Chapter 2

The Water and Food Model

This chapter presents a detailed description of the global water and food model, IMPACT-WATER, along with a brief review of relevant global modeling work focusing on state-of-the-art developments in global water modeling, particularly as they relate to agriculture. Appendix A provides more detailed technical documentation of the model for those interested, including the equations for the relationships incorporated in the model.

LITERATURE REVIEW

Global water models have taken advantage of recent developments in hydrological science, and system modeling technology, as well as numerous international and national efforts in global and regional water resources and food production assessments. Over the past ten years, hydrological and meteorological sciences have made great advances in land surface hydrology, and in providing knowledge, techniques, and prediction capabilities that are particularly useful in water resource applications. New technologies in remote sensing, radar, and geophysical exploration at multiple scales have been applied in data collection and modeling. The development of datasets and routing methods for the characterization of water movement over the land surface at the global scale has been particularly important to global freshwater assessment (Maidment 1999).

One comprehensive global hydrologic database is the climate data series provided by Climate Research Unit (CRU) of the University of East Anglia in England, which includes a 0.5-degree 1901–95 monthly climate time-series with precipitation, temperature, wind speed, net radiation, vapor pressure, and other data. The *Digital Atlas of the World Water Balance* developed at the Center for Research in Water Resources (CRWR) of the University of Texas at Austin features a compilation of global climate data in Geographic Information Systems (GIS) format, for use in characterizing the water balance of the earth, including both the description of vertical and horizontal processes affecting the movement of water over the land surface. The *World Water & Climate Atlas* developed at the International Water Management Institute (IWMI) is another data source, presenting rapid access of key climate variables for agriculture and water resources management including 30-year data from 30,000 meteorology stations around the world. Ongoing research has focused on improving databases, taking into account the impact of land uses and climate change.

Global climate models (GCM), or continental hydrologic models, have been created based on global climate datasets such as those described above (Asante 2000). Models such as those by Vorosmarty, Fekete, and Tucker (1996); Miller, Russell, and Caliri (1994); Lohmann et al. (1998); Alcamo et al. (1998); and Asante (2000) have been applied to calculate runoff and water storage at the global or continental scale. These models provide runoff generation and water balance at a scale around 10,000 square kilometers, and runoff at the river basin scale can also be extracted (Alcamo et al. 1998).

Several global water resources overviews have been published based on these global datasets and models and observed records. Margat (1995) studied the global water situation in 1990 and 2025, developing a set of global maps indicating regional variability of various water-related characteristics. Raskin, Hansen, and Margolis (1995) examined the future of water assuming a business-as-usual scenario based on anticipated economic development measured in terms of gross national product (GNP) growth and its past correlation with water demands. Gleick et al. (2002) summarize a wide range of global water resources data including both water supply from various sources and water demand in various sectors. Seckler et al. (1998) developed some scenarios of water demand and supply to 2025, identified countries and regions that will face serious water shortages in the next 25 years, and discussed some potential solutions to eliminate water scarcity including improving irrigation water use effectiveness and water supply expansion. WRI (1998) publishes water supply and demand data by country, which is updated annually. The Economic and Social Council of the United Nations (ECOSOC) presented the Comprehensive Assessment of the Freshwater Resources of the World to the UN (ECOSOC 1997). Goals of ongoing research in global freshwater assessment include improving long-term prediction with consideration of the change in global climate and the growing human impacts, improving the prediction of seasonal and interannual climate variability, and developing the relationship between hydrological and biochemical processes and food production (SCOWR 1997).

The United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro in 1992 concluded that water should be considered an integral part of the ecosystem and sustainable water resources development and management should be achieved at regional, national, and global scales. Since then, numerous international and national efforts have been undertaken to evaluate current water demand and supply situations and search for future solutions. Since agriculture has been, and will continue to be, the largest water consumer in most countries, global and regional water development and management for agriculture has been given high priority. Recently, the United Nations Educational Scientific and Cultural Organization (UNESCO) launched an investigation project, World Water Vision (WWV), which involved many national and international research and consulting agencies. Several documents based on this project were published in 2000, including an overall project report (Cosgrove and Rijsberman 2000), a specific report describing a vision of water for food and rural development (van Hofwegen and Svendsen 2000), and additional country reports (see Cosgrove and Rijsberman 2000 for details). See also Chapter 3 for more discussion of the WWV work as it relates to scenario development.

Besides global water modeling and assessments, other studies that contribute to water development and management include integrated basin management, field water management, crop water modeling, and system analysis techniques. Integrated basin/catchment management has been recognized as an important strategy for managing water uses and dealing with water scarcity at the river basin scale (Batchelor 1999). IWMI has completed substantial work on identifying ways to improve the productivity of water within basins (Molden, Sakthivadivel, and Habib 2001) and in modeling natural and artificial processes in river basins (Kite and Droogers 2001). The International Food Policy Research Institute (IFPRI) has developed integrated basinwide hydrologic-agronomic-economic models for efficient water allocation and economic water use efficiency analysis (Rosegrant et al. 2000). To deal with multiple objectives at the basin level, new problem-solving technologies in the areas of systems analysis, operations research, and decision support systems have emerged and been applied to deal with the growing complexities in water resources systems (McKinney et al. 1999). These types of basin studies will provide more detailed support for global water resources assessment.

Water resources research has also given priority to agricultural water management issues. Soil-plant-atmosphere-research (SPAR) provides an excellent opportunity to develop databases and modeling tools for field water management and crop water modeling. For practical purposes, the set of Irrigation and Drainage Papers published by FAO has guided crop field water management widely. Doorenbos and Pruitt (1977) and Allen et al. (1998) offer guidelines for computing crop water requirements. Doorenbos and Kassam (1979) established an empirical relationship between crop yield response and water stress that has been widely used because it is very simple and uses the most complete summary of available data for implementation of crop-water relationships (from FAO). Further, the data have been widely used for planning, designing, and operating irrigation supply systems and take account of the effect of the different water regimes on crop production (Perry and Narayanamurthy 1998).

Obviously, plentiful information exists for both global and regional water development and management analysis; however, the increased complexity of the physical aspects of water resources development introduces other economic, legal, social, and political intricacies. In recent decades, environmental concern, protection, and enhancement issues created additional complications. Furthermore, multiple objectives involved in water development are often disparate or incompatible, and water allocation conflicts between upstream and downstream users and between different sectors have materialized. New problem-solving technologies such as systems analysis, operations research, and decision support systems have emerged and have been applied to deal with these growing complexities in water resources systems (Yevjevich 1991; and McKinney et al. 1999). However, additional research is still necessary to conceptualize and quantify humanity's dependence on water today and in the future (SCOWR 1997); and policy analysis must integrate pieces of information into a consistent analytical framework and combine international and national efforts for policy-relevant regional and global water resources research.

The modeling exercise presented in this book attempts to draw upon these modeling efforts and integrate available information in water resources, agronomy, and economics in a comprehensive framework to analyze 30-year projections of domestic, industrial, livestock, and irrigation water demand and supply for 69 individual or aggregated river basins at a global scale, incorporating seasonal and interannual climate variability. Concepts related to water demand and supply in different sectors are presented and a systematic approach is developed to analyze the interrelationships among water availability, water infrastructure development, water management polices, and water demand, regionally and globally, in terms of sector, water scarcity, food production, demand, and trade.

The global modeling framework—IMPACT-WATER—combines an extension of the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) with a newly developed Water Simulation Model (WSM), based on state-of-the-art global water databases and models, integrated basin management, field water management and crop water modeling.

IMPACT-WATER MODEL

The IMPACT model provides a consistent framework for examining the effects of various food policies, the impact of different rates of agricultural research investment on crop productivity growth, and income and population growth on long-term food demand and supply balances and food security. The model comprises a set of 36 country or regional submodels, each determining supply, demand, and prices for

16 agricultural commodities, including eight crops. The country and regional agricultural submodels are linked through trade—a specification that highlights the interdependence of countries and commodities in global agricultural markets. The model uses a system of supply and demand elasticities incorporated into a series of linear and nonlinear equations to approximate the underlying production and demand functions. Details of the IMPACT methodology can be found in Rosegrant, Agcaoili-Sombilla, and Perez (1995) and Rosegrant, Meijer, and Cline (2002).

The primary IMPACT model simulates annual food production, demand, and trade over a 30-year period based on a calibrated base year. In calculating crop production, however, IMPACT assumes a "normal" climate condition for the base year as well as for all subsequent years. Impacts of annual climate variability on food production, demand, and trade are therefore not captured in the primary IMPACT model.

In reality, however, climate is a key variable affecting food production, demand, and trade. Consecutive droughts are a significant example, especially in areas where food production is important to local demand and interregional or international trade. More importantly, water demand is potentially increasing but supply may decline or may not fully satisfy demand because of water quality degradation, source limits (deep groundwater), global climate change, and financial and physical limits to infrastructure development. Therefore future water availability—particularly for irrigation—may differ from water availability today. Both the long-term change in water demand and availability and the year-to-year variability in rainfall and runoff will affect food production, demand, and trade in the future. To explore the impacts of water availability on food production, water demand and availability must first be projected over the period before being incorporated into food production simulation. This motivates an extension of IMPACT using WSM at the global scale.

WSM simulates water availability for crops accounting for total renewable water, nonagricultural water demand, water supply infrastructure, and economic and environmental policies related to water development and management at the river basin, country, and regional levels. Crop-specific water demand and supply are calculated for the eight crops modeled in IMPACT—rice, wheat, maize, other coarse grains, soybeans, potatoes, sweet potatoes and yams, and cassava and other roots and tubers—as well as for crops not considered (which are aggregated into a single crop for water demand assessment). Water supply in irrigated agriculture is linked with irrigation infrastructure, permitting estimation of the impact of investment on expansion of potential crop area and improvement of irrigation systems.

IMPACT-WATER—the integration of IMPACT and WSM—incorporates water availability as a stochastic variable with observable probability distributions to examine the impact of water availability on food supply, demand, and prices. This framework allows exploration of water availability's relationship to food production, demand, and trade at various spatial scales—from river basins, countries, or regions, to the global level—over a 30-year time horizon.

Although IMPACT divides the world into 36 spatial units, significant climate and hydrologic variations within large countries or regions make large spatial units inappropriate for water resources assessment and modeling. IMPACT-WATER, therefore, conducts analyses using 69 basins, with many regions of more intensive water use broken down into several basins. China, India, and the United States (which together produce about 60 percent of the world's cereal) are disaggregated into 9, 13, and 14 major river basins, respectively. 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. Other countries or regions considered in IMPACT are combined into 33 aggregated "basins."

WATER DEMAND

The term water demand is often used inconsistently in the literature, sometimes referring to water withdrawal and other times to water consumption or depletion. The specific definitions of water demand terms used in our model are listed in Box 2.1. The concepts of water demand included in this discussion are all defined at the basin scale, unless otherwise stated. Water demand is classified as irrigation demand and non-irrigation demand, the latter further disaggregated into domestic, industrial, and livestock water demand. More detailed descriptions of the different types of water demand and their inclusion in the model are discussed in the following sections. (See Appendix A for detailed technical documentation with equations of the relationships incorporated in the model.)

Irrigation Water Demand

Irrigation water demand is projected based on irrigated area, crop evapotranspiration requirements, effective rainfall, soil and water quality (salinity), and basin-level irrigation-water-use efficiency. 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.

Estimation of irrigation water demand requires extensive hydrologic and agronomic data support. Irrigated harvested crop area was assessed by Cai and Rosegrant (1999), crop growth periods in different countries or basins are collected from USDA–WAOB (1998), and the value of crop evapotranspiration coefficients by crop growth stages are estimated based on Doorenbos and Kassam (1979) and FAO

Box 2.1—Water demand definitions

Water Withdrawal. Water removed from a source and used for human needs, some of which may be returned to the original source and reused downstream with changes in water quantity and quality (Gleick 1998).

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

Beneficial Water Consumption. Water consumption that contributes to various benefits of water use; crop evapotranspiration in agriculture, for example, is considered to be beneficial water consumption.

Nonbeneficial Water Consumption. Water depleted from the source but not used for productive purposes, such as "salt sinks" (drainage with high salt concentration), evaporation loss of field drainage, and seepage in distribution systems that cannot be returned to a source for potential reuse.

Basin Efficiency (BE). Water use efficiency assessed at the river basin scale, taking account of return flow reuse. For irrigation, BE measures the ratio of beneficial water consumption to total irrigation water consumption at the river-basin scale.

Consumption Coefficient (DC). The ratio of water consumption over water withdrawal. The value of (1-DC) indicates the fraction of water returned to the water supply system.

(1998a). Reference evapotranspiration is taken from a half-degree grid of monthly average reference evapotranspiration on agricultural land for 1961–90 calculated by Alcamo et al. (1998) using a Taylor method based on global climate datasets (CRU and GIS coverage of croplands).

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

Livestock Water Demand

Livestock water demand in the base year is assessed based on livestock production, water price, and water consumptive use per unit of livestock production including beef, milk, pork, poultry, eggs, sheep and goats, and aquaculture fish production.

Consumptive use coefficients for water for livestock are estimated for the United States from Solley, Pierce, and Perlman (1998), Mancl (1994), and Beckett and Oltjen (1993) and are adapted to other countries based on FAO (1986). For all livestock products except fish it is assumed that the projections of livestock water demand in each basin, country, or region follow the same growth rate as livestock production. Livestock production is endogenously determined in the IMPACT-WATER model as a function of livestock prices, feed prices, and technological change in the livestock sector. Water demand for fish production is assumed to grow at the weighted average rate of livestock water demand growth.

Municipal and Industrial Water Demand

Industrial water demand depends on income (GDP per capita), water use technology improvements, and water prices. A linear relationship is assumed between industrial water demand intensity (cubic meters of water per $1,000 GDP), GDP per capita, and a technology variable that varies with time. The impact of water prices is captured through a specified elasticity of industrial demand with respect to water price. Domestic water demand includes municipal water demand and rural domestic water demand. Domestic water demand is estimated based on projections of population, income growth, and water prices. In each country or basin, income and price elasticities of demand for domestic use are synthesized based on available estimates from the literature. These elasticities of demand measure the propensity to consume water with respect to increases in per capita income and prices. Projections of consumptive use of water by municipal and industrial sectors are adjusted for the fraction of population living in coastal areas (that is, within 50 kilometers of the coast). For these areas, we assume that discharge from municipal and industrial water use systems goes to the ocean and will not be reused.

Committed Flow for Environmental, Ecological, and Navigational Uses

Rising public awareness of the fragility of environmental and ecological systems over the last two decades has generated demand for committed water flow for environmental and ecological purposes, political purposes, and instream uses such as recreation, hydropower generation, and navigation. Committed flow is defined here as the quantity of water set aside or otherwise managed for environmental purposes and instream use that cannot be used for other purposes in the locations where the water has been reserved. Much of the committed flow is brought about by legislative or regulatory processes. In this modeling framework, committed flow is estimated as a portion of average annual runoff.

WATER SUPPLY

Water supply refers to water available for use from many sources. Water supply concepts are also simulated at the basin scale in the model and are described in the following sections. Box 2.2 provides a list of definitions of the water supply terms used in the model.

Effective Rainfall and Rainfall Harvest

Effective rainfall is rainfall that can be effectively used for crop growth and is generally the only water source for rainfed crops. Effective rainfall can be increased through rainfall harvesting—the capture, diversion, and storage of rainwater for plant growth and other uses. Rainfall harvesting can increase water availability, soil

Box 2.2—Water supply definitions

Renewable Water. Water that can be renewed by natural cycling through the atmosphere and the earth. For each region, total renewable water includes internal renewable water (the flow of rivers and recharges of groundwater generated from endogenous precipitation) and the inflow of surface and groundwater from other regions.

Total Water Availability. For each region, total water availability is the sum of renewable water, artificial basin/regional water transfer, desalinated water, nonrenewable groundwater (available only for a limited period), and salt water (available only for limited uses).

Maximum Allowable Water Withdrawal (MAWW). Water withdrawal capacity available for agricultural and municipal and industrial water uses, based on physical capacity (surface water diversion capacity and groundwater pumping capacity) and environmental constraints.

Effective Rainfall. Rainfall that can be effectively used for crop growth, including rainfall intercepted by plant foliage, rainfall that can enter and be stored in the root zone, and artificial rainfall harvested.

Effective Water Supply for Irrigation (EWIR). Field water supply that can be fully used for crop evapotranspiration. For each region and time period, *EWIR* is subject to water availability, maximum allowed water withdrawal, water allocation between sectors, water quality (such as salt concentration), and water use efficiency. For crops, *EWIR* is further subject to crop acreage and crop patterns.

Irrigation Water Supply Reliability (IWSR). Ratio of actual irrigation water consumption over the gross irrigation requirement, which depends on net irrigation requirement and irrigation efficiency.

fertility, and crop production and can also provide broader environmental benefits through reduced soil erosion especially in arid and semi-arid regions. Although improved rainfall harvesting is often considered in connection with traditional agriculture, it also has potential in highly developed agriculture. Advanced tillage practices, contour plowing (typically a soil-preserving technique), and precision leveling are all examples of practices that can improve infiltration and evapotranspiration, thus increasing the share of rainfall that can be used effectively for crop growth.

Effective Water Supply for Irrigation

Effective water supply for irrigation (EWIR) is calculated at the basin level and depends on hydrologic processes such as precipitation, evapotranspiration, and runoff, as well as anthropogenic impacts. Anthropogenic impacts include water demand in agricultural, domestic, and industrial sectors; flow regulation through storage and flow diversion and groundwater pumping, water pollution, and other water sinks; and water allocation policies such as committed flows for environmental purposes or water transfers from agricultural to municipal and industrial uses.

WATER SIMULATION MODEL

River Basin Aggregation

The WSM uses river basins as the spatial element of modeling. For each basin, all surface reservoirs, along both the main river and its tributaries, are aggregated into an “equivalent basin reservoir,” and all groundwater sources are aggregated into a single groundwater source. Water demands in each basin are estimated separately for agricultural and nonagricultural uses (the latter including industrial and municipal uses) as well as committed flow for the environment. This aggregation assumes full water transfer capacity within each basin; water in one subbasin may be used for other subbasins where needed. Although defined in the model at the basin scale, water demands in the real world are generally located in proximity to the water source, and full water transfer between subbasins and different water supply systems is often constrained by engineering and economic feasibility. To avoid the potential “aggregation fallacy” created by this degree of basin aggregation, we introduce the concept of maximum allowable water withdrawal (MAWW), as defined in Box 2.2. The MAWW for a basin depends on source availability (including surface and groundwater), the physical capacity of water withdrawal for agricultural, domestic and industrial uses, instream flow requirements for navigation, hydropower generation, recreation, environmental purposes, and water demand. Total water withdrawal in each basin is constrained by its MAWW, which prevents water withdrawal beyond the basin's engineering capacity. With this constraint, the river basin aggregation method should be valid for modeling water supply and demand at the basin scale but this method is mainly used for global modeling. For detailed single-basin scale studies, spatial distribution of water supply and demand should be explicitly implemented with any analytical framework.

Model Formulation and Implementation

Based on the concepts discussed above, the WSM generates projections of water demand and water supply based on changes in water supply infrastructure and water allocation and management policy. The model is designed to simulate water demand and supply year by year (up to 30 years) for each basin or aggregated basin used in IMPACT-WATER. The model assumes that nonagricultural water demand, including municipal and industrial water demand and committed flow for instream uses, is satisfied as the first priority, followed by livestock water demand. The effective water supply for irrigation is the residual claimant, simulated by allowing a deficit between water supply and demand.

A traditional reservoir operation model is used (see Loucks, Stedinger, and Douglas 1981), incorporating all the previously discussed components of natural water availability, storage regulation, withdrawal capacity, and committed flow requirement. The objective of this optimization model is to maximize the reliability of water supply (that is, the ratio of water supply to demand). The model is applied for a monthly water balance within one year, and is run through a series of years by solving individual years in sequence and connecting the outputs from year to year. The ending storage of one year is taken as the initial storage of the next, with assumed initial water storage for the base year. For those basins with large storage capacity, interyear flow regulation will be active.

The time series of climate parameters is derived from 30-year historic records for the period 1961–90. In addition to a basic scenario that overlays the single historic time series over the 1995–2025 projection period, a number of alternative scenarios of hydrologic time series are generated by changing the sequence of the yearly historic records. These scenarios are used in WSM to generate alternative scenarios of water availability for irrigation. The model is run for individual basins but with interbasin and international flows simulated. The outflow from one basin becomes a source to downstream basins, which is important in many international river basins (such as the Nile, Mekong, Amazon, Indus, and Ganges-Brahmaputra).

Because of its global scope, the WSM relies more heavily on simplifying assumptions than do single-basin models. These assumptions include the aggregation of water storage at the river basin scale, the absence of irrigation effects on hydrologic processes, the priority of municipal and industrial water demands, and other assumptions noted above. The main advantage of the WSM is its integration of essential hydrologic and agronomic relationships with policy options for water resources development and management, mainly for irrigation. As such, the WSM is an effective tool for estimating irrigation water availability in the context of river basins for analysis at the global scale.

EXTENSION OF THE IMPACT MODEL

The original IMPACT model is updated to assess the effect of water availability on food production, demand, and prices by revising and adding several functional relationships. IMPACT examines supply and demand relationships for cereals, soybeans, roots and tubers, meats, milk, oils, and oilcakes and meals. Of these commodities, the treatment of cereals, soybeans, and roots and tubers is extended to include detailed analysis of the effects of water availability on commodity supply and demand and incorporates the following features.

1) Separate area and yield functions for rainfed and irrigated crops.
    - Water availability for irrigated area includes irrigation water and effective rainfall and groundwater extraction from the root zone.
    - Crop yields and yield growth rates are estimated separately for irrigated and rainfed areas based on differing inputs, investment, and agricultural research.
    - Farmers' responses to drought differ for irrigated and rainfed areas. In the case of drought, for example, farmers in rainfed areas generally maintain cultivated area while sacrificing yields, while farmers in irrigated areas tend to reduce cultivated area to maintain high yields.
2) Updated crop area and yield functions including water availability as a variable.
    - Potential irrigated crop area in the absence of water stress is a function of crop prices and potential irrigated area; actual crop area is a function of potential area and water-limited actual evapotranspiration relative to potential evapotranspiration.
    - Potential rainfed area in the absence of water stress is a function of crop prices; actual rainfed area is a function of potential rainfed area and water-limited actual evapotranspiration relative to potential evapotranspiration.
    - Potential irrigated and rainfed crop yields in the absence of water stress are a function of crop price, labor price, capital price, and technological change; actual irrigated and rainfed crop yields are a function of the potential yields and their respective water-limited evapotranspiration relative to potential evapotranspiration.

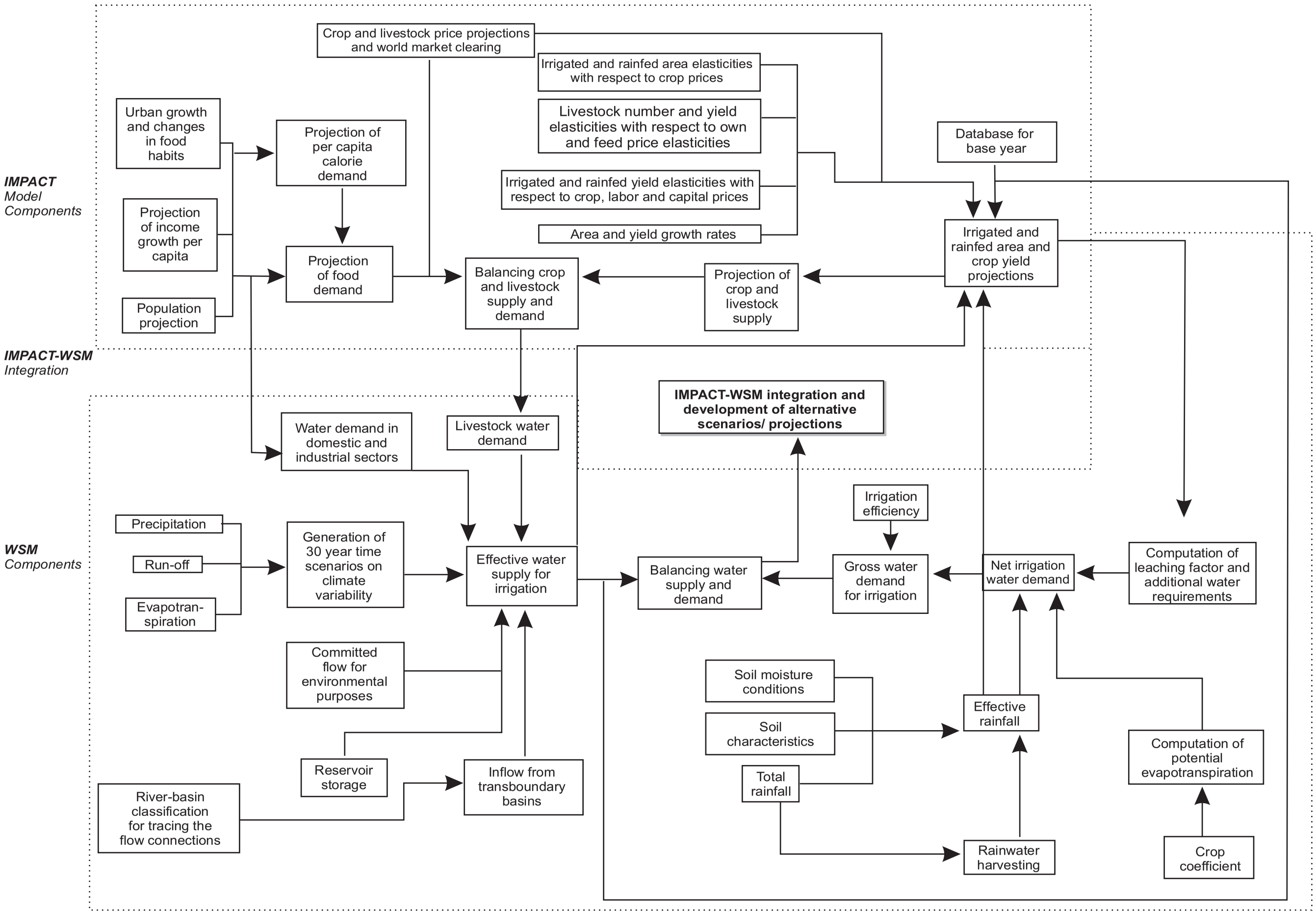
To determine the reduction of crop area harvested when water is limiting, a threshold level of relative evapotranspiration, E^*, is defined, below which farmers reduce crop area rather than impose additional moisture stress on existing crop area. The parameter E^* is an important policy and behavioral parameter that varies across countries and possibly across basins within countries. In developed countries characterized by large farms, E^* is assumed to be relatively higher, especially for irrigated crops. Water shortages are generally handled in these countries by fallowing a portion of the land while maintaining yields on remaining area, either by small reductions in area by most farmers or by some farmers fallowing all of their land with compensation from short-term sale of water rights, government drought insurance, or other mechanisms.

In developing countries characterized by many small farmers, on the other hand, E^* will likely be much lower, approaching the 0.60 considered the reference threshold level. In these countries, reduction in area caused by water shortages would imply complete fallowing of many small farms, eliminating the entire means of livelihood for these farmers. Under such circumstances, government irrigation management and local customs often favor spreading the water over as broad an area as possible to maintain some level of yield and income for the largest possible number of farms. For example, the *warabandi* system that governs many irrigation systems in India formally specifies that shortages be widely shared across farms.

LINKING IMPACT AND WSM

Figure 2.1 shows the integration of the water and food components in a consistent framework. IMPACT includes food production, demand, and trade components. Initial inputs into IMPACT, including growth in urban areas, income, and population, are used to project food and calorie demands, which in turn affect crop and livestock supply, demand, and prices. Elasticities for crop area, livestock number, and crop and livestock yield, as well as area and yield growth rates, are used in area and yield projections, which are in turn used in the calculations of crop and livestock supply. These projections of area, yield, and supply and demand are used in the WSM. The WSM includes functions of precipitation, runoff, evapotranspiration, water supply infrastructure, and socioeconomic and environmental policies. Water supply for irrigation is simulated accounting for year-by-year hydrologic fluctuations, irrigation development, growth of industry and domestic water uses, livestock water demand, environmental and other flow requirements (committed flow), and water supply and use infrastructure. This effective water supply for irrigation is then used as a variable in the irrigated and rainfed area and crop yield projections in IMPACT, and in the water supply and demand balance equations.

Figure 2.1—IMPACT-WATER: The structure and integration of the IMPACT and water simulation models



WSM first computes total EWIR in each time period, and then allocates the total EWIR to specific crops based on crop profitability, sensitivity to water stress, and irrigation water demand. Higher priority is given to crops that are more profitable, more drought sensitive, or require more irrigation water. WSM thus generates monthly effective irrigation water supply by crop and by basin over a 30-year time horizon and provides these variables as inputs into IMPACT. Other water parameters input into IMPACT include effective rainfall and maximum crop evapotranspiration by month, year, and basin.

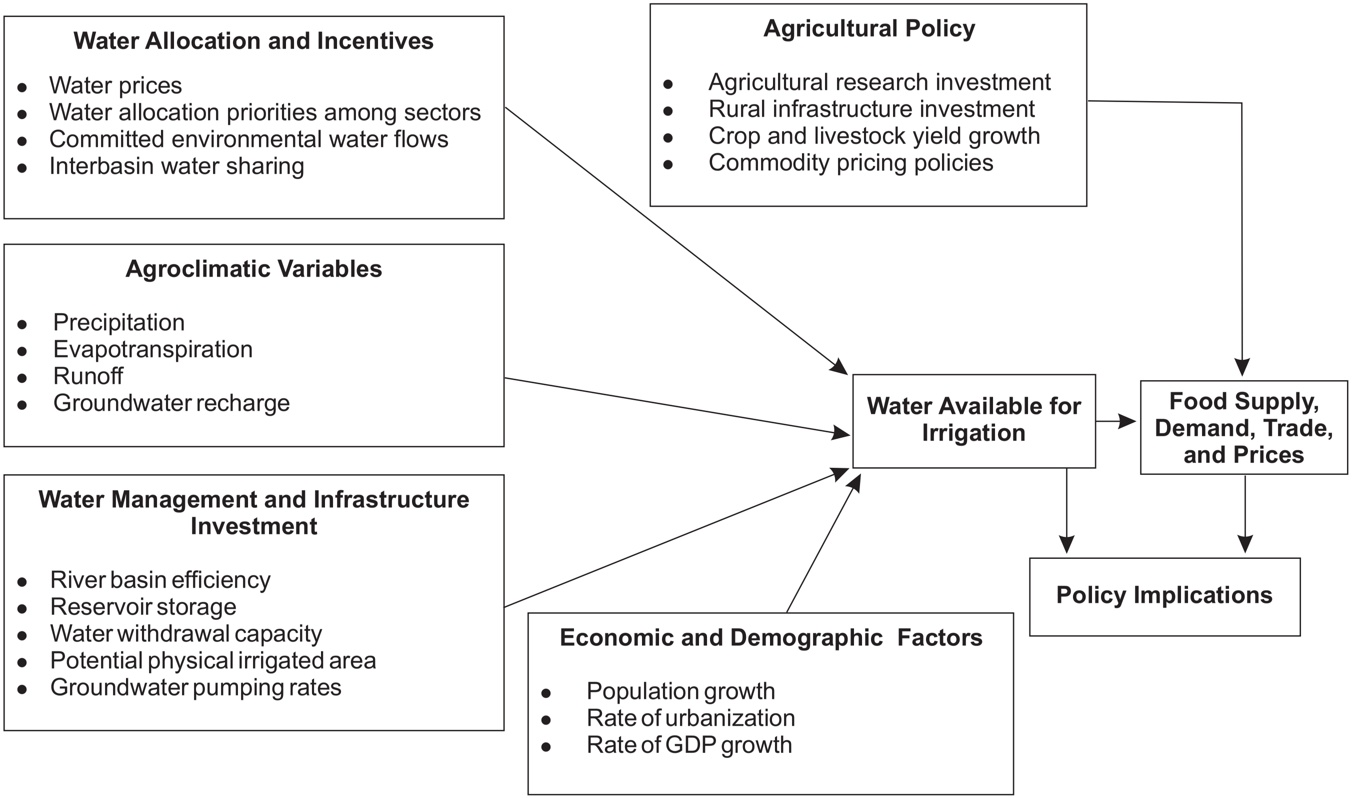
The effective water supply for irrigation and rainfed agriculture is then entered into the crop model. For each year it is initially assumed that there is no water shortage so that crop area and yield are at their potential levels fully determined by prices, irrigation investment, and technological change. Water availability for crops is then computed, and crop area and yield are adjusted based on relative evapotranspiration. Next, crop production and stocks are updated, food demand is computed, and net food trade and global trade balances are calculated. Global net trade should equal zero; if the trade balance condition is violated crop prices are adjusted and the model undertakes a new iteration. The loop stops when net trade for all commodities equals zero. Crop area, yield, production, and prices are thus determined endogenously.

Data requirements for the modeling are extensive and relate to agronomy, economics, engineering, and public policy. Appendix A provides a description of the data requirements for this study.

The integrated model provides a wide range of opportunities to analyze water availability and food security at the basin, country, and global levels. Many policy-related water variables are involved in this modeling framework including potential irrigated area and cropping patterns, water withdrawal capacity for both surface and groundwater, water use efficiency, water storage and interbasin transfer capacity, rainfall harvest technology, allocation of agricultural and nonagricultural uses, and allocation of instream and offstream uses. Investment and management reform can influence the future paths of these variables, which in turn influence food security at both national and global levels.

Figure 2.2 shows a framework for the scenario analysis based on the primary driving forces in IMPACT-WATER. Four classes of driving factors influence the amount of water available for irrigation including agroclimatic variables, water management and investment in infrastructure, water allocation and incentives, and economic and demographic factors. Some of these drivers—such as increases in infrastructure investment, water management improvement, and development of new water sources—may increase water availability for irrigation, while others—such as faster urbanization and increased committed flows for environmental purposes—may decrease water availability for irrigation. These driving forces can be varied in WSM, the output of which—reflecting the effects of these driving forces

Figure 2.2—IMPACT-WATER: Driving forces for scenario analysis



on effective water supply for irrigation and rainfed agriculture—can then be incorporated into IMPACT-WATER to compute food supply, demand, trade, and food prices. Additional agricultural policy drivers, such as investments in agricultural research and rural infrastructure, commodity pricing policies, and crop and livestock yield growth also directly affect food supply, demand, trade and prices. Policy implications related to these scenarios can then be explored based on outputs from both WSM and IMPACT-WATER. Further discussion of the use of critical drivers to develop alternative scenarios is provided in Chapter 3.

The purpose of this modeling exercise is to develop a tool for policy analysis in regional and global water resources development and management. As stated, many policy-related water variables are involved in this modeling framework including potential irrigated area and cropping patterns, MAWW for both surface and groundwater, water use efficiency, water storage and interbasin transfer facility, rainfall harvest technology (that is, to increase effective rainfall for crops), allocation of water to agricultural and nonagricultural uses, and committed instream flow requirements. In particular, water supply in irrigated agriculture is integrated with irrigation infrastructure, which permits the estimation of the impact of investment on expansion of potential crop area and improvement of irrigation systems. The remainder of this book consists of a series of different scenarios—including holistic alternative futures as well as assessments of the impacts of changes in policy and investment—and conclusions based on the scenario results.