Chapter 2
Global Water and Food Security: Megatrends and Emerging Issues

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Abstract Feeding the world's growing population will depend to a large extent on irrigation, but the future of irrigation water supplies is increasingly constrained by growth in other sectors. Other challenges, including declining water quality, falling groundwater tables, and growing environmental demands for water further constrain water availability for irrigation. Moreover, globalization and trade liberalization will increasingly impact water use and food production. Some of these challenges will be mediated by what we label the new ABCs of the future of water and food security: Aquaculture, Biotechnology, and Climate Change. In order to address these old and new challenges, fundamental changes in water management are necessary. With the right reforms in water management, implementation of appropriate economic incentives and investments in water infrastructure and agricultural research, progress can be made toward solving these challenges.

2.1 Introduction

Future food production will depend to a large extent on irrigation. Irrigation water supplies, however, are increasingly constrained by demands from other sectors, which could significantly reduce water availability for food production in the future. Furthermore, several other existing and emerging challenges impact on the provision of water for food production, and ultimately the food security of many people around the world.

An assessment of the current and future situation for water and food is crucial for understanding the potential impacts of new and emerging challenges. The following sections discuss current and projected food demand, production, yield, area and trade along with water consumption, based on assessments from the IMPACT-WATER modeling framework (see Appendix Chapter 2 for a short description of the model) (Rosegrant et al. 2002).[1] This is followed by analyses of the linkages between globalization, trade liberalization and water; and an in-depth examination

[1]For a full description of the model, see Rosegrant et al. (2002).

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of the potential impacts of aquaculture, biotechnology, and climate change in shaping future water and food outcomes.

2.2 The Food and Water Situation

2.2.1 Food

Slowing population growth and diet diversification are expected to lead to slower growth in cereal demand in the coming decades. Globally, cereal demand growth is projected to increase at 1.3% per year between 1995 and 2025, compared to 2.2% annually from 1965 to 1995. Even with this decrease in growth, the projected absolute increase in cereal demand by 2025 is substantial, particularly in developing countries. Globally, cereal demand is projected to increase by 828 million metric tons (mt), with most of the increase, 712 million mt, occurring in developing countries (Fig. 2.1). As a result of income growth and urbanization, dietary patterns are changing in much of the developing world. Consumer preferences are shifting from maize and other coarse grains toward wheat and rice, and greater per capita consumption of fruit, vegetables and meat.

Meat demand is projected to increase rapidly by 2025, with an increase of 138 million mt globally (Fig. 2.2), 86% of which is accounted for by the group of developing countries, where meat demand more than doubles. China alone accounts for 39% of total meat demand growth. The increase in meat demand also helps fuel the increase in cereal demand described above, as more animal feed is required for increased livestock production.

Continued productivity growth is crucial to meet increasing levels of food demand. However, projections show that future growth in cereal yields will slow

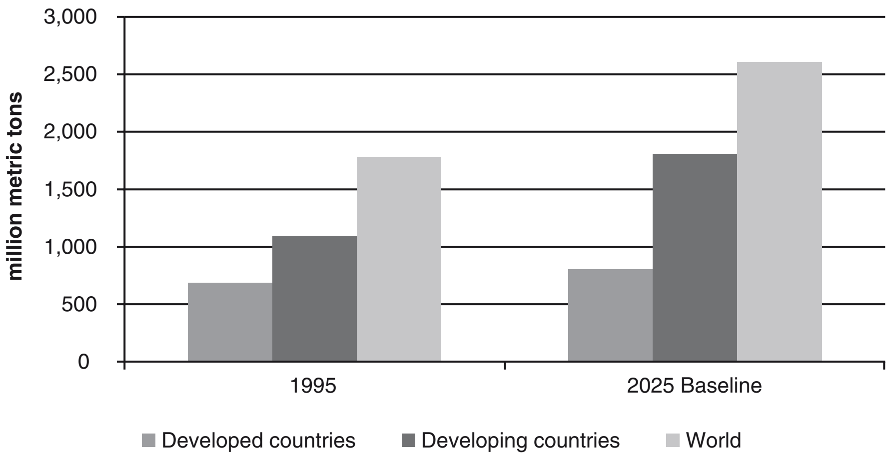

Fig. 2.1 Cereal demand in developing and developed countries, 1995 and 2025 baseline (Rosegrant et al. 2002)

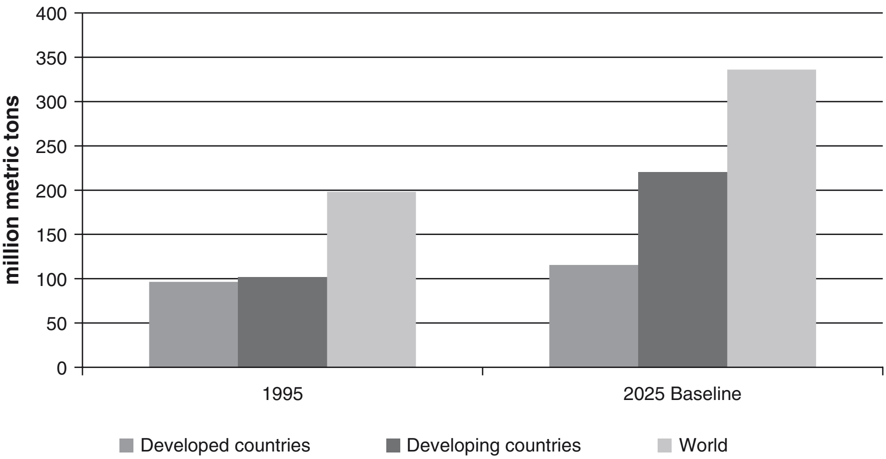

Fig. 2.2 Meat demand in developing and developed countries, and world, 1995 and 2025 baseline (Rosegrant et al. 2002)

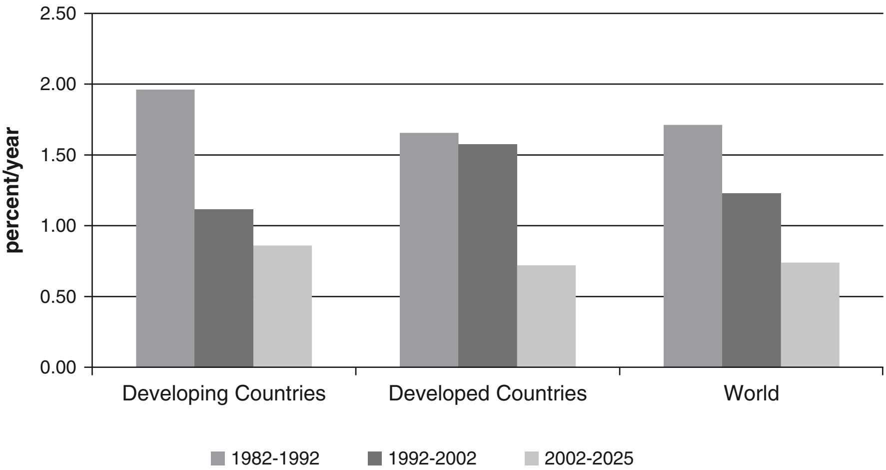

Fig. 2.3 Annual cereal yield growth rate in developing, developed countries, and world, 1982–1992, 1992–2002, 2002–2025 baseline (Rosegrant et al. 2002)

across nearly all regions compared to previous levels of growth. Globally, annual yield growth is projected to slow to 0.74% for the period 2002–2025, compared to 1.71% between 1982 and 1992, and 1.23% between 1992 and 2002 (Fig. 2.3). Water scarcity is a significant constraint to cereal production growth. Rosegrant et al. (2002) project that for the base year of 1995 grain harvests in developing countries fell short by 90 million mt as a result of water shortages. By 2025, the production shortfall is expected to grow to 296 million mt under business-as-usual conditions and to a much higher 440 million mt if investments in agricultural research and water infrastructure slow even more.

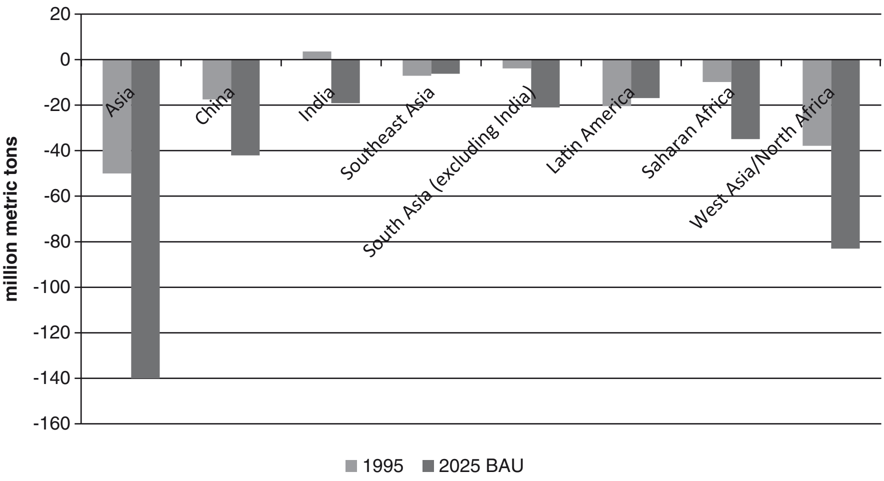

Fig. 2.4 Regional cereal net trade, 1995 and 2025 baseline (Rosegrant et al. 2002). Negative numbers indicate net imports

Projected gaps in national food balances will increase the dependence on food imports. Consequently, net cereal imports in developing countries are projected to increase from 108 million mt in 1995–245 million mt in 2025 (Fig. 2.4). Despite the growing abundance of food and unprecedented economic growth in many developing countries, food security and childhood malnutrition will continue to haunt many countries. Many developing and poor countries do not have the ability to produce all of their food due to environmental factors such as poor soil fertility, water unavailability, harsh environments (extreme heat, drought, or flooding) or cannot afford the high costs of agricultural inputs (for example, seed quality, or fertilizer). This problem will become more aggravated under climate change as labor is generally immobile and it is difficult for poor farmers to find alternative livelihoods.

Lack of food and lack of water are intrinsically linked and often lead to malnutrition. Water impacts on malnutrition outcomes in two ways: reduced food production as a result of growing water shortages affecting irrigated agriculture and increased malnutrition as a result of lack of access to safe drinking water (Rosegrant et al. 2001), particularly in sub-Saharan Africa (SSA). Safe drinking water supply as well as sanitation and hygiene have direct impacts on infectious diseases, especially diarrhea, schistosomiasis, and malaria. Access to safe drinking water is thus important in preventing malnutrition, particularly child malnutrition (WHO 2008). Both of these aspects are incorporated in the childhood malnutrition estimates of IMPACT-WATER. In SSA, the total number of malnourished children is projected to increase from 33 million to 36 million between 1997 and 2025 under business-as-usual (Fig. 2.5). However, South Asia will still have the largest number of malnourished children, with 50 million South Asian children projected to suffer from malnutrition in 2025.

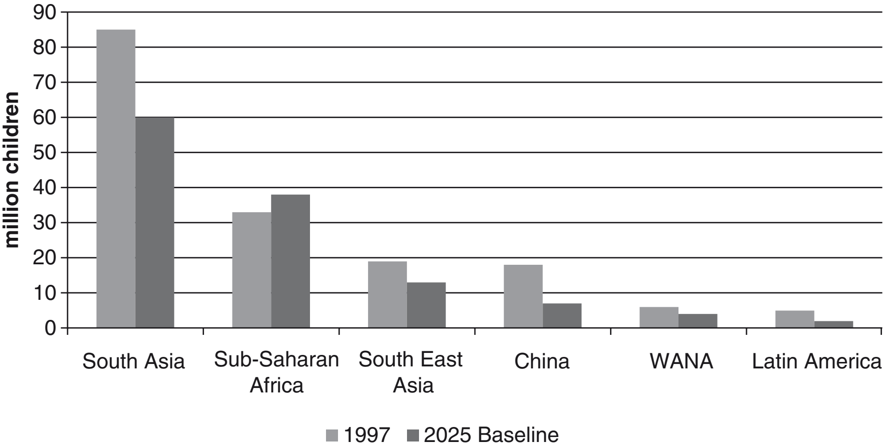

Fig. 2.5 Number of malnourished children by region, 1997 and 2025 baseline (IMPACT baseline calculations, July 2002)

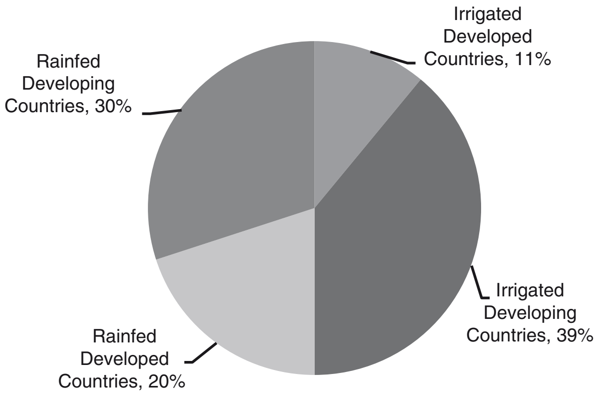

Fig. 2.6 Share of irrigated and rainfed production in cereal production increase 1995–2025 baseline (Rosegrant et al. 2002)

2.2.2 *Water*

Water makes a major contribution to both irrigated and rainfed food production, but irrigated cereal yields are, on average, 60% higher than rainfed yields. During 1995–2025, growth in food production is projected to be accounted for equally by rainfed and irrigated production, with developing countries accounting for 69% of total production increase (Fig. 2.6). About 80% of irrigated harvested cereal area was located in the group of developing countries in 1995 and almost all of future area expansion is expected to take place in this region.

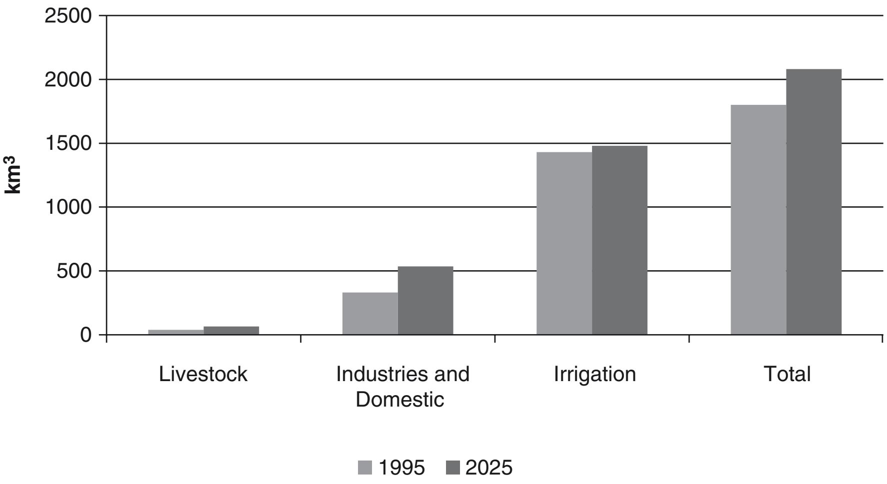

Fig. 2.7 Water consumption by different sectors, 1995 and 2025 baseline (Rosegrant et al. 2002)

New constraints will be placed on water supplies available for irrigation, however, as non-agricultural uses of water continue to increase dramatically. Although total water consumption[2] for non-irrigation uses[3] will still be much smaller than for irrigation (Fig. 2.7), in percentage terms, non-irrigation demands rise much more rapidly. Domestic and livestock uses are expected to increase by 71% between 1995 and 2025, while industrial uses will grow by 50%. In contrast, irrigation water consumption is expected to increase by only 4%.

Several other factors will also impact the availability of water for agricultural production. 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 increasingly come to the forefront in developing countries and all sectors will increasingly compete for unpolluted water supplies as water quality continues to degrade. Each of these problems is discussed in more detail in the following sections.

Groundwater is an invisible yet important natural resource. Annual global groundwater use was estimated at 925 cubic kilometers (km^3) in 1995 (Rosegrant et al. 2002). Irrigation is the primary user of groundwater in many areas; however, many major cities around the world also depend on groundwater for domestic water supplies. Excessive groundwater extraction can lead to both water scarcity and

[2]Water consumption refers to water withdrawn from a source and made unusable for reuse in the same basin through irrecoverable losses, including evapotranspiration, seepage to a saline sink or contamination (Gleick 1998).

[3]Non-irrigation uses include water demand for domestic, industrial and livestock uses (Rosegrant et al. 2002).

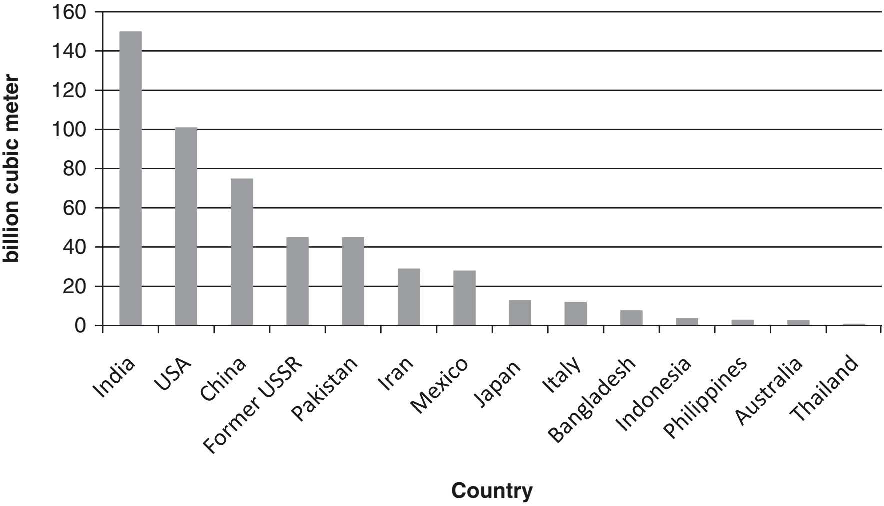

Fig. 2.8 Groundwater utilization in various countries of the world during the 1980s (Shah et al. 2003; Takeuchi and Murthy 1994; Llamas et al. 1992)

water quality concerns. The main problem dominating groundwater utilization is depletion due to overdraft (Rosegrant et al. 2002; Shah et al. 2000). Groundwater overdraft occurs when extraction exceeds water recharge, which in turn lowers the water table. As a consequence, pumping depths increase in order to maintain irrigation water supplies, resulting in higher pumping costs. Groundwater overdraft is associated with environmental problems, including declining water quality, land subsidence, and saline intrusion into aquifers, particularly in coastal regions, which could be worsened by climate change.

Studies conducted by Shah et al. (2003), Takeuchi and Murthy (1994) and Llamas et al. (1992) show groundwater extraction rates in various countries (Fig. 2.8). India had the largest extraction rate at 150 km^3 of groundwater utilized during the 1980s. This is not surprising, as 60% of Indian irrigated food grain production depends on groundwater from wells. The United States was the second largest groundwater user at 101 km^3; half the population in the United States draws its domestic water supply from groundwater (Morris 1997). In China, both population and economic activity have grown significantly during the last 25 years and much of this development has depended heavily on groundwater resources (Foster and Garduño 2004). The Hai He basin in China uses massive amounts of groundwater, with extraction estimated at 27,000 million cubic meters in 1988. The basin has reaped large socioeconomic returns from groundwater use, such as agricultural employment, poverty alleviation, grain production, and potable and industrial water supplies. On the other hand, high extraction rates resulted in water table declines of more than 15 m over the past 40 years (Foster and Garduño 2004).

Aside from overextraction, waterlogging and salinization are other threats to groundwater utilization and can lead to failure in crop production. Waterlogging occurs when soil becomes saturated due to a high or perched water table and is caused by over-irrigation, inadequate drainage and poor conjunctive use. This results in inferior plant growth, particularly in humid regions. Salinization, which sometimes occurs naturally, is a condition where salts accumulate in the soil through water evaporation from the upper soil layer and is more common in arid regions with high evaporation rates of irrigation water and less natural leaching or drainage (Rosegrant et al. 2002). Seawater intrusion is another problem that has been reported in coastal aquifers in Egypt, Turkey, China, and India (Shah et al. 2000), and is expected to increase significantly in costal aquifers as a result of climate change.

Pollution due to agricultural, industrial, and human activities as well as naturally occurring pollutants likewise threaten groundwater availability. Agricultural runoff carries fertilizer and pesticide residues, with possible adverse impacts on human health if groundwater sources used for drinking water are polluted. Naturally occurring arsenic has been reported in several delta areas affecting human health. The most prominent case is Bangladesh where the large-scale construction of tubewells for drinking water has led to widespread poisoning in the country (Harvey et al. 2002).

Is it possible to move to a regime of sustainable groundwater extraction while still meeting food demand growth? Rosegrant et al. (2002) assess the impact of phasing out unsustainable groundwater overdraft by 2025 in a low groundwater pumping scenario (LGW). Groundwater overdraft occurs when the ratio of pumping to recharge is greater than 1.0. The LGW scenario assumes that groundwater overdraft in all countries and regions using water unsustainably is phased out over 25 years beginning in 2000 by reducing annual groundwater pumping to recharge ratios to below 0.55 at the basin or country level (Rosegrant et al. 2002). The impact of the LGW scenario on total cereal production in 2025 is presented in Table 2.1. Globally, under the LGW scenario, irrigated cereal production would decline by 3%. This decline would be partially compensated by an increase in rainfed cereal production. Groundwater extraction under the LGW scenario would fall to 753 km^3 by 2025 compared to 922 km^3 under the baseline scenario, and 817 km^3 in 1995 (Rosegrant et al. 2002). Declines in cereal production under the alternative scenario are concentrated in the basins that currently experience large overdrafts, especially China and India (Table 2.1). As a result, the developing world as a whole would increase net imports from the group of developed countries, with major increases concentrated in

Table 2.1 Change in cereal production under a low groundwater pumping scenario, compared to the baseline, 2025 (Rosegrant et al. 2002)

	Irrigated	Rainfed	Total
	Change in million mt (and percentage)		
World	−35.0 (−3.1)	16.9 (1.2)	−18.1 (−0.7)
Developed countries	1.6 (0.6)	10.3 (1.4)	11.9 (1.2)
Developing countries	−36.7 (−4.2)	6.7 (1.0)	−30.0 (−1.2)
China	−15.7 (−4.0)	1.2 (0.9)	−14.5 (−2.7)
India	−16.8 (−9.4)	0.6 (0.7)	−16.2 (−6.2)
West Asia/North Africa	−2.7 (−5.1)	1.1 (1.8)	−1.6 (−1.4)

China and India. While these country-level shortfalls in demand and increases in imports are serious they may be a worthwhile trade-off for restoring sustainable groundwater supplies. To move towards such a sustainable development path, countries would need to increase agricultural research investments, and particularly in the hardest hit river basins, make investments and implement policy reforms to increase water use efficiencies at the basin level, encourage diversification from irrigated cereals to crops with more value per unit of water, and compensate farmers for reduced groundwater pumping.

Ecosystems rely on water for their functioning for the survival of plant and animal species. At the same time, water relies on ecosystems for water quantity and quality regulation. Wetlands, for example, help regulate water quantity by retaining water during times of heavy precipitation and releasing water during dry periods, and help regulate water quality through the removal of heavy metals and other contaminants (Bos and Bergkamp 2001).

A certain quantity and quality of water is required for aquatic ecosystems to help maintain ecosystem health and dependent species, and to ensure the continued provision of environmental services. As human demands for water continue to rise it is becoming increasingly important that water is reserved for these "environmental water requirements." Environmental water requirements can vary substantially, however, according to the specific characteristics of a given basin.

Smakhtin et al. (2004) attempted to estimate the volume of water required to maintain ecosystems at a global scale. Noting that environmental water requirements will vary based on the management objectives for a given basin, they estimate the environmental water requirements necessary to maintain ecosystems in a "fair" condition. This condition describes an ecosystem that has been moderately or considerably modified, including disruption of the biota, loss or reduction of some species, possible introduction of some alien species, and disturbances related to socioeconomic development. The environmental flow requirements of the 128 major river basins assessed varied substantially from basin to basin ranging from 21% of total water available in the basin in basins such as the Luni basin in India, and the Arabian Peninsula in Iraq and Jordan, to 49% in the Great Lakes basin in the United States and Canada. Using these environmental water requirement estimates, water availability and water use data, the authors were able to calculate a water stress indicator (WSI) and determine if basins could be classified as environmentally water scarce (classified as those basins with a WSI >1). Based on this method, several basins that would not normally be classified as water scarce fell into the category of environmental water scarcity, including the Ganges, parts of the Murray-Darling, the Orange, the Limpopo, the Nile, the Missouri, and the Dnieper, among others (Smakhtin et al. 2004). These results suggest that adequate flow reservation to maintain ecosystems in "fair" conditions could have a major impact on irrigation water use and future agricultural production in many areas.

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 and 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.

Many of these pollutants can significantly affect human health, particularly in developing countries where many citizens (especially in rural areas) are still not connected to an improved water supply.[4] For example, enteric pathogens (gastrointestinal organisms spread by contamination of foods mainly of animal origin) from untreated wastewater have substantial health and productivity impacts in many developing countries. Gleick (2002) estimates that, assuming the proportion of deaths to the total global population of today continues, 59–135 million people will die of preventable water-related diseases during 2002–2020. Even if the Millennium Development Goal (MDG) for water and sanitation[5] is met, an estimated 34–76 million people are still projected to die from water-related diseases.

The improvements necessary to make headway in reducing the morbidity and mortality of water-borne illnesses will require significant commitments from national governments and international donors. Many of the countries considered "high-priority" (with both a low level of access to sanitation and a high prevalence of diarrheal diseases) in terms of water supply and sanitation improvements are in Africa. The projected annual costs of meeting the water and sanitation MDG by 2015 are generally highest in South and Southeast Asia, West Pacific developing countries, and Sub-Saharan Africa. Evans et al. (2004) project these costs to be around US$9.5 billion annually for sanitation and US$1.8 billion annually for water supply improvements (Table 2.2, see also Winpenny, this volume).

In addition to the devastating toll that water pollution can have on human health, water quality can also have negative impacts on the agricultural sector. Salinity is one of the largest water quality problems facing the agricultural sector. Salts can be

Table 2.2 Total annual costs of meeting the water and sanitation MDG (Evans et al. 2004)

	Sanitation annual cost	Water supply annual cost
	(US$ million)	
Sub-Saharan Africa	1,531	491
Latin America	617	171
East Mediterranean & North Africa	206	57
Central & Eastern Europe	198	60
South and Southeast Asia	3,692	403
West Pacific developing countries	3,056	566
Developed countries	222	36
World	9,521	1,784

[4]According to WHO and UNICEF (2004), 1.1 billion people lack access to an improved water supply and 2.6 billion people lack access to improved sanitation worldwide.

[5]Millennium Development Goal Number 7, Target 10: To halve by 2015 the proportion of people without sustainable access to safe drinking water and basic sanitation.

hazardous to plants, reducing yields and growth, although the severity of the impact depends on various factors including the climate, soil type, irrigation frequency and type of crop being grown. Another water quality problem that can affect agriculture is related to the sodium absorption rate (SAR), which indicates the proportion of sodium to calcium and magnesium in the water. If the level of sodium is too high compared to the levels of calcium and magnesium, crusting can occur on the soil surface, leading to water infiltration and permeability problems.

As well as the physical limitations that water pollution places on crop production, water quality problems also create potential competition for funding. Although water supply and sanitation consumes relatively less water than agriculture and water treatment can create a source of irrigation water for peri-urban agriculture, the supply and sanitation sector can compete for funding with traditional irrigation investment. If funding from national governments and international donors is used for water supply and sanitation improvement, availability of financial resources for irrigation investments will likely decline as a result. Multilateral investment banks have favored water supply and sanitation over irrigation investment during the 1990s, for example. Lowered levels of investment for irrigation infrastructure and maintenance of current irrigation systems could have a major impact on agricultural productivity growth in the future.

2.3 Globalization and Trade Liberalization

2.3.1 Virtual Water Trade

There are significant links between globalization, water and agricultural trade. An important link that has been discussed in recent years is virtual water trade (Hoekstra and Hung 2003; Allan 1998). Virtual water is defined as the volume of water used to produce agricultural commodities, and can be measured as crop water depletion or irrigation water depletion. Crop water depletion is computed from effective precipitation (soil water or "green" water) and irrigation ("blue" water). This includes crop evapotranspiration and losses due to reservoir evaporation, percolation to saline aquifers and pollution. Irrigation water depletion is the volume of "blue" water used during crop production, and is smaller or equal to crop water depletion (de Fraiture et al. 2004).

When agricultural commodities enter the world market, the countries that produced these commodities are in effect trading or exporting water, whereas those countries purchasing these commodities are effectively importing water. At the same time, importing countries benefit from this trade as water intended for agriculture can be channeled to other uses (see also Ramirez-Vallejo and Rogers, this volume). Global water savings take place when agricultural exporters are more water efficient than importers whereas global irrigation water savings occur when exporters produce agricultural products under rainfed conditions while importers would have used irrigation water to produce the same agricultural commodities.

De Fraiture et al. (2004) estimate substantial irrigation water savings due to cereal trade. Cereals were used as an indicator of the trade impact on global water use because most irrigated areas around the world are used for cereals, data availability is relatively good, and knowledge of actual and future bilateral trade flows is well established. The majority of cereal trade occurs in the United States, Canada and the European Union where grains are cultivated in highly productive rainfed environments, allowing considerable conservation of irrigation water. The study's results demonstrate that out of 1,724 million mt of global cereal production in 1995, 12% was traded by the United States alone. The United States, Canada, Argentina, Australia and the European Union provided 80% of traded global cereal production, which was produced under highly effective rainfed conditions. On the other hand, importers are more diverse and spread out all over the world with around 25 countries in Asia, Middle East and Africa accounting for 80% of total imports. The top importers are China, Japan, Korea, Indonesia, Egypt, Mexico and Iran.

Rosegrant et al. (2002) use the IMPACT-WATER model to project virtual water flows to 2025. The results show that to produce cereal crops for export, total crop evaporation increases from 7% in 1995 to 8% in 2025, while irrigation water depletion remains at 5% for both years. Projections show an increase in cereal trade from water-abundant to water-deficit areas from 23% in 1995 to 38% by 2025, while global cereal trade grows from 214 million mt in 1988 to 345 million mt in 2025.

Water depletion through water evapotranspiration for cereal production was also measured to evaluate its impact on trade. Based on the IMPACT-WATER baseline scenario, evapotranspiration is expected to increase from 2,622 km^3 in 1995 to 2,758 km^3 in 2025, indicating an increase in global water savings from 190 km^3 in 1995 to 355 km^3 in 2025 (Rosegrant et al. 2002). On the other hand, water savings contributed by water productivity improvements during 1995–2025 accounted for 1,215 km^3. This indicates that without virtual water trade and without productivity improvements, crop evapotranspiration would be 51% higher. The results show that water productivity improvements are far more important than increased virtual water trade. Furthermore, economic and political processes are major driving forces behind trade whereas water scarcity plays a modest role in global trading patterns. Thus, while water scarcity continues to increase, virtual water will likely induce only small changes in trade patterns in the near future.

2.3.2 The Impact of Trade Liberalization

Countries around the world are increasingly affected by globalization, as the exchange of goods and services between countries increases in importance. Trade liberalization can also potentially have large impacts on the economies of many countries, especially in the developing world. Trade liberalization can help in poverty reduction through reduced trade barriers such as tariffs and quotas, reductions in output price protection and input subsidies, privatization of agricultural marketing and trade, and increased reliance on markets rather than planning and the public

Table 2.3 Trade liberalization scenario results using IMPACT Model, 2025 (Rosegrant and Meijer 2007)

	Annual economic benefits 2025 (billion US$)
West Asia/North Africa	1.9
Latin America	3.7
Sub-Saharan Africa	3.3
East Asia	3.0
South Asia	2.0
Southeast Asia	0.4
Developing countries	14.4
Developed countries	10.0
World	24.4

sector. The impact of trade liberalization was estimated using the IMPACT model. A comparison of net economic benefits between a trade liberalization scenario and a baseline scenario showed that both developed and developing countries benefit from trade liberalization (Table 2.3). The net economic benefits from full trade liberalization are estimated as the net benefits to producers (change in producer surplus) plus the net benefits to consumers (change in consumer surplus) plus the tax savings from removal of subsidies compared with the baseline. The results also show that prices for livestock and cereals would rise between 8% and 18% under trade liberalization. Moreover, livestock trade would increase substantially, while changes in cereal trade would be minor (Rosegrant and Meijer 2007). Despite the increases in international prices of livestock and cereals, annual economic benefits are estimated at US$14.4 billion for developing countries and US$10 billion for developed countries (Table 2.3) (Rosegrant and Meijer 2007). Estimates utilizing general equilibrium models show similar results. Delgado et al. (2003) estimate that OECD subsidies and border protection reduce agricultural exports from the developing world by US$37.2 billion (25%) annually.

In addition to overall trade liberalization, changes in specific trade agreements could have significant impacts on patterns of agricultural production and therefore on water use. An example for this is the Multi Fiber Agreement (MFA). Historically, textile and apparel exports from developing countries have been constrained by quotas implemented by developed countries under the MFA. During the Uruguay Round Agreement on Textiles and Clothing (ATC), it was agreed that quotas would gradually be phased out beginning in 1995, with complete removal by the end of 2004 (MacDonald et al. 2004; Diao and Somwaru 2001). As a result, developing countries were obliged to eliminate textile and apparel import barriers incompatible with the General Agreement on Tariffs and Trade (GATT).

MacDonald et al. (2004) used a dynamic computable general equilibrium (CGE) model to analyze how the global restructuring of textile and apparel production and consumption would affect China's textile industry, and applied an econometric partial equilibrium model to examine the impacts of changing industry demand on cotton consumption, regional cotton production, and cotton trade. The analysis showed that global textile and apparel trade increases due to the implementation of the ATC. Before the application of the ATC, annual growth of 8% was projected over the next 25 years. With the implementation of the ATC, however, growth would increase to 9%. Moreover, compared to the situation under the MFA, cotton production would increase in China, and decline in many countries that had been favored in the MFA. These changes in production would in turn influence the demand for agricultural water in cotton-producing countries.

The withdrawal of quotas under the MFA thus puts China, the world's largest producer and exporter of textiles, in more direct competition with other developing countries. The ability of China to maintain this status will depend on the availability of water for agricultural production, which is already severely constrained by competing demands and falling groundwater tables, particularly in north-central river basins like the Haihe, Huaihe and Huanghe (Yellow) basins, where cotton production is established (Lohmar et al. 2003).

2.4 Critical Emerging Factors for Future Water and Food Security: The ABCs

This section discusses three major water-related issues affecting agricultural productivity into the future, namely, aquaculture, biotechnology, and climate change – the new ABCs of the agriculture arena. Will aquaculture be a significant competitor with agriculture for scarce water resources and a threat to water quality? How will climate change influence agricultural production, water resources, and future irrigation investments? Can biotechnology turn around a gloomy future for food security through the conservation of water and other resources?

2.4.1 Aquaculture: A New Competitor for Water?

Fish cultivation or aquaculture began during the fourteenth century and gained in importance in the twentieth century (Brummett 2003). Aquaculture involves the reproduction, breeding, cultivation and marketing of aquatic plants and animals in a controlled or semi-controlled environment (FAO 2004a; Swann 1992). It is the fastest growing segment of animal food production (Rosegrant et al. 2004; FAO 2004a).

Aquaculture can be land or water-based. Land-based aquaculture can include ponds, fish tanks, irrigation canals, dams, and crop areas that utilize freshwater (for example, for rice-fish culture), and seawater-holding tanks that utilize saltwater. Water-based aquaculture occurs within bodies of water like rivers, lakes, coastal areas, oceans and high seas using pens and cages. Aquaculture environments range from freshwater to brackish water and coastal or marine ecosystems.

The two most important factors in aquaculture production are water quality and water quantity. The farming systems applied influence the quality of water used for aquaculture. Farming systems can be extensive, semi-intensive or intensive. Extensive aquaculture relies on natural food such as plankton for the fish without

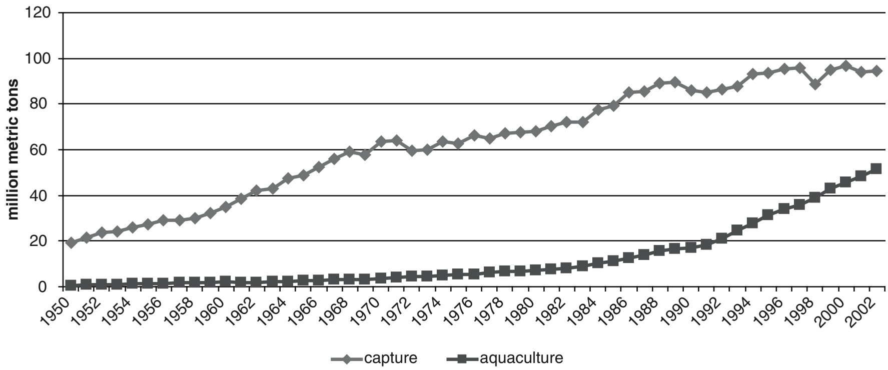

Fig. 2.9 Global capture fisheries and aquaculture production, 1950–2002 (FAO 2004b. FishStat+Database)

intentional human intervention, though natural discharges from streams, rivers, and runoff may bring in nutrients and other food organisms. Semi-intensive farming systems are defined as those in which natural food in the system is increased by organic (manure) and inorganic fertilizers to enhance the production of natural food, and are supplemented by low-cost feed. Intensive aquaculture is the most expensive type of fish farming system as it depends on high-cost, nutritionally complete supplement diets either in the form of small wild fish or formulated pellets. Extensive and semi-intensive farming systems are used in small-scale aquaculture, while intensive is used in large- or commercial-scale fish culture.

Global fish production was recorded at 128.8 million mt in 2002 (FAO 2004a), 71% from capture fisheries, and 29% from aquaculture operations, with the latter share growing rapidly (Fig. 2.9; see also Briones et al., this volume for an analysis of fish trade). Rosegrant et al. (2004) project that aquaculture will make up 68% of the total increase in fish production. Most of this increase is expected to occur in Asia, particularly China, often involving expansion of low-value freshwater fish culture using low-input, low-output systems (Delgado et al. 2003).

Projections by Rosegrant et al. (2004) show the important role of aquaculture in meeting the nutritional requirements and food security of the poor. In addition, aquaculture makes a considerable contribution to developing-country economies, with the economic value increasing seven-fold to US$49,335 million in 2002 while the value in developed countries increased from US$4,611 million in 1984 to US$10,652 million in 2002 (FAO 2004b, Fig. 2.10).

Mariculture made up the largest proportion of aquaculture production in 2002 at 50% (26.1 million mt), followed by freshwater aquaculture at 45% (23.0 million mt) and brackish water aquaculture at 5% (2.3 million mt). Recent declines in brackish water aquaculture growth were mainly due to the collapse of shrimp culture due to disease outbreaks in several developing countries (such as the spread of viruses like whitespot and yellowhead).

The boom in aquaculture production enhanced economic growth in developing countries, predominantly through increased income for poor fish farmers and increased protein in the diets of poor households. Of the three types of culture

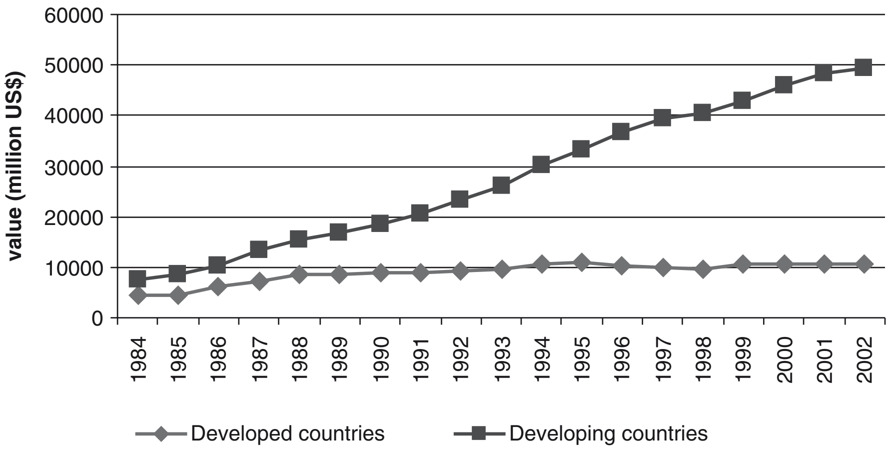

Fig. 2.10 Economic value of aquaculture in developed and developing countries, 1984–2002 (FAO 2004b)

environments, freshwater aquaculture offered the greatest economic value at US$23.6 million in developing countries, while marine and brackish water culture offered US$17.5 million and US$8.3 million, respectively in 2002 (FAO 2004b). Similar to other types of agricultural production, aquaculture can have detrimental effects in areas such as water quality and quantity, biodiversity (introduction of alien species), disease, escaped farmed species, and increased demand for fishmeal and fish oil (which could put more pressure on capture fisheries).

The projected extraordinarily rapid future growth in aquaculture could put substantial stresses on freshwater ecosystems. Fish culture operations, especially in intensive aquaculture, utilize fertilizers for pond preparation and require fishmeal or fish feed as food. Excess quantities of nitrates and phosphates from feed and fertilizers in the water can lead to eutrophication,[6] which triggers intense growth of aquatic plants. The overproduction of aquatic plants is called algal blooms. Algal blooms clog waterways and deplete dissolved oxygen levels during the decomposition process, hindering light penetration into deep water and affecting photosynthetic and other metabolic functions of aquatic organisms. Fish kills normally occur during the decomposition of the aquatic plants as decomposers such as bacteria deplete the water of dissolved oxygen needed by fish to thrive in waterbodies.

In addition to its impacts on water quality, aquaculture enhances water loss through pond seepage, evaporation, and intensity of production (i.e., stocking density, use of feeds and fertilizers and management). A study conducted by Beveridge and Phillips (1993) demonstrates that water loss due to seepage from ponds varies by at

[6]Eutrophication is a process where waterbodies such as lakes, estuaries or slow-moving streams receive excessive nutrients that stimulate excessive growth of plants (e.g. algae, periphyton attached algae or nuisance weeds) (USGS 2008).

least a factor of 10, reaching up to 2.5 cm/day depending on soil types and pond surface area. Evaporative losses can also be as great as 2.5 cm/day, although in the subtropics it is only around 0.5 cm/day. Under tropical conditions, assuming total losses from evaporation and seepage are 1–2 cm/day, a one-hectare fish pond will "consume" around 100–200 m^3 water/day. The total water requirements for ponds vary between 35 m^3 and 60,000 m^3 per ha per year to maintain an average water depth of 1.5 m throughout a growing season of 240 days and to counteract losses of between 1 and 2 cm/day (Beveridge and Phillips 1993). In order to avoid excess water losses from aquaculture, proper management should be given high priority. Additional research is needed to quantify the consumptive use of water by aquaculture and the degree to which it will compete with other water demands in the future.

2.4.2 Biotechnology for Agriculture

Biotechnology has the potential to provide powerful tools for the sustainable development of agriculture, fisheries and forestry and consequently, the food industry. The impact of biotechnology on future requirements for irrigation investment could be profound. The Convention on Biological Diversity defines biotechnology as any technological application that uses biological systems, living organisms or derivatives thereof, to make or modify products or processes for specific use (FAO 2000). Research and advancement in genetic modifications such as transgenic plants, microbes and animals show potential for developing stress-tolerant materials that can possibly address water scarcity, salinization, and groundwater contamination (USERC 2005).

Environmental stresses such as drought, salinity, or soil infertility adversely affect agricultural productivity. Table 2.4 provides a short summary of the role biotechnology can play in addressing drought and salinity stress. The physiological aspects of a plant determine its ability to endure water stress, including multiple biochemical

Table 2.4 Summary of the role of biotechnology in drought and salinity stress (World Water Vision 1999)

Issue	Response
Research needs	Understanding genetic and physiological determinants: Perception of stress Signal transduction Gene activation Protein expression
Likely impacts	Crops for marginal land Increased productivity Crops with less chemical and fertilizer inputs Crops which need less water Crops for saline soils
Policies	Education for water use Public participation in promoting research Long-term commitment and continuous support Private and public sector cooperation

pathways facilitating retention and/or acquisition of water, protecting chloroplast functions and maintaining ion homeostasis (property of a system that regulates its internal environment and tends to maintain a stable, constant condition). One way to address environmental stressors is the application of biotechnology through DNA techniques, molecular biology, and reproductive technological applications including gene manipulation and transfer, DNA typing, and cloning of plants and animals (FAO 2000; World Water Vision 1999).

Genetic engineering has significant potential to increase the productivity of agriculture, forestry and fisheries and help improve food security for the poor in developing countries. For example, FAO (2000) and Hossain et al. (2004) describe how rice has been genetically engineered to contain pro-vitamin A (beta carotene) and iron that could significantly improve the health of many low-income people. Rice biotechnology research has been conducted in laboratories in the developed world. The big multinational companies who invested heavily in upstream research of biotechnology have since withdrawn their financial support because of poor economic profitability due to the predominance of small and marginal farmers as well as the high transaction costs of enforcing intellectual property rights under weak judicial systems (Hossain et al. 2004).

In Asia, successful biotechnology research has been undertaken in public sector laboratories located in Japan, South Korea, India, China, the Philippines and at the International Rice Research Institute (IRRI). Technology progress has recently been made in herbicide tolerance and insect and disease resistance. IRRI and selected national agricultural research systems in developing countries have worked together on gene transfers. Major products are available and undergoing tests for their biosafety and health effects, including Bt rice for stem borer, sheath blight resistance, and iron- and vitamin A enriched rice (Hossain et al. 2004). All of these advances can help save irrigation water. In 1999, 82% of genetically modified plantings were in North America, with the United States accounting for 72%, while in Asia only China had a significant area planted to GMO (Genetically Modified Organism) crops. The Chinese government is the first administration to give approval for the commercialization of GM crops, releasing over 100 varieties of insect-resistant cotton, virus-resistant tobacco, papayas, green peppers and potatoes, and slow ripening tomatoes. Other Asian countries with significant biotechnology research include India, Thailand, and the Philippines (Pinstrup-Andersen 2000).

Aside from augmenting crop production, biotechnology has played a key role in removing organic solids like human waste from millions of liters of wastewater generated everyday (World Water Vision 1999). This was achieved through bioremediation (the use of living organisms to reduce or eliminate environmental hazards resulting from accumulations of toxic chemicals or other hazardous wastes). Table 2.5 shows the role of biotechnology in water quality and wastewater management.

Investment in agricultural research plays a key role in the continuous application of conventional and non-conventional breeding to provide information on the potential of agricultural crops that can withstand adverse environmental conditions like drought or salt tolerance. Future cereal yield growth will come both from incremental increases in yield potential in rainfed and irrigated areas and from improved

Table 2.5 A summary of the role of biotechnology in water quality and wastewater management (World Water Vision 1999)

Issue	Response
Research needs	Biochemical pathways for contaminant degradation
	Microbial stability in biotreatment systems
	Microbial ecology of consortia
	Scaling-up of microbial processes including field studies of new detection/remediation techniques
	New detection methods combined with in-situ monitoring packages
	Understanding genetic structure of key remediation organisms
	Low technology application in general wastewater management
Likely impacts	New biotechnology methods for purifying water that was previously not practically treatable
	Process integrated technologies where biotech options replace chemical options
	Decrease requirement and cost of water purification
	Developing tools for reclamation of degraded land
	Improvement of water quality
Policies	Foster application of available technology
	Incentives for improvisation of new technologies
	Awareness for value of clean water
	Fines/payment for polluters
	Incentives for effective water use
	Foster public/private cooperation
	Incentives to private sector for developing technology

stress resistance in diverse environments (together with policy reform and investments to remove constraints of attaining yield potentials). The rate of growth in yields will be enhanced by extending research both downstream to farmers and upstream to the use of tools derived from biotechnology to assist conventional breeding if concerns over risks from the use of transgenic breeding can be solved.

Current investments come mainly from the private sector and are oriented toward agriculture in higher-income countries because of their purchasing power. However, these biotechnologies should reach developing countries where expansion of agricultural production is much needed for food and nutrition security as well as income enhancement. FAO (2000) suggests that biotechnology efforts should be made available to resource-poor farmers, while at the same time ensuring access to a diversity of sources of genetic materials in developing countries. This needs to be addressed through public funding and dialogue between public and private sectors.

Investments in water use efficiency for irrigated and rainfed crop production should include breeding of crop varieties with high water use efficiency since this is a good indicator of the crop's ability to withstand environmental stresses, particularly drought. Condon et al. (2004) discussed three main processes that can be utilized in breeding crops for high water use efficiency: (a) moving more of the available water through the crop rather than being wasted as evaporation from the soil surface, drainage beyond the root zone or being left behind in the root zone during harvest, (b) acquiring more carbon (biomass) in exchange for water transpired by the crop (i.e., improving crop transpiration efficiency), and (c) partitioning more of the achieved biomass into the harvested product. These three processes are interdependent and their relevance is dependent on water availability during the crop cycle. Use of C_3[7] plants by measuring carbon isotope discrimination may provide information on improving water use efficiency of leaf gas exchange. However, recent findings show that improvements in leaf-level water use efficiency may not translate into higher water use or yield. Crop simulation modeling can be used to assess the likely impact on water use efficiency and yield of changing the expression of crop traits (Condon et al. 2004).

In spite of the broad prospects for GMOs, the use of biotechnology is controversial and public acceptance and safety issues must be resolved. There are four main categories of risks associated with biotechnology namely, (a) effects on human and animal health, (b) environmental consequences, (c) ethical concerns, and (d) socio-economic issues (Hossain et al. 2004). Risks of transferring toxins from one life form to another, creating new toxins or transferring allergic compounds from one species to another could lead to unexpected allergic reactions, with hazardous human health impacts. Environmental risks include the possibility of outcrossing, such as the development of aggressive weeds or wild relatives with increased resistance to diseases, or the rapid creation of new pest biotypes through adaptation to genetically modified plants, possibly upsetting the ecosystem balance. In addition, biodiversity may be lost due to displacement of traditional cultivars by a small number of genetically modified cultivars (FAO 2000). Risks related to value systems or cultural practices can be described as technology transcending. To address these issues, most Asian governments have begun setting regulations to enact biosafety policies (Hossain et al. 2004).

By directly addressing the major water-related stresses under both rainfed and irrigated farming, and by possibly offering solutions to important water quality problems, biotechnology could profoundly affect future demands for freshwater and future investment requirement in both irrigation and other water sectors. The role of biotechnology must therefore be considered in future planning for irrigation and water supply and sanitation investments.

2.4.3 Climate Change

Even though the linkage between climate change and the actual and potential impacts on social and natural environments and, in turn, on human health are still not well understood, there are strong indications that developing countries will bear the brunt of adverse consequences (IPCC 2001, see also Aggarwal and Singh, this volume). This is due both to more severe worsening in climate for many developing regions and to the fact that poverty remains entrenched in rural areas, and the

[7]C_3 plants utilize three carbon compounds for metabolic processes in photosynthesis. These plants thrive in areas where there is moderate light intensity and temperature, high level of groundwater availability and CO_2 concentration of 200 ppm or higher. Examples of these plants include rice, wheat, soybean and most other plants (SERC 2008).

capacity to adapt to global change is concomitantly weakest. Further, the largest impacts from global change will be on the rural areas in developing countries whose major direct and indirect source of employment and income – agricultural production – is particularly vulnerable to global change processes. The agriculture sector is the largest consumer of water resources, and variability in water supply is a major factor influencing welfare and health in poor areas. If water scarcity increases as a consequence of climate change, for example, then rural areas and the agriculture sector will likely lose out to wealthier and more powerful industrial and domestic water users in the quest for limited supplies.

An integrated global analysis of the impacts of climate change and climate variability on the availability and use of water and the production and consumption of food shows that many developing regions will be harder hit than developed regions. In this analysis, the IMPACT model is supported by two additional models. The first model is WATBAL, a global hydrology model that uses first-order data (climate, land cover, soil type, etc.) specified at a 0.5°×0.5° spatial grid for all global land points (excluding Arctic and Antarctica) to produce estimates of river basin runoff over a 30-year time horizon on a monthly time step. The river basin runoff data are used by IMPACT to define the water supply to each of the hydro-economic zones. A second external model, the Global Agro-Ecological Zones (GAEZ) model is used to determine potential crop yield. The GAEZ provides a standardized framework for the characterization of climate, soil and terrain conditions relevant to agricultural production, most notably the estimate of maximum potential crop yield in a gridded format that can be used by IMPACT. In GAEZ, crop modeling and environmental matching procedures are used to identify crop-specific limitations due to climate, soil, and terrain, under assumed levels of inputs and management conditions.

The models are driven by historical climate data, climate scenarios, socioeconomic data, and autonomous adaptation. Climate data are from the CRU 0.5 Degree 1901–1995 monthly climate time-series dataset (New et al. 2000). This dataset provides global gridded precipitation and temperature data at 0.5° × 0.5°. The secondary variable used in this study was vapor pressure, which is used to estimate potential evapotranspiration. The GCMs (Global Circulation Models) used in this analysis to provide precipitation and temperature for climate change scenarios include the Max Plank Institute Model ECHAM4 for B2 2020 and B2 2080 and the Hadley Center Model HadCM3 for A1 2020, A1 2080, B2 2020, and B2 2080 (the methodology and additional results are shown in Strzepek et al. 2004).

Figs. 2.11, 2.12, and 2.13 show the simulated impact of climate change on wheat production in the Zayandeh Rud basin of West Asia and North Africa (WANA) and the Rhine basin in the European Union. The climate scenarios apply the climate shock of the referenced climate change scenario to the baseline climate scenario during the period 1961–1990. Both irrigated and rainfed wheat production in the basin in WANA is significantly reduced due to climate change under all scenarios compared to the base 1961–1990 historical climate scenario. By contrast, climate change results in more favorable growing conditions for wheat in the European Union's Rhine River basin (Fig. 2.13).

Emerging evidence indicates that water resource variability may be a key determinant of economic growth and poverty alleviation in many African countries,

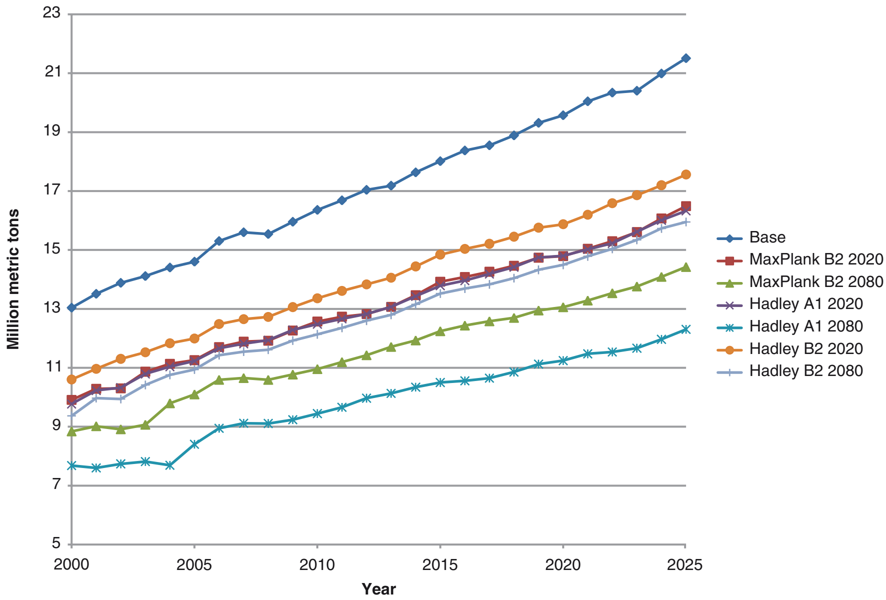

Fig. 2.11 Impact of climate change on irrigated wheat production in West Asia and North Africa, example of Zayandeh Rud basin (IMPACT-WATER Simulations 2004)

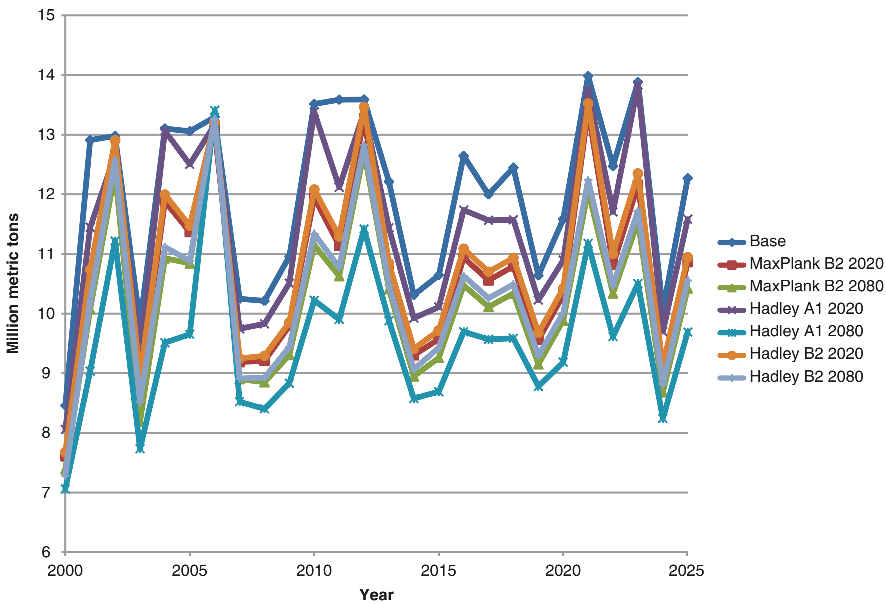

Fig. 2.12 Impact of climate change on rainfed wheat production in West Asia and North Africa, example of Zayandeh Rud basin (IMPACT-WATER Simulations 2004)

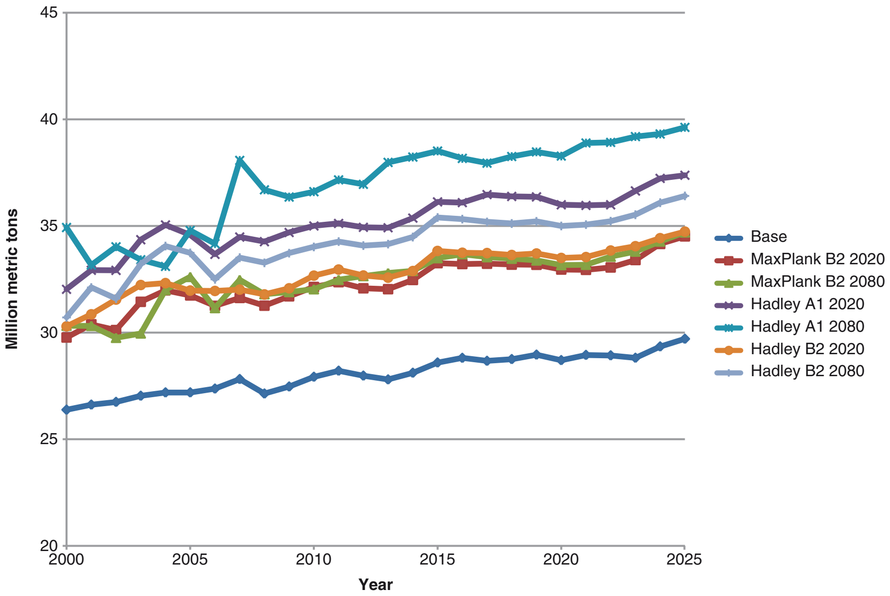

Fig. 2.13 Impact of climate change on irrigated wheat production in the European Union (Rhine River Basin) (IMPACT-WATER Simulations 2004)

including Ethiopia, Kenya, and Mozambique (World Bank 2005). In all rainfed-agriculture dependent countries in sub-Saharan Africa, for example, there is a clear correlation between rainfall and GDP. In these vulnerable countries, the primary water resource characteristic is extreme rainfall variability. This variability is most obviously manifest in endemic, devastating droughts and floods. Less well understood is the broad range of impacts this variability has on the national economy through direct and indirect linkages from agriculture and water resources through environment, energy, water supply and sanitation, industry and transport sectors.

Further research is necessary to clarify the scope and scale of the impacts of hydrological variability on economic performance, natural resources and socioeconomic conditions, and the manner in which water shocks are transmitted through the economy. Block et al. (2005) show that incorporation of stochastic hydrology into agricultural and water sector models can significantly change poverty results and the estimated impact of investments. Figure 2.14 compares projected poverty rates in Ethiopia under a static annual mean climate versus outcomes from an ensemble of climate time series from a stochastic model. The results show that the mean of the poverty rates for the ensemble is significantly higher than with a static climate due to the impacts of droughts and floods, and that there is a wide range of possible poverty outcomes suggesting potentially catastrophic conditions during drought years (Block et al. 2005).

Moreover, the use of a stochastic model significantly changes the estimated impact of investment in irrigation and rural roads growth in gross domestic product

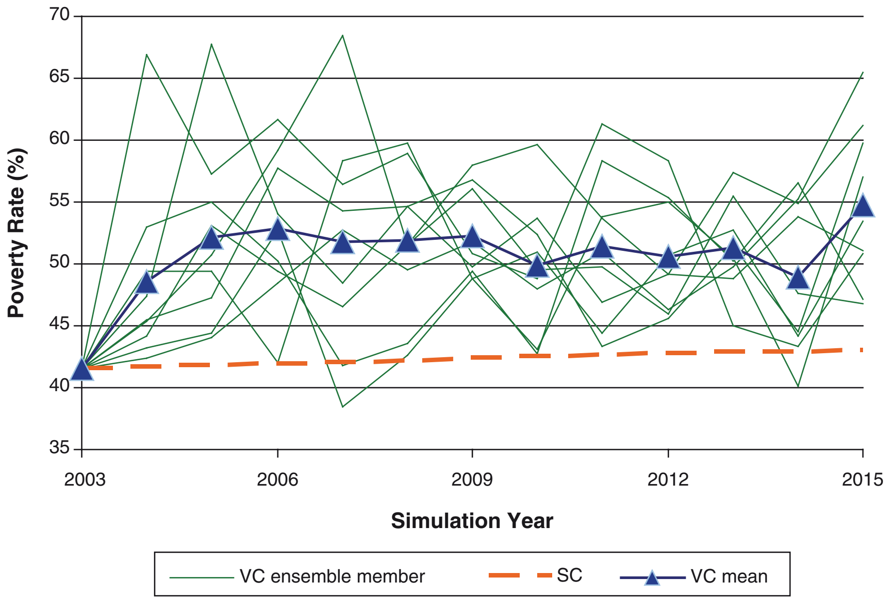

Fig. 2.14 Comparison of poverty rates under a static mean climate (red line) versus an ensemble of nine historic 12-year climate time series. Note: The mean of the nine ensembles for each year is plotted as a blue line (Block et al. 2005)

Table 2.6 Impact of high investment in irrigation and roads on GDP growth compared to baseline (Block et al. 2005)

Impact from investment	Deterministic	Stochastic
	(%)	
Irrigation		
GDP growth rate	19.5	53.3
Agric. GDP growth rate	12.0	111.9
Roads		
GDP growth rate	54.0	42.2
Agric. GDP growth rate	6.9	11.4

(GDP). As shown in Table 2.6, the impact of irrigation investment increases dramatically using the stochastic model compared to the deterministic model, because this model better captures the buffering impact of higher irrigation investment on economic growth. The impact of irrigation investment also increases significantly relative to investment in roads.

Climate change and variability in water supply, together with potential long-term changes in the cost of energy could also dramatically change the cost-benefit calculus for big dams for storage, irrigation, and hydropower, making these investments more attractive despite the environmental and human relocation issues that dams raise. The appropriate level and location of future irrigation investments could also change dramatically. Policy analysis of mitigation and adaptation strategies for increased food and water security should be undertaken to prepare strategies and pathways for reaction to future impacts of climate change (for additional discussion on climate change see Aggarwal and Singh, this volume).

2.5 Policy Implications

This chapter has described the current situation of world food and water supply as well as many of the current and upcoming challenges to future water and food security. Increasing water scarcity and declining water quality must be addressed through reforms in water management, along with the establishment of economic incentives among water users, increased water investments, and a renewed focus on agricultural research and technology for increasing crop productivity. This section discusses in more detail some policy changes that would be useful in dealing with increased water scarcity created by demands from aquaculture and increased variability due to climate change. Changing priorities for investment in agricultural research related to biotechnology and water management are also discussed.

2.5.1 Water Management Reform

One of the best ways to address many of the challenges facing the water sector discussed in this chapter – particularly increased competition from aquaculture and increased variability in water availability due to climate change – is water management reform, including appropriate policies that improve water use efficiency and supporting infrastructure investments. Some of these have been discussed in the section on water above, including phasing out groundwater overdraft in major affected basins. Other strategies include increasing committed environmental flows, and changing policies and levels of water pricing. Research in specific basins is needed to determine the potential for improvements in basin water use efficiency. Efficiency improvements across all water using sectors can have a major impact on overall water use efficiency.

Various methods can be used to improve water management practices across sectors. In the industrial sector, for example, recycling can improve efficiency and lead to substantial water savings. Beekman (1998) suggests that in many industries, water use could be reduced by around 50% as a result. Cooling water is one area that could potentially lead to major savings, as it makes up around half of current industrial water use. Some developing countries have already begun to make headway in these efforts. For example, Nickum (1994) has noted that industrial water recycling rates in Beijing increased from 61% in 1980 to 72% in 1985; and between 1977 and 1991, total industrial water use declined steadily while output increased.

Substantial water-efficiency improvements are possible in the domestic sector as well. Leak detection has promise in many developing countries where unaccountedfor-water can often reduce water use efficiency substantially. Various improved technologies such as low-flow showerheads and low-water or waterless toilets can also help to reduce household water use. Although savings in the domestic sector may be small (since little of domestic water withdrawn is actually used and the water lost from systems is reused elsewhere), they can make a big difference in coastal areas with large populations, where much of the water withdrawn is lost to the ocean. There are also economic benefits generated from lower water withdrawals since water treatment and recycling costs would decline (Gleick et al. 2002; Rosegrant 1997).

Other important water savings in the domestic sector come from wastewater reuse. Domestic wastewater can be reused for many purposes, such as landscaping and irrigation of lawns and golf courses, and toilet flushing. Wastewater reuse for irrigation has been touted for its potential by many authors, as it not only reduces water withdrawals but can also provide crops with a source of nutrients, thus reducing the amount of chemical fertilizers needed. Possible economic benefits of wastewater reuse have been suggested by Shuval (1990) by reducing inputs required for both water and fertilizer. Even with these promising aspects of wastewater reuse, these techniques should be used with caution. Adverse health effects can occur from wastewater reuse, for example from consumption of raw produce. Use of wastewater for the irrigation of fruit and other trees is quite promising, on the other hand, as the irrigation water does not reach the fruit.

The scope for improvements in the irrigation sector is quite large and exists at the technical, institutional and managerial levels. Drip irrigation, sprinklers, and the conjunctive use of surface and groundwater, and other technologies such as computer monitoring of crop water demand are all technical improvements that can help improve water-use efficiency. The establishment of effective water rights and water user associations, as well as the introduction of water pricing are all improvements to the institutions influencing water resources. Demand-based irrigation scheduling and improved maintenance of irrigation infrastructure are aspects of improved irrigation management that should also be considered.

2.5.2 Economic Incentives for Efficient Water Use

Another key to improving water-use efficiency is the use of markets or similar incentives in water management. Setting appropriate incentive prices for water can have a large impact on water withdrawals and consumptive uses across domestic, industrial and irrigation uses. The implementation of such policies is often politically unpopular, however, and can also have negative impacts on poor consumers and farmers if they are not designed and implemented properly.

Improvements in both efficiency and equity in the domestic and industrial sectors are possible through increased water prices. Industries in developing countries are likely to respond to such incentives, as they have not implemented many water-saving technologies. In the domestic sector, generalized subsidies should be replaced with subsidies targeted to the poor; other policies, such as increasing block tariffs, could help to ensure water availability to low-income users without direct subsidies.

Imposing water pricing for agriculture is more difficult. It is a politically charged issue as pricing can reduce farm incomes and decrease the stability of water rights. In addition, irrigation water pricing can be difficult and costly to administer in developing countries, as typically many farmers are connected to one large irrigation system. It is possible, however, to design water pricing systems that create incentives for efficient water use, recover some costs and protect farm incomes (see, e.g., Pezzey (1992) or Ringler et al. (2006)).

2.5.3 Water Investment

Even with the significant financial, environmental and social costs of developing new water supplies, some expansion is appropriate. Storage and withdrawal capacities need to be expanded in many parts of the developing world, including sub-Saharan Africa, some countries in South and Southeast Asia, and some parts of Latin America to reduce variability in supplies. Such investment decisions are politically sensitive, however, and the full social, economic, and environmental costs and potential benefits of development must be considered, including not only irrigation benefits but also health, household water use, and catchment improvement benefits.

As mentioned earlier, groundwater overuse is a major problem in many areas. Therefore sustainable development of groundwater resources can also offer opportunities for many countries and regions. Conjunctive use of surface and groundwater could be expanded significantly by (1) using wells for supplemental irrigation when canal water is inadequate or unreliable to reduce moisture stress and maximize irrigated crop yields; (2) pumping groundwater into canals to augment canal water resources, lower water tables, and reduce salinity; and (3) viewing a canal command and its embedded tubewells as an integrated system thereby optimizing joint use of canal and groundwater resources (Oweis and Hachum 2001; Frederiksen et al. 1993). It is crucial, however, that groundwater expansion is not undertaken without sufficient knowledge of the aquifer properties.

2.5.4 Agricultural Research and Technology

Agricultural research and technology will continue to be of major importance in dealing with the challenges facing agriculture in the future, as was discussed above. Increasing crop productivity is a major concern, which can be carried out through water management, agricultural research, and rural investments. Investment in crop breeding targeted to rainfed environments is crucial to future crop yield growth and must be continued. Research for irrigated areas should also be undertaken, with specific attention given to breeding crops for stress tolerance. Cereal yield growth could be further improved by extending research both downstream to farmers and upstream to the use of tools derived from biotechnology to assist conventional breeding, and, if concerns over risks can be solved, from the use of transgenic breeding.

Investments in rural infrastructure will also be important for improving access for rural farmers. Higher priority for agricultural extension services and access to markets, credit, and input supplies should be given in rainfed areas because successful development of rainfed areas is likely to be more complex than in high-potential irrigated areas given their relative lack of access to infrastructure and markets, and their more difficult and variable agroclimatic environments. Progress may also be slower than in the early Green Revolution because new approaches will need to be developed for specific environments and tested on a small scale prior to broad dissemination. Investment in rainfed areas, policy reform, and technology transfer, such as water harvesting, will therefore require stronger partnerships between agricultural researchers and other agents of change, including local organizations, farmers, community leaders, NGOs, national policymakers, and donors.

The appropriate mix of measures mentioned above can help to address current water problems and those of the future. With specific interventions geared toward the local physical conditions and socioeconomic situation, individual countries can implement an appropriate solution for their people.

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