Water for Food Production: Will There Be Enough in 2025?

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This year marks the 200th anniversary of the publication of Thomas Malthus's famous essay postulating that human population growth would outstrip the earth's food-producing capabilities. His writing sparked a debate that has waxed and waned over the last two centuries but has never disappeared completely. Stated simply, Malthus's proposition was that because population grows exponentially while food supplies expand linearly, the former would eventually outpace the latter. He predicted that hunger, disease, and famine would result, leading to higher death rates.

One of the missing pieces in Malthus's analysis was the power of science and technology to boost land productivity and thereby push back the limits imposed by a finite amount of cropland. It was only in the twentieth century that scientific research led to marked increases in agricultural productivity. Major advances, such as the large-scale production of nitrogen fertilizers and the breeding of high-yielding wheat and rice varieties, have boosted crop yields and enabled food production to rise along with the world population (Dyson 1996). Between 1950 and 1995, human numbers increased by 122% (US Bureau of the Census 1996), while the area planted in grain expanded by only 17% (USDA 1996, 1997c). It was a 141% increase in grainland productivity, supplemented with greater fish harvests and larger livestock herds, that allowed food supplies to keep pace with population and diets for a significant portion of humanity to improve.

Despite this remarkable success, concern about future food prospects has risen in recent years because of a marked slowdown in the growth of world grain yields, combined with an anticipated doubling of global food demand between 1995 and 2025 (McCalla 1994, FAO 1996). Whereas annual grain yields (expressed as three-year averages) rose 2–2.5 % per year during every decade since 1950, they registered growth of only 0.7% per year during the first half of the 1990s (Brown 1997, USDA 1997a, 1997b). Excluding the former Soviet Union, where the political breakup and economic reforms led to large drops in productivity, global grain yields increased an average of 1.1% per year from 1990 to 1995, approximately one-half the rate of the previous four decades (Brown 1997). Today, the principal difference between those analysts projecting adequate food supplies in 2025 and those anticipating significant shortfalls is the assumed level of productivity growth—specifically, whether annual productivity over the next three decades is likely to grow at closer to the 1% rate of the 1990s or the 2–2.5% rate of the previous four decades.

Water—along with climate, soil fertility, the choice of crops grown, and the genetic potential of those crops—is a key determinant of land productivity. Adequate moisture in the root zone of crops is essential to achieving both maximum yield and production stability from season to season. A growing body of evidence suggests that lack of water is already constraining agricultural output in many parts of the world (Postel 1996, UNCSD 1997). Yet to date, I am aware of no global food assessment that systematically addresses how much water will be required to produce the food supplies of 2025 and whether that water will be available where and when it is needed. As a result, the nature and severity of water constraints remain ill defined, which, in turn, is hampering the development of appropriate water and agricultural strategies.

In this article, I estimate the volume of water currently consumed in producing the world's food, how much additional water it will take to satisfy new food demands in 2025, and how much of this water will likely need to come from irrigation. I then place this expected irrigation demand in the context of global and regional water availability and trends. Finally, I discuss the policy and investment implications that emerge from the analysis.

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Total Water Consumed in Food Production

The volume of water consumed in producing current food supplies is much larger than estimates of agricultural water use typically suggest. These estimates have focused almost exclusively on the volume of water removed from rivers, lakes, and underground aquifers for irrigation. They typically neglect the soil moisture derived directly from rainfall that is consumed by agricultural cropping systems, pastures, and grazing lands. This omission is perhaps understandable, given that such rain-fed lands do not require investments in dams, canals, and other water infrastructure and do not figure into projected demands on regional water supplies. Yet it results in an incomplete and misleading picture of the volume of water actually used to produce the world's food-and, by extension, of future water requirements for food production.

Water consumed by crops and croplands. In general, there is a linear relationship between a crop's water consumption and its dry matter yield up to the point at which water is no longer limiting (Sinclair et al. 1984). The amount of dry matter produced per unit of water transpired—which is known variously as a crop's water-use efficiency or transpiration ratio—is the slope of this linear relationship, and it varies by crop, climate, and other factors. For example, climatic and other conditions being equal, C_4 crops, such as maize, tend to use water more efficiently than other grains because of their special anatomical and biochemical characteristics. A crop grown in a drier climate will transpire faster than the same crop grown in a more humid climate because of the larger vapor pressure gradient between the plant's stomata and the atmosphere. Thus, the volume of water a given crop uses will vary by crop type, climate, season, and other factors, but the basic linear relationship between dry matter production and transpiration generally holds for all crops and growing environments (Kramer and Boyer 1995).

In determining the amount of water consumed in producing the global food supply, several additional factors must be taken into account. Water is consumed not only through transpiration but also through evaporation from the soil and leaf surfaces. Under field conditions, evaporation is difficult to measure separately from transpiration, so the processes are typically referred to jointly as evapotranspiration. In addition, because only the edible portion of a crop contributes to food supplies, the portion of a crop's dry matter that is actually harvested (known as the harvest index) must also be taken into account. The water-use efficiency of the harvested yield is expressed as the harvested crop yield per unit of water evapotranspired and is often denoted by Ey. These values are shown in Table 1, along with the total 1995 production of each crop or crop category. Lacking detailed regional data, the estimated global crop water requirements shown in Table 1 were derived by multiplying the inverse of the midpoint of the Ey value for each crop or crop category by the 1995 global production of that crop. This calculation results in an estimated minimum water requirement for the 1995 global harvest of crops of approximately 3200 km^3 (3200 billion cubic meters).

Not surprisingly, wheat, rice, maize, and other grains—the staples of the human diet and also sources of feed for livestock—account for more than 60% of the total crop evapotranspiration requirement. Soybeans and other oilseed crops account for 17% of this requirement, and sugar cane alone accounts for approximately 6%. It is important to emphasize that the values in Table 1 do not reflect how much water is actually consumed in crop production but rather the minimum required for that production. Inefficiencies in irrigation that result in evaporative losses, for example, are not taken into account; I address such additional consumptive uses of water in a later section.

The plants from which the world's food commodities are harvested represent only a portion of total cropland biomass. The net photosynthetic product of the world's croplands has been estimated at 15 $\times 10^9$ t/yr (Ajtay et al. 1979, Vitousek et al. 1986). Assuming that an average of 2 g biomass is produced per 1 L of water evapotranspired (Monteith 1990, Postel et al. 1996), a total of 7500 km^3 would be consumed through evapotranspiration in cropland ecosystems—more than twice the estimated evapotranspiration of the crop plants themselves (Table 2). Because crop production depends on the productivity of the supporting ecosystem, this higher figure may more accurately reflect the total amount of water consumed through evapotranspiration on the world's croplands.

Water consumed by converted pasture and grazing land. The world's domesticated animals—including 1.3 billion cattle, 900 million pigs, and more than 12 billion chickens (FAO 1996)—contribute meat, milk, eggs, and other items to the human diet. Of the 2700 kilocalories available per capita per day on average worldwide (FAO 1995), approximately 16% comes from animal products. However, this share varies greatly by country

Table 1. Estimated water consumption by crops worldwide, 1995.[a]

Crop	Global production ($\times$ 1000 t)	Water-use efficiency of harvested yield[b] (kg/m^3)	Estimated water requirement (km^3/yr)
Wheat	541,120	0.8 –1.0	601
Rice	550,193[c]	0.7–1.1	611
Maize	514,506	0.8–1.6	429
Other grains	290,236	~ 0.6–1.2	323
Roots and tubers	609,488	~ 4.0–7.0	111
Pulses	55,997	~ 0.2–0.6	140
Soybeans	125,930	0.4–0.7	229
Other oilseeds	125,749	~ 0.2–0.6	314
Ground nuts	27,990	0.6–0.8	40
Vegetables and melons[d]	487,287	~ 10.0	49
Fruits (except melons)[d]	396,873	~ 3.5	113
Sugar cane[e]	1,147,992	5.0–8.0	177
Sugar beets[e]	265,963	6.0–9.0	36
Tobacco	6,447	0.4–0.6	13
Other[f]			21
Total			3207

[a]Data from FAO (1996) and Doorenbos and Kassam (1979).
[b]The midpoints of these ranges are used to calculate the crop water requirement. Water-use efficiency values were not available for all crops, so where necessary I have attempted to make a reasonable assumption based on available information; these assumed values are denoted by a tilde (~).
[c]Rough rice; to calculate milled-rice production, multiply by 0.7.
[d]Statistics on fruit and vegetable production in many countries are unavailable, and much of the reported data excludes production from small household and community gardens, which can be substantial in some countries. The United Nations Food and Agriculture Organization (FAO 1996) has attempted to estimate total production of fruits and vegetables but does not break down these estimates by crop type. Thus, I have applied a reasonable water-use efficiency value based on known values for crops in these categories. Nevertheless, the margin of error for the estimated water requirements of fruits and vegetables is larger than that for the other crops.
[e]Values are for production of cane and beets, not for the raw sugar derived from them; per unit of sugar, beets are significantly more water efficient than cane.
[f]Coconuts, olives, tree nuts, coffee, cocoa beans, tea, and hops; the water requirements for thes crops are little better than informed guesses, but this high margin of error does not significantly affect the global total.

and region: For example, 32% of the estimated 3410 calories per capita per day available in Europe comes from animal products, compared with just 7% of the average 2282 kilocalories per capita per day available in Africa (FAO 1995).

Livestock variously eat grass, hay, feed grain, and food waste. Although the feed grain and food waste are included in the crop production figures in Table 1, a separate calculation needs to be made to account for evapotranspiration on converted pasture and grazing land. Again, assuming an average biomass production rate of 2 g/L of water, the estimated water consumption occurring on pasture- and rangeland totals 5800 km^3/yr (Table 2; Vitousek et al. 1986, Postel et al. 1996).

Non-beneficial evapotranspiration of irrigation water and from aquaculture ponds. Irrigated lands—those receiving artificial water applications to supplement natural rainfall—totaled 249.5 $\times$ 10^6 ha in 1994, the most recent year for which data are available (FAO 1996). Because irrigation makes possible more than one harvest a year on the same parcel of land and allows farmers greater control over the watering of their crops, these lands are disproportionately important in global food production; they represent just 17% of the world's total cropland area but yield on the order of 40% of the world's food (Rangeley 1987, Yudelman 1994).

Shiklomanov (1996) estimated that in 1996 a total of approximately 2500 km^3 was withdrawn from rivers, lakes, and aquifers for irrigation. However, a portion of this water never benefits a crop. Some of it is lost to evapotranspiration as the water is stored in ponds or reservoirs, transported by canals, and applied to farmers' fields. Water percolating into the soil through unlined canals or running off the end of a farmer's field also represents inefficiency and can degrade both land and water quality. But because this water is not evapotranspired, it is theoretically available to be used again and so is not counted as a loss. No good global estimate of

Table 2. Total water consumed in food production, 1995.[a]

Activity	Estimated water consumption (km^3/yr)
Water consumed directly by crops and associated cropland biomass	7500
Water consumed by converted pasture and natural grazing land used by livestock	5800
Non-beneficial evapotranspiration of irrigation water[b]	500
Water consumed in aquaculture production	0[c]
Total	13,800

[a]Calculations based on information in Doorenbos and Kassam (1979), FAO (1996), Postel et al. (1996).
[b]See text for explanation.
[c]Negligible on a global basis.

nonbeneficial irrigation water losses exists, but they may amount to approximately 20% of the volume withdrawn (Perry 1996). Applying this figure to the 1995 estimate of irrigation withdrawals suggests unproductive evapotranspiration losses of 500 km^3, as shown in Table 2.

Water also evaporates from ponds used in fish farming, an increasing source of protein worldwide. These evaporation losses are difficult to estimate because aquaculture production can occur in coastal bays or estuaries, indoor tanks, or artificial ponds. Currently, evaporation from ponds is negligible relative to the total water consumed in food production. Yet fish farming is growing rapidly: Aquaculture production tripled between 1984 and 1995, from 7×10^6 t/yr to 21×10^6 t/yr, and in 1995 it accounted for 19% of the global fish harvest (McGinn 1997). As aquaculture expands, pond evaporation will increase and may factor significantly into the water budgets of water-short areas.

Summing the estimated volumes of water consumed by cropping systems, grasslands and pasture, and nonbeneficial evaporation of irrigation supplies yields an estimate of total water consumption for food production in 1995 of 13,800 km^3/yr—or nearly 20% of the total annual evapotranspiration occurring on the earth's land surface. For the 1995 population of 5.7 billion (PRB 1995), this global total translates to an annual average of approximately 2420 m^3 per capita.

Changing Structure of Global Food Sources

The structure and sources of the global food supply in 2025 will not be simply an extrapolation of past trends. Serious constraints exist on the expansion of grazing land, fisheries, and cropland, which suggests that most of the additional food required in the future will need to come from higher productivity on existing cropland. This shift has important implications for the volume and sources of water that will be required to satisfy future food needs.

Rangeland constraints. According to a global assessment of soil degradation (Oldeman et al. 1991), overgrazing has degraded some 680 ξ 10^6 ha of the world's rangelands since midcentury. This finding suggests that 20% of the world's pasture and range is losing productivity and will continue to do so unless herd sizes are reduced or more sustainable livestock practices are put into place. With the global ruminant livestock herd, now numbering about 3.3 billion, unlikely to increase appreciably, most of the increase in meat production will need to come from grain-fed livestock.

Fisheries constraints. The wild fish catch from marine and inland waters totaled 91×10^6 t in 1995, little more than in the late 1980s. On a per capita basis, the 1995 global fish catch was down nearly 8% from the 1988 peak (McGinn 1997). With the United Nations Food and Agriculture Organization (FAO 1993) reporting that all 17 of the world's major fishing areas have either reached or exceeded their natural limits, no growth can be expected in the oceanic catch. Aquaculture, the most rapidly growing source of fish, now accounts for one of every five fish consumed, a share that is expected to increase (McGinn 1997). Although fish is a more water efficient source of animal protein than virtually any other grain-fed source, the expansion of aquaculture will increase pressures on both cropland and water supplies in the future.

Cropland constraints. With production from both rangelands and fisheries reaching natural limits, most of the increased food supply in 2025 will need to come from cropland. However, on a net basis, cropland area is unlikely to increase appreciably. As much as 10^7 ha may be lost each year due to erosion, other forms of degradation, or conversion to nonfarm uses (Leach 1995, Pimentel et al. 1995). Because such losses are often not fully counted in official statistics—which show that cropland expanded an average of 1.6×10^6 ha/yr between 1979 and 1994 (FAO 1996)—net cropland expansion could well be close to zero or even negative. Moreover, possibilities for opening up new cropland are mostly in areas in which the long-term crop production potential is relatively low and the biodiversity and other ecological costs are very high, such as in Brazil and central Africa.

Implications for future water requirements. By definition, the water requirements of rain-fed crops are met by rainfall, which is supplied freely by nature and rarely counted in estimates of global agricultural water use. With net cropland area unlikely to expand much if at all, the potential for increased use of direct rainfall to meet crop evapotranspiration requirements is limited largely to improving the productivity of rainwater on existing croplands, both irrigated and rain-fed. Terracing, mulching, contour bunding (placing stones or vegetation along contours), and other methods of capturing rainwater to enhance soil moisture have proven effective at increasing yields of rain-fed crops (Unger and Stewart 1983, Critchley 1991, Reij 1991). Rain-fed production may also benefit from greater focus on boosting total crop output from the land—for example, through agroforestry and synergistic intercropping—as opposed to boosting the yields of single crops.

Table 3. Estimated 1995 crop consumption of rainwater and irrigation water and projections for 2025.

Year	Projected global crop evapo-transpiration requirement (km^3/yr)	Supply directly from rainfall (km^3/yr)	Supply from irrigation (km^3/yr)	Irrigation share of global crop evapo-transpiration requirement (%)
1995	3200	2300	900	28
2025	6400	3450	2950	46
Increase	100%	50%	227%	

Globally, the volume of water available for crop evapotranspiration will need to roughly double by 2025 if total crop production is to double. Although actual crop water requirements in 2025 will depend on the crop mix, the climate under which crops are grown, changes in the harvest index, and other factors, a doubling is a reasonable assumption. Because net cropland area is likely to expand minimally if at all, I assume no increase in the water use of related cropland biomass and focus on the direct evapotranspiration requirements of crops, an estimated 6400 km^3 in 2025.

How this additional water for crop evapotranspiration will be partitioned between rainfall and irrigation is impossible to project, especially given that the current partitioning of the crop water supply can be approximated only roughly. However, if 40% of the global harvest currently comes from irrigated land and if, on average, 70% of the soil moisture on this irrigated land comes from irrigation water (the other 30% comes directly from rainfall), then irrigation water would account for about 900 km^3 of the 3200 km^3 required for crop evapotranspiration in 1995; the other 2300 km^3 would have been supplied directly from rainfall (Table 3). It seems reasonable to assume that modest cropland expansion and enhanced rainwater productivity might allow productive use of rainfall for crop evapotranspiration to increase by 50% between 1995 and 2025. To satisfy the global crop water requirement in 2025, the volume of irrigation water consumed by crops would thus need to more than triple—from an estimated 900 km^3 in 1995 to 2950 km^3—and irrigation's share of total crop water consumption would rise from 28% to 46%. The volume of irrigation water annually available to crops as soil moisture would need to expand by 2050 km^3—equivalent to the annual flow of 24 Nile Rivers or 110 Colorado Rivers.

Prospects for Supplying the Needed Irrigation Water

Current trends in water use and availability strongly suggest that supplying an additional 2050 km^3 per year for consumptive agricultural use oN a sustainable basis will be extremely difficult. A variety of trends and indicators signal that water constraint on agriculture are already emerging both globally and regionally.

The global demand–supply outlook. Of the 40,700 km^3 that run to the sea each year in rivers and aquifers, only an estimated 12,500 km^3 are actually accessible for human use, of which human activities already appropriate an estimated 54% (Postel et al. 1996) By 2025, water withdrawals for irrigation could approach 4600 km^3/yr assuming 3500 km^3/yr of consumptive use (both beneficial and non-beneficial) and somewhat higher irrigation efficiency than at present. In addition, estimates by the Russia hydrologist Igor Shiklomanov (1993) suggest that worldwide household municipal, and industrial water use currently average approximately 240 m^3/yr per capita. Greater use of more efficient household and industria technologies could reduce this per capita requirement substantially (Postel 1992), but the resulting savings would be partially offset by the water needed to meet minimum drinking and household requirements of the more than 1 billion people now lacking them (Gleick 1996).

Assuming an average global per capita household, municipal, and industrial water use of 200 m^3/yr, the combined demand in these sectors would total some 1640 km^3 in 2025. Adding this amount to estimated irrigation withdrawals and reservoir losses suggests that global withdrawals in 2025 could total 6515 km^3. This estimate exceeds by 26% that of Shiklomanov (1996), in large part because of the higher global irrigation water requirement that emerges from the more detailed crop-water analysis carried out in this study.

Adding in greater instream flow needs to dilute pollution, human appropriation of accessible runoff in 2025 could exceed 70%, up from just over 50% at present, even with fairly optimistic assumptions about supply expansion (Postel et al. 1996). Both the dams and other infrastructure built to meet the higher demand, as well as the high level of human co-option of the supplies available, would cause much greater loss of valuable freshwater ecosystem services (Postel and Carpenter 1997), further decline of fisheries, and more rapid extinction of species that depend on aquatic ecosystems.

Global irrigation trends. Worldwide growth of irrigated area has dropped from an average of 2% per year between 1970 and 1982 to 1.3% per year between 1982 and 1994 and shows no sign of picking up speed. Rising construction costs for new irrigation projects and the declining number of ecologically and socially sound sites for the construction of dams and river diversions have led international donor institutions and governments to reduce irrigation investments. Irrigation lending by the four major donors—the World Bank, the Asian Development Bank, the US Agency for International Development, and the Japanese Overseas Economic Cooperation Fund—peaked in the late 1970s and dropped by nearly half over the next decade (Rosegrant 1997). Governments in many Asian countries—including China, the Philippines, Bangladesh, India, Indonesia, and Thailand—also cut back irrigation investments substantially during the 198Os. Although private investment has countered this trend somewhat, irrigation worldwide has been growing at a slower pace than population: Per capita irrigated area peaked in 1978 and fell 7% by 1994, the latest year for which data are available (Gardner 1997).

At the same time, the steady buildup of salts in irrigated soils is leading to a decline in the productivity of a portion of the existing irrigation base. Estimates suggest that salinization affects 20% of irrigated lands worldwide (Ghassemi et al. 1995) and may be severe enough on 10% of these lands to be reducing crop yields. Spreading at a rate of up to 2×10^6 ha annually (Umali 1993), salinization is offsetting a portion of the gains achieved by bringing new lands under irrigation. Together, spreading soil salinization and the declining rate in the expansion of irrigation have contributed significantly to the decline in grain yield growth witnessed during the first half of the 1990s.

Regional signs of water depletion and unsustainable use. Groundwater overpumping and aquifer depletion now plague many of the world's most important food-producing regions, including the north plain of China, the Punjab of India, portions of Southeast Asia, large areas of north Africa and the Middle East, and much of the western United States (Postel 1996). Failing water tables not only signal limits on the ability to expand future groundwater use but also indicate that a portion of the world's current food supply depends on water that is used unsustainably—and therefore cannot be counted as a reliable portion of the world's long-term food supply. Saudi Arabia, which as recently as 1994 was producing nearly 5×10^6 t of wheat by mining nonrenewable groundwater, illustrates this point well: When fiscal problems led the government to reduce the subsidies that had propped up this unsustainable wheat production, Saudi grain output plummeted 62% in two years, falling to 1.9×10^6 t in 1996 (USDA 1997a).

Many of the planet's major rivers are showing signs of overexploitation as well, adding to the evidence that it will be difficult to greatly increase agricultural water supplies. In Asia, where the majority of world population growth and additional food needs will be centered, many rivers are completely tapped out during the drier part of the year, when irrigation is so essential. According to a World Bank study (Frederiksen et al. 1993), essentially no water is released to the sea during a large portion of the dry season in many basins in Asia. These include the Ganges and most rivers in India, China's Huang He (Yellow River), Thailand's Chao Phraya, and the Amu Dar'ya and Syr Dar'ya in central Asia's Aral Sea basin. The Nile River in northeast Africa and the Colorado River in southwestern North America discharge little or no freshwater to the sea in most years (Postel 1996).

Increasing competition for water. Even as limits to tapping additional water supplies are appearing, agriculture is losing some of its existing water supplies to cities as population growth and urbanization push up urban water demands. The number of urban dwellers worldwide is likely to double to 5 billion by 2025. This trend will increase pressure to shift water out of agriculture to supply drinking water to growing cities, as is already happening in China, the western United States, parts of India, and other water-short areas.

In addition, rising public concern about the loss of fisheries, the extinction of aquatic species, and the overall decline of freshwater ecosystems is generating political pressure to shift water from agriculture to the natural environment, particularly in wealthier countries. In the United States, for example, the US Congress passed legislation in 1992 that dedicates 987×10^6 m^3 of water annually from the Central Valley Project in California, one of the nation's largest federal irrigation projects, to maintaining fish and wildlife habitat and other ecosystem functions. Among the objectives of the Central Valley Project Improvement Act is restoring the natural production of salmon and other anadromous fish to twice their average levels over the past 25 years (Gray 1994).

Further evidence of heightened competition for irrigation water comes from a county-level analysis of the 17 western US states (Moore et al. 1996), which found agricultural activities to be a factor in the decline of 50 fish species listed under the Endangered Species Act (ESA). This analysis also found that 235 counties contained irrigated land that drew water supplies from rivers harboring ESA-listed fish species. These findings suggest that US irrigated agriculture may face more widespread water losses because of legal obligations to protect species at risk.

Water, Population, and the Global Grain Trade

Finally, a growing imbalance between population size and available water supplies is eliminating the option of food self-sufficiency in more and more countries. As annual runoff levels drop below 1700 m^3 per person, food self-sufficiency becomes difficult, if not impossible, in most countries. Below this level, there is typically not enough water available to meet the demands of industries, cities, and households; to dilute pollution; to satisfy other ecological functions; and to grow sufficient food for the entire population. Thus, countries begin to import water indirectly, in the form of grain.

Of the 34 countries in Africa, Asia, and the Middle East that have annual per capita runoff levels below 1700 m^3, all but two (South Africa and Syria) are net grain importers; 24 (70%) of these countries already import at least 20% of their grain (Table 4). Collectively, their annual net grain imports, averaged over 1994–1996, totaled 48×10^6 t, which suggests that water scarcity is to some degree driving about one-fourth of the global grain trade. With approximately 1500 m^3 of water required to grow 1 t of grain in these countries (higher than the global average because of the higher evapotranspiration rates in drier climates; FAO 1997), these annual grain imports represent 72 km^3 of water.

As populations grow, per capita water supplies will drop below 1700 in m^3 per year in more countries, and countries that are already on the list of so-called water-stressed countries will acquire more people. By 2025, 10 more African countries will join the list, as will India, Pakistan, and several other Asian nations; China will only narrowly miss doing so. Given current population projections (PRB 1997), the total number of people living in water-stressed African, Asian, and Middle Eastern countries will climb 6.5-fold by 2025, from approximately 470 million to more than 3 billion (Table 5). With nearly 40% of the projected 2025 population living in countries whose water supplies are too limited for food self-sufficiency, dependence on grain imports is bound to deepen and spread

Table 4. Grain import dependence of African, Asian, and Middle Eastern countries with per capita runoff of less than 1700 m^3/yr.[a]

Country	Internal runoff per capita, 1995 (m^3/yr)[b]	Net grain imports as share of consumption (%)[c]
Kuwait	0	100
United Arab Emirates	158	100
Singapore	200	100
Djibouti	500	100
Oman	909	100
Lebanon	1297	95
Jordan	249	91
Israel	309	87
Libya	115	85
South Korea	1473	77
Algeria	489	70
Yemen	189	66
Armenia	1673	60
Mauritania	174	58
Cape Verde	750	55
Tunisia	393	55
Saudi Arabia	119	50
Uzbekistan	418	42
Egypt	29	40
Azerbaijan	1066	34
Turkmenistan	251	27
Morocco	1027	26
Somalia	645	26
Rwanda	808	20
Iraq	1650	19
Kenya	714	15
Sudan	1246	4
Burkina Faso	1683	2
Burundi	563	2
Zimbabwe	1248	2
Niger	380	1
South Africa	1030	–3
Syria	517	–4
Eritrea	800	Not available

[a]From WRI (1994), FAO (1995), and USDA (1997a).
[b]Runoff figures do not include river inflow from other countries, in part to avoid double-counting. Only Armenia, Azerbaijan, Djibouti, Iraq, Mauritania, Sudan, Turkmenistan, and Uzbekistan would have more than 1700 m^3 per capita in 1995 and 2025 if current inflow from other countries were included.
[c]Ratio of annual net grain imports to grain consumption averaged over the period 1994–1996.

Table 5. Number of people in African, Asian, and Middle Eastern countries with per capita runoff of less than 1700 m^3/yr, 1995, with projections for 2025.[a]

Region	Population 1995 ($\times 10^6$)	Population 2025 ($\times 10^6$)	Factor increase
Africa	295	908	3.1
Asia	86	1957	22.8
Middle East	86	185	2.1
Total	467	3050	6.5

[a]From WRI (1994), FAO (1995), and PRB (1995, 1997).

Conclusions and Implications

Water availability will be a serious constraint to achieving the food requirements projected for 2025. The need for irrigation water is likely to be greater than currently anticipated, and the available supply of it less than anticipated. Groundwater overdrafting, salinization of soils, and re-allocation of water from agriculture to cities and aquatic ecosystems will combine to limit irrigated crop production in many important food-producing regions. At the same time, more and more countries will see their populations exceed the level that can be fully sustained by available water supplies.

The common presumption that international trade will fill emerging food gaps deserves more careful scrutiny. With each 1 t of grain representing approximately 1000 t of water, water-stressed countries will increasingly turn to grain imports to balance their water budgets. The majority of people living in water-stressed countries in 2025 will be in Africa and South Asia, home to most of the 1 billion people who are currently living in acute poverty (UNDP 1996) and the 840 million people who are currently malnourished (FAO 1996). It is questionable whether exportable food surpluses will be both sufficient and affordable for poor food-importing countries.

Given the limited potential for sustainable increases in cropland area and the mounting barriers to expanding irrigated area, measures are urgently needed to ensure that the best rain-fed land now in production remains in production. Rain-fed land does not compete directly with urban and industrial uses for water in the way that irrigated land does. In a world of deepening water scarcity, rain-fed land will thus become increasingly important to global food security. Whether through land-use zoning or other means, it deserves premium protection.

Clearly, greater efforts are needed to raise the water productivity of the global crop base, both rain fed and irrigated. Boosting by half the productive use of rainwater for crop evapotranspiration, as assumed in this analysis, will be difficult. Small-scale water harvesting, terracing, bunding, and other means of channeling and storing rainwater to increase soil moisture will be crucial. Successful examples of these types of projects in Africa (Critchley 1991), India (Centre for Science and Environment 1997), and elsewhere suggest greater potential for drought-proofing and increased rain-fed production than has been realized to date.

Improving irrigation efficiency can also increase agricultural water productivity. The estimated 500 km^3 of unproductive evaporation of irrigation water theoretically represents potential water savings sufficient to grow 450×10^6 t of wheat, although only a portion of these losses could realistically and economically be captured. These savings increase the effective water supply without the need to build additional reservoirs or extract more groundwater. For example, researchers at the Sri Lanka-based International Irrigation Management Institute found that eliminating the flooding of rice fields prior to planting reduced water use by 25% (Seckler 1996). The portion of this reduction resulting from lower evaporative losses represents true water savings and effectively increases the available supply.

Efficient sprinklers, drip systems, and other methods of delivering irrigation water more directly to the roots of crops can also reduce unproductive evaporation. Research in the Texas High Plains has shown substantial water savings with low-pressure sprinklers that deliver water close to the soil surface rather than in a high-pressure spray (High Plains Underground Water Conservation District 1996). Water productivity gains of 20–30% or more are not uncommon when farmers shift to more efficient irrigation practices. Worldwide, however, such efficiency measures have spread slowly relative to their potential because of high up-front capital costs, relatively low crop prices, and heavy government subsidies that artificially lower irrigation water prices.

Improving the water-use efficiency of crops, shifting the mix of crops, and breeding crop varieties that are more salt tolerant and drought resistant may also increase agricultural water productivity. These gains do not come easily, however, because drawbacks can negate the potential benefits. For example, crop varieties that perform well under cooler temperatures may produce higher yields per unit of water consumed but have a lower harvest-index potential (Sinclair et al. 1984). Moreover, a good portion of the potential for improving crop water-use efficiency may already have been exploited. For example, breeders have already shortened the maturation time for irrigated rice varieties from 150 days to 110 days, substantially increasing that crop's water efficiency (IRRI 1995).

Finally, more equitable distribution of food may be necessary to satisfy the basic nutritional needs of all people as water constraints on agriculture increase. For the past three decades, the share of the world's grain supply fed to livestock has consistently ranged between 38% and 40% (Brown 1996). This large amount of grain—and, indirectly, water—could be used more productively to satisfy human nutritional requirements. For example, the diet of a typical US adult, with a relatively high percentage of calories derived from grain-fed livestock, includes enough grain to support the diets of four typical Indians.

Although it may be tempting to assert that the prospective shortage of water for crop production calls for stepped-up construction of large dams and river diversions to increase supplies, this conclusion is not sound. The aquatic environment is showing numerous signs of declining health, even at today's level of water use. Large dams and river diversions have proven to be primary destroyers of aquatic habitat, contributing substantially to the destruction of fisheries, the extinction of species, and the overall loss of the ecosystem services on which the human economy depends. Their social and economic costs have also risen markedly over the past two decades. Along with efforts to slow both population and consumption growth, measures to use rainwater and irrigation water more productively, to use food supplies more efficiently, and to alter the crop mix to better match the quantity and quality of water available offer more ecologically sound and sustainable ways of satisfying the nutritional needs of the global population.

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