Water for Agriculture: Maintaining Food Security under Growing Scarcity

Mark W. Rosegrant, Claudia Ringler, and Tingju Zhu

Environment and Production Technology Division, International Food Policy Research Institute, Washington, District of Columbia 20006-1002; email: M.Rosegrant@cgiar.org, c.ringler@cgiar.org, t.zhu@cgiar.org

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depletion, evapotranspirative demand, intersectoral competition, water security

Abstract

Irrigated agriculture is the main source of water withdrawals, accounting for around 70% of all the world's freshwater withdrawals. The development of irrigated agriculture has boosted agricultural yields and contributed to price stability, making it possible to feed the world's growing population. Rapidly increasing nonagricultural demands for water, changing food preferences, global climate change, and new demands for biofuel production place increasing pressure on scarce water resources. Challenges of growing water scarcity for agriculture are heightened by the increasing costs of developing new water, soil degradation, groundwater depletion, increasing water pollution, the degradation of water-related ecosystems, and wasteful use of already developed water supplies. This article discusses the role of water for agriculture and food security, the challenges facing irrigated agriculture, and the range of policies, institutions, and investments needed to secure adequate access to water for food today and in the future.

Contents

Water withdrawal: water removed from a source (e.g., rivers, lakes, and groundwater aquifers) and used for human needs

Water consumption: water made unusable for reuse in the same basin through irrecoverable losses including evapotranspiration, seepage to a saline sink, or contamination

1. INTRODUCTION

Water makes a major contribution to both rainfed and irrigated production, spanning a continuum from purely rainfed to purely irrigated with the majority of crops produced from rainwater. Globally, most food is produced from soil moisture that comes exclusively from precipitation. Irrigation systems also receive most of their water from precipitation (1, 2). However, as irrigated cereal yields are 60% higher, on average, than rainfed yields, strategies for yield improvements often focus on how to improve or expand access to irrigation, ideally in combination with fertilizers and other crop inputs (3, 4).

Without irrigation, the rapid increases in agricultural yields and outputs that have occurred over the past three decades could not have been achieved. Although irrigation is often associated with adverse environmental and sometimes also social impacts, it remains one of the most critical inputs into farming. Irrigation also contributes to poverty reduction, affordable food prices, and—through its significant multiplier effects—improvements in many other livelihood outcomes, such as health and nutrition (5–7). Moreover, irrigation systems often serve many other rural water uses, including those for rural domestic water supplies, household gardens, livestock, fishing, recreation, and other enterprises (8, 9). Although these are generally high-value water uses, it is often women or marginalized social groups (e.g., pastoralists or fishers) who depend on these activities. Irrigation also has multiplier effects for nonagricultural and urban areas (10–11) that increase nonagricultural outputs contributing to poverty reduction in both rural and urban areas.

2. TRENDS IN WATER USE IN GLOBAL FOOD PRODUCTION

Irrigation covers 20% of all cultivated land and accounts for about 40% of agricultural production (12). Global water withdrawals were estimated at about 5000 km^3 in 2000, and total water depletion or consumption—which refers to the volume of water that is permanently lost (through evapotranspiration or flow to salty sinks, etc.) and cannot be reused in the water system, typically a river basin—was estimated at about 2900 km^3 (3).

By 2050, the global population is expected to increase to 9.2 billion, 86% of whom will live in less-developed countries and 70% in rapidly growing urban areas. Fifty-three percent of cereal production growth during 2000–2050 is expected to be met from irrigated agriculture. A growing share of these cereals is projected to be used as animal feed to meet the rapidly growing demand for livestock production, particularly in Asia (13). Moreover, more affluent diets will translate into greater demand for more water-intensive crops, such as sugarcane and horticultural crops.

Global water consumption from irrigation, domestic, industrial, and livestock uses is expected to grow by 21% by 2050. Regionally, developing countries are expected to increase consumption by 25%, and in the developed regions, the increase is more moderate, at 11%. Global crop water consumption from both precipitation and irrigation is expected to increase at 0.7% per year, from 6400 km^3 in 2000 to 8600 km^3 by 2025 and to 9060 km^3 by 2050. Irrigation water depletion accounted for 22% of total crop water depletion in 2000. This share is expected to decline to 20% of total crop water depletion by 2050, despite higher growth in the expansion of irrigated area compared to the expansion of rainfed area (14). The reason is the higher projected relative expansion of irrigated area in wetter conditions, where a relatively smaller share of total crop water use is accounted for by irrigation water. Other estimates of the global share of irrigation water depletion in current global crop production are similar (around 20% to 30%) but vary widely across regions depending on the dominant mode of production (1, 15, 16). Rockström et al. (1) also find that the share of irrigation water depletion is likely to fall in the future.

Globally, irrigated harvested area is expected to increase by 0.24% annually during the period 2000–2050, and rainfed harvested area may increase by 0.13% per year. Total harvested area is projected to expand rapidly during 2000–2025 followed by a contraction during 2025–2050 as population pressure declines. Total harvested irrigated area is expected to increase from 421 million hectares (ha) in 2000 to 473 million ha by 2050. Asia continues to contribute the largest share to total irrigated area, followed by Latin America. In sub-Saharan Africa, only 6% of cultivated area is currently irrigated. Despite a projected more than doubling of irrigated area in sub-Saharan Africa, the region will still account for a very minor share—about 2%—of global harvested irrigated area by 2050 (3).

Growing scarcities of water and land are projected to increasingly constrain food production growth, causing adverse impacts on food security and human well-being goals, and have been an underlying factor of the food price spikes during the years 2005–2007.

Evapotranspiration: the sum of evaporation and plant transpiration from the earth's land surface to atmosphere

3. CHALLENGES TO WATER USE

Over the next decades, new constraints will be placed on water supplies available for irrigation as well as for rainfed agriculture. Demand for water use in agriculture will continue to increase as a result of growing population and economic growth. Nonirrigation demands are expected to grow even faster, putting pressure on supplies available for irrigation. Unsustainable groundwater use is constraining irrigation water supplies in many already water-scarce areas. Environmental demands for water will also vie for scarce water supplies in the future. Water quality problems are another factor that should be considered in water resources management, as all sectors will increasingly compete for unpolluted water supplies as water quality continues to degrade.

3.1. Increasing Intersectoral Competition

Sharp increases in nonirrigation water demands are expected over the next 50 years, with increases concentrated in the group of developing countries. Nonirrigation water consumption is expected to more than double by 2050, approaching more than 700 km^3 per year; developing countries are projected to contribute most of the increase in demand, and total nonirrigation water consumption in developed countries is expected to increase only moderately (3).

The projected rapid growth in livestock production is a significant factor in increasing water demand, particularly owing to the demand for water to grow crops that are used as livestock feed, such as maize, other coarse grains, and soybeans (17). However, high estimates of livestock water consumption, such as the 100,000 liters of water per kilogram of beef production estimated by Pimentel et al. (18) for the United States, are not representative of most livestock systems. A well-documented analysis by Beckett & Oltjen (19) of the highly water-intensive U.S. feedlot beef production system shows that 3682 liters of water are required to produce 1 kilogram of boneless beef. This figure is much lower compared to other studies, i.e., 10,060 liters per kilogram (20), 100,000 liters per kilogram (18), and 20,559 liters per kilogram (21, 22). On the basis of Beckett & Oltjen's findings (19), direct consumption of water accounts for only about 145 liters of water per kilogram of boneless beef, with the vast majority of water for beef production consumed by irrigated pasture and feed crops.

Peden et al. (23) examine the opposite extreme of livestock intensity—extensive beef production in northern Africa. In a typical northern African system, one head of cattle consumes 25 liters of water per day over a two-year period to produce 125 kg of dress weight meat and consumes crop residues for which no additional water input is required. This yields a direct water consumption of 146 liters per kilogram. Under the most extreme hot/dry conditions, direct consumption could double to nearly 300 liters per kilogram. Even these values overstate the direct consumptive use of livestock because much of the water consumed by livestock is recycled into the soil as urine providing soil nutrients and soil moisture (17). However, as noted below, if the competition for land for feed and biofuels increases even more rapidly, shifts of livestock production to more intensive systems will further boost the competition of livestock for water.

Given that water supply growth is limited but domestic, industrial, and livestock water demands are growing rapidly, a significant share of the additional water for these other uses will come from the irrigation sector. This transfer will lead to a substantial increase in water scarcity in terms of the amount of water available for irrigation compared to irrigation water demand, as the projected decline in irrigation water use for China and some countries in the Middle East and North Africa shows. As a result, the irrigation water supply reliability (IWSR) index, which measures the availability of water relative to full water demand for irrigation, declines from 0.71 globally in 2000 to 0.66 by 2050; the decline will be steeper in water-scarce basins. As water supply reliability declines, irrigators are hurt not only on average, but because irrigation water supply reliability decreases considerably in low-rainfall years. The problem will be compounded by increasing variability in rainfall, with significant increases in the number and severity of droughts in much of the world owing to climate change (24).

Growing competition over water resources will adversely affect freshwater ecosystems, which support human well-being through a range of provisioning, supporting, and regulating services, particularly in less-developed countries (25, 26). Long-term hydrological records have already shown a marked reduction in the annual discharge on some of the world's major rivers, particularly as a result of irrigation (27–29). The poor, whose livelihoods often depend most directly on ecosystem services, suffer most when ecosystems are degraded. The criticality ratio, the ratio of water withdrawal to total renewable water, is a broad indicator of environmental water stress. High criticality ratios (values above 0.40) signify more intensive use of river basin water, a high probability of lower water availability and quality, and absolute water shortages during low-flow periods. Environmental water stress is already high and increasing rapidly in critical areas in China, India, the United States, West Asia, and North Africa (29).

3.2. Degradation of Water and Land Resources and the Environment

Poor irrigation practices accompanied by inadequate drainage have often damaged soils through oversaturation and salt buildup. A notable example is the Aral Sea Basin in Central Asia, which shrank drastically as a result of excessive withdrawals for irrigation. It is estimated that on a global scale there are about 20–30 million hectares of irrigated lands severely affected by salinity. An additional 60–80 million hectares are affected to some extent by waterlogging and salinity (30). Pumping groundwater at unsustainable rates has contributed to the lowering of groundwater tables and to saltwater intrusion in some coastal areas. Rising human demands on water resources only increase pressure on ecosystems and intensify the need to maintain an adequate water supply to wetlands, lakes, rivers, and coastal areas to ensure the healthy functioning of ecosystems (31).

Land degradation reduces not only land productivity, but it can also reduce water-use efficiency. De Vries et al. (32) state that the 13% yield loss, as a result of severe degradation on 40% of agricultural land and moderate degradation on a further 9% of agricultural land, is equivalent to a decline in water-use efficiency of at least 13%.

3.3. Growing Water Pollution

Water pollution affects human health, economic development, and the environment. Water quality impairments can lead to increased competition among water users for the shrinking supplies of unpolluted water. Pollutants can include both human-induced pollution (such as salinization, microbiological contamination, eutrophication, excess nutrients, acidification, metal pollutants, toxic wastes, saltwater contamination, thermal pollution, and increases in total suspended solids) as well as natural pollutants (such as arsenic and fluoride). Poor water quality increasingly constrains agricultural and economic development in densely populated regions that experience water scarcity and are plagued by poor wastewater treatment. Water pollution reduces agricultural production and threatens the health of fish, other aquatic life, and humans. Salinity is one of the largest water quality problems facing the agricultural sector. In almost all developing countries, freshwater biodiversity and associated fisheries are on a decline, which negatively affects protein availability for the poor. Gleick (33) estimates that, assuming the proportion of deaths to total global population of today continues, 59–135 million people may die of preventable water-related diseases between 2002 and 2020. Even if the Millennium Development Goal for water and sanitation is met, an estimated 34–76 million people are still projected to die from water-related diseases.

3.4. Unsustainable Groundwater Use

Globally, about 15% to 35% of irrigation withdrawals are estimated to be nonsustainable; many of these withdrawals are from groundwater sources, which are nonrenewable or exploited beyond recharge rates (25). Annual global groundwater use was estimated at 925 km^3 in 1995 (29). Excessive groundwater extraction can lead to both water scarcity and water quality concerns. According to estimates, India has the largest extraction rate at 150 km^3 of groundwater and produces around half of its food from groundwater. China and the United States are two other key food producers that rely on groundwater (34, 35). Groundwater overabstraction in coastal areas can cause saltwater intrusion, making the aquifers unusable. In China, India, and elsewhere, falling groundwater tables have resulted in income losses to irrigating farmers, health risks from arsenic to fluorosis, and dried-up springs and small streams.

3.5. Water Use for Biofuel Production

Currently, around 1% of all water withdrawn for agricultural purposes is used to irrigate feedstocks for biofuels. The production of biofuels affects water resources in two ways: directly through water withdrawals for irrigation and the industrial processes of feedstock conversion and indirectly by increasing water loss through evapotranspiration that would otherwise be available as runoff and groundwater recharge (36). Biofuel production can also affect water quality by increasing nutrient loads in rivers and lakes.

Even though globally the amount of water withdrawn for the production of biofuels is modest, local water scarcity problems may worsen owing to irrigation of feedstocks (37). In many countries, there is little land and water available for biofuel expansion; the use of water for biofuel production in these areas is likely to affect existing water allocation across sectors as well as within agriculture and involve serious trade-offs between energy, environment, food security, and livelihood protection (38, 39). Comparing actual and projected land and water use for food production with and without additional demand for biofuels, De Fraiture et al. (40) find that, although biofuels are of lesser concern at the global level, local and regional impacts could be substantial. They argue that the strain on water resources in China and India makes it unlikely that policy makers will pursue biofuel options, at least those using traditional field crops.

However, these trade-offs can be reduced by careful planning of the development of biofuel crops (38). For instance, if biofuel crops, such as jatropha and sweet sorghum, are grown on marginal lands under rainfed conditions, their pressure on water and land resources can be minimized (38, 41). The negative impacts of rising energy prices and the introduction of biofuels can also be partially offset by the development and adoption of new technologies. For example, commercial technologies that allow conversion of cellulosic substances, like straws, stover, and leaves, to fuel will increase the productivity of food crops in producing biofuels (42). U.S. maize ethanol mandates, subsidies, and import tariffs have worked against the development of new generations of biofuels, but cellulosic ethanol credits have now been implemented, and blending mandates will be phased in beginning in 2010.

Care must also be taken in the development of second-generation biofuels, which will still require water resources that may prohibit their sustainable production in arid regions. If second-generation biofuels are based on crop residues, they may cause long-term degradation of soil quality. Other environmental considerations include their impacts on biodiversity and land use. Moreover, in the longer run, the challenges posed by biofuels for water (and land) scarcity are likely to become even more serious. Long-term modeling of climate change scenarios indicates that biofuels will likely become a major source of emissions reductions, if climate change mitigation is to be successful in reaching targets of 550 ppm of atmospheric CO_2 (43, 44).

3.6. Climate Change Impacts on Water for Agriculture

Climate change affects the global hydrological cycle in many ways, and these changes have serious implications for agricultural production and food security. This section reviews the main hydrological impacts of climate change and their implications for agricultural production and also discusses the need for adaptation of the water and agriculture sectors in response to climate change.

Some of the principal water-related climate changes include changes in the volume, intensity, and variability of precipitation. Changes in the timing and distribution of rainfall (i.e., rainfall variability) are associated with more frequent, severe flooding and drought in many regions. Areas where precipitation is expected to increase face more frequent and severe floods as well as increased erosion and reservoir sedimentation, whereas areas expecting decreases in rainfall face decreased water availability and increased droughts (45, 46). Although there is a high degree of uncertainty in predictions of future precipitation, increases in precipitation are mainly expected at high latitudes, and decreases are expected in subtropical and lower-latitude regions (46, 47).

Furthermore, rising temperatures will increase the rate of snow cap and glacier melt, affecting agricultural production in river basins fed by mountain ranges (48). Sea-level rise owing to the thermal expansion of seawater and the melting of continental glaciers will lead to inundation of low-lying coastal areas, with significant adverse effects, including salinization of coastal agricultural lands, damage to infrastructure, and tidal incursions into coastal rivers and aquifers (45). Important food-producing areas potentially affected by sea-level rise include Bangladesh and the Mekong Delta in Southeast Asia. In addition, higher temperatures will increase the rate of evaporation/evapotranspiration because of the greater water-holding capacity of the atmosphere, reducing the store of water in reservoirs and soils (46). These adverse effects of climate change on freshwater systems exacerbate the negative impacts of other stresses, such as population growth, changing economic activity, land-use change, and urbanization (45).

Agricultural productivity depends largely on the temporal and spatial distribution of rainfall and availability of water. Changes in the volume, timing, and intensity of rainfall can damage crop growth, disrupting food production and threatening food security. More than the impact of mean changes in climate, changes in climate variability and increases in climate extremes, such as floods and droughts, will have particularly detrimental effects on crop yields (46, 49). Furthermore, modeling results show that, although warming in high-latitude regions would increase crop yields, even slight warming in low-latitude or seasonally dry areas would have a detrimental effect on yields (46). Analyses of multiple climate change scenarios indicate that climate change will likely have a slightly to moderately negative effect on crop yields (50, 51), but crop irrigation requirements would increase (52–54), as would overall water stress in many areas dependent on irrigation (47, 54).

Climate change is also expected to have a significant effect on livestock and fisheries. In particular, climate variability and drought may lead to a loss in livestock productivity given the vulnerability of rangelands to water deficits. Climate change may also reduce pastoral and farming lands resulting from land degradation. The effects of climate change on fisheries include stress attributable to increased temperature and oxygen demand, decreased pH, declining water quality and volume, extreme weather events, increased frequency of disease, sea-level rise, and an uncertain supply of fishmeal and oils from capture fisheries (46).

The uncertainty over future rainfall patterns and water availability presents a challenge for both water management and agricultural systems as historic rainfall indicators are no longer good predictors for the future (45, 46). Adaptation by both sectors is important to ensure water and food security for future generations. Decision makers, from the farm level to the policy level, must be able to factor in uncertainty considerations in their decisions and choose options that are capable of dealing with multiple alternative futures. In water-stressed areas, adoption of irrigation (and improved varieties of irrigation), improvements in irrigation efficiency and development, as well as soil and water conservation technologies and techniques appear to be particularly promising adaptation options in the face of climate change (55–58). Investments in drainage infrastructure would be wise in areas facing increased precipitation and flooding (59). For livestock, altered rotation of pasture, modification of grazing times, the use of supplementary feeds, and integration within crop-livestock systems are several options to deal with the negative effects of climate change. Climate change considerations should also be integrated into development, infrastructure, and other policy decisions and plans. This will require better coordination across multiple institutions as well as better climate information, early warning systems, and information services that reach multiple stakeholders and decision makers (60).

4. POLICIES, INSTITUTIONS, AND INVESTMENTS TO ENSURE WATER AND FOOD SECURITY

Throughout history, the most common response to growing water demands has been to develop new supplies, but by the end of the twentieth century, most of the easily exploited water resources had been tapped. Increasing water supplies carries increasing financial and ecological costs. In Africa, substantial water resources are untapped, but the cost of exploiting them is, in most cases, high.

There is considerable scope for improved performance, water savings, and economic gains through water reallocation to high-value uses and through reduction in the number of withdrawals and increasing the degree of reuse, particularly if secure water rights and efficiency pricing for agricultural water can be effectively and equitably implemented (61).

4.1. Institutional Reform

Water is allocated through a variety of mechanisms, ranging from complete control by the government to a mixture of market and government allocation, to predominantly market allocation. The structure of any particular system of water allocation is influenced by the existing institutional and legal frameworks as well as the water resources infrastructure. Public allocation of water has usually been associated with water quantities, on the basis of physical norms and political influence. The state's role is particularly strong in intersectoral allocation, as the state is often the only institution that includes all users of water resources and has jurisdiction over all sectors of water use. User-based allocation requires collective action institutions with authority to make decisions on water rights and requires strong, but not necessarily formalized, property rights to water. Market-based allocation refers to an exchange of water-use rights. For markets to function effectively, the original allocation of water rights needs to be defined, an institutional and legal framework for trade is needed, and the basic necessary infrastructure to allow water transfers must exist (62). Most water allocation situations represent a mix of these three allocation mechanisms. Under growing water scarcity, the combination of appropriate mechanisms might well change, requiring a supportive enabling framework that allows flexible incorporation of elements of these three approaches.

There have been several broad institutional approaches to improving water-use efficiency and productivity. These include making the public sector more efficient, devolving more responsibility to farmer groups, and greater involvement of the private sector. Institutional reform of public irrigation agencies holds some promise for long-term improvements in system performance. Possible reforms include shifting from a line department to a semi-independent or public utility mode, applying financial viability criteria to irrigation agencies, franchising rights to operate publicly constructed irrigation facilities, and strengthening accountability mechanisms, such as providing for farmer oversight of operating agencies (63). Reform means fundamental change in the activities undertaken by an agency or set of agencies. These may include (*a*) river basin planning, (*b*) watershed management, (*c*) water resource allocation, (*d*) environmental monitoring and enforcement, (*e*) groundwater monitoring and control, and (*f*) technology transfer and/or advisory services to water user associations (64, 65). Farmers' participation in irrigation management at the tertiary and secondary level has been widely promoted by governments to improve local management. The level of success depends on the degree of farmer cooperation and their incentives to take on an expanded role (66).

Private sector irrigation development has been limited mainly to groundwater development and, to a lesser extent, smaller commercial surface water systems growing high-valued crops. Two-thirds of groundwater irrigation in India and Mexico is privately managed (6). In India and elsewhere in South Asia, public investments in large surface systems have facilitated private irrigation investment. More recently, private investment in treadle pumps has been taking off. Water rights are a key to establishing incentives for irrigation management. Although some system of water rights is found to operate in virtually any setting where water is scarce, systems that are not firmly grounded in formal or statutory law are likely to be more vulnerable to expropriation. If well-defined rights are established, the water user can benefit from investing in water-saving technology.

However, the establishment of formal water rights is not likely to be effective if it ignores existing customary arrangements (67, 68).

4.2. Role of Virtual Water Trade

The concept of virtual water can be used to examine the linkage between trade, food security, and water resources. Virtual water is defined as the volume of water used to produce a good or service, including agricultural commodities, where it can be measured in crop water depletion or in irrigation water depletion (69, 70). Considering water as a factor of production indicates that countries in which water is particularly scarce might benefit by importing water-intensive agricultural goods. The importation of agricultural products that require large amounts of water in their production thus can become an instrument to import water into a water-scarce country. That is, by substituting cereal and other food imports for irrigated agricultural production (so-called imports of virtual water), countries can effectively reduce their agricultural water use. Importing countries benefit from this trade as water originally intended for agriculture can be allocated to other uses. Global water savings take place when agricultural exporters are more water efficient than importers, and global irrigation water savings occur when exporters produce agricultural products under rainfed conditions and importers would have used irrigation water to produce the same agricultural commodities (71).

Examining the impact of trade on global water use, De Fraiture et al. (71) find substantial irrigation water savings owing to cereal trade. The authors show that the majority of cereal exports come from countries, such as the United States, Canada and the European Union, where grains are cultivated in a highly productive rainfed environment, allowing extensive conservation of irrigation water. Importing countries are more diverse and spread out all over the world, including large importers such as China, Japan, Korea, Indonesia, Egypt, Mexico, and Iran. On the basis of simulation modeling, Rosegrant et al. (29) estimate an increase in cereal trade from water-abundant to water-deficit areas from 23% in 1995 to 38% by 2025, because food demand growth outstrips food production growth in water-deficit areas.

Virtual water (also known as embedded water, embodied water, or hidden water): the water used in the production of a good or service

Looking at the case of China, Liao et al. (72) highlight the importance of considering water as a factor of production in global agricultural trade. The authors argue that previous studies suggesting that China will increase the export of labor-intensive agricultural products, such as vegetables and fruits, following World Trade Organization accession are unrealistic owing to water scarcity in China. Rather, they suggest that China may import more wheat and export fewer vegetables and fruits than has typically been predicted, given concerns over water constraints.

Overall, economic and political processes are major driving forces behind food trade, whereas water scarcity plays a modest role in global trade patterns. The level of trade protection of, and domestic support for, agricultural production (e.g., tariffs, duties, and subsidies) by countries distorts the virtual water movement worldwide (73). The Organisation for Economic Co-operation and Development countries generally have the highest agricultural trade barriers (although Australia, for example, has open trade policies), but many developing countries have also maintained barriers to agricultural trade to protect domestic agricultural economies. Trade liberalization can also potentially have large positive impacts on the economies of many countries, especially in the developing world. But these income benefits to developing countries from agricultural trade liberalization are the result of increased food prices and increased access to developed country markets, so trade liberalization can actually increase pressure on developing country water resources. Evidence is mixed on the impact of liberalization on water use because of the complex changes in comparative advantage and incentives that come into play with trade liberalization. Ramirez-Vallejo & Rogers (73) found that full liberalization of agriculture would generate a significant net effect on virtual water flows mainly from the relocation of meat trade, with the United States and Latin America increasing virtual water exports and all other regions reducing water imports. Berrittella et al. (74) found that overall trade liberalization has a small effect (less than 10%) on water use. Water use may go up for partial liberalization and down for more complete liberalization. This is because different crops respond differently to tariff reductions, but also because trade and competition matter too. Trade liberalization tends to reduce water use in water-scarce regions and increase water use in water-abundant regions.

4.3. Economic Incentives

Economic incentives for water management include prices, taxes, subsidies, quotas, and ownership/rights. These incentive measures, when implemented appropriately, can affect the decision-making process and motivate water users to conserve and use water efficiently in irrigation and in other uses. At the zero or low levels of current water prices, irrigation water use is highly price inelastic; however, in many cases, prices high enough to induce significant changes in water allocation (or recover capital costs) can severely reduce farm income (75–78). Irrigation water pricing for full capital cost recovery in existing systems is highly unlikely for most irrigation systems in both the developing and developed world (79–81).

Water pricing policies can improve efficiency and sustainability when combined with appropriate supporting policies (82–84). But there are significant barriers to using direct pricing of water, especially in developing countries. Water pricing may conflict with the idea that the provision of water services is a basic right to all individuals if water prices rise to a level that low-income households cannot afford. The high costs of measuring and monitoring water use, where infrastructure and institutions are weak, can also be a major constraint to implementation of water pricing. Adding to the difficulty of pricing reform, both long-standing practices and cultural and religious beliefs have treated water as a free good, and entrenched interests benefit from the existing system of subsidies and administered allocations of water (61).

Water markets, which are underpinned by secure water rights, empower water users and can be a better option to improve water-use efficiency. By requiring user consent to any reallocation of water and compensating the user for any water transferred, marketable rights to water induce water users to consider the full opportunity cost of water, including its value in alternative uses, thus providing incentives to economize on the use of water and gain additional income through the sale of saved water. Finally, a properly managed system of tradable water rights will provide incentives for water users to internalize (take account of) the external costs imposed by their water use, reducing the pressure to degrade resources (85, 86). But as noted above, there are important institutional and legal requirements for effective water markets. Water markets can be found in a limited number of developed and developing countries. In Asia, informal groundwater markets prevail, whereas in Chile, Australia, and the United States, surface water markets can be found. Water trading efficiency depends on the prevailing infrastructure, the legal environment, the water scarcity situation, and the number of buyers and sellers with varying needs in the market (87–93).

An alternative system to implement incentives in water allocation would be to pay farmers to use less water on the basis of the charge-subsidy approach suggested by Pezzey (94) for pollution control (95, 96). This approach, in which the government, irrigation agency, or river basin authority acts as a broker of water transfers, would establish base water rights at major turnouts, with allocation below the turnout handled by water user associations. For demand greater than the base water right, an efficiency price equal to the value of water in alternative uses would be charged to the users; for demand below the base right, the same efficiency price would be paid to the water users. The establishment of base water rights would increase the political feasibility of water pricing by formalizing existing water rights. With efficiency prices paid on only the marginal demand above the base right, and farmers being paid if they reduce water use, nonpunitive incentives are introduced. The reliance on water user associations to manage water below the turnout improves local accountability, transparency, and the flexibility of water allocation. Information costs would be reduced because local irrigators with expert knowledge of the value of water would bear the costs and generate the necessary information on the value and opportunity costs of water below major turnouts (61).

4.4. Investment in Infrastructure and Water Supply

Because new investments are increasingly expensive and politically sensitive, some of the increasing demand for water must be met from the carefully selected, economically efficient development of new water through impoundment of surface water, sustainable exploitation of groundwater resources, and expansion in the development of nontraditional water sources. Hard infrastructure investment has a role to play in the future in some regions but a reduced one compared with past trends when dam-building and expansion of irrigated area drove rapid increases in irrigated area and crop yields, particularly in developing countries.

Future construction of irrigation and water supply projects will require balanced development approaches that are acceptable to diverse constituencies. The full social, economic, and environmental costs of development must be considered, but so must the cost of failure to develop new water sources. Project design must ensure comprehensive accounting of full costs and benefits, including not only irrigation benefits but also health, household water use, and catchment improvement benefits. Of utmost importance is improved design and implementation of compensation programs for those who are displaced or negatively affected by water projects (29).

Sustainable development of groundwater resources also offers significant opportunities for many countries and regions where groundwater extraction remains below natural recharge, including southern China; central, western, and eastern sub-Saharan Africa; much of Southeast Asia; and localized regions elsewhere. Groundwater irrigation is more flexible than surface water irrigation and can be used in conjunction with surface water to improve water-use efficiency (97, 98).

Deficit irrigation: a practice whereby water supply is reduced below maximum levels, and mild stress is allowed with minimal effects on crop yield

4.5. Increasing Water-Use Efficiency

The scope for increasing water-use efficiency in agriculture is large—simply because agriculture uses the largest volumes of water. At the same time, enhancing water-use efficiency is a highly complex task because much of the apparent losses at the system level is reused elsewhere in the hydrologic basin. Conserving water ideally should be achieved without adversely affecting third parties who rely on return flows or downstream water reuses; without simply taking water away from farmers, thereby reducing crop yields and farm incomes; without causing long-term adverse impacts on water quality and farm soils; and by taking into account the full scarcity value of water for all the ecosystem services this resource provides.

At the irrigation system level, water use can be reduced during transport from the source to the farm, typically along canals (conveyance efficiency), from the farm gate to the field (distribution efficiency), and during application to crops (application efficiency). For example, conveyance efficiency can be increased by lining canals; distribution efficiency can be enhanced by lining and maintaining on-farm canals; and application efficiency can be increased by using more sophisticated irrigation technologies, such as drip or sprinklers, or through the application of deficit irrigation (99, 100). At the plant level, several water-use ratios can be changed to reduce water use, including the consumptive efficiency, which indicates how much water is not taken up by plant roots; the ratio of water use for transpiration (direct crop water use) versus for evaporation (nonbeneficial evaporation from the soil); the transpiration efficiency, which describes the ratio of the mass of carbon dioxide taken up by plant photosynthesis versus the amount of water transpired; the biomass efficiency, which relates crop biomass to carbon dioxide assimilated by photosynthesis; and finally yield efficiency or harvest index, which relates harvested yield to the crop biomass produced (99). Some of these water conservation options are also available for rainfed agriculture and for pastures and grazing lands used by livestock. Finally, water use can also be saved under some conditions through substitution by other crop inputs, such as fertilizer or labor (101). The increase in crop yield and improvement in water application and basin-wide efficiencies contribute to the increase in water productivity, but the major contribution comes from the crop yield increase. However, the actual water savings from increasing water-use efficiency at the system level are often below the potential suggested by typically low system-wise efficiency figures, as downstream recovery of irrigation drainage water and recharge and extractions of groundwater result in basin-wide efficiencies substantially greater than those for individual systems (100, 102).

4.6. Increasing Crop Yields

Increasing crop yields, for example, through closing the yield gap between developed and developing regions and between rainfed and irrigated crops can save significant water resources and help conserve ecosystems and remaining forest areas in the developing world. If agricultural research investments can be sustained, the continued application of conventional breeding and the recent developments in nonconventional breeding offer considerable potential for improving cereal yield growth, particularly in rainfed environments. Three major breeding strategies include research to increase the harvest index, plant biomass, and stress tolerance (particularly drought resistance). The first two methods increase yields by altering the plant architecture, whereas the third focuses on increasing the ability of plants to survive stressful environments (29). The first of these may have only limited potential for generating further yield growth owing to physical limitations, but there is considerable potential from the latter two (103, 104). For example, the New Rice for Africa, a hybrid between Asian and African species, was bred to fit the rainfed upland rice environment in West Africa. It produces over 50% more grain than current varieties when cultivated in traditional rainfed systems without fertilizer. In addition to higher yields, these varieties mature 30 to 50 days earlier than current varieties and are far more disease and drought tolerant than previous varieties (105, 106).

5. CONCLUSIONS

Irrigation is, and will remain, the largest single user of water, but its share of world water consumption is projected to decline. Growing scarcities of water and land are projected to progressively constrain food production growth, slowing progress toward the goals of food security and human well-being. In the absence of policy and investment reform, water for the environment and for food production will increasingly conflict in many parts of the world. Water pollution will affect growing populations in developing countries, harming both agricultural and economic development. Adverse impacts from climate change on agricultural production are expected to become more pronounced, especially in developing countries. Even under moderate climate change scenarios, impacts are projected to be negative for dryland areas in Africa, Asia, and the Mediterranean. Increasing water scarcity for agriculture not only limits crop area expansion but also slows irrigated cereal yield growth in developing countries. Despite recent commitments to increase investment in irrigation, particularly in sub-Saharan Africa, projected irrigation expansion will be insufficient to reduce rapidly growing levels of net food imports in the developing world. Moreover, given that water supply growth is limited and that domestic and industrial water demand are growing rapidly, a significant share of the additional water for domestic and industrial uses will come from the irrigation sector. This transfer will lead to a substantial increase in water scarcity for irrigation.

The most promising avenue for addressing water shortfalls into the future is water management and incentive policy reform to enhance the efficiency of existing water use, supported by infrastructure investment to modernize and upgrade existing irrigation and water delivery systems. Improvements in the irrigation sector to increase water-use efficiency must be made at the technical, managerial, and institutional levels. Key to inducing higher water efficiency gains in all sectors is introducing market (or market-style) incentives into water-use decision making. Although much can be done in the irrigation sector to conserve water, enhanced domestic sewage treatment and industrial recycling and effluent treatment can go a long way in improving water availability in many developing countries.

Water scarcity could severely and easily worsen if policy and investment commitments from national governments and international donors and development banks weaken. Policy reform, including agricultural research and management in rainfed areas and changes in the management of irrigation and water supplies, is therefore urgently needed to ensure sustainable water access and affordable food prices.

SUMMARY POINTS

1. Agriculture continues to be the largest user of freshwater resources through 2050 for all regions, although its share is expected to decline relative to industrial and domestic uses. Sectoral competition and other water scarcity-related problems will intensify.
2. Growing water scarcity will increasingly constrain food production growth, causing adverse impacts on the goals of food security and human well-being. An increasing share of food production stems from often unsustainable groundwater use.
3. Reliability of agricultural water supply is projected to decline without improved water management policies.
4. Water pollution will increasingly constrain water availability and food production, particularly in developing countries. Water quality problems are more difficult to resolve and have long-run consequences.
5. Although globally the amount of water withdrawn for biofuels is modest, local water scarcity problems may worsen owing to direct and indirect impacts from agricultural water use for feedstock production, and scenarios for climate change mitigation show that biofuel production is likely to expand dramatically in the future.
6. Climate change will affect water resources for all uses and, in particular, water use in agriculture through gradual changes in precipitation, runoff, evaporative demands, and sea-level rise in productive delta areas, as well as through increased numbers of extreme events, including floods, droughts, and storm surges.
7. Water conservation and productivity enhancements in rainfed and irrigated agriculture are needed to offset the growing impacts of water scarcity on the environment and risks to farmers.
8. There is significant untapped potential to use economic incentives for agricultural water management. A number of alternative approaches to implementing incentives are available; the appropriate choice of approach should be conditioned on institutional, infrastructural, and legal capacity.

FUTURE ISSUES

1. High uncertainty remains regarding the impacts of climate change on agricultural water use.
2. Higher energy costs will affect water supply and use in uncertain ways, increasing the cost of groundwater and pump irrigation, and increasing the viability of large storage systems that can be used for irrigation.
3. Water quality will increasingly constrain agricultural production and availability for other uses, but little research has been done on how to reduce adverse impacts in developing countries.
4. More research on the implementation of appropriate economic incentives for agricultural water management is needed.
5. The appropriate role of state, market, and local collective action institutions needs to be identified for sustainable agricultural water management under increasing scarcity.

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Contents

Errata

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