Final Report Prepared for

Regional Agricultural Trade and Productivity Project (RATP), Nile Equatorial Lakes Subsidiary Action Program (NELSAP)

Assessment of Agricultural Models and Data Sets for Nile Basin DSS Extension

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Contents

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I (the consultant) am responsible for any errors involved in this report.

Executive Summary

The Nile Basin Initiative's (NBI) Water Resources Planning and Management (WRPM) program recently initialized a plan for the design and development of a decision support system (DSS) for water and land management in the Nile Basin (NBI-DSS). Accompanying this effort, the Regional Agricultural Trade and Productivity Project (RATP) with the Nile Equatorial Lakes Subsidiary Action Program (NELSAP) will work with WRPM to develop agricultural components of the DSS. The extended DSS is expected to have the capability to predict food production, demand and trade in the Nile Basin (NB) region. To support the NBI-DSS extension, this consultancy work conducts the following tasks for NELSAP/ RATP:

1. Describe the current agricultural module in the NBI-DSS;
2. Discuss model extension, suggest modules for the simulation and prediction of food production, demand and trade, and describe the connection of the suggested modules with the existing one in the DSS;
3. Assess the readiness of the database and suggest data items required for the agricultural extension;
4. Prepare terms of reference (TOR) and roadmap for carrying out recommended activities.

The data and modules proposed in the NBI-DSS development plan are necessary for assessing crop production from a hydrologic perspective. However, those are not sufficient to assess crop production in a comprehensive manner to account both water and non-water agricultural inputs, and also standard economic methods are needed to assess food demand and trade. Thus the extension will need both additional modules and data beyond what is proposed in work packages of the NBI-DSS Conceptual Design and Development Plan.

Comparing different options of models, it is recommended to develop a partial equilibrium model with detailed representation of the agricultural sector of the countries in the Nile region and an aggregated representation of the rest of the world. This model will integrate food production, demand and trade components. The production component will be coupled with the hydrology and water resources simulation models to be developed in the NBI-DSS to estimate water and land availability for crop production. Irrigated and rainfed crops will be modeled separately when assessing food production. To keep the model development within the time and funding limits of this project, the regional partial equilibrium model may focus on the trade between the Nile countries and the rest of the world, but not directly simulate country-to-country food trades among the Nile basin countries. The intra-regional trade between countries will be analyzed using a country-level trade-scenario model based on food supply, demand and surplus/deficit in individual countries. The trade-scenario model will be connected to the regional partial equilibrium model for both intra- and inter-regional trade analysis.

The major data items required for the extension of the agricultural model include a map identifying irrigated and rainfed crop areas, a more realistic estimate of crop evapotranspiration, and crop yields for a baseline year. Other required data items include agricultural inputs in addition to water including fertilizer, pesticides, labor, machinery, seed, water use efficiency, water productivity, and agricultural planning data. Food demand and trade modeling will need the following additional data items: population, nutritional demand, food trade history, crop prices, self-sufficiency condition and plan, as well as food trade trends and national policies. The data items for crop production (Table 1) may require a separate consultant aside from the model development consultant, whereas the food demand and trade data may stay with the model development consultant.

Although it is hard to claim that existing or ongoing NBI projects will provide ready-to-use data for the agricultural extension of NBI-DSS, these projects will provide some data support for the agricultural module to be developed within the DSS. Although data processing under proper coordination among the projects may still take a big effort, this approach should be much easier than collecting the primary data items if these data development projects did not exist. The open cropland and crop evapotranspiration databases constitute another type of source for the data collection and compilation. Both data and model development work will encourage the involvement of local partners.

This project will need to coordinate with the work packages underlying the NBI-DSS Conceptual Design and Development Plan, including the coordination of modeling and data compilation efforts, with special monitoring on the timing of the DSS work packages and the additional work for the agricultural extension.

Abbreviations

DSS	Decision Support System
ET	Evapotranspiration
EWUAP	Efficient Water Use for Agricultural Production
ENDIS	Eastern Nile Drainage and Irrigation System
FAO	Food and Agriculture Organization of the United Nations
FPU	Food Production Units
GIS	Geographical Information System
HRU	Hydrologic Response Units
IFPRI	International Food Policy Research Institute
IWMI	International Water Management Institute
IWRM	Integrated Water Resources Management
NB	Nile Basin
NBI	Nile Basin Initiative
NELSAP	Nile Equatorial Lakes Subsidiary Action Program
RATP	Regional Agricultural Trade and Productivity Project
SEBAL	Surface Energy Balance Algorithm for Land
SVP	Shared Vision Program
TOR	Terms of Reference
WB	World Bank
WRPM	Water Resources Planning and Management

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1. Introduction

The Nile Basin Initiative (NBI)'s Water Resources Planning and Management (WRPM) Project plans to develop a decision support system (DSS) for the Nile Basin (NBI-DSS), which is one of four components of the WRPM identified under the Shared Vision Program (SVP). The NBI-DSS is expected to provide "*... a shared knowledge base, analytical capacity, and supporting stakeholder interaction, for cooperative planning and management decision making for the Nile River Basin*", and assist to "*enhance the capacity to support basin wide communication, information exchange, and identifying trans-boundary opportunities for cooperative development of the Nile Basin water resources*" (NBI, 2008).

Ultimately, the DSS is intended to improve the overall net benefit from water resources management in the Nile Basin (NB) and support the regional socioeconomic development (WRPM-NBI, 2008). The Regional Agricultural Trade and Productivity Project (RATP), an effort of the Nile Equatorial Lakes Subsidiary Action Program (NELSAP), plays a leading role in the NBI's core agricultural functions and food security vision. Specifically, the RATP intends to work with the WRPM to develop agriculture components and integrate those with the activities already planned for the NBI-DSS development. The enhanced NBI-DSS is expected to have the capability to predict food production, demand and trade in the NB region. Using the enhanced tool, the RATP wishes to enhance the foundation for knowledge-based water resource management and capacity building to support more productive and economically sustainable agriculture in the NB.

The RATP-DSS Workshop in April 2009 identified the following objectives for enhancing the agricultural function of the NBI-DSS:

- *Present and future food demand & supply and their effects on changes in land and water use*
- *Irrigated and rainfed agricultural expansion and intensification potential and its impact on the basin's water balance*
- *Options for improving productivity levels under irrigated and rainfed systems*
- *Drought and flood impacts on food production*
- *Opportunities and challenges for agriculture products markets*
- *Impact of other sectors (urban, industrial, etc.) on agriculture*

Recently WRPM has prepared a Conceptual Design and Development Plan for the NBI-DSS. **However, to address the objectives stated above, additional efforts beyond the Plan are needed. The successfulness of agricultural extension of the NBI-DSS will need appropriate agricultural production, demand and trade models as well as reliable data sets.** This consultancy work discusses such need and prepares term of reference (TOR) for the future projects. Specifically the following tasks have been undertaken for NELSAP/ RATP:

- Describe the current agricultural module in the Nile Basin DSS.

- Describe the existing regional agricultural models, including their structure (major modules), objectives and level of detail.
- Assess the readiness of the database for each selected model to be applied in the Nile Basin countries.
- For each selected model, identify the major adjustments to be made in (i) methodology; (ii) modeling blocks; and (iii) database for all Nile Basin countries.
- Evaluate the readiness for connecting each model with the current agricultural module under the NBI-DSS.
- Prepare (i) TOR and (ii) Roadmap to carry out activities for strengthening the DSS agricultural module that RATP developed during the implementation phase (Nov. 2009 – June 2012)

These tasks basically follow up on the outcomes of the 2009 RATP-DSS Workshop in Addis Ababa, 2009; they are also based on the Nile Basin DSS documentation and other relevant project documents, as well as communications with RATP and WRPM staff and personnel from international development agencies such as the World Bank, the Food and Agricultural Organization (FAO), as well as several international research agencies. This report describes the results for these six tasks, with an emphasis on the model and data assessment as well as a roadmap for carrying out the suggested activities.

2. Background – NBI-DSS

2.1. General functions of the NBI-DSS

The conceptual framework of the NBI-DSS is shown in Figure 1. In general, the DSS will simulate the changes of the hydro-climatic systems and engineered systems in both short and medium term, evaluate the ecological, economic and social impacts of these changes, and support decision-making based on the results of this impact assessment. The consequence of the decision combined with natural changes (e.g., climate variability and climate change) will initialize another round of modeling analysis that will be focused on adaptive management. The DSS includes an information management system, a regional river basin planning model, and a suite of analytical tools to support multi-objective analysis of investment alternatives. It also contains tools to assist national governments with the design and evaluation of alternative development paths and the identification of joint investment projects at the sub-regional and regional level (Figure 2). The areas of concern to be addressed include (Seid, 2009):

- Water resources development through engineering structures
- Optimal water resources utilization through non-structural interventions
- Hydropower potential
- Rainfed and irrigated agricultural production
- Flood control
- Drought management
- Watershed and sediment management
- Navigation.

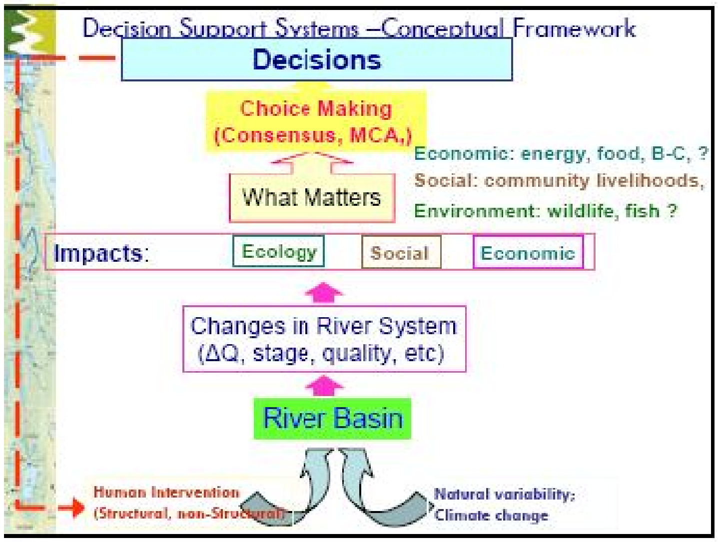


Figure 1: The conceptual framework of the NBI-DSS (Source: Seid, 2009)

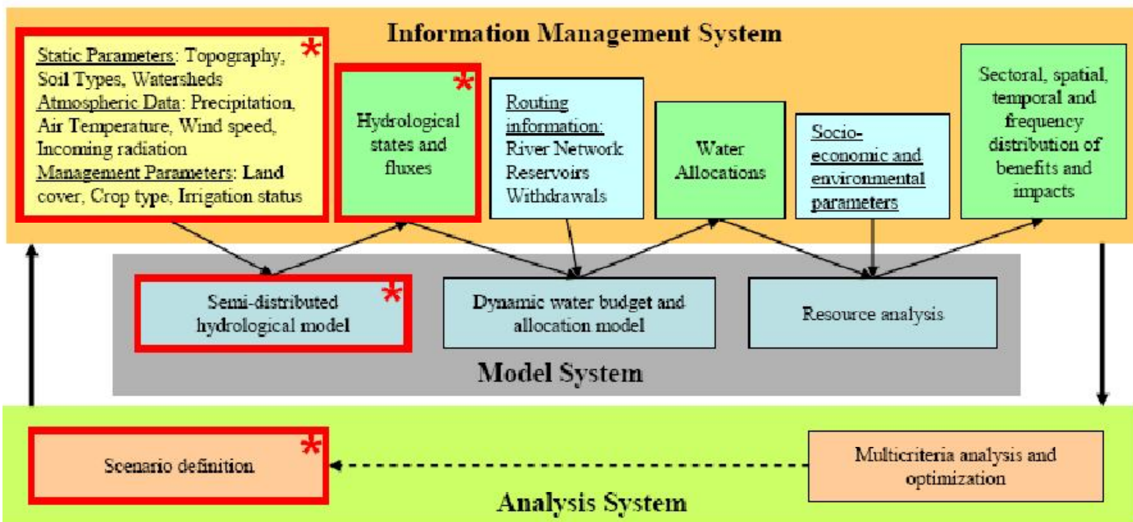


Figure 2: Schematic of the NBI-DSS (Source: Seid, 2009)

Recently WRPM has prepared a Conceptual Design and Development Plan for the NBI-DSS, which is structured into a number of parallel tasks that are grouped into three independent work packages:

- Work Package 1: Software Development and System Implementation, which consists of detailed design update and technical specifications, including a systems' ontology and the definition of model structures.
- Work Package 2: Data Compilation, Processing and Pilot Test Applications executed in parallel but independently that involve end users and the NBI-DSS core and national teams.

- Work Package 3: Supervision and Monitoring, which consists of coordinating/synchronizing the aforementioned parallel activities and organizing quality assurance processes.

One of the major tasks for Work Package 1is the development of a semi-distributed watershed hydrologic model that includes reservoir and groundwater storage regulations and water withdrawals for human uses. The model is based on a node-link network that depicts upstream-downstream relationships, including various water sources nodes (catchments, groundwater, rainfall harvesting, etc.) and water demand nodes (municipal and industrial, agricultural, hydropower, navigational, ecological, etc.) As for other widely-used watershed hydrologic models, hydrologic response units (HRUs) will be used as the fundamental spatial units in which hydrologic processes are simulated. WRPM has already signed a contract with DHI, an international consulting firm in Denmark for Work Package 1.

Although Work Package 1 will include some modules for crop production, as to be described in details in next section, these modules are mainly developed for hydrologic simulation and basin-wide water resources availability and allocation, and these modules are not sufficient to address the agriculture production, demand and trade issues as targeted by RATP.

On the other hand, from a water balance perspective, Work Package 1 will estimate land availability, soil moisture and evapotranspiration flux, which are key inputs for crop production modeling; it will also simulate reservoir and aquifer storage and streamflow, which determine irrigation water availability. Thus, it is important to build the new agriculture module on the modeling work which has already been coordinated and under development by WRPM.

For Work Package 2, WRPM has prepared a draft request for proposals (RFP) on data collection for the DSS implementation. The draft is currently awaiting clearance from the World Bank (WB). Although many items are directly related to the RATP's agricultural extension effort, Work Package 2 focuses on data required to calibrate, validate and test the suite of models and analytical tools in the DSS with case studies from the Nile Basin. Examples of these data include hydro-meteorological time series, soil maps with hydrologic attributes, current uses of water in the basin, water infrastructure, basic socioeconomic data, such as demography and population distribution. It should be noted that the socioeconomic data will be directly useful for food demand and trade modeling that will be included in the agricultural extension. **However, for the purposes of RATP, additional work is needed to compile data for agricultural production, demand and trade. Particularly, the non-water data items such as non-water agricultural inputs (e.g., fertilizer and pesticides, labor, etc.), food demand parameters (e.g., nutrient requirements), and food trade variables (e.g., prices, imports and exports) are not included in Work Package 2.**

For Work Package 3 on project supervision and monitoring, the NBI-DSS implementation plan (Concept Design and Development Plan) led by WRPM will need to be coordinated with the RATP effort on agricultural extension. The DSS group has developed documents for the three work packages and a consulting firm has already started the tasks in Work Package 1. **As long as the RATP terms of reference (TOR) are released, the two parts will be coordinated in a consistent context in order to develop effective agricultural functions for the NBI-DSS. The collaboration is needed on both model development and data compilation. If possible, a technical staff from RATP, who should have expertise on agriculture development, may join the NBI-DSS group, as liaison of RATP in the DSS group.**

2.2. Agricultural modules of the NBI-DSS

The NBI-DSS implementation plan includes the development of agricultural modules that are expected to address the following questions:

- What are the crop water requirements for major agricultural areas in the Nile Basin
- What are water consumption patterns (by country/region) and trends?
- What are the potential impacts of alternative developments on the system-wide water balance?
- Which parts of the basin rely on rainfed and irrigated agriculture (spatial information)?
- What are the trends in the development/expansion of each of these types of agricultures? If these trends continue, what would be the impacts on water use/availability patterns in the future?
- How much water is required for the specific proposed irrigation developments under study? What is the tradeoff of this use with other uses (by sector)?
- What are the impacts of rainfall variability on rainfed agriculture?

The *repository of key knowledge* to address these questions includes:

- Land use/cover (distribution/location, spatial coverage, key attributes, etc)
- Major irrigation and schemes (current and planned)
- Evapotranspiration estimates
- Soil map with hydrologic attributes
- Hydro-meteorological time series data

Key analytical tools will be available within the modeling system of the DSS, including:

- Crop water requirements estimation
- Crop yield response to water (mainly irrigated agriculture) (The crop yield model is a yield-water model that follows the FAO's CROPWAT method, which depends on estimates of potential and actual crop evapotranspiration).
- Impact of different land use/cover types on water balance (runoff generation)
- Water balance model
    - Impact of consumptive use on water balance
    - Impacts of existing developments

The data and modules proposed in the NBI-DSS development plan are necessary for assessing crop production from a water perspective. However, the data and modules are not sufficient for assessing crop production in a comprehensive manner because crop production depends on both water and non-water inputs, such as labor, machinery, fertilizer, pesticides, and seed (based on agricultural research), etc. Moreover, although WRPM proposes some economic analysis tools, which are to be used for benefit-cost analysis, tradeoffs (by sectors, upstream/downstream) analysis, demand projection/analysis tools, these tools need to be extended to include standard economic methods that assess food demand and trade. This extension will need additional model development that is beyond what is specified in Work Package 1 of the NBI-DSS Development Plan, and additional data support beyond what is proposed in Work Package 2.

3. Agriculture Model Extension

The model extension considers the objectives for enhancing the NBI-DSS (see the list of the objectives in the introduction section) and the model development under Work Package 1 of WRPM (see Section 2). The basic idea is to extend the model development under Work Package 1 so as to address all the objectives. Specifically, the extended DSS needs to simulate irrigated and rainfed crops using reliable data sets, including climatic and hydrologic simulations from the existing DSS modules. The DSS also needs to incorporate both water and other agricultural inputs in the crop production simulation. Food demand and trade will be estimated with an economic module that will be coupled with the DSS. Finally, the extended DSS will be used to test the various options of increasing agricultural productivity and food security in the Nile region.

In summary, agriculture modules should be extended to 1) account for both water and non-water inputs in the production of irrigated and rainfed crops using microeconomic production theory; 2) simulate and predict food demand and trade markets; and 3) take advantage of the water resources information and modeling support of the NBI-DSS. This section describes these aspects of model extension.

3.1. Crop production model

As discussed above, some components in the proposed NBI-DSS are directly related to food production, such as crop water requirement and crop yield simulation. From a hydrologic perspective, crop yield depends on the actual crop evapotranspiration (ET) relative to the potential ET. Simulation of crop ET should take soil moisture and meteorologic driving forces (such as temperature and wind speed, etc.) into account. Work Package 1 will cover this element. However the final crop yield also depends on other inputs such as labor, fertilizer and pesticide and seed. Crop area is also a function of economic variables, such as food prices, and policy variables such as subsidies. **Thus, the food production model should jointly consider hydrologic, agronomic and economic factors for more realistic food production simulation.**

A key methodology for crop production modeling is simulating irrigated and rainfed crops separately. This is necessary because of the requirement of RATP to assess the potential of rainfed agriculture and irrigated agriculture, and the complementary and tradeoff relations between the two. It is also necessary to have split production functions since the inputs, both water and non-water inputs, and land availability are usually different for irrigated and rainfed crops. The existing irrigated and rainfed crop area and yield in different countries or regions within the NB is a required data set. Also, the projections of such split items will be important to assess the role of rainfed and irrigated agriculture in the future of the Nile Basin. The data requirements for separate irrigated and rainfed crop production simulation are further discussed in Section 4. **Thus different crop production functions and data sets will be prepared for irrigated and rainfed crops, separately; moreover, land availability for the two categories of crops will be assessed according to water, landscape and soil conditions.**

Modeling crop production includes the simulation of a baseline and the prediction of benchmarks under various scenarios. **The baseline is usually made for a particular year and the model results should match the observation as close as possible by a calibration procedure.** Remote sensing is useful for obtaining the data that are required for the calibration but difficult or expensive to measure in field, for example, crop ET (Bastiaanssen and Samia, 2003). The important baseline modeling results should include irrigated and rainfed area and yield by crop (including all major crops) for a recent year (e.g., 2007). The model should also be verified with a number of other years. **The benchmarks will represent projections for future years (e.g., 2015, 2020, 2025, and 2030) under the various scenarios of investment and agricultural and water management policies, including national development strategies**.

The following options can be considered for the crop production simulation, which are listed from easy to difficult regarding model implementation difficulty and data requirements:

- Option 1: Use a baseline of crop area and yield and focus on water impact only. Estimate potential and actual crop ET from other programs such as EWUAP (a project involving a consultant for ET and crop area estimates); and estimate crop yield using a method similar to AquaCrop, CropWat and ClimWat (FAO)
- Option 2: Option 1 but using a more detailed hydrologic-agronomic model (e.g., The Soil Water Atmosphere Plant – SWAP, Van Dam et al., 1997) for selected locations
- Option 3: Option 1 plus an economic model to determine crop yield and area based on both water and non-water inputs

Option 1 is basically the crop module proposed in the NBI-DSS development plan with data (e.g. crop ET) support from other programs.

Option 2 needs a detailed field-scale hydrologic-agronomic model such as SWAP. It is feasible to implement such a model in some selected locations but not to implement it everywhere in the basin. Option 2 can also consider a watershed model that simulates both hydrology and crop growth, for example, Soil and Water Assessment Tool (SWAT) (Neitcsh, 2005), a semi-distributed watershed model that has been used worldwide. Actually, the semi-distributed hydrologic model being developed under NBI-DSS Work Package 1 has similar functions as SWAT in hydrology. It is possible that the DSS basin-scale hydrologic model is integrated with the crop growth functions, as presented in SWAT. However, this can be taken as a future plan only and the current time framework and funding availability of the RATP project may not support the development.

While Options 1 and 2 simulates crop production using agronomic functions, Option 3 uses integrated agronomic-economic functions, which are based on empirical economic models and crop response to water and other environmental conditions such as soil salinity (Dinar and Letey, 1996). There will be two further options to implement the agronomic-economic functions of crop production. One is to develop an agricultural production function (yield and area function) using an econometric method based on surveys of crop yield and area and both water and non-water inputs such as fertilizer, labor, cost on seed etc. (see Cai et al., 2006 for an example in the Mapio Basin in Chile). This function will be created for each demand site (a region or a sub-basin). The functions of all demand sites can be combined into the NBI-DSS to calculate food production using water and non-water inputs. In this way, an integrated hydrologic-agronomic-economic model (Rosegrant et al., 2001; Cai et al., 2003) can be developed for basin-wide water allocation and agricultural development. The model can be used to explore optimal water allocation and water use plans with regard to agricultural and environmental objectives. The challenge for this option is the cost of the agricultural surveys, although some existing empirical models and the values of key parameters can be referred to the literature.

The other choice for the agricultural production function is to use an empirical economic model (e.g., Colby Douglas functions) characterized by price elascity of agricultural inputs and a water response coefficient based on crop water deficit, as shown in the following equation:

$$y = y_0 \cdot w \cdot \prod_{i=1}^{I} {p_i}^{\xi_i} \qquad (1)$$

in which I is the index of agricultural inputs such as labor, machinery, fertilizer, pesticides and seed, p_i is the price (cost) of an input, ξ_i is the price elascity, y0 is the potential crop yield (or area), and *w* is the water response coefficient, which can be calculated following the FAO method (Doorenbos and Kassam, 1979):

$$w = 1 - k_y \cdot \left(1 - {}^{ETa}/_{ETc}\right) \qquad (2)$$

in which k_y is the yield response coefficient, *ETa* is the actual crop ET and *ETc* is the reference crop ET.

The crop production function described by Equations 1 and 2 are used by IFPRI’s IMPACT-WATER (See Appendix A) and IWMI’s WATERSIM (which has the similar functions as IMPACT-WATER). In these models the crop production functions have already been developed for several countries in the Nile Basin. Thus starting with the existing food production functions, the extension will focus on more detailed food production simulation in the NB countries, which will be coordinated with the water and land simulation in the NBI-DSS. In this way, the food production function will be based on hydrologic modeling while considering economic and agronomic factors. Detailed discussions are provided in a later section on model integration.

For either choice, the production function will be developed for irrigated and rainfed crops separately. The production function with irrigated crops will be connected to the water supply function of the NBI-DSS and the production function with rainfed crops will be connected to the rainfall variability (seasonal and annual) simulation from the NBI-DSS. The area for both irrigated and rainfed crops will be based on the land availability assessment by the NBI-DSS.

3.2. Agriculture demand and trade model

For the food demand and trade model, there are a number of global models including partial equilibrium models and economic-wide models. Many partial models, such as IMPACT (IFPRI), AGLINK (OECD), ESIM (USDA, Stanford Univ.), World Food Model (WFM, FAO), and FAPRI (Iowa State University) have a detailed agricultural component. Although these models simulate the global economy, some of them have a regional or country focus. For example, AGLINK has a focus on OECD countries, FAPRI has a focus on the U.S. while ESIM contains 13 countries/regions including EU countries and U.S., adding the rest of the world. Unfortunately, it seems that there is not a global food trade model that focuses on the Nile region. The direct use of a global model, such as IMPACT and WFM, may not be the best because the simulation of the study region is not detailed enough. In particular, the global models do not simulate the country-to-country trade paths, which inhibits them from being used to simulate the trade between the countries within the Nile Basin.

IMPACT (IFPRI) is distinguished from other economic-wide or partial models because it is combined with WATER, a water simulation model (Cai and Rosegrant, 2002). IMPACT-WATER simulates irrigated crops and rainfed crops separately. Irrigated crops depend on effective rainfall and irrigation water while rainfed crops depend only on effective rainfall. The details of IMPACT-WATER can be seen in Appendix A.

The choice between partial models and economic-wide models depend on data availability. Although some country-level general equilibrium models exist (e.g., Diao et al. 2005 and Willenbockel et al., 2008), the extension of such models to the whole region may exceed the financial limits for this project. With a partial model, the impact of other sectors, such as industrial and urbanization development, on agricultural development cannot be modeled rigorously. However, the impact in terms of water and land can be captured by considering non-agricultural water and land requirement as external constraints on agriculture. This is reasonable for the Nile Basin given the dominating role of agriculture in most countries in the region at present and the likelihood of this dominance persisting over the next few decades. **Therefore, the choice of a partial model is more reasonable for this project**.

Another issue for the choosing the food demand and trade model is the simulation of food market and trade. One of the purposes of the agricultural study led by RATP is to explore the food trade markets between Nile Basin countries, as well as ones between the whole Nile region and the rest of the world. The ideal approach is to have a partial agricultural demand and trade model that can simulate the equilibrium trade prices within the region, as well as producers' and consumers' prices and then simulate the country-by-country trade. Unfortunately, although such a model would be desirable, the development of the model could possibly exceed the time and funding limits for the RATP project, although it can be taken as an option.

An approximate approach that could be implemented more quickly and affordably is to specify food trade between countries using prescribed trade scenarios that are based on food surplus or deficit in individual countries, existing or potential export-import relationships (e.g., market accessibility), and regional and national food trade planning. Such a trade-scenario model can be coupled with the regional demand and trade model (Figure 3). The key connection that characterizes the coupling is that the trade within the Nile region the trade-scenario model specifies will affect the trade between the NB countries and the rest of the world. Meanwhile, the world market, which decides the trade between the rest of the world and the Nile region, will affect the demand and trade within the Nile region. The balance of the two mechanisms will be the key component of the integrated models (Figure 3). These easily implementable, coupled models may be sufficient to address the intra-region and international trade issues, as the FAO project (Riddell et al., 2006), presented below and summarized in Appendix B, illustrates.

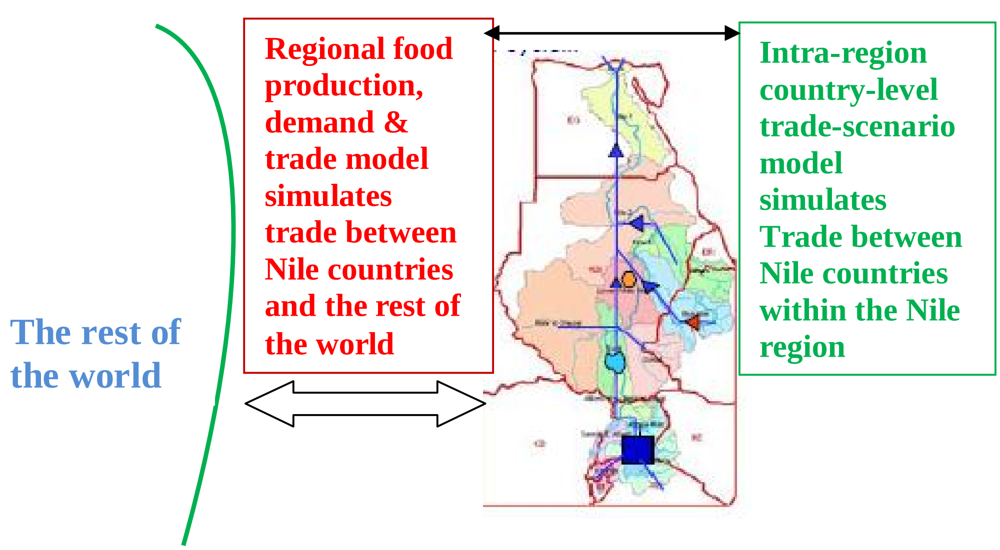


Figure 3: Coupling an inter-regional trade model with an intra-regional trade-scenario model

The trade-scenario model can follow the work that the FAO conducted on irrigation and trade development in sub-Saharan Africa (Riddell et al., 2006, see summary in Appendix B). The FAO study projected a baseline of food production (from both irrigated and rainfed), demand, and surplus or deficit by crop for each of the sub-Saharan African countries in 2030. Based on the existing trade activities between the countries within the region, trade potentials are estimated according to the potential of irrigation development. The analysis followed a premise that irrigation development will initialize and sustain food trade between sub-Saharan African countries and thus contribute to food security in the region. The analysis was conducted using a simple spreadsheet-based model. The RATP project can adopt such a model for country-level, intra-regional trade-scenario model.

3.3. Coupling agriculture models with other models in NBI-DSS

Determining a means to link the rest of the DSS modules to the crop production model and food demand and trade modules will be critical for the success of the agriculture extension of the DSS. The unique requirement for the NBI-DSS extension is to connect the proposed hydrologic components within the DSS to food trade analysis so that the virtual water trade that accompanies the food trade between the Nile countries, together with agricultural technology development strategies, can be explored to analyze food security in the region.

The coupling of agriculture models with other models in the NBI-DSS are displayed in Figure 4, including the connection between NBI-DSS and a crop production model, and a food demand and trade model. As discussed above, the crop production model can be embedded within the DSS through a tight link, while the food demand and trade model can be connected with the DSS via a soft linkage through data exchange, particularly if the selected model is operated by another institute (method 1 in Figure 4). The other method (method 2 in Figure 4) is to have a consistent model that allows food production, demand and trade to stay together in one model and then couple that model with the rest of the modules of the DSS. Option 3 described in Section 3.2 with the choice of an existing food production, demand and trade model will provide such a model. The structure of the modeling framework including the model components and connects under **method 2** is shown in Figure 5. In the following section, the coupling of the food production, demand and trade model with the hydrological models in the DSS is described with more details using IMPACT-WATER as an example.

One challenge to coupling the food production, demand and trade model with the hydrologic models lies in the different spatial units used in the two types of models. For example, IMPACT-WATER defines *food production units* (FPU) as the fundamental units used to simulate food production. A FPU represents an area (usually watersheds) in which similar agricultural production conditions occur. The FAO and other agencies use a similar unit called agro-ecological zones. The hydrologic modeling of NBI-DSS will use *hydrologic response units* (HRUs) as the spatial units. Since FPUs and HRUs are both based on watersheds or sub-watersheds, the food production, demand and trade model can be coupled with its hydrologic counterpart. It is assumed that one or an aggregation of multiple HRUs can represent a FPU. The crop production data should be prepared at the HRU or directly at FPU level.

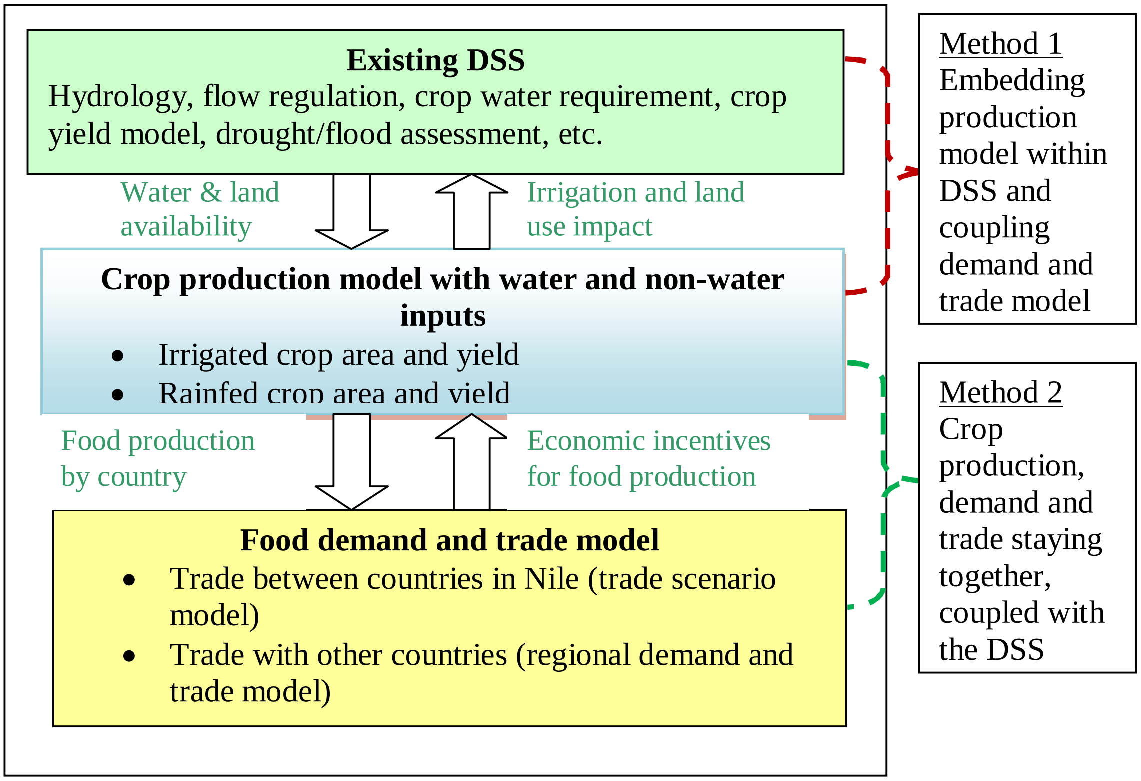


Figure 4: Integration of NBI-DSS with suggested agricultural modules

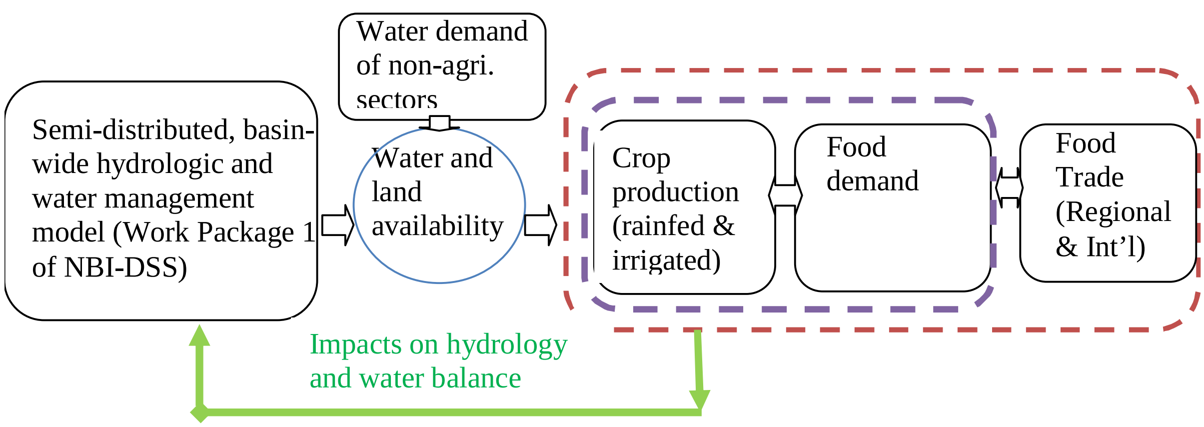


Figure 5: Model components for the extended NBI-DSS

Food demand and trade is analyzed at the *country* or *regional* level. One country or region includes one or more FPUs. The coupling of HRUs, FPUs and countries for integrated food production, demand and trade modeling is indicated in Figure 6.

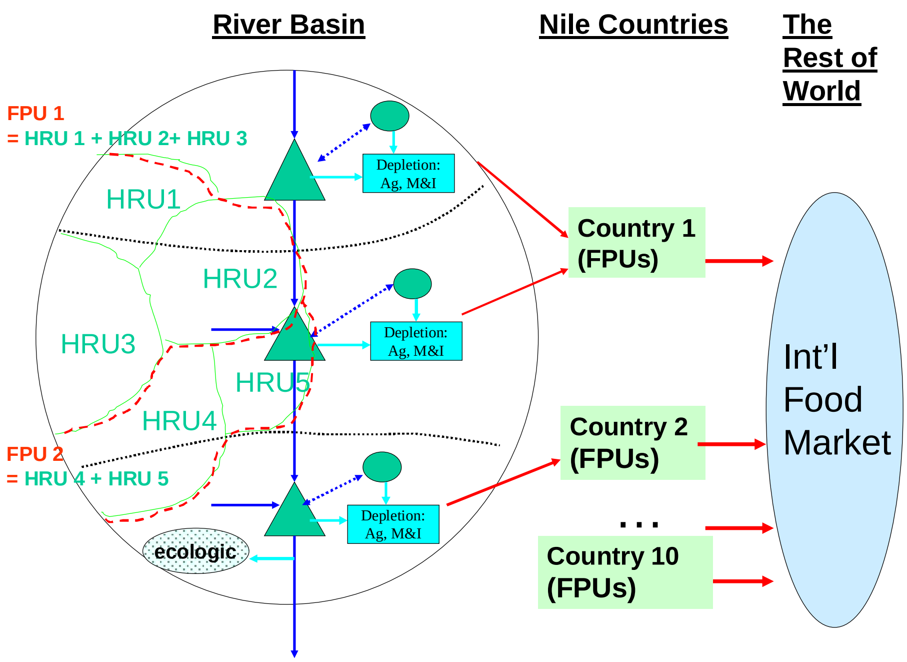


Figure 6: The coupling of HRUs, FPUs and countries for integrated food production, demand and trade modeling in the Nile region. Note that one FPU can include one or more than HRUs and one country can include one or more than FPUs.

3.4. Other model selection considerations

There are two other model selection considerations. One is related to the participation of national and local partners while the other is related to the knowledge right. It would be more effective for training and capacity building and the subsequent development of the project to have national and local partners participate in the data compilation and model development stages. The possible role of local partners in data compilation will be discussed in the ensuing data requirement section of this report. They can also take on an active role in the development of model extensions, such as the development of FPU in each country associated with water availability and water supply and food production at the FPU level and the development of the trade-scenario model, which will include a spreadsheet of food supply and demand for each of the individual countries. The NBI-DSS team (probably assisted by a regional research agency) can coordinate the work of the local partners.

Another concern is the so-called knowledge right and the convenience of using an existing model. For example, if IFPRI can provide the IMPACT-WATER to NBI-DSS and allow the DSS staff or country partners to run the model, there is no concern. However, IMPACT-WATER is a complex model that has been always been run by

IFPRI staff and has never been open to the public. There will be no problem coupling IMPACT-WATER and DSS during the project period. However, after the project, it will be problematic for IFPRI to run the model as requested without additional cost. If RATP insists that any models used for the project should be handled to the DSS group for training, decision support analysis and future development, then a new model may have to be developed. **This model could be a reduced version of an existing partial equilibrium model that simulates food production, demand and trade in a consistent context, (e.g., IMPACT-WATER), albeit with a more detailed depiction on the Nile region and simpler depiction on the rest of the world, as shown in Figure 3. This new model will belong to the NBI after the project is finished.**

Moreover, the knowledge right issue of the agricultural extension outputs should be considered together with the whole NBI-DSS development.

4. Data Requirement and Data Availability Assessments

This section follows the existing work on data processing for Nile Basin water and land management and discusses the additional data requirements for food production, demand and trade modeling, starting from existing data sources. Data are required to address the RATP objectives for this project (see the list in the introduction section) and to support the model development described above. This section describes the required data items, sources and methods for data compilation, which are related, but additional to the data compilation work specified in Work Package 2 (NBI-DSS). Figure 6 shows three categories of data that WRPM Work Package 2 covers, the new data compilation effort by RATP, and the joint effort of these two programs. All of these categories collectively form the complete database for the extended NBI-DSS. Under this context, the Nile DSS and the RATP will have a common interest in making the best data on all aspects of agriculture available.

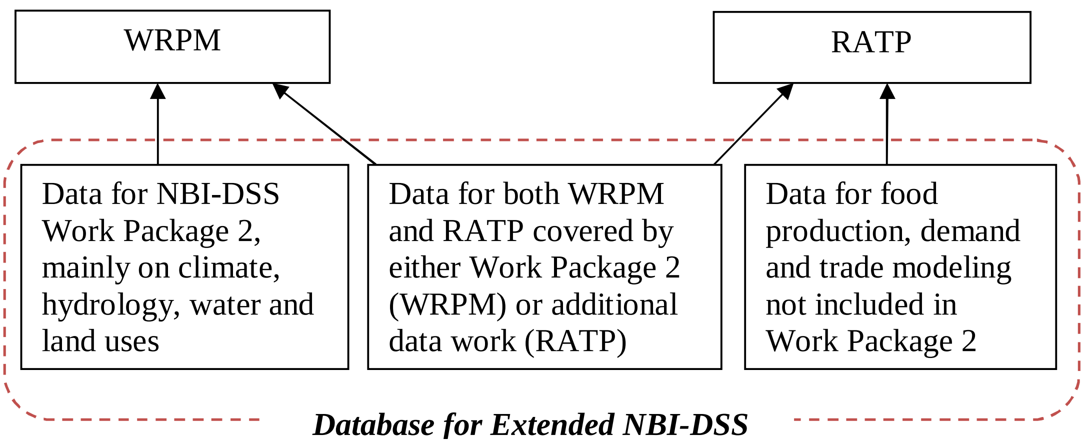


Figure 6: Data components for the extended NBI-DSS

4.1. Existing data sources

To what extent can the DSS implementation with the agriculture extension use the data from existing data sources, including the outputs from finished or ongoing projects sponsored by NBI and the open databases which are available to the public? **Several ongoing and recently finished projects collect data for agriculture development, including EWUAP, ENDIS and FAO Nile**.

EWUAP uses remote sensing and field survey data to assess land use /land cover, water consumption, soil and land suitability, and agricultural production (area and yield). It also assesses the socioeconomic factors and projects the impact of climate change on agriculture in the Nile region. However, based on a discussion with the DSS group, the outputs from EWUAP are not ready for use since they have not been verified by field surveys and additional work is needed to use the output for the delineation of the crop area map (A. Seid, personnel communication, 2009).

ENIDS focuses on the productivity assessment of irrigated agriculture, including water use efficiency, irrigation design and planning and irrigation management in the eastern Nile Basin region only. The outputs from ENDIS can provide necessary data for the RATP effort. It is possible that to extend the studies that the ENIDS project has done to Upper Nile Basin countries through RATP so that basin-wide irrigation system data can be collected.

FAO Nile develops the baseline and projections of water use and productivity in the Nile Basin region and explores basin-wide agricultural development options that could take place between now and 2030. The data outputs of the project include geo-referenced (GIS) information products integrating physical and socioeconomic data for water resources management in the basin. The products include agricultural water productivity case studies, a basin wide survey of agricultural water use, scenarios of demand for agricultural production and a transboundary hydro-meteorological monitoring network. In particular, FAO Water Report 31, *Demand for products of irrigated agriculture in sub-Saharan Africa*, is a publication related to FAO Nile. It provides a baseline and 2030 projection in of irrigated agriculture in sub-Saharan Africa, a region which includes some Nile Basin countries (see details in Appendix B). The data used by that project should be directly used for this RATP project.

However, there is a somewhat complex situation with FAO-Nile. FAO-Nile developed Nile Basin Decision Support Tools (NB-DST). Modules and data from the NB-DST have been transferred to the NBI-DSS group and are reflected in the DSS implementation plan. However, the information products from the last phase of the project are *not* ready to be released to any NBI programs at this moment in spite of their importance (probably the most important component) to the project (J. Burke, personnel communication).

Although it is hard to claim that these sources, based on existing or ongoing NBI projects, will provide ready-to-use data for the agricultural extension of NBI-DSS, one should feel confident that these projects will provide some data support for the agricultural module to be developed with the DSS. Data processing with proper coordination among multiple projects may still take a big effort, although this should be much easier than collecting all of the primary data items if those data development projects did not exist.

Besides those projects listed above, there are numerous other projects conducted for individual countries or the whole Nile Basin, including those supported by U.N. and World Bank. These projects can also provide useful data.

Another type of existing data sources that are useful for the DSS extension are the open databases, which can be downloaded online or requested without cost. For example, there are at least four datasets for land use and land cover with resolution of 30 arc-seconds, which are derived from remote sensing products IGBP, MODIS, GLC, and UMD, respectively (See Table 1 for the web access). With the support from U.S. NASA, institutes including the University of Washington and the University of Montana have been developing real-time ET using MODIS. These results should be available to the public soon (T. Tang, personnel communication).

Finally national data sources of water resources and agriculture will contribute to this project through the national partners of the NBI network.

4.2. Data processing methods

The data processing methods include 1) processing existing data items including consistence check and error filtering and other quality control procedures; 2) extracting data from remote sensed images, which usually needs verification with field data; 3) collecting data by field surveys; and 4) deriving some items from available data items using a particular program, for example the derivation of irrigated and rainfed crop area and yield from gross area and yield. The use of the various methods is given in Tables 1 and 2 with different data items.

4.3. Data requirements for agriculture production models

With respect to the additional data needed to enhance the agriculture-related modules in the NBI-DSS, WRPM, upon request from RATP, contracted an individual consultant to identify priority data types (Droogers, 2009). The outputs of this consultancy were discussed in the regional workshop organized jointly by RATP and WRPM in April 2009. Accordingly, the items with the highest priority include 1) a land cover and crop area map; 2) more realistic estimates of crop ET based on remote sensing data; and 3) some socioeconomic data including water supply coverage, cost of infrastructure, crop prices, poverty, water productivity, etc. Based on this work, Table 1 shows the data items required for crop production modeling, including the potential sources and methods for collecting and compiling the data.

The international consultants will need to work with local partners, which can take advantage of the existing national and regional network of collaboration under the various NBI programs, especially WRMP and SELSAP, including NBI Secretariat (who interacts with the decision making bodies within the countries), Regional Project Steering Committee (RPSC), National DSS offices and Stakeholders/Domain Experts consultation bodies.

The existing irrigated and rainfed crop area and yield in different countries or regions within the NB is the required data set to assess the baseline of crop production. Also, the projections of such split items will be important to assess the role of rainfed and irrigated agriculture will have in the future of the Nile Basin. FAO (2003) has produced such data at the country level based on a 1997 assessment in 1997, which was used in the FAO Water Report 31 on irrigation and trade in sub-Saharan Africa. Cai et al. (2007) published a method for splitting the irrigated and rainfed area and yield from gross area and yield using hydrologic-agronomic inputs, which could serve as a valuable reference for future work on this matter. Also Bastiaanssen and Samia (2003) presented a method to predict irrigated and rainfed yield using remote sensing data. These methods can be considered to develop split irrigated and rainfed crop cover data at a finer spatial scale and for more recent years.

4.4. Data requirements for food demand and trade models

Table 2 shows the data items required for food demand and trade modeling, including the potential sources and methods to collect and compile the data. **Compared to some data items for crop production, the data items for food demand and trade may not require a separate consulting project but rather having the selected model developer and local partner to assess the data.** This is because most of the data items just need to be collected and processed from existing sources; moreover, the model consultant may have a portion of the data from their previous work.

Besides the data for crop production and food demand and trade, other related data should be collected, including but not limited to water demand of non-agricultural sectors and data for environmental risk analysis.

Water demand of non-agricultural sectors: Baseline and projection of water demand for non-food sectors such as industry, domestic, livestock and environmental water requirement. IFPRI and IWMI have country and regional data assessment for a recent year (2005). Additional work is needed to update the data to a more recent year and to a finer spatial scale (for example, the food production units). Additional work is also needed to have a projection of the water demand of these sectors. IFPRI and IWMI’s work can be used as a basis for estimating the water demand of non-agricultural sectors as well.

Environmental risk assessment: soil erosion and salinization, water quality change, ecosystem change (e.g., wetland degradation and biodiversity change) associated with irrigation expansion and other agricultural input changes such fertilizer and pesticide uses. Some national and regional observation data, as well as international monitoring data, should be available. Both baseline and future trends should be assessed through joint work with international consultants and local partners.

Table 1: Data requirements for crop production models

Data Items	Sources	Data Compilation Methods
1. Crop land map: • Crop land vs. other land uses • Food crops vs. non-food crops • Land by crop • Irrigated vs. rainfed crop land • Current vs. future	Products IGBP, MODIS, GLC, and UMD, resolution of 1km, not differentiated by crop http://edc2.usgs.gov/glcc/ http://duckwater.bu.edu/lc/mod12q1.html http://www-tem.jrc.it/glc2000/ http://www.geog.umd.edu/landcover/1km-map/download.html Global data set of monthly irrigated and rainfed crop areas (for 26 crops) around the year 2000 http://www.geo.uni-frankfurt.de/ipg/ag/dl/forschung/MIRCA/index.html EWUAP remote sensing based land use /land cover, including irrigated land map FAO Nile and FAO statistics: FAOSTAT, AQUASTAT; FAO world soil map National and regional agricultural statistics	Integrate remote sensing and field survey data with verification by country partners Use international database and previous project outputs as a basis International consultants take lead Assess land productivity based on soil, landscape and climate attributes, which should be established as attributes of the cropland coverage Develop crop land map for a baseline year (e.g., 2008) and verify it with other selected years Assess the change of crop land in the future with urbanization development and climate change
2. Irrigated and rainfed crop area and *actual* and *potential* yield in a baseline year	FAO Nile and other FAO estimate in 1997 (data available at the country level) IWMI- PODIUM (data available at the country level) Country and regional agricultural statistics	A program can be used to split gross area and yield into irrigated and rainfed (e.g., Cai et al., 2007); remote sensing data can be used to identify irrigated and rainfed area too (e.g., Bastiaanssen and Samia, 2003) The results should be verified by local partners International consultants take lead

Table 1: Data requirements for crop production models (Continued)

Data Items	Sources	Data Compilation Methods
3. Crop evapotranspiration (ET): Potential and actual for the baseline year and other selected years	FAO CROPWAT EWUAP remote sensing-based estimate for the baseline year International database: University of Washington and University of Montana, historical and real-time assessment	International database and previous project outputs should be used as a basis. Comparison and verification crossing multiple sources should be conducted. Annual variability should be assessed. Remote sensing results should be verified with field data International consultants take lead
4. Agricultural inputs additional to water including fertilizer, pesticides, labor, machinery and seed.	FAO statistics: FAOSTAT Country and regional agricultural statistics	Country partners take lead Data should be collected for a baseline year and input change in the future should be predicted Both the amount and cost of the inputs should be collected
5. Water supply and water use Infrastructures: water storage (reservoirs), irrigation systems, and rainfall harvesting systems	ENIDS FAO AQUASTAT IWMI – PODIUM IFPRI – IMPACT-WATER	Numerous international and national assessments should be used as a basis. International consultants take lead with collaboration from national partners Water use efficiency should be assessed for irrigation systems; and effective rainfall use ratio should be assessed for rainfall harvesting systems

Table 1: Data requirements for crop production models (Continued)

Data Items	Sources	Data Compilation Methods
6. Water productivity	Challenge Program of Water and Food (CPWF), CGIAR, Basin Focus Project for Nile http://cpwfbfp.pbworks.com/	Compile existing data from other projects Water productivity can be computed by other data items such as crop yield and actual ET Water productivity values in terms of yield, calorie and profit per unit of water consumption should be compared Water productivity should be assessed for irrigated and rainfed crops, separately
7. Crop pattern and farming systems	FAO/WB (2001)	Use the FAO/World Bank report (2001) as a start and update the data with local partner
8. Agricultural planning data (used for future food production projection) including crop land and yield change, irrigation planning	Agricultural planning report from countries International report from FAO (e.g., FAO Water Report for sub-Saharan Africa and similar reports from IFPRI)	Country partners take lead with collaboration of international consultants

Table 2: Data requirements for food demand and trade models

Data Items	Sources	Data Compilation Methods
1.Population and GDP: current and future	UN and national population surveys and projections	Food demand and trade data are usually aggregated into country units for the modeling purposes Data collection mainly from existing sources for countries; light processing, compilation and verification effort might be needed; either international consultants or national partners can prepare these data items. Data will be collected for historical year series
2. Nutritional demand: current and future	IFPRI (IMPACT), FAO (FAO Nile)	
3. Calories from the various commodities: cereals, non-cereal staple food crops, other food crops, dairy and livestock products, tropical beverages	FAO Nile, FAOSTAT, IFPRI (IMPACT)	
4. Agricultural demand (calories per day) by sector: food, industry, feed, seed, waste, and discr.	FAOSTAT, IFPRI (IMPACT)	
5. Food trade (by different crop types) between NB countries: import and export food and calories	FAO Trade and Food Security Database (2005), national records	
6. Food trade (by different crop types) between NB countries and the rest of the world: import and export food and calories	IFPRI, FAO Trade and Food Security Database (2005)	
7. Crop prices - producers and consumers prices in the baseline year; international food trade prices	IFPRI, FAO Trade and Food Security Database (2005)	
8. Food aid: food and calories by crop; share of aid	IFPRI, FAO Trade and Food Security Database (2005), national documents	

Table 2: Data requirements for food demand and trade models (continued)

Data Items	Sources	Data Compilation Methods
9. Domestic supply and self-sufficiency: baseline and benchmarks, annual national or regional calorie surpluses and shortfalls by staple crop	National planning reports	Assessment based on existing international and national work is needed. International consultant should take lead with collaboration from national partners
10. Trends and national policies on food trade: policy on trade and self-sufficiency	IFPRI, national planning reports	
11. Virtual water trade	IWMI	The analysis will be based on food import/export and water consumption in the food export countries/regions. Analysis should be conducted inter-Nile Basin countries and the rest of the world and intra-Nile Basin

5. Conclusions

To address the RATP objectives for agricultural development analysis, additional work including data and models is needed beyond the WRPM's NBI- DSS Conceptual Design and Development Plan. The NBI-DSS food production function needs to be enhanced by considering hydrologic, agronomic and economic factors consistently, and new models are needed to simulate food demand and trade. Additional data items are needed to support the new modeling work.

Given the timing and funding availability for this RATP effort, a partial equilibrium model with detailed representation of the agricultural sector of the countries in the Nile region and an aggregated representation of the rest of the world is recommended. This model will integrate food production, demand and trade components. The production component will be coupled with the hydrology and water resources simulation models to be developed in the NBI-DSS to estimate water and land availability for separated irrigated and rainfed crop production. The regional partial equilibrium model will simulate the trade between the Nile countries and the rest of the world and the intra-regional trade between countries will be analyzed using a country-level trade-scenario model based on food supply, demand and surplus/deficit in individual countries.

The major data items required for the extension of the agricultural model include a map identifying irrigated and rainfed crop areas, a more realistic estimate of crop evapotranspiration, and crop yields for a baseline year. Other required data items include agricultural inputs in addition to water including fertilizer, pesticides, labor, machinery, seed, water use efficiency, water productivity, and agricultural planning data. Food demand and trade modeling will need the following additional data items: population, nutritional demand, food trade history, crop prices, self-sufficiency condition and plan, as well as food trade trends and national policies. The data items for crop production may require a separate consultant aside from the model development consultant, whereas the food demand and trade data may stay with the model development consultant together with the national partners. The existing or ongoing NBI projects and other relevant international projects will provide data support for the agricultural module to be developed within the DSS. The open cropland and crop evapotranspiration databases constitute another type of source for the data collection and compilation. Both data and model development work will encourage the involvement of local partners.

The recommended data and model development will reasonably address the RATP objectives for agricultural development analysis within the time and funding limit. It is important to note that this project will need to coordinate with the work packages underlying the NBI-DSS Conceptual Design and Development Plan, including the coordination of modeling and data compilation efforts, with special monitoring on the timing of the DSS work packages and the additional work for the agricultural extension.

References

Bastiaanssen, W. and A. Samia. (2003). A new crop yield forecasting model based on satellite measurements applied across the Indus Basin, Pakistan, *Agriculture, Ecosystems and Environment* 94 (2003) 321–340.

Cai, X., C. De Fraiture, and M. Hejazi (2007). Retrieve irrigated and rainfed crop data using general maximum entropy approach, *Irrigation Science*, 25: 325-338.

Cai, X., Rosegrant M.W., and C. Ringler (2006). *Modeling Water Resources Management at the Basin Level: Methodology and Application to the Maipo River Basin*. Research Report 149, International Food Policy Research Institute, Washington DC. pp150.

Cai, X. and M.W. Rosegrant. (2002). Global water demand and supply projections: Part 1: A modeling approach, *Water International*, 27(2):159-169.

Droogers, P. (2009), Consultant report on data requirement for agricultural extension of NBI-DSS, submitted to Water Resources Planning and Management Program, Nile Basin Initiatives.

Diao, X. and A. Nin Pratt with M. Gautam, J. Keough, J. Chamberlin, L. You, D. Puetz, D. Resnick, and B. Yu. (2005). *Growth options and poverty reduction in Ethiopia, A spatial, economy wide model analysis for 2004–15.* DSG Discussion Paper No. 20, Washington, D.C. International Food Policy Research Institute.

Dinar, A., and J. Letey. 1996. Modeling economic management and policy issues of water in irrigated agriculture.Westport, Conn.: Praeger Publishers

Doorenbos, J. and A. H. Kassam (1979). Yield response to water, U. N. Food and Agriculture Organization (FAO) Irrigation and drainage paper 33, Rome, Italy.

Neitsch, S.L., J.G. Arnold, J.R. Kiniry, R. Srinivasan, and J.R. Williams (2005). Soil and Water Assessment Tool Theoretical Documentation, version 2005. Temple, TX: Grassland, Soil and Water Research Laboratory, Agricultural Research Service. Available at: www.brc.tamus.edu/swat/doc.html. Accessed 1 November 2006.

Riddell, P.J., M. Westlake and J. Burke (2006). *Demand for products of irrigated agriculture in sub-Saharan Africa*, Water Report 31, FAO Land and Water Development Division, Rome, Italy.

Seid, A. (2009), presentation on NBI-DSS given to Joint Nile Basin Initiative (NBI), NELSAP, RATP Workshop on Decision Support System, Kigali, April 2009.

Van Dam, J. C., Huygen, J., Wesseling, J. G., Feddes, R. A., Kabat, P., Van Walsum, P. E. V., Groenendijk, P., and C.A. Van Diepen.(1997). “Theory of SWAP, Version 2.0.” Technique Document 45, Wageningen Agricultural University.

Water Resources Planning and Management Program (WRPM), Nile Basin Initiatives (NBI), (2008). Nile Basin DSS, Conceptual Design and Development Plan, PART I DSS Development Plan, PART II DSS Conceptual Design.

Willenbockel, D., Robinson, S., Arndt, C. and H. Ahmed (2008). *A Country Study on the Economic Impacts of Climate Change: The Case of Ethiopia*, report for the World Bank.

Appendices

A. An introduction to IFPRI's IMPACT-WATER
B. A summary of the FAO's report on irrigation and trade development in sub-Saharan Africa

Appendix A: IMPACT-WATER Model

The IMPACT-WATER model was originally developed at the International Food Policy Research Institute (IFPRI) and the International Water Management Institute (IWMI).

IMPACT

IFPRI's IMPACT model offers a methodology for analyzing baseline and alternative scenarios for global food demand, supply, trade, income and population. IMPACT covers 36 countries and regions (which account for virtually all the world's food production and consumption, see Boxes A.1 and A.2 in Appendix A), and 16 commodities including all cereals, soybeans, roots and tubers, meats, milk, eggs, oils, oilcakes and meals (Box A.1 in Appendix A). IMPACT is a representation of a competitive world agricultural market for crops and livestock. It is specified as a set of country or regional submodels, within each of which supply, demand, and prices for agricultural commodities are determined. The country and regional agricultural submodels are linked through trade, a specification that highlights the interdependence of countries and commodities in the 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. World agricultural commodity prices are determined annually at levels that clear international markets. Demand is a function of prices, income, and population growth. Growth in crop production in each country is determined by crop prices and the rate of productivity growth. Future productivity growth is estimated by its component sources, 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.

WATER

The WATER model projects water availability and demand that evolves over the next three decades (from a base year of 2005), taking into account the availability and variability in water resources, water supply infrastructure, and irrigation and non-agricultural water demands, as well as the impact of alternative water policies and investments on water supply and demand. The model operates at the level of 124 major basins featured with specific combinations of human and natural characteristics. Furthermore, 281 global food production units (FPU) are defined by the intersections of economic regions and river basins (Figure A0-1). For each FPU, the WATER model simulates annually and seasonally water demand and water supply based on long-term climatology and hydrology; projected water infrastructure capacities; and projected water demands of domestic, industrial, livestock and irrigation sectors based on drivers that included population and income growth, changes of irrigated areas and cropping patterns, and improvement of water use efficiencies. More detailed outputs are simulated for agriculture, including effective rainfall for rainfed crops and both effective rainfall and irrigation water for irrigated crops. Major food crops in the world are included such as rice, wheat, corn, barley and other gains, sugarcane, soybean, potato, sweet potato and roots and tubers. Split rainfed and irrigated crop area and yield are assessed for individual crops.

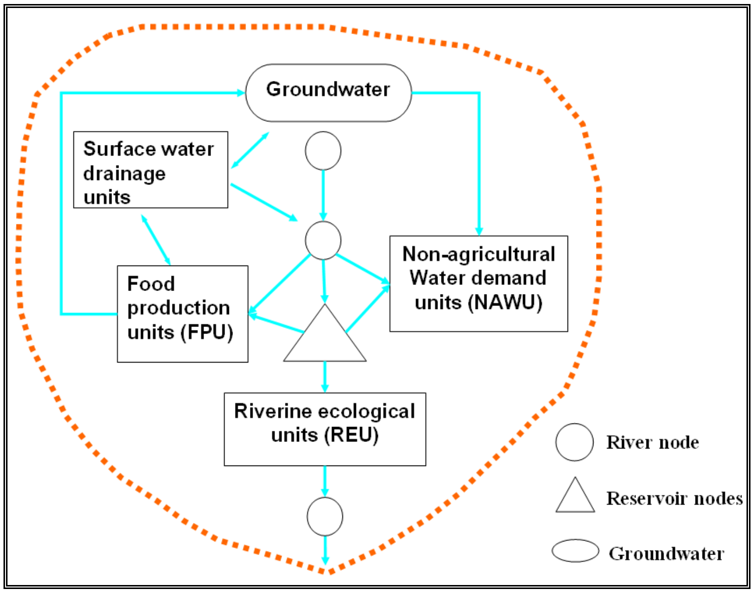


Figure A0-1: Network Representation of IMPACT-WATER

The WATER was implemented by river basin. Each basin is represented by a node-link network (Figure A0-1), which includes four types of source nodes: 1) surface water drainage units (SWDU), 2) river nodes (RD) representing reaches of the main river or tributaries; 3) groundwater sources (GWS), treated as single tanks, and 4) reservoirs (RSV) that represent the total combined storage available within the basin under study. The network also includes three types of demand nodes: 1) food production units (FPU) for irrigation water demand; 2) non-agricultural water demand units (NAWU) for municipal and industrial water demand; and 3) riverine ecological units (REU) that each has minimum flow requirements. The links in the network include: 1) streamflow paths such as river channels; 2) water supply-demand paths such as diversion channels; 3) interactions between surface and ground water; and 4) return flow paths from both water use nodes and sources nodes. Based on this network, the WATER simulates monthly water balance with storage regulation and committed flow constraints. A detailed description of the WATER is given in Cai and Rosegrant (2002). More recently Yang et al. (2009) calibrated the modeled flow discharges to available observation from both national sources and international sources (e.g., the Global Runoff Data Centre - GRDC). The calibration represents a significant improvement of the model since it has a number of water demand and supply parameters that must be estimated within plausible ranges.

Extensive data has been drawn from highly disparate databases in agronomy, economics, engineering, and public policy to support the IMPACT-WATER (Table A.1). Because of its global scope, the WATER 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, etc. The main advantage of the WATER is its integration of essential hydrologic and agronomic relationships with policy options for water resources development and management, mainly for irrigation. As such, the WATER is an effective tool for estimating water availability for both rainfed and irrigated agriculture in the context of river basins for analysis at the global scale.

Coupled WATER and IMPACT: IMPACT-WATER

WATER was coupled with the IFPRI's IMPACT model to evaluate water implication of agricultural and food production systems (Figure A0-2). In the water module, water available for food production is represented as a function of precipitation, runoff, water supply infrastructure, and socioeconomic and environmental policies. Crop water demand and water supply for irrigation are simulated, taking into account annual hydrologic fluctuations, irrigation development, growth of industrial and domestic water uses, environmental and other flow requirements (committed flow), and water supply and use infrastructure. In the food module, crop harvested areas and crop yields are calculated through crop-wise irrigated and rainfed area as well as yield functions. These functions include water availability as a variable, through which IMPACT is connected with the global WATER. The combined water-food modeling framework provides a wide range of opportunity for analysis of water availability and food security at basin, country and global scales. Many policy-related water variables are involved in this modeling framework, including potential irrigated area and cropping patterns, maximum allowed water withdrawal due to infrastructure capacity and environmental constraints, water use efficiency, water storage and inter-basin transfer facility, rainfall harvest technology, allocation of agricultural and non-agricultural uses, and allocation of instream and offstream uses. For the sake of exploring alternative futures, investment and management reform can influence the future paths of these variables, which influence food security at both national and global scales. A detailed description of the coupled models is provided in Rosegrant et al. (2002).

The food and water module are coupled spatially by a strategic cyclical scaling approach which attempts to meet in the middle of top-down and bottom-up processes and build on local scale knowledge. IMPACT is a partial equilibrium economic model and uses a top-down approach from the global food market to country and region level food production and demand analysis. WATER, as many other physical models, uses a bottom-up approach from FPU to basin. As shown in Figure A0-3, FPU is a connecting unit for IMPACT and WATER, i.e., FPU, which can be understood as sub-basin, is the fundamental unit of water simulation and it is also a fundamental unit of food production simulation. FPU is connected to "economic regions" which are the spatial units for national or regional food supply and demand analysis and are further connected to the global food market. By the structure shown in Figure A0-3, the water and food modules are combined endogenously and solved in a consistent framework. The policy incentives coming from the top (e.g., global market and national/regional food policies) drive the water allocation and food production at the bottom (e.g., FPU) (top-down), which is scaled up to the basin level and affects hydrology and ecosystems (bottom-up).

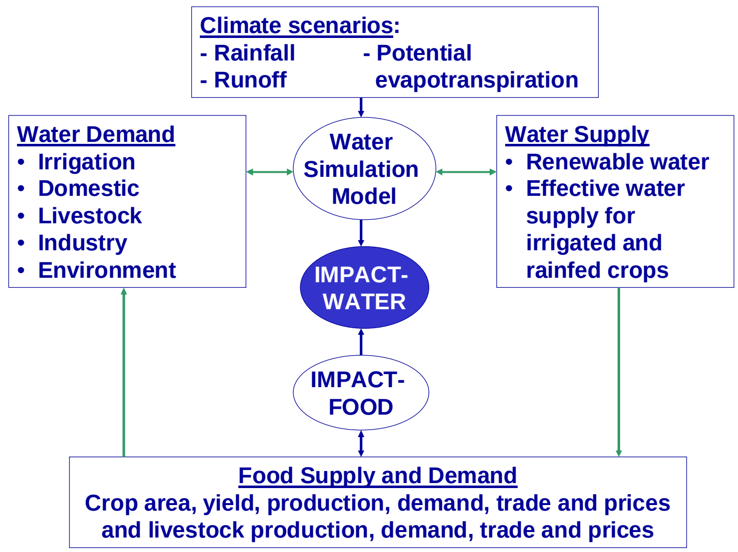


Figure A0-2: Coupled Water and Food Model: IMPACT-WATER

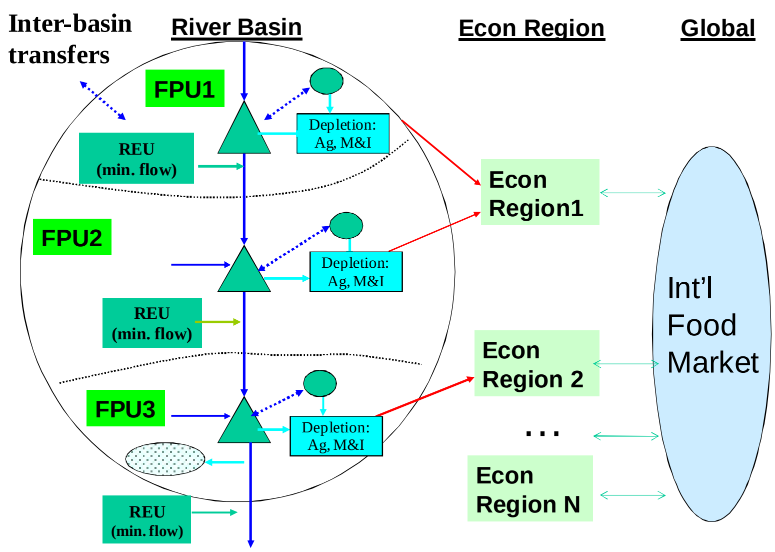


Figure A0-3: Coupling Water and Food Model Crossing Scales

Appendix A

Model Formulation and Implementation: The Business-as-Usual Scenario

This appendix is based on three methodology papers and describes the equations used in the IMPACT model and the Water Simulation Model (WSM)—in particular, the connection between the water demand and supply components and the food production, demand, and trade components is highlighted. The data requirements are also described. For IMPACT, see Rosegrant, Meijer, and Cline (2002); for WSM, see Cai and Rosegrant (2002); and for the combined IMPACT and WSM model, see Rosegrant and Cai (2000).

INTERNATIONAL MODEL FOR POLICY ANALYSIS OF AGRICULTURAL COMMODITIES AND TRADE (IMPACT)

Basic IMPACT Methodology

IFPRI's IMPACT model offers a methodology for analyzing baseline and alternative scenarios for global food demand, supply, trade, income and population. IMPACT covers 36 countries and regions (which account for virtually all the world's food production and consumption, see Boxes A.1 and A.2), and 16 commodities including all cereals, soybeans, roots and tubers, meats, milk, eggs, oils, oilcakes and meals (Box A.1). IMPACT is a representation of a competitive world agricultural market for crops and livestock. It is specified as a set of country or regional submodels, within each of which supply, demand, and prices for agricultural commodities are determined. The country and regional agricultural submodels are linked through trade, a specification that highlights the interdependence of countries and commodities in the 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. World agricultural commodity prices are determined

Box A.1—IMPACT countries, regions, and commodities

1. United States of America
2. European Union (EU15)
3. Japan
4. Australia
5. Other developed countries
6. Eastern Europe
7. Central Asia
8. Other former Soviet Union (other FSU)
9. Mexico
10. Brazil
11. Argentina
12. Colombia
13. Other Latin America (other LA)
14. Nigeria
15. Northern Sub-Saharan Africa
16. Central and western Sub-Saharan Africa
17. Southern Sub-Saharan Africa
18. Eastern Sub-Saharan Africa
19. Egypt
20. Turkey
21. Other West Asia and North Africa (WANA)
22. India
23. Pakistan
24. Bangladesh
25. Other South Asia
26. Indonesia
27. Thailand
28. Malaysia
29. Philippines
30. Viet Nam
31. Myanmar
32. Other South East Asia
33. China
34. South Korea
35. Other East Asia

1. Beef
2. Pork
3. Sheep and goats
4. Poultry
5. Eggs
6. Milk
7. Wheat
8. Rice
9. Maize
10. Other coarse grains
11. Potatoes
12. Sweet potato and yams
13. Cassava and other roots and tubers
14. Soybeans
15. Meals
16 Oils

Box A.2—Definitions of IMPACT countries and regions

WESTERN WORLD

1. Australia
2. European Union (EU 15): Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, the Netherlands, Portugal, Spain, Sweden, and the United Kingdom
3. Japan
4. United States
5. Other developed countries:
   Canada, Iceland, Israel, Malta, New Zealand, Norway, South Africa, and Switzerland
6. Eastern Europe:
   Albania, Bosnia-Herzegovina, Bulgaria, Croatia, Czech Republic, Hungary, Macedonia, Poland, Romania, Slovakia, Slovenia, and Yugoslavia

FORMER SOVIET UNION (FSU)

7. Central Asia:
   Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan
8. Other Former Soviet Union:
   Armenia, Azerbaijan, Belarus, Estonia, Georgia,
   Latvia, Lithuania, Moldova, Russian Federation, and Ukraine

DEVELOPING COUNTRIES AND REGIONS

Central and Latin America

9. Argentina
10. Brazil
11. Colombia
12. Mexico
13. Other Latin America:
    Antigua and Barbuda, Bahamas, Barbados, Belize, Bolivia, Chile, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, French Guiana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Saint Kitts and Nevis, Saint Lucia, Saint Vincent, Suriname, Trinidad and Tobago, Uruguay and Venezuela

Sub-Saharan Africa

14. Central and western Sub-Saharan Africa:
    Benin, Cameroon, Central African Republic, Comoros Island, Congo Republic, Democratic Republic of Congo, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Ivory Coast, Liberia, Sao Tome and Principe, Senegal, Sierra Leone, and Togo

(continued)

Box A.2—Continued

15. Eastern Sub-Saharan Africa: Burundi, Kenya, Rwanda, Tanzania, and Uganda
16. Nigeria
17. Northern Sub-Saharan Africa:
    Burkina Faso, Chad, Djibouti, Eritrea, Ethiopia, Mali, Mauritania, Niger, Somalia, and Sudan
18. Southern Sub-Saharan Africa: Angola, Botswana, Lesotho, Madagascar, Malawi, Mauritius, Mozambique, Namibia, Reunion, Swaziland, Zambia, and Zimbabwe

West Asia and North Africa (WANA)

19. Egypt
20. Turkey
21. Other West Asia and North Africa:
    Algeria, Cyprus, Iran, Iraq, Jordan, Kuwait, Lebanon, Libya, Morocco, Saudi Arabia, Syria, Tunisia, United Arab Emirates, and Yemen

South Asia

22. Bangladesh
23. India
24. Pakistan
25. Other South Asia:
    Afghanistan, Maldives, Nepal, and Sri Lanka

Southeast Asia

26. Indonesia
27. Malaysia
28. Myanmar
29. Philippines
30. Thailand
31. Viet Nam
32. Other Southeast Asian countries:
    Brunei, Cambodia, and Laos

East Asia

33. China (including Taiwan and Hong Kong)
34. Republic of Korea
35. Other East Asia:
    Democratic People's Republic of Korea, Macao, and Mongolia

Rest of the world (ROW)

36. Cape Verde, Fiji, French Polynesia, Kiribati, New Guinea, Papua New Guinea, Seychelles, and Vanuatu

annually at levels that clear international markets. Demand is a function of prices, income, and population growth. Growth in crop production in each country is determined by crop prices and the rate of productivity growth. Future productivity growth is estimated by its component sources, 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.

IMPACT TECHNICAL METHODOLOGY

Crop Production

Domestic crop production is determined by the 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 (nonprice) growth trend 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, a projected nonprice exogenous trend factor reflecting technology improvements, 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:

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

Yield response:

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

Production:

$$QS_{tni} = AC_{tni} \times YC_{tni}; \quad (3)$$

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)
Π	=	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

Incorporation of Water in Crop Area Functions

Reduction of crop harvested area ΔAC is calculated as:

$$\Delta AC_i = 0, \ \ if \ \ \frac{ETA}{ETM} > E^*, \ otherwise \qquad (4)$$

$$\Delta AC_i = AC_i \cdot \left[1 - \left(\frac{ETA^i}{ETM^i} / E^{*i}\right)\right] \ \ for \ irrigated \ areas \qquad (5)$$

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

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.

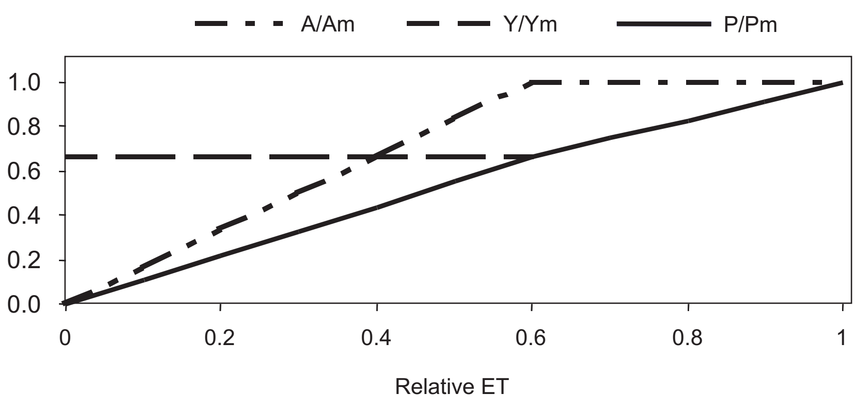
Actual crop evapotranspiration includes irrigation water which can be used for crop evapotranspiration (*NIW*) and effective rainfall (*PE*),

$$ETA^i = NIW^i + PE^i$$

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 A.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 the total available water can be totally applied in the remained irrigated area.

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 a region with arid or semi-arid climate, even in a very dry region, the harvested rainfed area did not reduce to zero. However, a general empirical relationship between rainfed harvested area and ETA/ETM is not available from the 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 (g). This coefficient for a crop is estimated based on evaluation of rainfed harvested area and effective rainfall in recent years.

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



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

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.

Incorporation of Water in Crop Yield Function

Reduction of crop yield is calculated as:

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

in which b 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 they are "penalized" if water availability in some crop growth stages (month) is particularly lower than the seasonal level. All other items have been previously defined.

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 livestock slaughter 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:

$$AL_{tni} = \alpha_{tni} \times (PS_{tni})^{\varepsilon_{iin}} \times \prod_{j \neq i} (PS_{tnj})^{\varepsilon_{ijn}} \times \prod_{b \neq i} (PI_{tnb})^{\gamma_{ibn}} \times (1 + gSL_{tni}); \tag{8}$$

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.

Demand Functions

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. The demand for other uses is estimated as a proportion of food and feed demand (Equation 15). Note that total demand for livestock consists 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

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

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

Demand for feed:

$$QL_{tnb} = \beta_{tnb} \times \sum_{l} (QS_{tnl} \times FR_{tnbl}) \times (PI_{tnb})^{\gamma_{bn}} \times \prod_{o \neq b} (PI_{tnb})^{\gamma_{bon}} \times (1 + FE_{tnb}); \qquad (14)$$

Demand for other uses:

$$QE_{tni} = QE_{t-1,ni} \times \frac{(QF_{tni} + QL_{tni})}{(QF_{t-1,ni} + QL_{t-1,ni})}; \qquad (15)$$

Total demand:

$$QD_{tni} = QF_{tni} + QL_{tni} + QE_{tni}; \qquad (16)$$

where
QD = total demand
QF = demand for food
QL = derived demand for feed
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
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.

Prices

Prices are endogenous in the model. 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 17). Consumer prices are obtained by adding the MI value to the world price and reducing it by the CSE value (Equation 18). 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 19).

Producer prices:

$$PS_{tni} = [PW_i \ (1 - MI_{tni})](1 + PSE_{tni}); \tag{17}$$

Consumer prices:

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

Intermediate (feed) prices:

$$PI_{tni} = [PW_i \ (1 + 0.5\,MI_{tni})](1 - CSE_{tni}); \tag{19}$$

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.

International Linkage—Trade

The country and regional submodels are linked through trade. Commodity trade by country is the difference between domestic production and demand (Equation 20). 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. In the 1995 base year, changes in stocks are computed at the 1994-96 average levels. Therefore, production and demand values are not equal in the base year. Stock changes in the base year are phased out during the first three years of the projection period to achieve long-run equilibrium—that is, a supply-demand balance is achieved with no annual changes in stocks.

Net trade:

$$QT_{tni} = QS_{tni} - QD_{tni}; \tag{20}$$

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

The rest of the variables are as defined earlier.

ALGORITHM FOR SOLVING THE EQUILIBRIUM CONDITION

The model is written in the General Algebraic Modeling System (GAMS) programming language. The solution of the system of 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 17, the market-clearing condition.

$$\sum_{n} QT_{tni} = 0; \tag{21}$$

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.

Determination of Malnutrition

To explore food security effects, IMPACT projects the percentage and number of malnourished preschool children (0–5 years old) in developing countries. A malnourished child is a child whose weight-for-age is more than two standard deviations below the weight-for-age standard set by the U.S. National Center for Health Statistics/World Health Organization. The estimated functional relationship used to project the percentage of malnourished children in the model is as follows:

$$MAL = -25.24 * \ln(KCAL_t) - 71.76\ LFEXPRAT_t - 0.22\ SCH_t - 0.08\ WATER_t \qquad (22)$$

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.

The percentage of malnourished children derived is then applied to the projected population of children 0-5 years of age to compute the number of malnourished children:

$$NMAL_t = MAL_t \times POP5_t, \qquad (23)$$

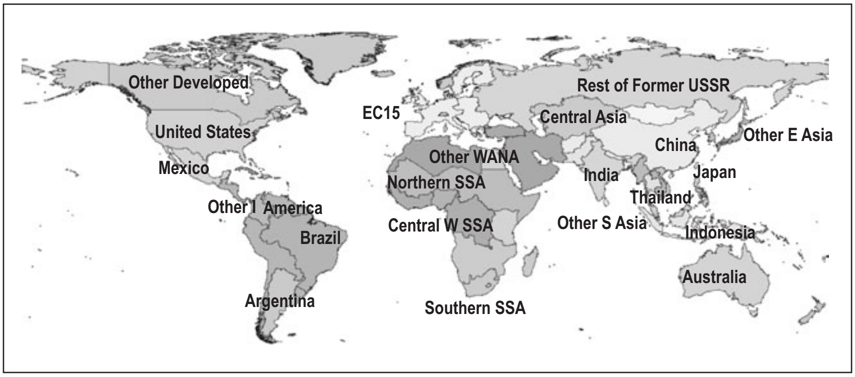
where *NMAL* = number of malnourished children, and
POP5 = number of children 0-5 years old in the population.

WATER SIMULATION MODEL

The model is based on a river basin approach. Figure A.2 presents maps of the spatial units used in the modeling exercise, including 9 basins in China, 13 basins in

Figure A.2—IMPACT-WATER spatial elements

(a) Combined basins



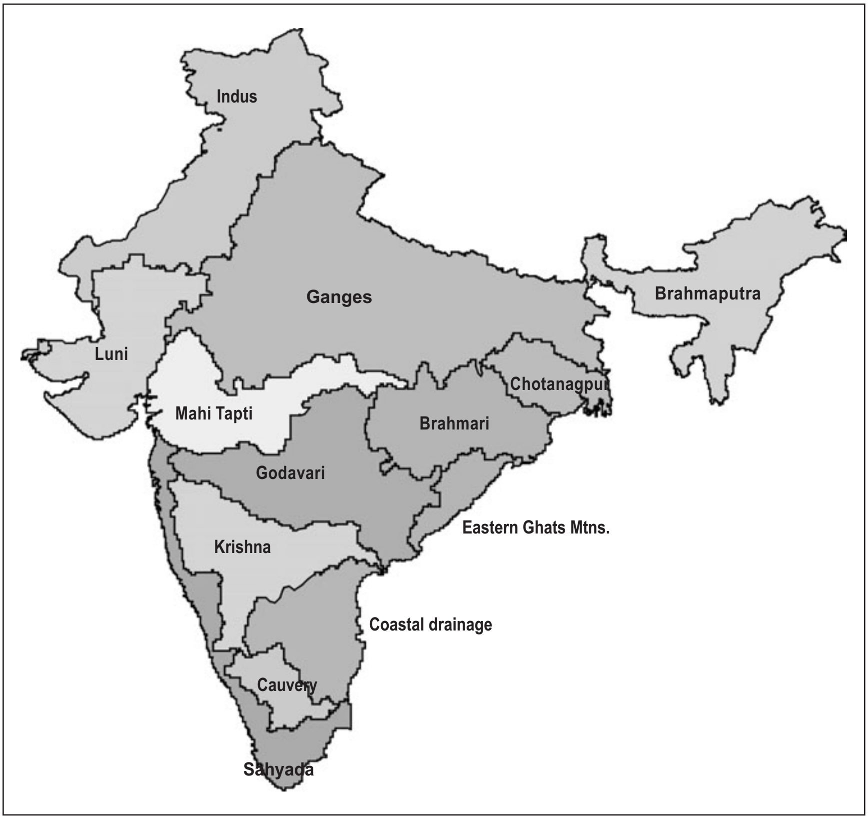
Source : Authors' assessments.

(b) Major basins in China

Source : Authors' assessments based on HPDGJ (1989) and Qian (1991).

Figure A.2—Continued

(c) Major basins in India



Source : Authors' assessments based on Revenga et al. (1998).

India, 14 basins in the United States (not pictured), and 33 "aggregated basins" in other countries or regions (See Box A.1). 1995 is treated as the base year, in which all demand and supply items are assessed and calibrated. Projections of water demand and supply are made for the 30 years from 1995 to 2025.

WATER DEMAND

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):

$$NCWD = \sum_{cp}\sum_{ct} kc^{cp,ct} \cdot ET_0^{ct} \cdot A^{cp} = \sum_{cp}\sum_{ct} ETM^{ct,cp} \cdot A^{cp} \qquad (24)$$

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:

$$NIRWD = \sum_{cp}\sum_{st} \left(kc^{cp,st} \cdot ET_0^{st} - PE^{cp,st}\right) \cdot AI^{cp} \cdot (1 + LR) \qquad (25)$$

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:

$$IRWD = NIRWD / BE \qquad (26)$$

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 is not considered in the current modeling framework.

Livestock Water Demand

Livestock water demand (LVWD) in the base year is estimated based on livestock production (QS_{lv}) and water consumptive use per unit of livestock production (w_{lv}), including beef, milk, pork, poultry, eggs, sheep and goats, and aquaculture fish production. For all of the livestock products except fish, 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 is determined as a linear function of livestock production, assuming no change in consumptive water use per unit of livestock production

$$LVWD = QS_{lv} \, . \, w_{lv} \tag{27}$$

The water demand for fish production is assumed to grow at the weighted average of livestock water demand growth.

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.

$$IWDI = \alpha + \beta \cdot GDPC + \gamma \cdot T \tag{28}$$

in which α is the intercept; β is the income coefficient, reflecting how industrial water use intensity changes with GDPC; and g is the time coefficient, mainly reflecting the change of water use technology with technology change. It is found that $\alpha > 0$, $\partial IWDI \big/ \partial GDPC = \beta < 0$, and $\partial IWDI \big/ \partial T =$ 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).

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 method 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

$$\phi_{dwd} = \phi_{pop} + \eta \cdot \phi_{gdpc} \tag{29}$$

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

Committed Flow for Environmental, Ecological, and Navigational Uses

In the modeling framework here, 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.

Demand for Water Withdrawals

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

$$DWW = DWP / DC = (IRWD + INWD + DOWD + LVWD) / DC \tag{30}$$

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:

$$DC = \rho \cdot \left(\frac{WDPDO + WDPIN + WDPLV}{WDPT} \right)^{\psi} \tag{31}$$

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.

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):

$$W = W_0 \cdot \left(\frac{P}{P_0}\right)^{\xi} \tag{32}$$

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.

Committed Flow for Environmental, Ecological, and Navigational Uses

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WATER SUPPLY

Assuming minimum environmental and ecological flow requirements as a predetermined hard constraint in water supply, we focus on the determination of offstream water supply for domestic, industrial, livestock, and irrigation sectors. Two steps are undertaken to determine offstream 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 offstream 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 A.3). 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:

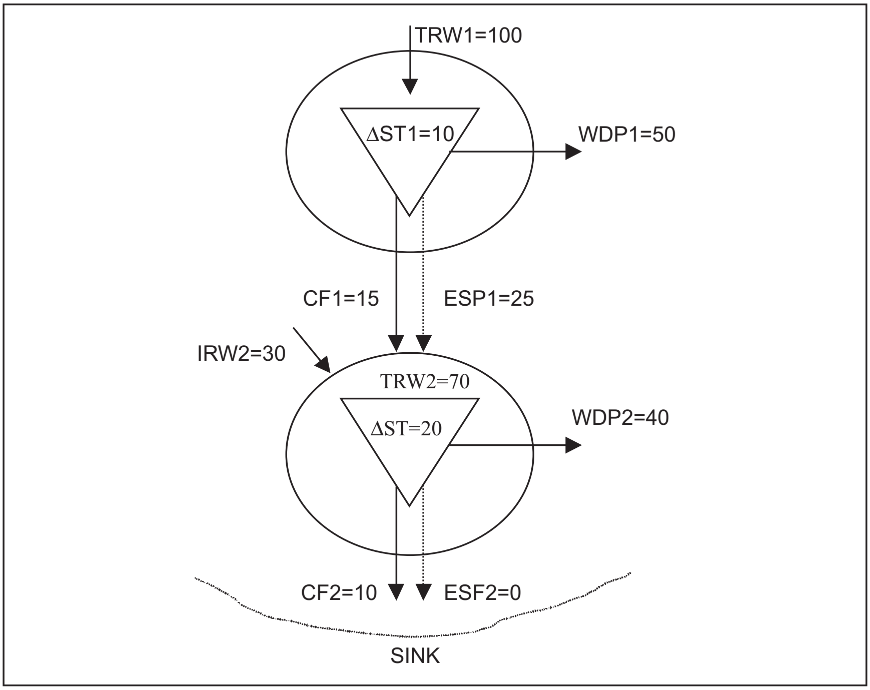
$$ST^{t} - ST^{t-1} = ROFF^{t} + INF^{t} + OS^{t} - SWDP^{t} - RL^{t} - EL^{t} \qquad (33)$$

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 desalinized water; *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:

$$\sum_{t} SWDP^{t} / DC \leq SMAWW \qquad (34)$$

Other constraints related to the items in Equation 8 include that flow release (RL) must be equal or greater than the committed instream flow; monthly reservoir evaporation is calculated based on reservoir surface area, and climate characteristics.

Figure A.3—Connected flow among river basins, countries, regions



Source : Authors' assessments.
Notes : TRW indicates total renewable water; IRW, internal renewable water; WDP; water consumption; CF, committed flow; ESP, excess spill; and ΔST, storage change.

Depletion from the groundwater source (*GWDP*) is constrained by maximum allowed water withdrawal from groundwater (*GMAWW*):

$$\sum_t GWDP^t / DC \leq GMAWW \qquad (35)$$

The estimation of the *SMAWW* and *GMAWW* in the base year (1995) is based on the actual annual water withdrawal and annual groundwater pumping in 1995 (WRI 2000). Projections of *SMAWW* and *GMAWW* are based on assumptions on future surface and ground water development in different countries and regions. In particular, the projection of *GMAWW* is based on historic pumping and potential groundwater source (measured by groundwater recharge).

A traditional reservoir operation model is developed, including all of the above relationships of natural water availability, storage regulation, withdrawal capacity, and committed flow requirements. The model is formulated as an optimization model. The model is run for individual years with month as the time period. The objective is to maximize the reliability of water supply (that is, ratio of water supply over demand, less or equal to 1.0), as

$$\max \left[\begin{array}{l} \dfrac{\sum_t (SWDP^t + GWDP^t)}{\sum_t \left(DOWD^t + INWD^t + LVWD^t + IRWD^t\right)^+} \\ \omega \cdot \min_t \left(\dfrac{SWDP^t + GWDP^t}{DOWD^t + INWD^t + LVWD^t + IRWD^t}\right) \end{array} \right] \quad (36)$$

and as can be seen, the objective function also drives the water application according to the water demand in crop growth stages (months) by maximizing the minimum ratio among time periods (12 months). The weight item w is determined by trial-and-error until water supply is distributed to months approximately proportional to monthly water demand.

Once the model solves for total water that could be depleted in each month ($SWDP^t$ and $GWDP^t$) for various off-stream uses under constraints described above, the next step is to determine water supply for different sectors. Assuming domestic water demand is satisfied first, followed in priority by industrial and livestock water demand, irrigation water supply is the residual claimant. Monthly non-irrigation water demands are calculated based on their annual value multiplied by monthly distribution coefficients. Water supply represented in depletion for different sectors is calculated as:

$$\begin{gathered} EFPFO^t = min\ (DOWD^t, SWDP^t + GWDP^t) \\ WDPIN^t = min\ (INWD^t, SWDP^t + GWDP^t - WDPDO^t) \\ WDPLV^t = min\ (LVWD^t, SWDP^t + GWDP^t - WDPDO^t - WDPIN^t)\ and \\ WDIR^t = min\ (IRWD^t, SWDP^t + GWDP^t - WDPDO^t - WDPLV^t) \end{gathered} \quad (37)$$

Finally, total water available for crop evapotranspiration (NIW) is calculated by introducing the basin efficiency (BE) for irrigation systems and discount of salinity leaching requirement, that is,

$$TNIW^t = BE\ .\ WDIR^t\ /\ (1 + LR) \quad (38)$$

TET can be further allocated to crops according to crop irrigation water demand, yield response to water stress (*ky*), and average crop price (P_c) for each of the major crops considered in a basin, including rice, wheat, maize, other coarse grains, soybeans, potatoes, sweet potatoes, and roots and tubers.

The allocation fraction is defined as:

$$\pi^{i,t} = \frac{ALLO^{i,t}}{\sum_{cp} ALLO^{i,t}} \quad \text{and,} \tag{39}$$

$$ALLO^{i} = AI^{i} \cdot ky^{i} \cdot \left[1 - PE^{i,t} / ETM^{i,t}\right] PC^{i} \tag{40}$$

in which $ETM^{cp,t} = ET_0^{cp,t} \,.\, kc^{cp,t}$ is the maximum crop evapotranspiration; π is a scaled number in the range of (0,1) and the sum of over all crops is set to equal 1. The effective water supply allocated to each crop is then calculated by

$$NIW^{i,t} = TNIWt \,.\, \pi^{i,t} \tag{41}$$

Thus, irrigation water is allocated based on profitability of the crop, sensitivity to water stress, and irrigation water demand (total demand minus effective rainfall) of the crop. Higher priority is given to the crops with higher profitability, which are more drought sensitive, and/or that require more irrigation water.

Effective Rainfall

Effective rainfall (*PE*) depends on total rainfall (*PT*), previous soil moisture content (*SM0*), maximum crop evapotranspiration (*ETM*), and soil characteristics (hydraulic conductivity K, moisture content at field capacity Z_s, and others). *PE* is calculated by an SCS method (USDA, SCS 1967), given *PT*, *ETM*, and effective soil water storage:

$$PE^{cp,st} = f \cdot \left(1.253 PT^{st^{0.824}} - 2.935\right) \cdot 10^{(0.001 ETM^{cp,st})} \tag{42}$$

in which f is the correction factor that depends on the depth of irrigation, that is,

$f = 1.0$ if depth of irrigation per application, DI, is 75mm, (43)

$f = 0.133 + 0.201 * ln(Da)$ if $DI<75$mm per application, and (44)

$f = 0.946 + 0.00073 * Da$ if $DI>75$mm per application. (45)

Depth of irrigation application is 75mm to 100mm for irrigated land, and 150mm to 200mm for rainfed land.

If the above results in *PE* greater than ET_m or *PT, PE* equals the minimum of ET_m or *PT*. When $PT<12.5$mm, $PE=PT$.

Global precipitation grids (half degree) (1961–90, monthly data) from the University of East Anglia are used to extract the total rainfall on the crop land in IMPACT regions/countries/basins. With crop-wise *ETM* and total rainfall, crop-wise monthly effective rainfall (time series over 30 years) is calculated by the SCS method described above.

Moreover, the effective rainfall for crop growth can be increased through rainfall harvesting technology. Rainfall harvesting is the capture, diversion, and storage of rainwater for plant irrigation and other uses, and can be an effective water conservation tool, especially in arid and semi-arid regions. Water harvesting can provide farmers with improved water availability, increased soil fertility, and higher crop production in some local and regional ecosystems, and can also provide broader environmental benefits through reduced soil erosion. Although improved water harvesting is often considered in connection with traditional agriculture, it also has potential in highly developed agriculture. Advanced tillage practices can also increase the share of rainfall that goes to infiltration and evapotranspiration. Contour plowing, which is typically a soil-preserving technique, should also act to detain and infiltrate a higher share of the precipitation. Precision leveling can also lead to greater relative infiltration, and therefore a higher percentage of effective rainfall. A coefficient (l, λ>1) is used to reflect the addition of effective rainfall from rainfall harvesting at various levels,

$$PE^{*cp,st} = \lambda \cdot PE^{cp,st} \tag{46}$$

MODEL IMPLEMENTATION

The model implementation procedure is shown in Box A.3. The model is applied for a monthly water balance within one year. It is run through a series of years by solving individual years in sequence and connecting the outputs from year to year. The time series of climate parameters are derived based on past 30-year historical records, 1961–90. In addition to a basic scenario that overlays the single historic time series over the 1995–2025 projection period, a number of scenarios of hydrologic time series can be generated by changing the sequence of the yearly records. Water supply uncertainty from various hydrologic levels can then be identified from the statistics of multiple hydrologic scenarios.

The ending storage of one year is taken as the initial storage of the next year, with assumed initial water storage for the base year. For those basins that have large storage, interyear flow regulation is active in this modeling framework.

Water demand for non-irrigation sectors (*DOWD*, *INWD*, and *LVWD*) is updated year by year (see Equations 27, 28, and 29) Infrastructure is updated by

Box A.3—Model implementation procedure

Base Year (such as 1995)
For each group i of (group1 .. group5)
For each individual/aggregated basin j in group i
Given water demand and supply parameters in the base year
(including estimated initial reservoir storage and external inflow)
Solve WSM for water supply
Calculate outflow from basin j
End of group i
End of all groups
Projected years (such as 1996-2025)
For each year k of (1996 -2025)
For each group i of (group1 .. group5)
For each individual/aggregated basin j in group i
Update water demand and supply parameters, including initial reservoir storage from the end of year k-1, and inflow from other units in the groups previously solved (for group 1, inflow is equal to 0)
Solve WSM for water supply
Calculate outflow basin j
End of group i
End of all groups in year k
End of all years

projections of reservoir storage, water use efficiency, and maximum allowed water withdrawal (*MAWW*).

The model is run for individual basins, but with interbasin/international flow simulated. The outflow (*RL*) from one basin becomes a source to downstream basins, which is important to many international river basins such as the Nile (Sudan, Ethiopia, Egypt, Uganda, Burundi, Tanzania, Kenya, Zaire, and Rwanda); Mekong (China, Laos, Burma, Thailand, Cambodia, and Viet Nam); Indus (Pakistan, India, Afghanistan, and China); Ganges-Brahmaputra (China, India, Bangladesh, Bhutan, and Nepal); Amazon (Brazil, Peru, Bolivia, Colombia, Ecuador, Venezuela, and Guyana); Danube (Romania, Yugoslavia, Hungry, Albania, Italy, Austria, Czechoslovakia, Germany, Russia, Poland, Bulgaria, and Switzerland); Niger (Mali, Nigeria, Niger, Algeria, Guinea, Chad, Cameroon, Burkina Faso, Benin, Côte D'Ivoire); Tigris-Euphrates (Iraq, Iran, Turkey, and Syria); and Rio Grande (United States and Mexico).

To trace the flow connection between major international river basins, we classify the 69 basins or aggregated basins (see Figure A.2) into five groups according to the flow direction between those basins:

Group 1 : without upstream inflow,

Group 2 : with upstream inflow only from group 1,

Group 3 : with upstream inflow from group 2, and with/inflow from group 1,

Group 4 : with upstream inflow from group 3 and with/ inflow from group 1 and 2, and

Group 5 : with upstream inflow from group 4 and with/ inflow from group 1, 2, and 3.

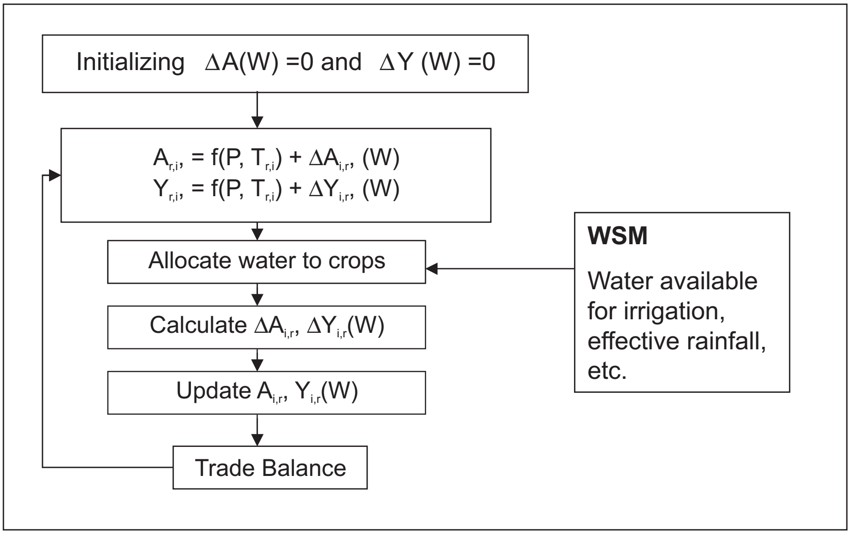
Group 1, without any inflow, is first solved; and then group 2, with inflow from one or more basins of group 1, and so on. One group is ready to be solved with inflows from all the groups that have flow release to basins in the current group. The implementation of this spatial connection allows the model to deal with water transfer between basins and water sharing in international river basins.

CONNECTING IMPACT AND WSM

The WSM calculates effective irrigation water supply in each basin by crop and by period ($NIW_{i,t}$), over a 30-year time horizon. The results from the WSM are then incorporated into IMPACT for simulating food production, demand, and trade.

Figure A.4 shows the flow chart of the IMPACT-WATER program. For each year, initially, it is assumed that there is no water shortage, $\Delta AC(W)$ and $\Delta YC(W)$ are zero, and crop area harvested and crop yields are determined based on price, labor, fertilizer, and other inputs, and technological change. Then water availability for crops is computed, $\Delta AC(W)$ and $\Delta YC(W)$ are calculated, and crop area (A) and yield (Y) are updated, based on equations 39–40. Next, crop production and stock are updated, and net food trade and the global trade balance calculated (global net trade should equal zero). If the trade balance is violated, then crop prices are adjusted, and the model undertakes a new iteration. The loop stops when net trade equals zero. Thus, crop area and yield are determined endogenously based on water availability, price, and other agricultural inputs.

Figure A.4—Flow chart of the IMPACT-WATER program



Source : Compiled by authors.

INPUT DATA

Extensive data are required for the IMPACT-WATER modeling framework. The information is drawn from highly disparate databases and requires an interdisciplinary and international collaboration of professionals in agronomy, economics, engineering, and public policy. Table A.1 describes the major data and their sources, which are classified into six classes: water supply infrastructure, hydrology, agronomy, crop production and non-irrigation water demand, and water policies. The data have been prepared for river basins (in China, India and the United States) and countries and regions. Some data have been estimated for a 30-year time horizon including precipitation, runoff, and evapotranspiration; other data are calibrated for the base year and are then determined by the model for future years (including irrigated and rainfed crop area and yield, and crop area and yield reduction from to water shortages). As indicated above and in Table A.1, some data came directly from other sources, some are treated based on other sources, and some are estimated according to related literature.

Table A.1—Input Data

Category	Details	Sources
Infrastructure	Reservoir storage	ICOLD (1998)
	Withdrawal capacity	WRI (2000); Gleick (1993)
	Groundwater pumping capacity	WRI (2000)
	Water distribution, use and recycling situation	Scenario Development Panel, World Water Vision
Hydrology	Watershed delineation	WRI
	Precipitation	CRU (1998)
	Potential evapotranspiration	Alcamo et al. (2000)
	Runoff	Alcamo et al. (2000)
	Groundwater recharge	WRI (2000); Gleick (1999)
	Committed flow	Authors' assessments
	Water pollution (salinity)	Authors' assessments
Agronomy	Crop growth stages	Rice provided by FAO; wheat and maize by CIMMYT; and other crops by USDA
	Crop evapotranspiration coefficients (kc)	FAO (1998); Doorenbos and Kassam (1977)
	Yield-water response coefficient (ky)	FAO (1998); Doorenbos and Pruitt (1979)
Crop production	Irrigated and rainfed area (baseline): actual harvested and potential	FAO (1999); Cai (1999)
	Irrigated and rainfed yield (baseline): actual and potential	FAO (1999); Cai (1999)
Non-irrigation water demand	Industry	Shiklomanov (1999) for the Scenario Development Panel, World Water Vision
	Domestic	Shiklomanov (1999) for the Scenario Development Panel, World Water Vision
	Livestock	Mancl (1994); Beckett and Oltjen (1993); FAO (1986)
Water policies	Committed flows	Authors' assessments
	Water demand growth	Authors' assessments
	International water sharing agreements	Authors' assessments based on WRI (2000)
	Investment	Authors' assessments

Source: Compiled by authors.

Notes: CIMMYT indicates the International Wheat and Maize Improvement Center; FAO, the Food and Agriculture Organization of the United Nations; ICOLD, International Commission on Large Dams; WRI, World Resources Institute; and USDA, the United States Department of Agriculture.

GIS and other methods are used to treat these parameters. For example, original hydrologic data are represented in a grid, and a GIS program is used to extract the value and aggregate grids into IMPACT spatial units. Other data are given in smaller spatial units (such as for China, the United States, and districts in India), and the GIS program is applied to overlay the data at the smaller scales. Many other intermediate programs were developed to estimate the required data or transfer the original data to the format required by the models. Data required for agricultural modeling by IMPACT are described in Rosegrant et al. (2001).

Table A.2—Water demand and supply data

Region/ Country	Average annual precipitation (mm)	Average annual ET_0 (mm)	Internal water (km^3)		Inflow (km^3)		
			average	variance	average	maximum	minimum
United States							
Ohio and Tennessee	1,160	970	235.3	48.2	148.0	178.0	107.0
Rio Grande	405	1,795	9.7	4.0	0.0	0.0	0.0
Columbia	596	1,005	270.8	34.0	0.0	0.0	0.0
Colorado	268	1,452	32.1	8.4	0.0	0.0	0.0
Great Basin	549	947	44.0	10.9	0.0	0.0	0.0
California	558	1,685	101.3	38.2	0.0	0.0	0.0
White-Red	827	1,360	127.9	46.7	0.0	0.0	0.0
Mid Atlantic	1,072	871	252	38.3	0.0	0.0	0.0
Mississippi							
Downstream	1,278	1,216	116.5	31.6	95.0	105.0	50.0
Upstream	826	848	191.2	40.1	0.0	0.0	0.0
Great Lakes-Red	760	768	202.8	18.6	0.0	0.0	0.0
South Atlantic-Gulf	1323	1365	285.4	58.4	0.0	0.0	0.0
Texas-Gulf	824	1512	78.1	25.3	0.0	0.0	0.0
Missouri	592	996	150.6	41.7	0.0	0.0	0.0
U.S. average/total	**n.a.**	**n.a.**	**2,098**	**444**	**243**	**283**	**157**
China							
Huaihe	880	957	93.8	7.8	0.0	0.0	0.0
Haihe	503	1,196	42.3	9.1	0.0	0.0	0.0
Huanghe	529	1,099	71.6	16.0	0.0	0.0	0.0
Changjian	1,236	945	908.1	79.9	0.0	0.0	0.0
Songliao	530	877	198.9	24.4	0.0	0.0	0.0
Inland	235	1,035	59.9	8.7	0.0	0.0	0.0
Southwest	1,707	1,074	702.8	53.7	0.0	0.0	0.0
ZhuJiang	1,513	1,118	407.6	54.3	0.0	0.0	0.0
Southeast	1,611	1,075	145.2	34.2	0.0	0.0	0.0
China average/total	**n.a.**	**n.a.**	**2,630**	**288**	**0**	**0**	**0**
India							
Sahyadri Ghats	1,095	2,311	109.7	16.9	0.0	0.0	0.0
Eastern Ghats	1,133	2,259	15.7	3.8	0.0	0.0	0.0
Cauvery	964	2,291	14.4	4.0	0.0	0.0	0.0
Godavari	1,030	2,242	111.4	26.3	0.0	0.0	0.0
Krishna	847	2,322	90.6	15.5	0.0	0.0	0.0
Indian-Coastal-Drain	905	2,328	28.6	7.9	0.0	0.0	0.0
Chotanagpur	1,449	2,065	42.6	10.0	0.0	0.0	0.0
Brahmari	1,322	2,133	105.3	17.3	0.0	0.0	0.0
Luni River Basin	641	2,290	24.5	11.2	0.0	0.0	0.0
Mahi-Tapti-Narmada	1,007	2,205	87.1	19.4	0.0	0.0	0.0
Brahmaputra	2,453	1,320	624.4	62.9	290.5	348.5	254.0
Indus	737	1,799	75.6	9.7	174.3	209.1	152.4
Ganges	1036	2,035	391.3	57.7	116.2	139.4	101.6
India average/total	**n.a.**	**n.a.**	**1,721**	**263**	**581**	**697**	**508**

(continued)

Table A.2—Continued

Region/ Country	Average annual precipitation (mm)	Average annual ET_0 (mm)	Internal water (km^3)		Inflow (km^3)		
			average	variance	average	maximum	minimum
European Union 15	1,013	783	1,124.6	128.9	0.0	0.0	0.0
Japan	1,512	798	274.3	56.8	0.0	0.0	0.0
Australia	512	1,580	548.1	282.9	0.0	0.0	0.0
Other developed countries	1,138	1,128	4,395.9	132.1	0.0	0.0	0.0
Eastern Europe	697	705	264.7	66	112.0	0.0	0.0
Central Asia	288	1080	204	45.6	20.0	0.0	0.0
Rest of former Soviet Union	512	661	4,005.9	241	222.0	330.0	144.0
Mexico	1,306	1,781	325.8	49.8	2.5	5.0	0.3
Brazil	1,740	1,873	6,454.9	441.3	1,900	2,350	1,600
Argentina	875	1,407	389.6	112.4	623.0	1,410.0	343.0
Colombia	2,233	1,517	1,627.8	105.6	0.0	0.0	0.0
Other Latin America	1,592	1,708	4,371.9	200	0.0	0.0	0.0
Nigeria	1,077	2,280	260.3	32.9	43.7	69.0	23.4
Northern Sub-Saharan Africa	832	2,399	610.2	114.5	224.8	352.0	70.0
Central and western Sub-Saharan Africa	1,552	1,982	2,479.1	179.7	313.5	420.0	248.3
Southern Sub-Saharan Africa	960	2,104	1,125.9	125.1	0.0	0.0	0.0
Eastern Sub-Saharan Africa	1,114	2,093	327.6	66.1	24.5	80.0	10.0
Egypt	57	1,621	2.3	0.7	58.8	184.0	27.5
Turkey	586	1,304	114.9	31.9	0.0	0.0	0.0
Other WANA	417	1,605	77.4	16.9	50.5	143.0	21.5
Pakistan	424	1,952	110.5	26.3	186.0	372.0	55.8
Bangladesh	2,222	1,787	166.5	22	1,167	2,334	350.1
Other South Asia	1,257	1,467	279.1	15.7	31.2	62.0	6.2
Indonesia	2,643	1,819	2,005.3	236	0.0	0.0	0.0
Thailand	1,506	2,323	229.1	25.9	120.0	240.0	36.0
Malaysia	2,792	1,790	399.3	47.6	0.0	0.0	0.0
Philippines	2,342	1,756	199.6	29.1	0.0	0.0	0.0
Viet Nam	1,913	1,517	219.6	24.2	546.0	1092.	163.8
Myanmar	2,105	1,976	942.1	107	110.0	220.0	33.0
Other Southeast Asia	1,995	2,150	345.7	24.3	420.0	840.0	126.0
South Korea	1,358	952	43.8	12	2.5	5.0	0.5
Other East Asia	891	824	136	15	7.7	14.0	2.0
Rest of the world	1,622	1,504	685.3	72.4	0.0	0.0	0.0

Sources: Compiled by authors based on WRI (1998), Shiklomanov (1999), HPDGJ (1989), Qian (1991), NIHWR (1998), and CMWR (1990-98) for river basins in China; USGS (1998) for river basins in the united States; and ESCAP (1995) and IMWR (1998-2000) for river basins in India.

Notes: AGR indicates the fraction of agricultural water consumption; DC, the consumption coefficient (th ratio of consumption over withdrawal); and BE, basin efficiency.

Aside from some parameters already presented above, Table A.2 summarizes the water demand and supply parameters. (These items have all been previously described.

NOTES

1. For i belonging to livestock, QL and QE are equal to zero.

Appendix B:

A Summary of FAO Water Report "Demand for products of irrigated agriculture in sub-Saharan Africa" by Riddell, Westlake and Burke

Prepared by Ximing Cai, University of Illinois, July 2009

This study conducted by FAO represents a comprehensive study that addresses food production, demand and trade in sub-Saharan Africa, which includes the whole Nile Basin region. The premise of the study is that irrigation development will initialize and may sustain food trade between the sub-Saharan African countries and thus contribute to food security in the region. This study is an important reference for the RATR effort and can be used as a starting point for food trade analysis in the NB region. This document provides a summary of the FAO study and discusses the relevance of the study to the RATP effort.

Food production in Sub-Saharan Africa mainly depends on rainfed agriculture, which however is highly volatile. The concentration of inputs around irrigated production offers a means to service specific export-market demand. Sustained investment in both rainfed and irrigated production is necessary, but approaches and patterns of investment will have to innovate in order to overcome the disappointments of the past. The FAO study attempts to quantify how much of this production shortfall could be met by irrigated production. The study is based on projections derived from the analysis prepared for *World agriculture towards 2015/2030: an FAO perspective* (FAO, 2003). The study has attempted to establish a perspective on the demand for irrigated production in the sub-Saharan Africa region with projections to 2030.

The report first describes the existing and potential irrigated production under the particular conditions of irrigation in the region. Then using FAO's data sources from existing and ongoing projects, a baseline obtaining in the period 1997–99 is presented, based on a statistical analysis of the demand, supply and scope for increased irrigated production, expressed *inter alia* in terms of: (i) self-sufficiency ratios (SSRs) for a range of commodity groups; (ii) water and land resources; (iii) current irrigation; and (iv) reported yields under irrigation for a wide range of crops and locations. Following the baseline description, the impacts of irrigation in terms of the potential marketing and processing advantages and social benefits, the issues of yield growth, and the implications for the natural resource base are examined. Furthermore, to assess the reality of food markets in the region, the report reviews relevant international agreements and then presents an analysis of the broad market prospects for the main cropping groups. Implications are provided on the scope for regional and intraregional trade in maize, wheat and rice, which are considered to be the crops whose production may be justified by an irrigation-oriented approach. Finally recommendations for an appropriate irrigation sector response are presented.

<u>*Potential of irrigation*</u>: Although Sub-Saharan Africa continues to face significant supply problems with respect to all commodity groups except beverages and industrial crops, the supply challenge is not homogeneous when considered at the regional and

national levels. The differences may be explained by differences not only in natural resource endowments but also in terms of skills, aspirations, the status of any existing national irrigation sectors and agriculture, land-use and trade policies. The vast irrigation potential of sub-Saharan Africa remains largely untapped, and where irrigation is already taking place, significant gains can be made in terms of improving the yields and the sophistication of the farming systems. Thus even all other things being equal, irrigation has an obvious role to play in meeting existing demands. However, in order to establish the demand for water and any comparative advantage in specific irrigated crops, it is necessary to appreciate the impacts of irrigation on the supply chain in the context of the environmental and cultural diversity of sub-Saharan Africa. There is potential for irrigation to close the large and projected widening gap between sub-Saharan Africa calorie consumption and production. Specifically, there are huge national markets in rice, notably the Gulf of Guinea that could be satisfied by domestic production if consumer prices and quality could compete with imports. Rice either requires irrigation or has significantly higher yields when irrigated and sub-Saharan Africa is no exception. Where wheat and maize are grown or can potentially be grown, they also generally have much higher and more reliable yields when produced on irrigated land.

Potential of market Within all of sub-Saharan Africa, the only country with a major surplus of maize, wheat or rice in the period 1997/99 was South Africa with an estimated average of 990,000 tonnes of maize per year. Measured in calories, the demand for staple food crops exceeded supply in every sub-Saharan Africa country including South Africa. FAO projections to 2030 show these deficits increasing across sub-Saharan Africa and trend data show food import bills rising. Thus, in the absence of very substantial increases in production, there will be little potential for regular trade in basic foodstuffs between sub-Saharan Africa countries. However, there will be potential for crossborder trade where natural markets span borders and for opportunistic trading when good rainfed growing conditions and irrigation development lead to exceptional national surpluses. While the impact on food availability of such surpluses is to be welcomed, they often lead to substantial price instability, both in the country achieving the surplus and in other countries in the region. The potential for this has been demonstrated recently in South Africa, where maize prices both domestically and in neighbouring Swaziland have been highly unstable, as South Africa has swung between surplus and deficit. The apparent grain deficits in the Niger in 2005 were also as a result of regional price volatility, not absolute regional scarcity of grain. Indeed, the harvest in coarse grains (sorghum and millet) in neighbouring Nigeria had been good in 2004/05 with Nigeria exporting to the Sudan through the World Food Programme.

Complexity of demand: It is not possible to be highly specific about the demand for irrigated production *per se* beyond broadly concluding that the most pressing demand is in cereals, notably maize, rice and wheat, for which both rainfed and irrigated production present options. Despite this, only rice, sugar and vegetables offer immediate targets for new investment given current irrigation costs and world prices for higher quality rice. The economic factors and incentives to concentrate production through irrigation exist in terms of pure calorie demand. While this may be no surprise, current trends in commercial food import bills indicate that public and private initiatives in irrigated development are highly lagged, with real growth rates in irrigated areas averaging only 0.9 percent/year and with a continuing legacy of non-performing irrigation schemes. Indeed, in many specific cases, growth rates are actually negative. The prime conclusion is that the sub-Saharan Africa region can obviate the need for expansion of its irrigated areas simply by closing yield gaps on production from existing equipped irrigated areas. However, while an agronomic solution in the short to medium term can offset the costs of expanding the irrigated area, investment in the post-harvest and value-added chain will remain a priority. As far as the natural resource base is concerned, while land and water do not pose technical limits at a regional level, they can be a local absolute constraint. Even so, where this is the case, these constraints can be exacerbated by institutional and/or regulatory shortcomings rather than a lack of resources or areas equipped for irrigation.

It is the systemic factors in the irrigated subsector – high costs, rising labour rates and the impact of HIV/AIDS, and the overall structure of the industry – that mean it is not geared to produce high volumes of high-quality cereals where they are needed. For example, the small artisanal production centres , notably for rice in the Gulf of Guinea and Sudano-Sahelian regions, cannot produce to the scale and quality demanded/ preferred by urban dwellers. At the same time, the incentives for commercial growers to produce staples under irrigation in the South and Eastern regions are generally limited by the need to do this as part of a rotation with a high-value cash crop (not least to obtain credit or to be eligible for inputs such as fertilizer).

It is difficult to see how large-scale, low-margin cereal production can generate the service fees sufficient to guarantee service cost recovery unless indirect subsidies are factored into farmgate prices that are supported by governments as buyers of first resort. Some central costs can be mitigated by participatory irrigation management; but this has not proved to be the universal panacea that was once hoped. Beyond economic and technical considerations, the overall picture is one of a general failure to structure the irrigated subsector to balance and buffer the volatility of the rainfed sector in a consistent fashion (to maintain domestic producer and consumer price stability) while also developing regional and export markets in both irrigated staples and cash crops.
This strategic failure to match the structure of the irrigated subsector to changing demand patterns in sub-Saharan Africa may not always be overcome despite rising demand and rising food import bills. Some absolute issues such as agroclimatic suitability cannot be addressed through more public expenditure or private investment. However, others such as the relative involvement of public and private agents or the provision of marketing chains can be addressed where political capital is adequate. What then can be offered as recommendations to at least improve the structure of irrigated production?

Other factors: The market growth depends not solely on crop production and demand. At present there is very little evidence of publicly funded irrigation assets performing as designed. At the same time, most of the small scale private irrigation is not organized efficiently to supply markets and sustain growth. At a regional level, there is a fundamental structural mis-match between styles of production and the character of national and regional demand. This can be expected to seriously hinder an appropriate regional response. Transport and marketing costs for bulk production are high and with very little value-added processing, the scope for regional markets development will be limited unless spatial and value chain ‘friction’ is overcome. It appears very easy for imported grain products to enter the regional hinterland, but very difficult for domestic production to get out.

<u>*Recommendations from the study*</u>:

- Ensure that the scaling is right. This applies to the scaling of small-scale irrigation initiatives to address local demand as much as to identifying profitable irrigated farming systems. Matching the structure of the irrigated subsector to the structure of demand is the key. It is crucial to be clear about the style of irrigation that will make an impact, and the scale at which producers will enter the market. This implies a regional response rather than a set of individual national responses.
- Realize the value of the existing asset base where supply chains, storage and processing can be concentrated to address specific, well-identified markets. The conditions conducive for scaling up irrigated production (including the incentive for both small-scale and large-scale private investment) will take time to coalesce.
- Prior to new public expenditure or the encouragement of private investment, ensure that the full implications of price impacts are taken into account.
- Assess the costs of supplying into crop markets sensibly. In addition to financial costs, there will also be significant political costs accruing to the kind of changes necessary to establish the enabling environment for successful, sustainable irrigation. These will involve: the devolution of planning and decision-making functions to civil society; the commercialization (in the sense of efficient, costeffective and transparent service delivery) of public services in the sector; the deregulation of markets; the attraction of private investment; and the establishment of reliable water rights systems and allocation mechanisms.

With these provisions in mind and the political and institutional constraints notwithstanding, irrigated production opportunities in sub-Saharan Africa can be realized where natural resources and markets coincide. However, this can only be achieved through focusing a great deal more attention on production costs, price formation, effective water allocation mechanisms, economically efficient water use, and strong, responsive institutions.