International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model Description

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INTRODUCTION

IMPACT – the International Model for Policy Analysis of Agricultural Commodities and Trade – was developed at IFPRI at the beginning of the 1990s, upon the realization that there was a lack of long-term vision and consensus among policy makers and researchers about the actions that are necessary to feed the world in the future, reduce poverty, and protect the natural resource base. In 1993, these same long-term global concerns launched the 2020 Vision for Food, Agriculture and the Environment Initiative. This initiative created the opportunity for further development of the IMPACT model, and in 1995 the first results using IMPACT were published as a 2020 Vision discussion paper: *Global Food Projections to 2020: Implications for Investment* (Rosegrant, Agcaoili-Sombilla and Perez, 1995), in which the effects of population, investment, and trade scenarios on food security and nutrition status, especially in developing countries, were analyzed.

IMPACT has been used in several important research publications, which examine the linkage between the production of key food commodities and food demand and security at the national level. Such examples can be found in the paper looking at the relationship between meat-intensive diets in developed nations and food security in developing countries, *Alternative Futures for World Cereal and Meat Consumption* (Rosegrant, Leach and Gerpacio, 1999); or the article *Global Projections for Root and Tuber Crops to the Year 2020* (Scott, Rosegrant and Ringler, 2000), which gives a detailed analysis of roots and tuber crops and their importance to the food economies of the poor. The report *Livestock to 2020: The next food revolution* (Delgado *et al.*, 1999) assesses the rise in livestock demand in developing countries that was trigged by rising incomes in recent decades, and considers the current and expected future developments of this “livestock revolution”, as well as its implications for policy.

The IMPACT model has also been employed in regional studies, such as the *Asian Economic Crisis and the Long-Term Global Food Situation* (Rosegrant and Ringler, 2000) and *Transforming the Rural Asian Economy: the Unfinished Revolution* (Rosegrant and Hazell, 2000), which were both written in response to the Asian financial crisis of 1997 and which try to assess its impact on the regional food economy. The most comprehensive set of results for IMPACT are published in the book *Global Food Projections to 2020* (Rosegrant *et al.*, 2001). These projections – which were presented in 2001 at the IFPRI-sponsored conference in Bonn entitled: *Sustainable Food Security for All by 2020* – are presented with details on the demand system and other underlying data used in the projections work, and cover both global and regionally-focused projections. This publication is also the first in a series of research outputs that IFPRI hopes to use to provide policy advice on the necessary investments that need to be made by national and regional policy makers in order to sustain the levels of food production and nutrition that are required by projected global demographic and economic changes. IMPACT also provided the first comprehensive policy evaluation of global fishery production and projections for demand of fish products in the book *Fish to 2020: Supply and Demand in Changing Global Markets* (Delgado, Wada, Rosegrant, Meijer and Ahmed, 2003). A complete list of the research published using the IMPACT modeling framework is provided in Appendix 1, including reports for international organizations, such as the World Bank, the Asian Development Bank, the FAO, and national governments.

While the primary IMPACT model has gained recognition within the policy research community as a leading agricultural sector model for the assessment of the global food production and the performance of global food markets, it assumes "normal" base climate conditions, which is maintained throughout its 30-year projections horizon. As such, the impacts of annual climate variability on food production demand and trade are not embodied within the model or reflected in its results. The recognition that the long-term change in water demand and availability—and particularly the rapidly increasing demand in non-agricultural water uses—as well as the year-to-year variability in rainfall and runoff would affect future food production, demand, and trade led to a renewed effort on the part of IFPRI and partner collaborators to make more explicit linkages between food production and water availability in an integrated modeling framework. The result of this research has led to the development of the IMPACT-WATER model, which integrates the primary IMPACT model with a water simulation module (WSM) that balances water availability and uses within various economic sectors, at the global and regional scale.

IMPACT-WATER – through the combination of the IMPACT and WSM models – incorporates water availability as a driving variable with observable flows and storage to examine the impact of water availability on food supply, demand and prices. This framework allows exploration of the relationship between water availability and food demand at trade at a variety of spatial scales – ranging from river basins, countries and more aggregated regions, to the global level. Water supply and demand and crop production are first assessed at the river-basin scale, and crop production is then summed to the national level, where food demand and trade are modeled. While the primary IMPACT model divided the world into 36 countries and regions, the IMPACT-WATER model uses a finer disaggregation of 281 "food-producing units" – which represent the spatial intersection of 115 economic regions and 126 river basins – out of recognition of the fact that significant climate and hydrologic variations within regions make the use of large spatial units inappropriate for water resource assessment and modeling. Of the countries represented within the IMPACT-WATER model, China, India and the United States (which together produce about 60 percent of the world's cereals) have the highest level of sub-national disaggregation and are divided into 9, 13 and 14 major river basins, respectively, while the other countries or regions considered in IMPACT are combined into the remaining 90 basins.

Ongoing research has also expanded the set of agricultural crop commodities to 40, which include fish from both capture and aquaculture, groundnuts, cotton, fodder crops and major dryland grains and pulses, such as sorghum, millet, chickpeas and pigeonpeas. Given the prominence of many of dryland crops in the semi-arid tropics and their important linkage to livestock through feed, along with other fodder crops, we felt these additions were necessary to fully understanding the drivers behind projected future growth in global oil, meat and milk demand. The importance of many of these commodities, including aquaculture, in global water demand also warranted their full inclusion into the model.

Policy analyses based on alternative scenarios analyzed with IMPACT-WATER were published in an IFPRI book titled *World Water and Food to 2025: Dealing with Scarcity* (Rosegrant, Cai and Cline, 2002). Another paper that has used results from IMPACT-WATER to make policy evaluations is a study prepared for the North American Commission for Environmental Cooperation titled *Modeling Water Availability and Food Security: A North American Application of the IMPACT-WATER Model* (Rosegrant, Runge and Cai), which looked at implications of NAFTA on water use and agricultural production in North America. IMPACT-WATER is also currently used for a World Bank report on the role of agriculture to achieve the Millennium Development Goals and a small effort by the US EPA on the role of greenhouse gas mitigation for rice in China.

For the sake of ease in documentation and citations and because IMPACT-WATER forms the basis for all work with this model, we will simply refer to the current model as IMPACT—not to be confused with the older model which lacks integration with WSM.

The next section discusses the food and water components of the IMPACT model, including a technical description that shows the equations and the sources of the data used in the model. A general overview of the countries/ regions and commodities is given in Appendix 2, while the definitions of the river basins are shown in Appendix 3. After a description of the commodities, in Appendix 4, a schematic overview of the integrated modeling framework is given in Appendix 5.

THE MODEL

I. Basic Methodology on Food

Encompassing countries and regions in the world and the main agricultural commodities produced in the world (see Boxes 1 and 2 at the end of the document), the system of equations on food offers a methodology for analyzing baseline and alternative scenarios for global food demand, supply, trade, income and population. Within each country or regional sub-model, supply, demand, and prices for agricultural commodities are determined. These country and regional agricultural sub-models are linked through trade.

Supply and demand functions incorporate supply and demand elasticities to approximate the underlying production and demand functions. World agricultural commodity prices are determined annually at levels that clear international markets.

I.A. Food Supply

I.A.a. Crop Production

Domestic crop production is determined by area and yield response functions. Harvested area is specified as a response to the crop's own price, the prices of other competing crops, the projected rate of exogenous (non-price) growth trends in harvested area, and water (Equation 1). The projected exogenous trend in harvested area captures changes in area resulting from factors other than direct crop price effects, such as expansion through population pressure and contraction from soil degradation or conversion of land to nonagricultural uses. Yield is a function of the commodity price, the prices of labor and capital, water, and a projected nonprice exogenous trend factor. The trend factor reflects productivity growth driven by technology improvements, including crop management research, conventional plant breeding, wide-crossing and hybridization breeding, and biotechnology and transgenic breeding. Other sources of growth considered include private sector agricultural research and development, agricultural extension and education, markets, infrastructure, and irrigation., and water (Equation 2). Annual production of commodity *i* in country *n* is then estimated as the product of its area and yield (Equation 3).

Area response:

$$AC_{tni} = \alpha_{tni} \times (PS_{tni})^{\varepsilon_{iin}} \times \prod_{j \neq i}(PS_{tnj})^{\varepsilon_{ijn}} \times (1 + gA_{tni}) - \Delta AC_{tni}(WAT_{tni}); \tag{1}$$

Yield response:

$$YC_{tni} = \beta_{tni} \times (PS_{tni})^{\gamma_{iin}} \times \prod_{k}(PF_{tnk})^{\gamma_{ikn}} \times (1 + gCY_{tni}) - \Delta YC_{tni}(WAT_{tni}); \tag{2}$$

Production:

$$QS_{tni} = AC_{tni} \times YC_{tni}; \tag{3}$$

where AC = crop area
YC = crop yield
QS = quantity produced
PS = effective producer price
PF = price of factor or input *k* (for example labor and capital)
$\prod$ = product operator
i, j = commodity indices specific for crops
k = inputs such as labor and capital
n = country index
t = time index
gA = growth rate of crop area
gCY = growth rate of crop yield
ε = area price elasticity
γ = yield price elasticity
α = crop area intercept
β = crop yield intercept
ΔAC = crop area reduction due to water stress
ΔYC = crop yield reduction due to water stress
WAT = water variable

I.A.a.1 Incorporation of Water in Crop Area Functions

Reduction of crop harvest area ΔAC is calculated as:

$$\Delta AC^{i} = 0, \mathit{if}\ \frac{ET_{a}}{ET_{m}} > E^{*},\ \mathit{otherwise} \tag{4}$$

$$\Delta AC^{i} = AC^{i} \cdot \left[1 - \left(\frac{ETA^{i}}{ETM^{i}} / E^{*i}\right)\right] \mathit{for\ irrigated\ area} \tag{5}$$

$$\Delta AC^i = AC^i \cdot \left[1 - \left(ky^i \cdot (1 - \frac{ETA^i}{ETM^i} / E^{*i}) \right)^{\gamma} \right] \textit{for rainfed areas} \qquad (6)$$

where ETA = actual crop evapotranspiration in the crop growth season
ETM = potential crop evapotranspiration in the crop growth season (see description later in Equation 24)
$E*$ = threshold of relative evapotranspiration, below which farmers reduce crop area
ky = crop response coefficient to water stress.

Actual crop evapotranspiration includes irrigation water which can be used for crop evapotranspiration (*NIW*) and effective rainfall (*PE*), $ETA^i = NIW^i + PE^i$ where for rainfed crops, NIW = 0. The determination of NIW for irrigated crops and PE for both rainfed and irrigated crops will be described later. The determination of E* is empirical. For irrigated area, farmers can reduce area and increase water application per unit of the remaining area. Assuming E* = ky - 0.25, Figure 1 shows relative irrigated yield, area and production versus relative ET. As can be seen, for irrigated area, when ETa/ETm > E*, farmers will maintain the entire crop area, and yield is reduced linearly with ETa/ETm; and when ETa/ETm < E*, farmers will reduce the crop area linearly with ETa/ETm, and maintain constant crop yield corresponding to E*. Equation 5 is derived based on the assumption that total available water can be applied in the remaining irrigated area.

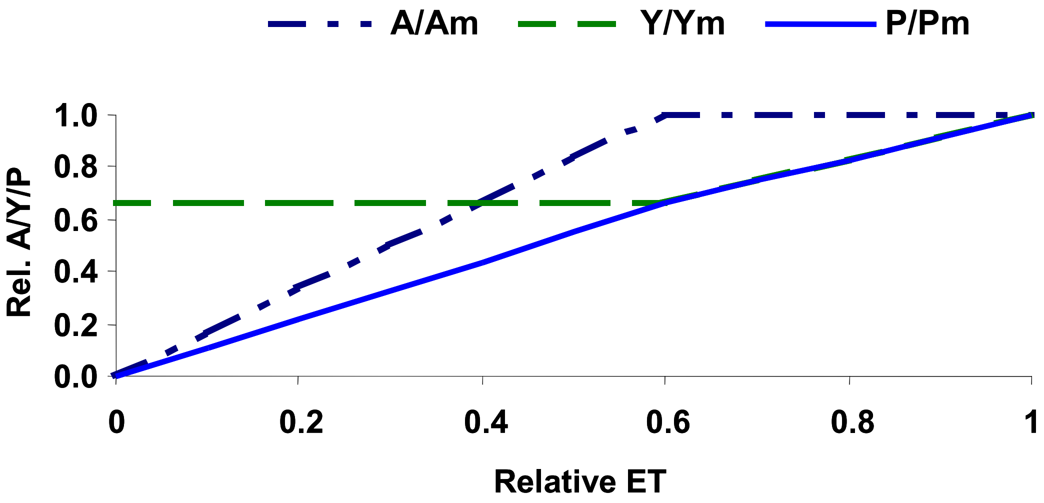

Figure 1. Relative irrigated yield, area, and production versus relative crop evapotranspiration

Source: Rosegrant et al (2002).

Notes: E* = 0.6; A indicates area; Am, maximum area; Y, yield; Ym, maximum yield; P, production; and Pm, maximum production.

For the same crop, the value of E* is generally much lower for rainfed areas than for irrigated areas. For rainfed area, theoretically, when ETa/ETm < E*, farmers will give up all the area. However, in the real world this may not true. Historic records show that in regions with arid or semi-arid climate, even in a very dry region, the harvested rainfed area does not decline to zero. However, a general empirical relationship between rainfed harvested area and ETa/ETm is not available from existing studies. We assume the FAO yield-water relationship can be applied to harvested area and water, which is shown in Equation 6, but with a calibration coefficient (γ). This coefficient for a crop is estimated based on the evaluation of rainfed harvested area and effective rainfall in recent years.

Equations 5 and 6 capture the effect of extreme water shortages on the crop area decision. The parameter E* will vary with respect to the sensitivity of crops to water stress. When E* equals 1 all adjustments to water shortages are realized through area reduction while crop yield is maintained. For crops that are highly sensitive to water stress, (that is, ky > 1.0), E* in fact approaches a value of 1.0 (for example, 0.9 or more). For these crops, water shortages are handled by leaving a portion of the land fallow while maintaining yields on the remaining area, a strategy that maximizes crop production and returns given the constrained water availability. For relatively drought-tolerant crops, E* has a lower value. For these crops, maximization of production and returns requires spreading the water over as broad an area as possible to maintain production while reducing crop yields. E* can be estimated based on a yearly series of historical data including crop area and yield in different basins/countries, or can be estimated through a field survey. The modeling framework currently only incorporates a relationship between E* and the crop response to water stress (ky). The assumed relationship is E* = ky - 0.25 for irrigated crops and approximately E* = ky*0.6 for rainfed crops.

I.A.a.2 Incorporation of Water in Crop Yield Function

Reduction of crop yield ΔYC is calculated as:

$$\Delta YC = YC^i \cdot ky^i \cdot (1 - ETA^i / ETM^i) \cdot \left[\frac{\min\limits_{t \subset growthstages} \left((1 - ETA_m^{it} / ETM_m^{it}) \right)}{(1 - ETA^i / ETM^i)} \right]^{\beta} \tag{7}$$

in which β is the coefficient to characterize the penalty item, which should be estimated based on local water application in crop growth stages and crop yield. Here crop yield reduction is calculated based on seasonal water availability (that is, seasonal ETA), but is "penalized" if water availability in some crop growth stages (months) is substantially below the seasonal level. All other items have been previously defined.

I.A.b. Livestock Production.

Livestock production is modeled similarly to crop production except that livestock yield reflects only the effects of expected developments in technology (Equation 9). Total number of livestock slaughtered is a function of the livestock's own price and the price of competing commodities, the prices of intermediate (feed) inputs, and a trend variable reflecting growth in the livestock slaughtered (Equation 8). Total production is calculated by multiplying the slaughtered number of animals by the yield per head (Equation 10).

Number slaughtered:

$$\mathrm{AL}_{\mathrm{tni}} = \alpha_{\mathrm{tni}} \times (\mathrm{PS}_{\mathrm{tni}})^{\varepsilon_{\mathrm{iin}}} \times \prod_{\mathrm{j}\neq \mathrm{i}} (\mathrm{PS}_{\mathrm{tnj}})^{\varepsilon_{\mathrm{ijn}}} \times \prod_{\mathrm{b}\neq \mathrm{i}} (\mathrm{PI}_{\mathrm{tnb}})^{\gamma_{\mathrm{ibn}}} \times (1+\mathrm{gSL}_{\mathrm{tni}}); \tag{8}$$

Yield:

$$YL_{tni} = (1 + gLY_{tni}) \times YL_{t-1,ni}; \tag{9}$$

Production:

$$QS_{tni} = AL_{tni} \times YL_{tni}; \tag{10}$$

where AL = number of slaughtered livestock
YL = livestock product yield per head
PI = price of intermediate (feed) inputs
i, j = commodity indices specific for livestock
b = commodity index specific for feed crops
gSL = growth rate of number of slaughtered livestock
gYL = growth rate of livestock yield
α = intercept of number of slaughtered livestock
ε = price elasticity of number of slaughtered livestock
γ = feed price elasticity

The remaining variables are defined as for crop production.

I.B. Demand

Domestic demand for a commodity is the sum of its demand for food, feed, and other uses (Equation 16). Food demand is a function of the price of the commodity and the prices of other competing commodities, per capita income, and total population (Equation 11). Per capita income and population increase annually according to country-specific population and income growth rates as shown in Equations 12 and 13. Feed demand is a derived demand determined by the changes in livestock production, feed ratios, and own- and cross-price effects of feed crops (Equation 14). The equation also incorporates a technology parameter that indicates improvements in feeding efficiencies. Demand for feedstock for biofuels production (Equation 15) is derived from the implied demand that various alternatives for the development of ethanol and biodiesel. The demand for other uses is estimated as a proportion of food and feed demand (Equation 16). Note that total demand for livestock consist only of food demand.

Demand for food:

$$QF_{tni} = \alpha_{tni} \times (PD_{tni})^{\varepsilon_{iin}} \times \prod_{j \neq i} (PD_{tnj})^{\varepsilon_{ijn}} \times (INC_{tn})^{\eta_{in}} \times POP_{tn}; \qquad (11)$$

where

$$INC_{tn} = INC_{t-1,ni} \times (1 + gI_{tn}); \qquad (12)$$

and

$$POP_{tn} = POP_{t-1,ni} \times (1 + gP_{tn}); \qquad (13)$$

Demand for feed:

$$\mathrm{QL}_{\mathrm{tnb}} = \beta_{\mathrm{tnb}} \times \sum_{\mathrm{l}} (\mathrm{QS}_{\mathrm{tnl}} \times \mathrm{FR}_{\mathrm{tnbl}}) \times (\mathrm{PI}_{\mathrm{tnb}})^{\gamma_{\mathrm{bn}}} \times \prod_{\mathrm{o} \neq \mathrm{b}} (\mathrm{PI}_{\mathrm{tnb}})^{\gamma_{\mathrm{bon}}} \times (1 + \mathrm{FE}_{\mathrm{tnb}}); \qquad (14)$$

Demand for Biofuels:

$$QB_{tni} = f(GM_{tni}, EP_{tni}, PSE_{tni}) \qquad (15)$$

Demand for other uses:

$$QE_{tni} = QE_{t-1,ni} \times \frac{(QF_{tni} + QL_{tni})}{(QF_{t-1,ni} + QL_{t-1,ni})}; \qquad (16)$$

Total demand:

$$QD_{tni} = QF_{tni} + QL_{tni} + QB_{tni} + QE_{tni}; \tag{17}$$

where QD = total demand
QF = demand for food
QL = derived demand for feed
QB = demand for biofuel feedstock
QE = demand for other uses
PD = the effective consumer price
INC = per capita income
POP = total population
FR = feed ratio
FE = feed efficiency improvement
PI = the effective intermediate (feed) price
GM = government blending mandates
EP = energy price
PSE = producer subsidy equivalents of both subsidies and trade measures
i,j = commodity indices specific for all commodities
l = commodity index specific for livestock
b,o = commodity indices specific for feed crops
gI = income growth rate
gP = population growth rate
ε = price elasticity of food demand
γ = price elasticity of feed demand
η = income elasticity of food demand
α = food demand intercept
β = feed demand intercept

The rest of the variables are as defined earlier.

I.C. Prices

Prices are endogenous in the system of equations for food. Domestic prices are a function of world prices, adjusted by the effect of price policies and expressed in terms of the producer subsidy equivalent (PSE), the consumer subsidy equivalent (CSE), and the marketing margin (MI). PSEs and CSEs measure the implicit level of taxation or subsidy borne by producers or consumers relative to world prices and account for the wedge between domestic and world prices. MI reflects other factors such as transport and marketing costs. In the model, PSEs, CSEs, and MIs are expressed as percentages of the world price. To calculate producer prices, the world price is reduced by the MI value and increased by the PSE value (Equation 18). Consumer prices are obtained by adding the MI value to the world price and reducing it by the CSE value (Equation 19). The MI of the intermediate prices is smaller because wholesale instead of retail prices are used, but intermediate prices (reflecting feed prices) are otherwise calculated the same as consumer prices (Equation 20).

Producer prices:

$$PS_{tni} = [PW_i \ (1 - MI_{tni})](1 + PSE_{tni}); \tag{18}$$

Consumer prices:

$$PD_{tni} = [PW_i \ (1 + MI_{tni})]\,(1 - CSE_{tni}); \tag{19}$$

Intermediate (feed) prices:

$$PI_{tni} = [PW_i \ (1 + 0.5\,MI_{tni})]\,(1 - CSE_{tni}); \tag{20}$$

where PW = the world price of the commodity
MI = the marketing margin
PSE = the producer subsidy equivalent
CSE = the consumer subsidy equivalent

The rest of the variables are as defined earlier.

I.D. International Linkage—Trade

The country and regional sub-models are linked through trade. Commodity trade by country is the difference between domestic production and demand (Equation 21). Countries with positive trade are net exporters, while those with negative values are net importers. This specification does not permit a separate identification of both importing and exporting countries of a particular commodity.

Net trade:

$$QT_{tni} = QS_{tni} - QD_{tni} + QSt_{tni}; \tag{21}$$

where QT = volume of trade
QS = domestic supply of the commodity
QD = domestic demand of the commodity
QSt = held stock of the commodity
i = commodity index specific for all commodities

The rest of the variables are as defined earlier.

I.E. Algorithm for Solving the Equilibrium Condition

Our systems of equations are written in the General Algebraic Modeling System (GAMS) programming language. The solution of these equations is achieved by using the Gauss-Seidel method algorithm. This procedure minimizes the sum of net trade at the international level and seeks a world market price for a commodity that satisfies Equation 22, the market-clearing condition.

$$\sum_{n} QT_{tni} = 0; \tag{22}$$

The world price (PW) of a commodity is the equilibrating mechanism such that when an exogenous shock is introduced in the model, PW will adjust and each adjustment is passed back to the effective producer (PS) and consumer (PD) prices via the price transmission equations (Equations 17–19). Changes in domestic prices subsequently affect commodity supply and demand, necessitating their iterative readjustments until world supply and demand balance, and world net trade again equals zero.

I.F. Determination of Malnutrition

To determine how the aforementioned scenarios affect food security within Sub-Saharan Africa, we project their nutritional impacts, namely the resultant percentage and number of malnourished children under the age of five. Any child whose weight-for-age is more than two standard deviations below the weight-for-age standard set by the U.S. National Centre for Health Statistics/ World Health Organization is considered malnourished. The IMPACT-WATER model is able to project this number for each scenario, thereby allowing us to compare the relative abilities of various scenarios to foster improvements in food security. The percentage of malnourished children under the age of five is estimated from the average per capita calorie consumption, female access to secondary education, the quality of maternal and child care, and health and sanitation (Rosegrant et al., 2001). The precise relationship used to project the percentage of malnourished children is based on a cross-country regression relationship of Smith and Haddad (2000), and can be written as follows:

$$\Delta_{t,t2000}\mathrm{MAL} = -\,25.24\ \cdot \ln\left(\mathrm{KCAL}_t \big/ \mathrm{KCAL}_{t2000}\right) - 71.76\ \cdot \Delta_{t,t2000}\mathrm{LFEXPRAT} \\ -\,0.22 \cdot \Delta_{t,t2000}\mathrm{SCH} - 0.08 \cdot\ \Delta_{t,t2000}\mathrm{WATER} \tag{23}$$

where *MAL* = percentage of malnourished children
KCAL = per capita kilocalorie availability
LFEXPRAT = ratio of female to male life expectancy at birth
SCH = total female enrollment in secondary education (any age group) as a percentage of the female age-group corresponding to national regulations for secondary education, and
WATER = percentage of population with access to safe water.
$\Delta_{t,t2000}$ = the difference between the variable values at time t and the base year t2000.

Most of this data comes from the following sources: the World Health Organization's Global Database on Child Growth Malnutrition, the United Nations Administrative Committee on Coordination- Subcommittee on Nutrition, the World Bank's World Development Indicators, the FAO FAOSTAT database, and the UNESCO UNESCOSTAT database. The per capita calorie consumption variable is derived from two components; these include the amount of calories obtained from commodities included in the model as well as calories from commodities outside the model. Knowing this percentage, the projected number may be calculated using the following equation:

$$\mathrm{NMAL}_t = \mathrm{MAL}_t\ \times\ \mathrm{POP5}_t, \tag{24}$$

where *NMAL* = number of malnourished children, and
POP5 = number of children 0–5 years old in the population.

Observed relationships between all of these factors were used to create the semi-log functional mathematical model, allowing an accurate estimate of the number of malnourished children to be derived from data describing the average per capita calorie consumption, female access to secondary education, the quality of maternal and child care, and health and sanitation.

II. Basic Methodology on Water (Water Simulation Module)

The model is based on an optimization approach which minimizes water shortages within the river basin. In the original IMPACT-WATER model, the world was divided into 126 major river basins of various sizes with the goal of achieving accuracy with regard to the basins most important to irrigated agriculture.

II.A. Water Demand

II.A.a Irrigation Water Demand

Irrigation water demand is assessed as crop water requirement based on hydrologic and agronomic characteristics. Net crop water demand (NCWD) in a basin in a year is calculated based on an empirical crop water requirement function (Doorenbos and Pruitt 1979):

$$NCWD = \sum_{cp}\sum_{ct} kc^{cp,ct} \cdot ET_0^{ct} \cdot A^{cp} = \sum_{cp}\sum_{ct} ETM^{ct,cp} \cdot A^{cp} \tag{25}$$

in which *cp* is the index of crops, *ct* is the index of crop growth stages, *ET*0 is the reference evapotranspiration [L], *kc* is the crop coefficient, and *A* is the crop area.

Part or all of crop water demand can be satisfied by effective rainfall (PE), which is the rainfall infiltrated into the root zone and available for crop use. Effective rainfall for crop growth can be increased through rainfall harvesting technology. Then net irrigation water demand (*NIRWD*), with consideration of effective rainfall use and salt leaching requirement, is:

$$NIRWD = \sum_{cp}\sum_{st}\left(kc^{cp,st} \cdot ET_0^{st} - PE^{cp,st}\right) \cdot AI^{cp} \cdot (1 + LR) \tag{26}$$

in which AI is the irrigated area., LR is the salt leaching factor, which is characterized by soil salinity and irrigation water salinity.

Total irrigation water demand represented in water depletion (*IRWD*) is calculated as:

$$IRWD = NIRWD / BE \tag{27}$$

in which *BE* is defined as basin efficiency. The concept of basin efficiency was discussed, and various definitions were provided by Molden, Sakthivadivel, and Habib (2001). The basin efficiency used in this study measures the ratio of beneficial water depletion (crop evapotranspiration and salt leaching) to the total irrigation water depletion at the river basin scale. Basin efficiency in the base year (1995) is calculated as the ratio of the net irrigation water demand (*NIRWD*, Equation 25) to the total irrigation water depletion estimated from records. Basin efficiency in future years is assumed to increase at a prescribed rate in a basin, depending on water infrastructure investment and water management improvement in the basin.

The projection of irrigation water demand depends on the changes of irrigated area and cropping patterns, water use efficiency, and rainfall harvest technology. Global climate change can also affect future irrigation water demand through temperature and precipitation change, but was not considered in the original modeling framework.

II.A.b. Livestock Water Demand

Livestock water demand (*LVWD*) in the base year is estimated based on livestock numbers (QS_{lv}) and water consumptive use per unit of livestock (w_{lv}), including beef, milk, pork, poultry, eggs, sheep and goats, and aquaculture fish production. For all of the livestock products it is assumed that the projection of livestock water demand in each basin, country, or region follows the same growth rate of livestock production. Then livestock water demand was determined as a linear function of livestock production, assuming no change in consumptive water use per unit of livestock production

$$LVWD = QS_{lv} \cdot w_{lv} \qquad (28)$$

II.A.c. Industrial Water Demand

Projection of industrial water demand depends on income (gross domestic production per capita (GDPC) and water use technology improvement. A linear relationship between industrial water demand intensity (IWDI per cubic meter of water per $1,000 GDP) and GDP per capita and a time variable (T) is estimated by regression based on historical records (Shiklomanov 1999 for industrial water consumption; World Bank 1998) and adjusted according to our perspectives on future industrial water demand in different regions and countries.

$$IWDI = \alpha + \beta \cdot GDPC + \gamma \cdot T \qquad (29)$$

in which α is the intercept; β is the income coefficient, reflecting how industrial water use intensity changes with *GDPC*; and γ is the time coefficient, mainly reflecting the change of water use technology with technology change. It is found that α>0, $\partial IWDI / \partial GDPC = \beta < 0$, and $\partial IWDI / \partial T = \gamma < 0$ for all basins and countries, which shows that in future years, the industrial water use intensity will reduce with the *GDPC* and *T* (*T* = 95 for 1995; 100 for 2000; and so on).

II.A.d. Domestic Water Demand

Domestic water demand (DOWD) includes municipal water demand and rural domestic water demand. Domestic water demand in the base year is estimated based on the same sources and methods as those used for industrial water demand assessment. Domestic water demands in future years are projected based on projections of population and income growth. In each country or basin, income elasticities (η) of demand for domestic use are synthesized based on the literature and available estimates. These elasticities of demand measure the propensity to consume water with respect to increases in per capita income. The elasticities utilized are defined to capture both direct income effects and conservation of domestic water use through technological and management change. The annual growth rate of domestic water demand ϕ_{dwd} is a function of the growth rate of population (ϕ_{pop}) and that of income (GDPC, ϕ_{gdpc}), as

$$\phi_{dwd} = \phi_{pop} + \eta \cdot \phi_{gdpc} \tag{30}$$

where $\partial \phi_{\mathrm{dwd}} / \partial \phi_{\mathrm{gdpc}} = \eta < 0$ implies that per capita domestic water demand will actually decline with income growth, which occurs in some developed countries where current per capita domestic water consumption is high; and $\partial \phi_{\mathrm{dwd}} / \partial \phi_{\mathrm{gdpc}} = \eta > 0$ implies that per capita domestic water demand increases with income growth, which occurs in all developing countries.

II.A.e. Committed Flow for Environmental, Ecological, and Navigational Uses

In the modeling framework, committed flow is specified as a percentage of average annual runoff. Data is lacking on this variable for most basins and countries, so an iterative procedure is used to specify this variable where data is lacking. The base value for committed flows is assumed to be 10 percent, with additional increments of 20–30 percent if navigation requirements are significant (for example, Yangtze River basin); 10–15 percent if environmental reservation is significant, as in most developed countries; and 5−10 percent for arid and semi-arid regions where ecological requirements, such as salt leaching, are high (for example, Central Asia). The estimated values for committed flows are then calibrated for the base year relative to basin inflow, outflow, and consumptive use.

II.A.f. Demand for Water Withdrawals as Depletion

Off-stream water demand items described above are all expressed in water depletion/consumption terms. The demand for water withdrawal is calculated as total water depletion demand (DWP) divided by the water depletion coefficient:

$$DWW = DWP / DC = \left(IRWD + INWD + DOWD + LVWD\right) / DC \tag{31}$$

The value of the water depletion coefficient in the context of the river basin mainly depends on the relative fraction of agricultural and nonagricultural water use (that is, larger agricultural water use corresponds to a higher value of water depletion coefficient), as well as water conveyance/distribution/recycling systems and pollution discharge and treatment facilities. In the base year, DC is calculated by given water depletion (WDP) and water withdrawal (WITHD), and DC in the future is projected as a function of the fraction of non-irrigation water use:

$$DC = \rho \cdot \left(\frac{WDPDO + WDPIN + WDPLV}{WDPT} \right)^{\psi} \tag{32}$$

This regression function is made based on historical non-irrigation water depletion and total water depletion in different basins or countries, resulting in regression coefficients $\rho>0$, and $\psi<0$ for all basins and countries.

II.A.g. Price Impact on Water Demand

A classic Cobb-Douglas function is used to specify the relationship between water demand (*W*) and water price (*P*), based on price elasticity (ξ):

$$W = W_0 \cdot \left(\frac{P}{P_0}\right)^{\xi} \tag{33}$$

where *W*0 and *P*0 represent a baseline water demand and water price, respectively. This relationship is applied to agricultural, industrial, and domestic sectors, with price elasticity (ξ) estimated for each of the sectors.

II.B. Water Supply

Assuming minimum environmental and ecological flow requirements as a predetermined hard constraint in water supply, we focus on the determination of off-stream water supply for domestic, industrial, livestock, and irrigation sectors. Two steps are undertaken to determine off-stream water supply by sectors. The first is to determine the total water supply represented as depletion/consumption (WDP) in each month of a year; and the second is to allocate the total to different sectors. Particularly, irrigation water supply is further allocated to different crops in the basin.

To determine the total amount of water available for various off-stream uses in a basin, hydrologic processes, such as precipitation, evapotranspiration, and runoff are taken into account to assess total renewable water (TRW). Moreover, anthropogenic impacts are combined to define the fraction of the total renewable water that can be used. These impacts can be classified into (1) water demands; (2) flow regulation through storage, flow diversion, and groundwater pumping; (3) water pollution and other water losses (sinks); and (4) water allocation policies, such as committed flows for environmental purposes, or water transfers from agricultural to municipal and industrial uses. Therefore, water supply is calculated based on both hydrologic processes and anthropogenic impacts through the model, including the relationships listed above.

A simple network with a two-basin framework can be used as an example (Figure 2). Water availability in the downstream basin depends on the rainfall drainage in the basin and the inflow from the upstream basin(s). Then surface water balance at the basin scale can be represented as:

$$ST^{t} - ST^{t-1} = ROFF^{t} + INF^{t} + OS^{t} - SWDP^{t} - RL^{t} - EL^{t} \qquad (34)$$

in which *t* is the modeling time interval; *ST* is the change of basin reservoir storage; *INF* is the inflow from other basin(s); *OS* represents other sources entering water supply system, such as water desalinized; *RL* is the total release, including the committed instream flow and spill in flooding periods; *EL* is the evaporation loss (mainly from surface reservoir surface); and *SWDP* is the total water depletion from surface water sources which is equal to water withdrawal minus return flow. *SWDP* is determined from this water balance equation, with an upper bound constrained by surface maximum allowed water withdrawal (*SMAWW*) as:

$$\sum_{t} SWDP^{t} / DC \le SMAWW \qquad (35)$$