchers, and policy makers, were reviewed. Irrigated agriculture has played a vital role in meeting food and fiber demands on a relatively small proportion of total arable land. This role is presently expanding to also include biofuel and industrial materials production. At the same time, water availability is almost universally declining where intensive irrigation has been developed. This has been mainly due to declining water resources, inadequate storage capacity, or greater competition from non-agricultural uses. Although certain priorities may be specific to a location or region, the unifying priorities for irrigated agriculture, in order to meet unprecedented demands by a worldwide population that is increasing both in size and in industrialization, are to increase water productivity, sustain ecosystems, find synergy and avoid conflict among agriculture, urban and environmental uses of water resources.

Introduction

Irrigated agriculture has been practiced by human civilization for some 6,000 years and has enabled parts of the world to be inhabited where precipitation is too sparse or erratic to produce adequate rainfed crops. Irrigation enhances the production potential of cultivated lands several times over dryland crops, and is largely responsible for sustaining the unprecedented human population of 6.6 billion as of 2007. Literature reviewed in this paper suggested that, although only about 15-20 percent of the world's cultivated land is irrigated, this portion produces about 40 percent of the harvested crop yield. Projected estimates of world population range from 9 to 14 billion by 2050, and most population expansion is expected in developing nations. Irrigated agriculture is expected to supply about two-thirds of additional needed food.

At the same time, many regions have already experienced limitations in irrigated crop production, the primary constraint usually being water resources. Presently, approximately 70 percent of worldwide freshwater diversions and withdrawals from surface and groundwater are for agriculture (IWMI 2007). Although not all of this water is consumptively used, it is often returned in a lesser quality. Numerous civilizations have developed and declined around irrigation, while a few have managed to achieve some level of sustainability (van Schilfgaarde 1994). It is clear that many of the forces that have determined whether a society based on irrigation survives are at work today but on a much greater and more complex scale. Competition for limited water resources for agricultural, municipal, industrial, and recently environmental and recreational purposes is escalating worldwide. Many regions where irrigation has been developed are threatened by groundwater depletion. Salinity and impaired water quality continue to degrade cultivated land and reduce biodiversity and environmental quality. Many irrigation distribution networks go through repeated cycles of decay and rehabilitation; even with infrastructure in good repair, inefficiencies abound due to institutional, social, and policy arrangements. The list of problems and unsustainable practices seems overwhelming, but many feel that the combination of hindsight, technology (both old and new), and enlightened policies can and must move irrigated agriculture to a new level of efficiency and sustainability that can simultaneously feed and allow the other water-based needs of an ever expanding population to be met.

The objectives of this paper are to review the priorities perceived as critical for irrigated agriculture in meeting demands of the 21st century. This paper is not intended to belabor precise definitions of various terminology used in assessing the outcome of allocating water for irrigated crops (e.g., irrigation efficiency, water use efficiency, water productivity), as this has been addressed in other works (e.g., Tanner and Sinclair 1983; Burt et al. 1997; Zoebl 2006; Perry 2007). It is hoped that this review will help to put irrigated agriculture in perspective as a vital component of human civilization.

Materials and Methods

Material for this review was drawn primarily from journal articles, monographs, and symposium proceedings (i.e., International Conference on Evapotranspiration and Irrigation Scheduling held in San Antonio, Texas, USA in 1996; 4th Decennial National Irrigation Symposium held in Phoenix, Arizona, USA in 2000), from the National Research Council’s report on Water Implications of Biofuels Production in the United States (NRC 2007), and from the International Water Management Institute (IWMI) Comprehensive Assessment of Water Management in Agriculture (IWMI 2007). A survey targeted to irrigation professionals was also initiated by the

On Farm Irrigation Committee's task committee on Putting Irrigated Agriculture in Perspective through EWRI in early 2008. Although survey results are presently incomplete, we anticipate presentation of these results in the 2008 EWRI World Environmental and Water Resources Congress and in future journal articles.

Results and Discussion

Tanner and Sinclair (1983) presented a critical review of investigations of the ratio of biomass to evapotranspiration (ET) and its relationship to water use efficiency (crop yield per consumptive use of water) and efficient water use (economic return per investment of water). Based on theoretical considerations, which were supported by data obtained from climates ranging from humid to arid, they concluded that the greatest potential gains in water use efficiency on a national scale reside in irrigated crop production in humid regions, and recommended "greater emphasis on water management and irrigation technology in these humid regions."

Clothier (1989) identified six areas of ongoing research, as well as two underdeveloped research areas, that should be pursued to increase irrigation efficiency (more marketable yield per unit of water). The six areas of ongoing research were related to either crop meteorology (stomatal behavior, evaporation, local advection, and regional ET), or soil physics (micro- and macroscale soil variability, redistribution of root zone water following irrigation, and soil solute transport). He noted that plant root dynamics and sensing plant and soil water status remained underdeveloped, and urged that these be expanded. He also noted the irony that irrigation science has developed with emphasis on either soil water or crop meteorology, with relatively little attention on the plant itself.

NATO Workshop on Sustainability of Irrigated Agriculture, 1994

Pereira et al. (1996) proposed a research agenda for sustainable irrigated agriculture based on a North Atlantic Treaty Organization (NATO) workshop held in 1994, with the additional aim of integrating "existing and potential science and technology into improved irrigation system performance, in order to ensure sustainable irrigated agriculture." Workshop participants included irrigation researchers and practitioners from both developed and developing countries.

They recommended that, although specific problems vary by country or region, a holistic approach should be taken in all research endeavors that integrate "technical, environmental, social, and economic" aspects. This holistic approach was a basic prerequisite for achieving sustainability, whereby the needs of present generations are met without compromising the needs of future generations. In particular, environmental quality should no longer be externalized as has been in the past, but should be considered intrinsic to basic living needs. Also, slowing worldwide population growth was identified as an urgent priority.

Specific research priority areas were identified and ranked as follows, with the same number indicating a tie among workshop participants: (1) Environmental and health impacts; (1) Water quality management; (2) Rehabilitation and modernization of irrigation systems; (3) Technology and rules for the use of water, saline affected water and water with a high organic loading (i.e., sewage effluent); (3) Policy issues; (3) User participation in planning and managing irrigation and drainage systems; (4) Basin wide, integrated water resources planning; (4) Human resources development; (5) Water savings (reducing demand and waste); (5) Irrigation and drainage system performance; (6) Rainfed agricultural water management and water harvesting; (6) Economics in the development of both irrigated and rainfed agricultural schemes; (7) Land and water institutional issues; and (8) Availability of land and water resources.

<u>The International Conference on Evapotranspiration and Irrigation Scheduling, 1996</u>

The International Conference on Evapotranspiration and Irrigation Scheduling was held in San Antonio, Texas, USA in 1996, and was jointly sponsored by the American Society of Agricultural Engineers (ASAE), the Irrigation Association (IA), and the International Commission on Irrigation and Drainage (ICID). The Proceedings contained 178 papers occupying 1156 pages, suggesting that ET and irrigation scheduling research and technology transfer were high priorities for irrigated agriculture in the mid 1990s. Most papers stated that increasing water use efficiency, increasing crop productivity, or otherwise maintaining crop productivity with less water (making it available to competing users; i.e., environmental, urban, or other agricultural) was the ultimate goal. Two papers discussed priorities in terms of a larger scope and are briefly discussed here.

Howell (1996) reviewed the impact that irrigation scheduling research since the early 1970s had on irrigation water use. He recommended six areas of research and technology transfer deemed to have the greatest impact on improving irrigation efficiency and crop productivity. These were ET estimation, ET spatial variability, irrigation water balance (i.e., better accounting of fluxes into and out of real world systems), integrated irrigation scheduling with feedback control (i.e., exploit a broader source of feedback data), sensor and information technology, and water quality constraints.

Fereres (1996) offered various starting points for irrigation scheduling, depending on the extent that a country may be developed. Climate and soil data sets were identified as the first step in optimizing irrigation scheduling under the constraints of water supply typical of less developed countries, whereas more sophisticated irrigation scheduling approaches such as early detection of crop water stress and automation would be meaningful for more developed countries.

Both Howell (1996) and Fereres (1996) discussed barriers to adoption of irrigation scheduling; these included deep-rooted behavior and attitudes of farmers, which may well be reinforced by increasing technical complexity.

The 4th Decennial National Irrigation Symposium, 2000

The 4th Decennial National Irrigation Symposium was held in Phoenix, Arizona, USA in 2000, and was sponsored by ASAE and IA. This symposium addressed a broad range of irrigation topics; several keynote addresses and papers on irrigation development that discuss larger scope priorities are briefly reviewed.

Postel (2000) provided a synopsis of her highly acclaimed book *Pillar of Sand: Can the Irrigation Miracle Last?* (Postel, 1999). Postel and many others have observed that nearly all civilizations that developed based upon irrigation ultimately failed, mainly due to salinity build up but also for other reasons such as drought, disease, war, overpopulation, dysfunctional governing bodies, and other environmental degradation. By 2000, irrigated agriculture produced 40 percent of all food and fiber on 17 percent of arable land. Therefore, it is reasonable to conclude that modern civilization is highly based on irrigation just as those in the past were. Furthermore, all of the conditions that caused previous civilizations to fall are present today but on a much larger scale. However, Postel argued that the combination of hindsight, appropriate technology, and reversal of long-standing water policies and societal customs that traditionally discouraged conservation provides the impetus for redesigning a sustainable irrigated agriculture, this being despite seemingly insurmountable obstacles imposed by an ever-expanding world population.

Chapman (2000) provided an overview of the irrigation manufacturing industry, and shared the consensus that irrigated agriculture will be called upon to provide enough food for an expanding world population, and will be required to do so with less water resources. He showed that many advances in irrigation technology were the result of innovative growers and both privately and publicly funded research. However, he stated that private industry has been very limited in the amount of resources that it can devote to research and development, and called for greater support for publicly funded research for “water storage, application, utilization, conservation, and management.” He then listed twenty two specific problem areas, which included precision agriculture applications (e.g., site-specific management of all farm inputs, particularly pesticides, and continuous feedback sensors), inter-cropping and relay crops, aquifer recharge, better rainfall utilization and harvesting, drainage, leaching and salinity management, and to “develop a fact-based response to the anti-irrigation lobby” that would elucidate the vital role that irrigation plays in alleviating poverty by providing food security.

Keller (2000) traced the development of river basins into three general eras, which he termed Exploitation, Conservation, and Augmentation. The Western United States had reached the Conservation era where nearly all basins have approached closure (i.e., all water supply is encumbered for use, and no additional water is available for any purpose). This then requires irrigation systems to be “reengineered” from both a technical and policy standpoint, which is intrinsic to rational water resource planning, management, and conservation. Reengineering generally involves changing flow pathways (i.e., evaporative, surface, and subsurface) so that water is conserved and available for a more urgent use.

Heermann (2000) reviewed the 1st, 2nd, and 3rd National Irrigation Symposia held in 1970, 1980, and 1990, respectively, and offered his speculation on irrigation's future. When the 1st National Irrigation Symposium was held in 1970, its primary aim was to foster better cooperation between research, industry, and extension. There were five technical sessions, including microirrigation (termed subsurface and trickle), surface (gravity) irrigation, sprinkler irrigation, water supply automation, and irrigation scheduling.

In 1980, the 2nd National Irrigation Symposium consisted of three main areas, including advances in irrigation systems, advances in irrigation systems management, and future needs of irrigation. Priorities, which included input from farmers, included the need for improved irrigation scheduling, greater automation of water delivery, more accurate estimates of crop water requirements, reduced energy requirements, and resolving salinity issues.

By 1990 at the 3rd National Irrigation Symposium, it was clear that the competing water users (municipal, industrial, environmental, and recreational) would permanently divert water from agriculture, and developing workable compromises between all parties had emerged as a new imperative. A more holistic approach, in both research and practice, was needed that considered resource stewardship and environmental protection. But these new priorities enhanced, rather than diminished, the need for continued development in technical areas. Water quality had become a more serious problem than water quantity. Continued development in salinity management would be required. Turfgrass and urban landscape irrigation had emerged as a distinct technical area. The rapid development in desktop and portable computers continued to spur advances in in-situ sensors, remote sensing, automation of irrigation systems, crop water use models, and integration of databases for irrigation management, all of which could contribute to producing more crops with less water.

At his keynote address at the 4th National Irrigation Symposium in 2000, Heermann's look at the present and visions of the future implied that the priorities identified in 1990 had intensified. The need for cooperation rather than antagonism between competing water uses remained, but at the same time, he called for a collective effort to prevent undue limitations in irrigation, which will be increasingly vital in averting food shortages. Closer cooperation between research, industry, and extension (e.g., Chapman 2000), should be pursued to ensue that new innovations will be practical and above all improve profitability for the producer, unlike some previous efforts such as automation of surface irrigation systems. He urged continued efforts between industry and producers in reducing non-point pollutants to avoid having additional regulations imposed.

Howell (2001) reviewed the state of irrigation in the United States and in the world, examined the role that irrigation plays in enhancing water use efficiency in agriculture, and discussed various pathways for increasing water use efficiency. As of 1996, irrigation was practiced on about 263 million hectares (Mha), or about 15 percent of the world's cultivated land, producing about 36 percent of the total harvest. This was similar to proportions estimated by Postel (1999; 2000) as 17 percent of cultivated land irrigated producing 40 percent of all food and fiber. Two-thirds of irrigated land is in Asia; about 49 percent of irrigation is in China, India, and the United States. The per capita irrigated area has remained stable at about 0.045 ha per person since the 1960s. Most increases in food production in developing countries will have to come from irrigated land, and this will comprise a combination of expanded area, yield increases, and greater cropping intensity.

Additional availability of freshwater is highly variable across the earth, but the general consensus is that overall supplies where irrigation has been developed are declining due to groundwater overdrafts, restrictions in surface water diversions, degradation of water quality, competition by competing users, or has become less reliable due to climate change. Therefore, enhancing water use efficiency at the watershed, basin, and field levels will be a priority for irrigated agriculture to meet ever increasing demands.

Citing Wallace and Batchelor (1997), Howell (2001) offered four general pathways for improving irrigation efficiency at the field scale, and noted that considering only one will not likely be successful. These included agronomic (enhanced rainfall capture, crop varieties, reduced evaporation measures such as conservation tillage), engineering (irrigation systems resulting in reduced application losses and/or improved distribution uniformity, elimination of runoff), management (demand-based irrigation scheduling, salinity management, slight to moderate deficit irrigation), and institutional (irrigation scheme or district management transfer to farmers, policy incentives for conservation and penalties for waste, training and extension). In addition to irrigation efficiency, there may be opportunities at the basin or watershed scale for "dry" water savings by reducing water losses to sinks or pollutants.

Skogerboe (2000) advocated that irrigation schemes in developing countries adopt two institutional measures developed in the American West: water rights and local management / ownership. Developing countries are expected to experience the majority of the world's population expansion in the coming decades, and as stated before, the majority of food production increases will come from irrigated agriculture. Many existing irrigation schemes are in need of rehabilitation and modernization, and are administered by a centralized government agency at tremendous expense. Numerous countries are therefore engaging in irrigation management transfer (IMT) of irrigation schemes and districts to localized entities, often consisting of farmers. Because centrally-administered irrigation schemes have poor track records for overall water use efficiencies, IMTs may have the potential for tremendous increases in food production and poverty alleviation. The success of

IMTs, however, has largely been contingent on arrangements that result in farmers' self empowerment, whereby efficiency and productivity lead directly to greater prosperity, an arrangement largely taken for granted in developed countries. Clyma (2000) describes a management process for public and private organizations that has shown to be effective for improving irrigation performance for a given entity.

Hargreaves (2000) urged developed nations to focus capital, technology transfer, and education into undeveloped countries to develop water and land resources necessary to avert a world crises in food, water, and environmental sustainability. He believed that existing land and water resources were more than adequate to meet growing populations, noting that less than eight percent of the annual renewable amount of freshwater resources has been utilized for all purposes. In undeveloped nations, development of water storage (i.e., dams) and irrigation distribution infrastructure will be necessary to halt slash and burn agriculture. He argued that modern hydraulic structures will have far less long-term environmental consequences compared with the rampant soil erosion, water pollution, decline in biodiversity, and decline in watershed storage capacities resulting from slash and burn agriculture and other unsustainable practices.

ASCE 150th Anniversary Jubilee Papers, 2002

The American Society of Civil Engineers (ASCE) celebrated its 150th Anniversary Jubilee in 2002, and the ASCE Journal of Irrigation and Drainage Engineering included a special section of commemorating papers. Three papers addressed overall priorities of irrigated agriculture.

Bouwer (2002) recommended an integrated approach for water management where coordination between all users (municipal, industrial, agricultural) is emphasized. He argued that there is enough freshwater available to support at least three times the present world population, with water shortages due to mismatch between population and precipitation distributions. Most of the world's water (97 percent) occurs as saltwater in oceans, with 2 percent as snow and ice in the polar and mountainous regions, leaving only 1 percent as liquid freshwater. Of this 1 percent, 98 percent occurs as groundwater, and 2 percent as surface water. This works out to an annual renewable water supply of 7,000 m^3 per capita, or over three times the 2,000 m^3 annual per capita required for living standards considered adequate in industrialized nations, and many times greater than what a large portion of the world's population is presently subsisting on. He advocated development of additional water storage (e.g., dams, aquifer recharge) in developing nations, but also pointed out that importing food from water-rich nations (i.e., virtual water) can be less expensive than developing water resources for water-short nations. Numerous other options exist for water resource management, such as conjunctive use, water banking, irrigation of agricultural crops with municipal or industrial effluent, or augmentation of supplies by desalinization. However, each of these is fraught with issues such as water rights complicated by indeterminate aquifer boundaries, salinity buildup, or nonpoint pollutants, and so each requires careful and rational scientific and engineering approaches to avoid undue risk to health standards or environmental quality.

Bouwer (2002) addressed the potential impacts of global climate change on water resource management with a very insightful discussion of the numerous counteracting forces and processes, such as interactions between carbon dioxide concentrations, ET, plant growth, and crop yield. Many predictive efforts have only resulted in exasperating uncertainties, which in turn have escalated the controversy. Nonetheless, the hydrologic infrastructure base for many regions and entire nations was designed based on relatively limited climatic records, which did not anticipate the earlier snowmelt, runoff, and longer dry seasons associated with climate change. There is serious concern that water storage and conveyance will become completely inadequate in the near future, at a time when the welfare of not only agriculture but also growing urban populations (e.g., the American Southwest) will depend on this infrastructure like never before. He provided a succinct passage taken from Kimball (2003), who in the end concluded that “It behooves future water resource planners and growers to try to be as flexible as possible.”

So far this discussion has assumed, either explicitly or implicitly, that the primary objective of irrigation is for biological optimization of applied water (i.e., greatest crop per drop). However, English et al. (2002) point out that the biological objective does not necessarily coincide with the economic objective of maximizing net returns, and argue that the converging pressures of water competition and scarcity, environmental concerns, and expanding human population will prompt economic, not biological, optimization strategies to prevail. They state that economic optimization has already been implemented on a “limited and largely intuitive” basis, and formalize this concept for a variety of situations (e.g., limited or unlimited available water, multiple fields and crops, leaching for salinity control, efficiency, and environmental impacts). Negative environmental impacts of irrigation are often associated with leaching and/or runoff of non-point pollutants, which in turn are associated with excessive pumping and energy costs, coupled with excessive nitrogen and/or other chemical application. Therefore, maximizing net benefits can have mitigating effects on environmental impacts. For saline conditions, matching irrigation to leaching requirement remains a formidable challenge, but they present evidence to support the basis of economic optimization leading to reduced soil salinity and long-term sustainability. Biological optimization entails a relatively simple relationship between crop yield and ET, but economic optimization is far more complex and will require multi-objective optimization, more sophisticated physical models, better field sensing technology, and analytical tools previously not considered in irrigation management.

Tanji and Keyes (2002) reviewed the history, legislation, and policies of irrigation and drainage in the United States, water quality programs and constituents of concern, and provide a prognosis of irrigation from a water quality standpoint drawn from the National Research Council’s report on “A new Era for Irrigation” (NRC 1996). In brief, their conclusions were similar to those of other works cited herein regarding the critical priorities of irrigated agriculture in the United States. They also anticipated that return flows from irrigation will require treatment, especially if there is to be greater utilization of impaired waters, in order to meet quality standards for the next user and satisfy environmental goals. Since agriculture can no longer be viewed as an isolated entity but an integral component of diverse water users, they called for greater interaction with other disciplines (e.g., soil and crop scientists, hydrologists, regulators, economists, and policy makers) in seeking solutions to water quantity and quality problems in the coming decades.

Implications of Biofuel Production

The first decade of the 21st century has seen events and changes that were not likely to have been anticipated by even the most astute prophets. The terrorist attacks on September 11, 2001, the subsequent military action in the Middle East, evidence of accelerated global warming and climate change, unprecedented oil and natural gas prices, and a volatile world economy, have linkages that have made both energy independence and reductions in greenhouse gas production extremely urgent priorities for industrialized nations, particularly the United States. This has spurred renewed interest and rapid development of renewable and "green" energy resources such as wind, solar, and biofuels. Regardless of one's stance on climate change, greenhouse gases, or the long-term feasibility of biofuels, it is clear that biofuel demand has greatly expanded the role of irrigated agriculture to that of renewable energy production, which has firm linkages with the environmental, industrial, and municipal sectors.

Because large-scale biofuel production is a fairly recent development, there is a paucity of literature on its implications for irrigated agriculture; however, the National Research Council's report on Water Implications of Biofuels Production in the United States (NRC, 2007) provided an overview.

In 2006, ethanol production in the United States was approximately 18.6 million m^3 (4.9 billion gallons), mostly derived from grain corn, with less than 379,000 m^3 (100 million gallons) derived from grain sorghum. This represents 3.6 and 2.4 percent of the total annual gasoline demand on a volume and energy basis, respectively. Ethanol derived from cellulose (e.g., native grasses, corn stocks, wheat straw, and other biomass) is expected to become significant in the near future. President Bush called for ethanol production to reach 132.7 million m^3 (35 billion gallons) annually by 2017, or 15 percent of U.S. liquid transportation fuels. The U.S. Department of Energy and Department of Agriculture estimated that ethanol production could reach 227.4 million m^3 (60 billion gallons), or 30 percent of the projected gasoline demand, by 2030 using grain and cellulose feedstocks. Biodiesel production was much less, at about 379,000 m^3 (100 million gallons) derived primarily from soybean oil, with very little derived from other vegetable oils and recycled grease. Projected ethanol production from both grain and cellulose assumed a cropland base of 176 Mha (434 million ac). As of 1997, irrigated cropland in the U.S. was about 22 Mha

(54.3 million ac), or about 18 percent of the total harvested cropland of 122 Mha (301 million ac) (Howell, 2001).

It is unclear how this doubling of cropped land if food production is not reduced will impact irrigated agriculture. While much of the increase may be in rainfed agriculture, increase in irrigated agriculture is also likely. The demand for irrigation water would be expected to increase, but to what extent is presently difficult to pinpoint. The production of crops for biofuels was not expected to drastically change the aggregate national water consumptive use during the next decade. However, expansion or intensification of irrigation in some regions was expected to exacerbate already stressed water resources. It is conceivable that changes in cropping patterns may reduce water use in other areas. Crop water requirements have been fairly well established for traditional crops; however, crops designed for biofuel may have different responses to water, which will likely vary by region. The extent that cellulose is used in the overall feedstock mix causes additional uncertainty on overall water requirements, since cellulose generally has much less water requirements than grain feedstocks. Greater commodity prices may justify conversion to advanced irrigation systems, such as level basin, low-energy precision application (LEPA), or subsurface drip irrigation (SDI). These systems can potentially result in greater application efficiency and distribution uniformity (i.e., “dry” water savings) when property designed, installed, and managed, but have a much smaller effect on consumed water than diverted or withdrawn water. Use of impaired water or effluent may be an additional resource that would otherwise be unsuitable for food crop production. Assessing the impacts of biofuel production on water resources will provide a new drive for irrigated land inventories and ET mapping using fine-resolution remote sensing.

Biofuel refineries (biorefineries) also require water. Although the overall consumptive use for biorefineries is far less than that of irrigated crop production, new biorefineries will likely strain local or regional water supplies, especially for rural areas. Present consumptive water use for processing grain corn into ethanol is just over four to one (i.e., four gallons of procession water are required for every gallon of ethanol product). Cellulose is presently estimated between two and six gallons per one gallon of finished ethanol.

Climate change and greater atmospheric carbon dioxide concentrations may result in increased crop yields, but also increase crop water requirements. Greater rainfall during the growing season in some areas (e.g., humid Midwest and Eastern U.S.) may compensate for greater crop water requirements, whereas decreased rainfall and earlier mountain snowmelt in other areas (e.g., arid Western U.S.) may severely reduce the production potential.

<u>Comprehensive Assessment of Water Management in Agriculture, 2007</u>

The International Water Management Institute (IWMI) organized the Comprehensive Assessment for Water Management in Agriculture to address the overarching question: “Can water in agriculture be developed and managed to help end poverty and hunger, ensure environmentally sustainable practices, and find the right balance between food and environmental security?” (IWMI 2007). This effort was the result of over 700 individuals, organizations, institutions, and networks, and their final report underwent extensive and rigorous peer review. Their overall conclusion was “Yes, if we act now.” Like Bouwer (2002) and Hargreaves (2000), they concluded that enough renewable freshwater exists to meet the triple goal of ensuring food security, reducing poverty, and sustaining ecosystems. One of the key requirements is to increase water productivity.

The Comprehensive Assessment considered several scenarios, which included investments in rainfed or irrigated production systems, enhancing food trade (e.g., “virtual water transfer”), and a combination of each element. Much of the world’s low-yielding cultivated land has untapped potential, and the greatest potential for yield increases are in the rainfed areas of Sub-Saharan Africa, Asia, and Latin America, where many of the impoverished live. But there is also great potential to increase crop water productivity on existing irrigated land, especially in parts of Asia and Eastern Europe. Some expansion of new irrigated area will be required, with the best prospects being in Sub-Saharan Africa. Without increases in land productivity, the harvested area and crop ET (largely met by additional freshwater withdrawals) would have to double by 2050. With a combination of productivity increases in both rainfed and irrigated production systems and enhanced agricultural trade, the required increases in cropped area and irrigation withdrawals could be substantially less; the most optimistic estimates were 9 and 13 percent, respectively. In any case, the definite increase in agricultural water use underscores the need for integrated water resources management, where agriculture is no longer viewed as an isolated system, but a prerequisite to human survival.

The Comprehensive Assessment recommended eight specific policy actions, briefly quoted here as “(1) Change the way we think about water and agriculture; (2) Fight poverty by improving access to water and its use; (3) Manage agriculture to enhance ecosystem services; (4) Increase the productivity of water; (5) Upgrade rainfed systems – a little water can go a long way; (6) Adapt yesterday’s irrigation to tomorrow’s needs; (7) Reform the reform process – targeting state institutions; (8) Deal with tradeoffs and make difficult choices.”

Conclusion

Over the past 30 years, irrigation professionals have been increasingly focusing on the challenges of irrigated agriculture in meeting future food demands in an environmentally sustainable manner. The evolution of priorities appears to have grown to greater urgency, diversity, and complexity, and it does not appear that one set of priorities have been completely supplanted by others. A persistent priority has been the need to produce more crop yield with less water, both in rainfed and irrigated agriculture. This has been expressed in numerous ways such as water use efficiency, irrigation efficiency, crop water productivity, etc. Each of these measures vary widely in their precise definitions, but all works reviewed herein share the consensus that achieving greater production with less water is absolutely essential. Doing so will require continued advances in technology, but with the caveat that technology alone seldom leads to desired outcomes, even in highly industrialized countries. Numerous barriers exist to efficient irrigation practices, and these barriers are often institutional as well as technical. Much attention has been given to declining water resources or increased competition for available supply in irrigated regions. While it is true that some watersheds are at or past their sustainable limit, enough renewable freshwater exists on earth to support a much greater human population. The problem is that freshwater distribution does not match population distribution. The problem of water shortage and inequitable distribution can be overcome through a variety of measures, such as new water resources development, virtual water transfer (moving food rather than water), integrated water management, focus on supplementing rainfed agriculture and localized management of irrigation infrastructure combined with societal arrangements that encourage efficiency. There is increasing concern about what effects climate change will have on water resources, but uncertainties have so far precluded any consensus. In response to the threat of climate change, soaring oil costs, and world economic and political instability, biofuel production has emerged as a new industry that will place even greater demands on irrigated agriculture. These future uncertainties combine with the known challenges to underscore the importance of solving water management challenges with a more integrated, holistic approach.

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