Water Constraints and Environmental Impacts of Agricultural Growth

Mark W. Rosegrant and Ximing Cai

Water, the environment, and food production are closely interrelated at the local, regional and global levels. With rapidly increasing water demands, the competition among household, industrial, environmental, and agricultural water uses has been escalating in many regions. Although the achievements of irrigation in ensuring food security and improving rural welfare have been impressive, past experiences also indicate problems and failures of irrigated agriculture, often related to environmental issues including groundwater overdraft, water quality reduction, waterlogging, and salinization. Hydrological records over a long period have shown a marked reduction in the annual discharge on some of the world's major rivers (OECD), due in significant part to growth in agricultural water consumption.

These developments raise the question of whether water scarcity will constrain food production growth, particularly in the developing world. This paper assesses the impact of water supply on future food production growth, and the tradeoffs between increased allocation of water to environmental purposes, the elimination of groundwater overdraft, and food production. The analysis uses an integrated global water and food model and employs alternative scenario assessments to examine the degree to which water will constrain future food production, and the implications of competition for water between agriculture and the environment.

Methodology

In order to explore the relationships among water, environment, and food production, a global modeling framework, IMPACT-WATER, has been developed that combines an extension of the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) with a newly developed Water Simulation Model (WSM). IMPACT is a partial equilibrium agricultural sector model representing a competitive agricultural market for crops and livestock. Demand is a function of prices, income, and population growth. Growth in crop production in each country is determined by crop and input prices and the rate of productivity growth. World agricultural commodity prices are determined annually at levels that clear international markets. IMPACT generates projections for crop area, yield, production, demand for food, feed and other uses, prices, and trade; and for livestock numbers, yield, production, demand, prices, and trade (Rosegrant et al.).

In this paper, the IMPACT model is integrated with a basin-scale model of water resource use, the Water Simulation Model (WSM), to create a linked model, IMPACT-WATER. The linkage is made through (*a*) incorporation of water in the crop area and yield functions; and (*b*) simultaneous determination of water availability at the river basin scale, water demand by irrigation and other sectors, and crop production. IMPACT-WATER divides the world into sixty-nine spatial units, including macro river basins in China, India, and the United States, and aggregated basins over other countries and regions. Domestic and industrial water demands are estimated as a function of population and income. Water demand in agriculture is projected based on irrigation and livestock growth, climate, and basin-level irrigation water use efficiency. Then water demand is incorporated as a variable in the crop yield and area functions for each of eight major food crops including wheat, rice, maize, other coarse grains, soybean, potato, yam and sweet potato, and cassava and other roots and tubers. Water requirements for all other crops are estimated as a single aggregate demand.

Water availability is treated as a stochastic variable with observable probability

This paper was presented at the ASSA winter meetings (Atlanta, GA, January 2002). Papers in these sessions are not subjected to the journal's standard refereeing process.

Mark W. Rosegrant is a senior research fellow at the International Food Policy Research Institute (IFPRI) and Ximing Cai is a postdoctoral fellow at IFPRI.

Amer. J. Agr. Econ. 84(3) (August 2002): 832–838

distributions. WSM simulates water availability for crops at a river basin scale, taking into account precipitation and runoff, water use efficiency, flow regulation through reservoir and groundwater storage, nonagricultural water demand, water supply infrastructure and withdrawal capacity, and environmental requirements at the river basin, country, and regional levels. Environmental impacts can be explored through scenario analysis of committed instream and environmental flows, salt leaching requirements for soil salinity control, and alternative rates of groundwater pumping. For a detailed description of the integrated model, see Cai and Rosegrant.

IMPACT-WATER thus provides a modeling framework that allows a wide range of analysis of relationships among water, environment, and food at the basin, country or region, and global levels. In this paper, IMPACT-WATER is used to examine the impact on food production in the United States of increasing the amount of water reserved for environmental purposes and the impact of elimination of groundwater overdrafting throughout the world.

Baseline Assumptions and Projections

The starting point for the analysis is a baseline scenario that incorporates our best estimates of the policy, investment, technological, and behavioral parameters driving the food and water sectors. In the water component, the model utilizes hydrologic data (precipitation, evapotranspiration, and runoff) that recreates the hydrologic regime of 1961–91 (Alcamo). Non-irrigation water uses, including domestic, industrial, and livestock water uses are projected to grow rapidly. Total non-irrigation water consumption in the world is projected to increase from 370 cubic kilometers (km^3) in 1995 to 620 km^3 in 2025, an increase of 68%. The largest increase of about 85% is projected for developing countries. Moreover, instream and environmental water demand is accounted as committed flow that is unavailable for other uses, and ranges from 10% to 50% of the runoff depending on runoff availability and relative demands of the instream uses in different basins. The global potential irrigation water demand is 1758 km^3 in 1995 and 1992 km^3 in 2021–25, increasing by 12.0%. The developing world is projected to have much higher growth in potential irrigation water demand than the developed world between 1995 and 2021–25, with potential consumptive demand in the developing world rising from 1445 km^3 in 1995 to 1673 km^3 in 2021–25, or 13.6%.

Moderate increases are projected for water withdrawal capacity, reservoir storage, and water management efficiency, based on estimates of current investment plans and the pace of water management reform. Water demand can be defined and measured in terms of withdrawals and actual consumptive uses. The potential demand or consumptive use for irrigation water is defined as the irrigation water requirement to meet the full evapotranspirative demand of all crops included in the model over the full potential irrigated area. Potential demand is thus the demand for irrigation water in the absence of any water supply constraints. Actual irrigation consumptive use is the realized water demand, given the limitations of water supply for irrigation. Total global water withdrawals are projected to increase by 23% between 1995 and 2025, from 3906 km^3 (groundwater pumping 817 km^3) in 1995 to 4794 km^3 (groundwater pumping 922 km^3) in 2025. Reservoir storage for irrigation increases by 621 km^3 (18%) over the next 25 years. The worldwide average basin efficiency increases from 0.56 in 1995 to 0.61 in 2025.

Global consumptive use of water will increase by 16%, from 1800 km^3 in 1995 to 2085 km^3 in 2025. Assuming non-irrigation water demand will be satisfied with the first priority, water available for irrigation water consumption will only increase by 3.9%, from 1430 km^3 to 1485 km^3, which is considerably lower than the 12% increase in potential irrigation demand. Therefore, of critical importance, irrigation water demand will be increasingly supply-constrained, with a declining fraction of potential demand met over time. The situation is especially serious in developing countries, where potential demand increases by 13.6%, and the increase of supply, and therefore the increase in actual consumptive use of irrigation water, is only 4.4%.

This tightening constraint is shown by the irrigation water supply reliability index (IWSR), which is defined as the ratio of water supply available for irrigation over potential demand for irrigation water. For developing countries, the IWSR declines from 0.79 to 0.71 in 2025. Relatively dry basins that face rapid growth in domestic and industrial experience, slow improvement in river basin efficiency, or rapid expansion in potential irrigated area show even greater declines in water supply reliability. The developed countries as a whole show a sharp contrast to the developing world. Irrigation water supply in the developed world is projected to increase by 7.0 km^3, while the corresponding demand decreases by 5.0 km^3. As a result, after initially declining from 0.86 to 0.84 in 2010, the IWSR improves to 0.89 in 2025 as domestic and industrial demand growth slows in later years (and actually declines in the United States and Europe) and efficiency in agricultural water use improves. The divergence between trends in the developing and developed countries indicates that agricultural water shortages will become worse in the former even as they improve in the latter, providing a major impetus for the expansion in virtual water transfers through agricultural trade.

The global yield growth rate for all cereals is projected to decline from 1.5% per year during 1982–95 to 1.0% per year during 1995–2025; and in developing countries, average crop yield growth will decline from 1.9% per year to 1.2%. Increasing water scarcity for agriculture is a significant cause of the slowdown in cereal yield growth in developing countries, as shown by the projected relative crop yields for irrigated cereals. Relative crop yield is the ratio of the actual projected crop yield with respect to the economically attainable yields at given crop and input prices under conditions of zero water stress. Table 1 shows the relative crop yield for cereals in irrigated areas for selected basins, countries, and aggregated regions. The relative crop yield for cereals in irrigated areas in developing countries is projected to decline from 0.86 in 1995 to 0.74 in 2021–25. The fall in the relative crop yield index is a significant drag on future yield growth. For developing countries as a group, the drop from 0.86 to 0.74 represents an annual loss in crop yields foregone due to increased water stress, compared with the base year of 0.72 metric tons (mt) per hectare, or an annual loss of cereal production by 2025 of 139 million mt, more than the total rice production in China in 1995.

Increase in Environmental Water Flows in the United States

Two alternative scenarios are defined to examine the impact on food production of an increase in committed water flows to environmental purposes in the United States. The first scenario (high environmental flows, or HEF scenario) simulates an increase in committed environmental flows in all U.S. river basins and a reduction in groundwater overdrafting by approximately one-half in the Colorado, California, Rio Grande, White-Red River basins during 2000–2025. The second scenario maintains the assumptions of higher environmental flows and reduced groundwater overdrafting, but also increases basin-level irrigation water use efficiency in each U.S. basin (HEFE scenario). This scenario examines whether improvement in river basin efficiency can compensate for the effect of greater environmental flows and reduce any negative impacts on food production. Under these scenarios, 70 km^3 of water is transferred from water withdrawal for irrigation, livestock, domestic and industrial uses to environmental flows by 2021–25, or 13% of the withdrawal in the United States under the baseline in 2021–25. This amount also constitutes an increase in environmental flows of 9% in 2021–25, compared with the baseline.

Basin efficiency in the baseline increase between 1995 and 2025 by 3% to 11% in different river basins, with higher percentage increases in those basins where water infrastructure is already highly developed, such as the California and Colorado River basins. HEFE assumes BE increases by 10–20% in U.S. river basins. In the Colorado and California river basins, for example, BE is increased to 0.9 (the level of irrigation efficiency in Israel).

The results show that there is indeed a tradeoff between increased environmental flows and food production in the United States, but that these impacts vary considerably across river basins, and that the impacts can be at least partly mitigated by investments and management improvement to increase river basin efficiency. Irrigation water consumption declines nationally by 17% under HEF and HEFE in 2025, compared with the baseline projection. Decreases vary by basin, with small decreases in the basins of Ohio and Tennessee, Mississippi (downstream) and Great Lakes, and larger decreases in the Rio Grande, Columbia, Colorado, California, and Missouri basins. Under HEF, production declines relative to the 2021–25 baseline in irrigated areas are 16.5% for rice, 24.2% for wheat, 13.9% for maize, 16.6% for other grains, 11.7% for soybeans, and 15.8% for potatoes. Increased environmental flows of water have a much larger effect on food production in dry basins such as Rio Grande, Colorado, and the Texas Gulf, and in basins where irrigation currently contributes more to total production, such as and Missouri, Arkansas-White-Red River basins, and

Table 1. Relative Yield Index for Developing Countries, Developed Countries, the World, and Selected Basins and Countries, 1995, 2010, and 2025

Basin/countries/regions	1995	2010	2025
Colorado (United States)	0.90	0.85	0.85
White-Red (United States)	0.92	0.84	0.87
Missouri (United States)	0.93	0.86	0.83
Hai-Luan-He (China)	0.74	0.70	0.63
Yellow (China)	0.80	0.72	0.70
Songliao (China)	0.84	0.73	0.69
China	0.86	0.76	0.75
Luni (India)	0.72	0.68	0.74
Indus (India)	0.84	0.75	0.73
Ganges (India)	0.83	0.70	0.69
India	0.84	0.76	0.72
West Asia and North Africa	0.72	0.69	0.67
Developed countries	0.89	0.86	0.86
Developing countries	0.86	0.80	0.74
World	0.87	0.81	0.77

Source: IMPACT-WATER simulations.

basins in California. These basins account for 95% of the cereal production shortfall under HEF, compared with baseline in 2021–25.

The results from HEFE show that, for the same irrigation water reduction as in HEF, greater basin-level irrigation efficiency improvements partially compensate for production losses. The outcomes for irrigated production for HEFE fall between those of the baseline and HEF. Compared with the baseline values for the whole country, total irrigated cereal production declines by 9.8%, compared with 16.2% with HEF, soybeans by 8.0% (11.7% with HEF), and potatoes by 11.2% (15.8% with HEF).

Compared with the baseline projection, total annual cereal food production in the United States in 2021–25 declines by 12.8 and 7.2 million metric tons under HEF and HEFE, respectively, total cereal demand declines by 1.4 and 0.7 million metric tons, and total cereal exports decline by 11.8 and 7.1 million metric tons. Exports of soybeans decline by about 0.45 and 0.31 million metric tons under HEF and HEFE, respectively. Production and trade of potatoes is relatively more affected because irrigated potatoes contribute around 80% of total production. HEF results in 2.2 million metric tons of potato imports instead of the 1.3 million metric tons exported under the baseline. Substantial export declines occur in later years, when irrigation water withdrawal is increasingly constrained by declining water availability. Nevertheless, the declines are not devastating, with annual cereal exports reaching an average of 112 million mt annually in 2021–25, or 89% of baseline exports, even under HEF. This is largely explained by the fact that irrigation contributes less than 20% of the total cereal crop production in the United States. The decline of irrigation water use under HEF and HEFE causes 16.2% and 9.8% declines in irrigated cereal production in 2021–25, relative to the baseline. Thus, total cereal production in the United States falls by about 3.2% in 2021–25, relative to the baseline. The international food market will be only slightly affected by such changes, with an increase of real international prices relative to the baseline of less than 2% in 2025.

Global Elimination of Groundwater Overdraft

Many regions in the world, including northern India, northern China, some countries in West Asia and North Africa (WANA), and the western U.S. states have experienced significant groundwater depletion due to pumping in excess of groundwater discharge. In any given aquifer, groundwater overdraft occurs when the ratio of pumping to recharge is greater than 1.0. However, given the large macrobasins utilized in the IMPACT-WATER model and the unequal distribution of groundwater resources in these basins, there will be areas within these basins where available groundwater resources are subject to overdraft, even if the whole-basin ratio shows pumping to be less than recharge. Postel, drawing upon several sources, estimates that the total annual global groundwater overdraft is 163 km^3. Utilizing the Postel estimate of groundwater overdraft, the threshold point at the whole-basin level at which localized groundwater overdraft occurs is set at 0.55. Using this benchmark, a number of basins and countries experience groundwater overdraft in the base year, including the Rio Grande River Basin and the Colorado River Basin in the western United States, where the ratio of annual groundwater pumping to recharge is greater than 0.6, the Hai-Luan River Basin in northern China, where the ratio is 0.85; several river basins in northern and western India with ratios in excess of 0.8; Egypt, with a ratio of 2.5; and other WANA, with a ratio of 0.8.

It is possible for regions and countries that are unsustainably pumping their groundwater to return to sustainable use in the future. The low groundwater pumping (LGW) scenario assumes that groundwater overdraft in those countries/regions unsustainably using their water will be phased out over the next 25 years through a reduction in the ratio of annual groundwater pumping to recharge at the basin or country level to below 0.55.

Compared with levels in 1995, under LGW, groundwater pumping in these countries/regions will decline by 163 km^3, including a reduction by 11 km^3 in the United States, 30 km^3 in China, 69 km^3 in India, 29 km^3 in WANA, and 24 km^3 in other countries. The projected increase in pumping for areas with more plentiful groundwater resources remains almost the same as under the baseline scenario, and total global groundwater pumping in 2025 falls to 753 km^3, representing a decline from the value in 1995 of 817 km^3 and from the baseline 2025 value of 922 km^3.

Phasing out of groundwater mining would reduce total cereal production by 17 million mt from baseline projections in 2025. Irrigated cereal production will decline by 35 million mt, but rainfed production will increase by 18 million mt, because the shortfall in irrigated production results in price increases that stimulate increased rainfed production. International wheat prices are projected to be 11% higher in 2025 than baseline projections, rice prices 7% higher, and maize prices 6% higher. Total developing country cereal production declines by 27 million mt in the LGW scenario compared to the baseline, with irrigated production declining by 34 million mt and rainfed production increasing by 7 million mt. Cereal production actually increases by 10 million mt in developed countries because the increase in world prices generates production increases that more than compensate for the direct reductions due to the fall in groundwater pumping. The elimination of groundwater overdraft would also cause a fall in global soybean production of 1.9 million mt (0.8%), in potato production of 4.3 million mt (1.1%), and in sweet potatoes of 1.5 million mt (0.7%). Production of cassava and other sweet potatoes, which is virtually all rainfed, will actually increase by 1.8 million mt (0.7%), as increases in prices of other staples shifts some demand to cassava, pushing up prices and inducing slightly higher production.

Although substantial, the estimated global production cost of elimination of groundwater overdraft is much less than that calculated by some analysts. For example, using an estimate that it takes 1000 m^3 of water to produce 1000 kg of cereal, Postel estimates that the approximately 160 km^3 water deficit is equal to 160 million tons of grain. But a significant amount of overdraft water is for non-cereal crops; the amount of reduction of cereal production due to 1000 m^3 less overdraft of water is considerably less than 1000 kg (560 kg/1000 m^3 for rice and 390 kg/1000 m^3 for non-rice cereals in the developing world according to our estimates); and the cereal price effects of the cutback in pumping induces partially offsetting increases in area and yield.

Instead, the biggest impacts under LGW are concentrated in the basins that currently experience large overdrafts. Cereal production falls by 14 million mt in India, with a few basins particularly hard hit, including the Ganges basin, which has a decline in cereal production of 8 million mt, and the Indus basin, where cereal production falls by 4 million mt. In China, cereal production falls by 17 million mt, including 8 million mt in the Haihe River Basin and 6 million mt in the Yellow River Basin. Cereal demand also falls in these countries, with a 3.5 million mt drop in cereal consumption in India, 3.1 million mt in China, with the difference made up by increased imports. Compared with the baseline scenario, LGW results in an increase of cereal imports of 7.0 million mt in India, 6.5 million mt in China, 1.7 million mt in WANA and 0.8 million mt in other developing countries, in 2021–25.

Simulations of improvements in basin irrigation efficiency targeted within the overdrafting basins show that water sector policies to compensate for the loss in production and consumption from reduced groundwater pumping would require a focus beyond the basins most affected. Although improvements in irrigation efficiency in the specific overdrafting basins could in theory compensate for these declines in groundwater use, the required efficiency improvements would be huge and likely unattainable. In the Indus basin an improvement in BE in 2025 from 0.59 to 0.76 would be required to generate enough cereal production to compensate for the reduction in groundwater overdraft. In the Yellow River in China, the required improvement in BE in 2025 would be from 0.62 to 0.82.

Alternatively, could increased rainfed cereal production within the overdrafting countries compensate for the irrigated production decline due to reduced groundwater pumping? This question is addressed by a scenario combining elimination of groundwater overdraft with higher rainfed agriculture development. The reductions of irrigation production due to reduced groundwater pumping can be offset by an increase in rainfed area and yield within the same regions, but the required increase in rainfed cereal yields would be very large. In 2025, average rainfed cereal yields would need to be 13% or 0.6 metric tons per hectare higher than baseline projections in China, 20% or 0.3 metric tons per hectare in India, and 0.3 metric tons per hectare in WANA. In addition, rainfed cereal area would need to increase by 0.6 million hectares in China, 0.8 million hectares in India, and 0.10 million hectares in WANA. But the greater expansion in rainfed area is itself environmentally damaging, requiring encroachment on fragile lands. Moreover, the yield increase would require substantial additional investments in agricultural research and management for rainfed areas and it is not clear that these yield increases are achievable in rainfed areas, even with increased investments.

Conclusions

Rapid growth in non-agricultural demand, relatively slow growth in water supply investments, and moderate progress in water use efficiency derived from water policy and management reforms will lead to growing water shortages for agriculture in much of the world. The resulting water supply constraints will reduce food crop yield growth, particularly in developing countries. With irrigation deficits becoming more severe in many basins and countries even under the baseline, a further decrease in water available for agriculture, whether due to increased environmental reservation, reduced groundwater pumping, or growth in other non-agricultural demands, will further reduce agricultural production growth.

However, in the two important examples of reduced agricultural water availability assessed here, it is shown that local and river basin effects are more severe than global aggregates, and that concerted policy efforts could significantly mitigate the negative effects. In the U.S. case, the results suggest that significant additional diversions of water for environmental purposes could be achieved without devastating impacts on aggregate U.S. food production and trade. Although local impacts on agricultural employment and related sectors can be severe under a scenario of rapidly increasing competition for scarce water resources, the most important impacts occur in specific basins where production shortfalls are concentrated. It would be here that interventions are needed to compensate farmers who are negatively affected by environmental diversions. An additional possibility would be to introduce policy reforms, such as more aggressive water pricing, to constrain municipal and industrial uses, which are assumed to be the first claimant on water. Increased investments in agricultural research could induce increases in agricultural productivity that would further compensate for the diversion of water from agriculture.

The global food production impact of the elimination of groundwater overdraft is relatively small, but the impacts for specific countries and basins are quite large. In China and India, significant reductions in cereal production and consumption are accompanied by increased cereal imports. While the seriousness of these country-level shortfalls in demand and increases in imports should not be minimized, they may be a worthwhile tradeoff for restoring sustainability of groundwater supplies and it may be necessary for these countries to rely more on imports to meet the decline in irrigated production compared to the baseline. Agricultural research investments should be increased, and, particularly in the hardest hit river basins (such as the Yellow and the Ganges), investments and policy reforms (including elimination of power subsidies for pumping) should be implemented to increase basin efficiency and encourage diversification out of irrigated cereals into crops that give more value per unit of water.

References

Alcamo, J.P. *Personal communications on Global Change and Global Scenarios of Water Use and Availability: An Application of Water GAP*. University of Kassel, Germany: Center for Environmental System Research (CESR), 2000.

Cai, X., and M.W. Rosegrant. "Global Water Demand and Supply Projection—A Modeling Approach. 1. Methodology." *Water International*, in press.

OECD (Organization for Economic Co-operation and Development). *The Athens Workshop. Sustainable Management of Water in Agriculture: Issues and Policies*, Paris, 1998.

Postel, S. *Pillar of Sand: Can the Irrigation Miracle Last?* New York: W.W. Norton, 1999.

Rosegrant M.W., M.S. Paisner, S. Meijer, and J. Witcover. *Global Food Projections to 2020: Emerging Trends and Alternative Futures*. Washington DC, International Food Policy Research Institute, 2001.