Initial 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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Acknowledgements

Executive Summary

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
GEM	General equilibrium models
HRU	Hydrologic Response Units
IFPRI	International Food Policy Research Institute
IWMI	International Water Management Institute
IWRM	Integrated Water Resources Management
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	Term of References
WB	World Bank
WRPM	Water Resources Planning and Management

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1. Introduction

The Water Resources Planning and Management (WRPM) Project, a working force of the Nile Basin Initiative (NBI), plans to develop a decision support system (DSS) for the Nile Basin (NBI-DSS), which is one of four components of the WRPM under the Shared Vision Program (SVP). The NBI-DSS will 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*". Ultimately the DSS is intended to improve the overall net benefit from water resources management in the Nile and support the regional socioeconomic development (WRPM-NBI, 2008).

The Regional Agricultural Trade and Productivity Project (RATP) under the Nile Equatorial Lakes Subsidiary Action Program (NELSAP) plays a leading role in NBI's core agricultural functions and food security vision. RATP aims at enhancing the foundation for knowledge-based water resource management and building capacity to support more productive and economically sustainable agriculture in the Nile. Specifically RATP intends to work with WRPM to develop agriculture components, which will be integrated with the planned activities for the NBI-DSS development. The enhanced NBI-DSS is expected to have a capability of the prediction of food production, demand and trade in the Nile Basin (NB) region. The RATP-DSS Workshop in April 2009 identified the following objectives for the NBI-DSS agriculture enhancement:

- *Present and future food demand & supply and their effect on the changes in land and water use*
- *Irrigated and rain-fed agricultural expansion and intensification potential and its impact on the basin water balance*
- *Options to improve productivity levels under irrigated and rain-fed systems*
- *Droughts and floods impact on food production*
- *Opportunities and challenges for agriculture products markets*
- *Impact of other sectors (urban, industrial, etc.) on agriculture*

The successfulness of the effort will depend on effective agricultural production, demand and trade models and reliable data sets. To support the NBI-DSS extension, this consultancy work conducts the following tasks for NELSAP/ RATP:

- Describe the current agricultural module in the Nile Basin DSS.
- Describe the existing regional agricultural models: how they are structured (major modules), what questions they address and how detailed they are.
- Assess the readiness of the data base for each selected model to be applied in the Nile Basin countries.
- For each selected model, prepare the major adjustments to be made in (i) methodology; (ii) modeling blocks; and (iii) data base 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 by RATP during the implementation phase (Nov. 2009 – June 2012)

These tasks basically follow up the outcomes of the RAPT-DSS Workshop in Addis Ababa, 2009 and they also refer to the Nile Basin DSS documentation and other relevant project outcomes. This report describes the outputs from these tasks, with an emphasis on the model and data assessment and a roadmap to carry out the suggested activates.

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, evaluate the impacts of the changes from the ecological, economic and social aspects, and support decision making based on the impact assessment. The consequence of the decision together with natural changes (e.g., climate variability and climate change) will initialize another round of modeling analysis in the manner of adaptive management. The DSS will include an information management system, a regional river basin planning model, and a suite of analytical tools to support multi-objective analysis of investment alternatives, as well as the core national tools to assist in 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 potentials, rainfed and irrigated agricultural production, floods control, drought management, watershed and sediment management and navigation.

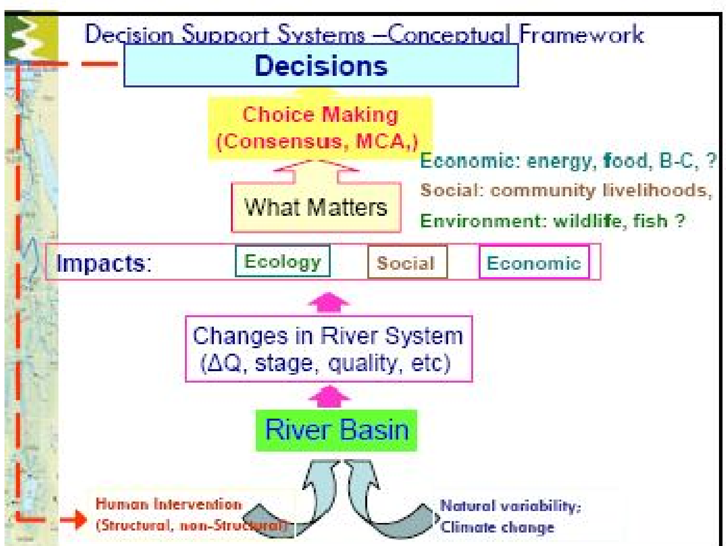

Figure 1: The conceptual framework of the NBI-DSS (After Seid, 2009)

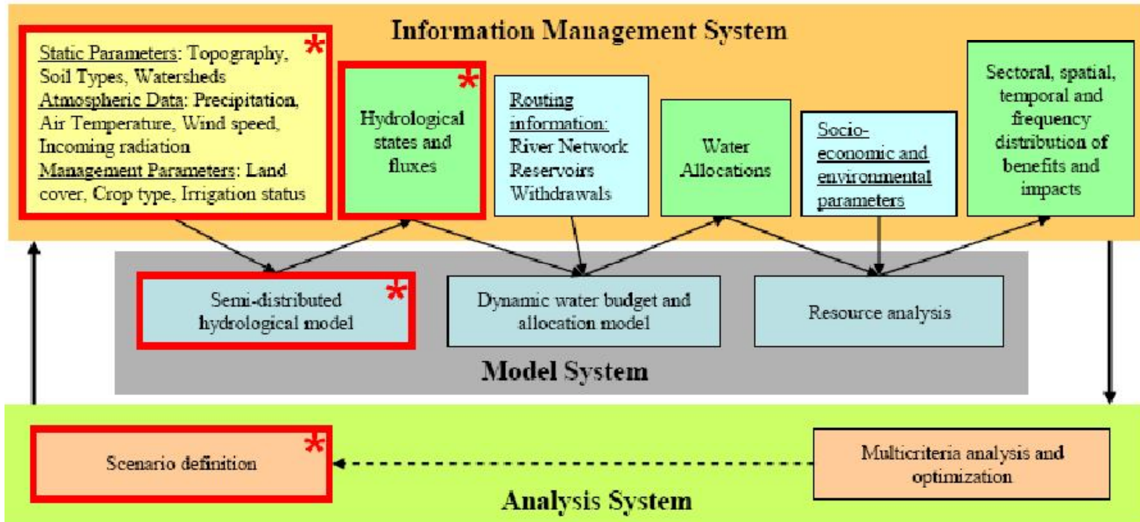

Figure 2: The Schematic of the NBI-DSS (After Seid, 2009)

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

- Work Package 1: Software Development and System Implementation, consisting of detailed design update and technical specification including a systems ontology and the definition of model specifics.
- Work Package 2: Data Compilation, Processing and Pilot Test Applications, being executed in parallel but independently, involving end users and the NBI DSS core and national teams.
- Work Package 3: Supervision and Monitoring, coordinating/synchronizing the parallel activities and organizes quality assurance processes.

For Work Package 1, WRPM has already made a contract with DHI, an international consulting firm in Denmark, especially for the development of a semi-distributed watershed hydrologic model including reservoir and groundwater storage regulation and water withdrawals for human uses. The model is based on a node-link network that depicts the upstream-downstream relation, including the various water sources nodes (catchments, groundwater, rainfall harvesting, etc.) and water demand nodes (municipal and industrial, agricultural, hydropower, navigational, ecological, etc.) As common watershed hydrologic models, hydrologic response units (HRUs) will be used as the fundamental spatial units to simulate the hydrologic processes. **Among the essential physical processes, the estimate of soil moisture and evapotranspiration flux is the key for crop growth from the perspective of water. Reservoir and aquifer storage and stream flow, which are explicitly simulated in the model, determine irrigation water availability**.

For Work Package 2, WRPM has prepared a draft request for proposals (RFP) on data collection for the DSS implementation. The draft is with the World Bank (WB) for clearance. Although many items are directly related to the RAPT effort on agriculture extension, 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 form the Nile Basin. Examples of such data include hydro-meteorological time series, soil maps with hydrologic attributes, data on current uses of water in the basin and system data (water infrastructure, etc), basic socio-economic data, such as demography and distribution, etc. It should be noted that the socio-economic data will be directly useful for food demand and trade modeling that will be included in the agricultural extension.

For Work Package 3 on project supervision and monitoring, it seems that the NBI-DSS implementation plan (Concept Design and Development Plan) led by WRPM will go with the RAPT effort on agricultural extension. The DSS group has developed documents for the three work packages and the activities in Work Package 1 are already under work with a consultant firm. **As long as the RAPT TORs are released, the two parts will be coordinated in a consistent context in order to develop the NBI-DSS with effective agricultural functions.**

2.2. Agricultural modules of the NBI-DSS

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

- What are the crop water requirements for major growing areas in the Nile Basin? What are water consumption patterns (by country/region) and trends?
- What are the impacts of alternative developments on system wide water balance?
- Which parts of the basin rely on rain fed agriculture (spatial information)? And which parts rely on irrigation?
- What are the trends in the development/expansion of each? What would be the impacts on water use/availability patterns in future?
- How much water is required for the specific irrigation developments in question? What is the tradeoff with other uses (by sector)
- What are the impacts of rainfall variability on rainfed agriculture?

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
- Time series data on hydrology, meteorology

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

- Crop water requirements estimation
- Crop yield response to water (mainly irrigated agriculture)
- Impact of different land use/cover types on water balance (runoff generation)
- Water balance model: Impact of consumptive use on water balance; impacts on existing developments

The crop yield model is a yield-water model which follows the method of FAO CROPWAT. The method depends on the estimate of potential and actual crop evapotranspiration (ET).

The data and modules proposed in the NBI-DSS development plan are necessary for assessing crop production from the water perspective. However the data and modules are not sufficient to assess crop production in a comprehensive manner, because crop production depends on both water and non-water inputs such as labor, machinery, fertilizer and 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, those tools need to be extended to include standard economic methods to assess food demand and trade. Such extension will need additional data support beyond what is proposed in Work Package 2 of the NBI-DSS Development Plan.

3. Agriculture Model Extension

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 may also need to incorporate both water and other agricultural inputs in the crop production simulation. Food demand and trade will be estimated by an economic module to 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. Thus agriculture modules should be extended to 1) account both water and non-water inputs in crop production, separated by irrigated and rainfed crops, using the production theory in microeconomics; 2) simulate and predict food demand and trade market; 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 water perspective, crop yield depends on the actual crop evapotranspiration (ET) relative to the potential ET. Simulation of crop ET should involve soil moisture and climatic driving forces (such as temperature and wind speed, etc.) However the final crop yield depends on other inputs such as labor, fertilizer and pesticide, seed, etc. Crop area is also a function of economic variables such as food prices and policy variables such as subsidies. Thus exact food production should jointly consider hydrologic, agronomic and economic factors.

A key issue for the crop production modeling is to simulate irrigated and rainfed crops separately. This is necessary because of the requirement of RAPT to assess the potential of rainfed agriculture, as well as the 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 the required data set. Also the projections of such split items will be important to assess the role of rainfed and irrigated agriculture in future of the Nile Basin. The data requirement for separate irrigated and rainfed crop production simulation is further discussed in Section 4.

Modeling of 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 data is useful for obtaining the data items that are required for the calibration but difficult or expensive to measure in field, for example, the crop ET (Bastiaanssen and Samia, 2003). The important baseline modeling results should include the 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 following options might 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 similar method as 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 the model everywhere in the basin. Option 3 will need an agricultural production model, which may not exist for the Nile Basin but developing such a model is feasible within the time and fund availability of the RATP project.

Under option 3 there will be two further options on the economic function of crop production. One is to develop an agricultural production function (yield and area function) using an econometric method, combine the function into the NBI-DSS, and calculate food production in DSS using water and non-water inputs. The function is to be created for each demand site (a region or a sub-basin). With such a function, the model will be developed as the so-called integrated hydrologic-economic model for basin-wide water allocation and agricultural development (Cai et al., 2006). Such a model will be embedded in the DSS. It should be noted that if a crop production function with both water and non-water inputs is to be developed, then the data on those non-water inputs such as fertilizer, labor, cost on seed etc. will have to be collected.

The other choice on the agricultural production function is to start with the existing food production structure in an existing global food production, demand and trade model (e.g., IFPRI's IMPACT-WATER, see Appendix A; IWMI's WATERSIM, which has the similar functions as IMPACT-WATER) and develop a regional extension with more detailed food production simulation in the NB countries (details are provided in a later section on model integration). This extension will have water supply and crop water demand inputs from NBI-DSS. In this way, the food production function together with food demand and trade can be embedded in the NBI-DSS.

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.

3.2. Agriculture demand and trade model

For the food demand and trade model, there are a number of world models including partial equilibrium models and economic-wide models. Many partial models have a detailed agricultural component, to name a few, IMPACT (IFPRI), AGLINK (OECD), ESIM (USDA, Stanford Univ.), World Food Model (WFM, FAO), and FAPRI (Iowa State University). Although these are the world models, some of them have a region or country focus, for example, AGLINK has a focus on OECD countries; FAPRI has a focus on the U.S.; ESIM contains 13 countries/regions including EU countries and U.S., adding the rest of the world. Unfortunately it seems that no such a food trade model has a focus on the Nile region. Thus no model might be directly used for the NBI-DSS extension. Direct use of a world model such as IMPACT and WFM may not be the best because the simulation of the study region is not detailed enough. Especially, the world models do not simulate the country-to-country trade path and then they cannot be 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 split irrigated crops and rainfed crops. Irrigated crops depend on effective rainfall and irrigation water, and rainfed crops depend on effective rainfall only. The details of IMPACT-WATER can be seen in Appendix A.

Between general equilibrium models (GEMs) and partial equilibrium models, the latter might be chosen given the focus on agricultural development in the Nile region. Another difficulty with GEMs is the data limitation and model complexity. Although some GEMs at the country level exist (e.g., Diao et al. 2005 and Willenbockel et al., 2008), extension of such models to the whole region may go beyond the financial limit 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 sub-Saharan Africa given the dominating role of agriculture in most countries in the region at present at in next decades.

One of the purposes of the agricultural study led by RATP is to explore the food trade markets between the Nile countries, as well as between the Nile countries and 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. Such a model does not seem to exist and a new development is needed, but it may go beyond the time and fund limit for the RATP project.

An approximate approach is to specify food trade between countries by prescribed trade scenarios based on food surplus or deficit in individual countries, existing or potential export-import relationships (e.g., market accessibility), and regional and national planning on food trade. 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 specified by the trade-scenario model 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). The coupled models may be sufficient to address the intra-region and international trade issues, without having much difficulty in implementing the models, as shown by the FAO project (Riddell et al., 2006) as introduced below and summarized in Appendix B.

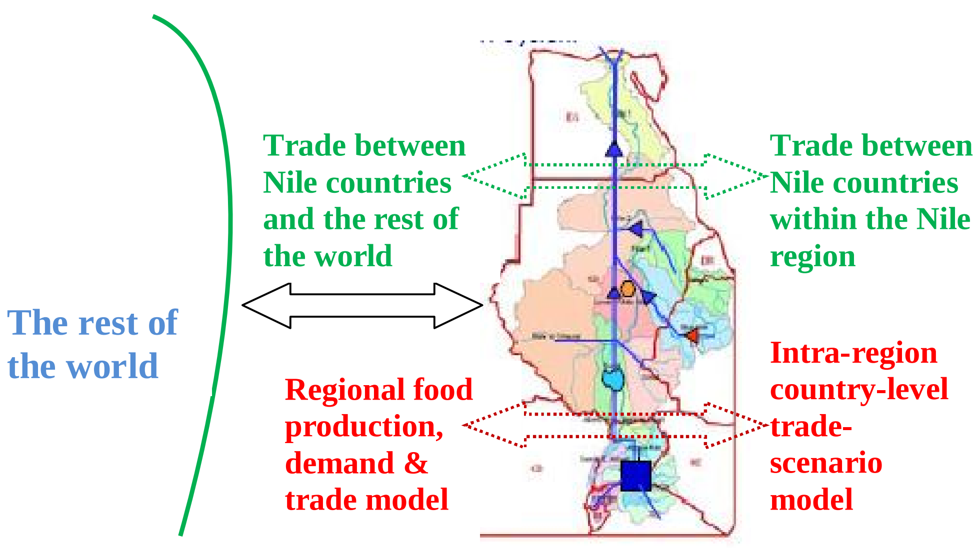

Figure 3: Coupling an inter-regional trade model with an intra-regional trade-scenario model

The trade-scenario model can follow the work conducted by FAO 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 proposed according to the potentials of irrigation development. The analysis followed a premise that irrigation development will initialize and sustain food trade between the sub-Saharan African countries and thus contribute to food security in the region. The analysis was conducted by a simple spreadsheet-based model. The RAPT 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

How to link the rest of the DSS modules to the crop production model and food demand and trade modules will be critical for the successfulness 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 going with 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 can be displayed by 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 is to be connected with the DSS by 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 staying together and the model is coupled 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, for example, IFPRI's IMPACT-WATER. In the following, using IMPACT-WATER as an example, the coupling of the food production, demand and trade model with the hydrological models in the DSS is described with more details.

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

Food demand and trade is analyzed at the *country* or *region* 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 shown in Figure 5.

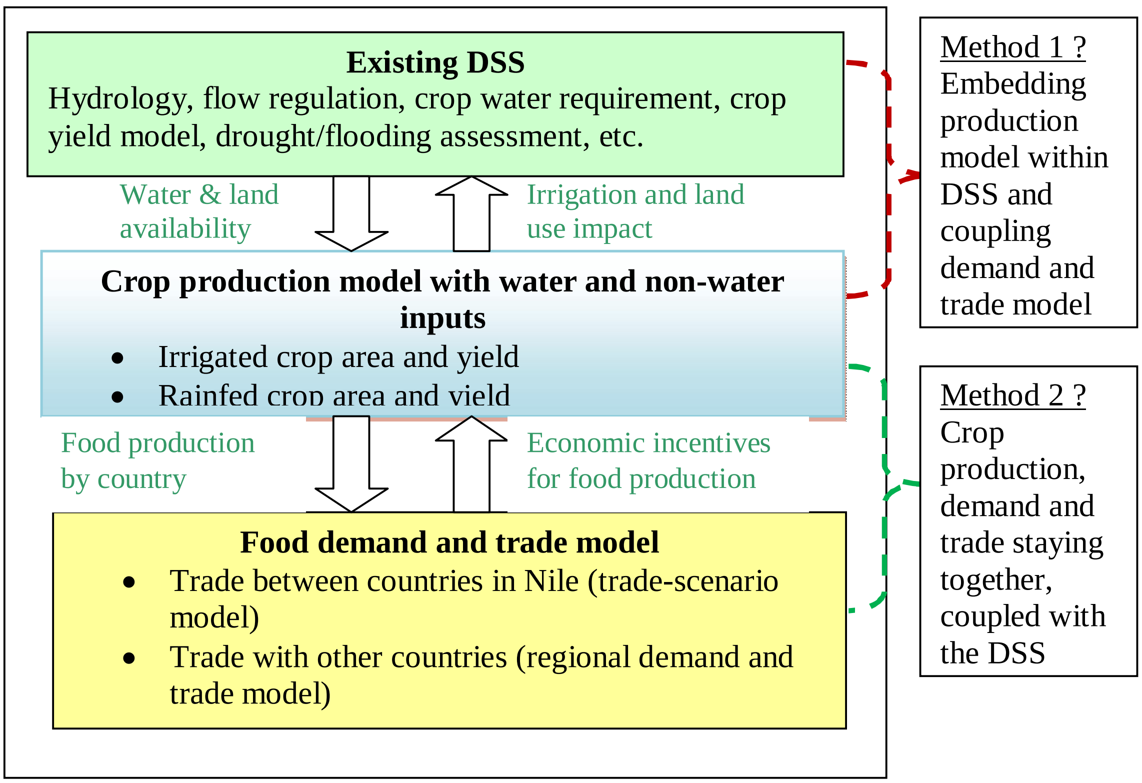

Figure 4: Integration of NBI-DSS with suggested agricultural modules

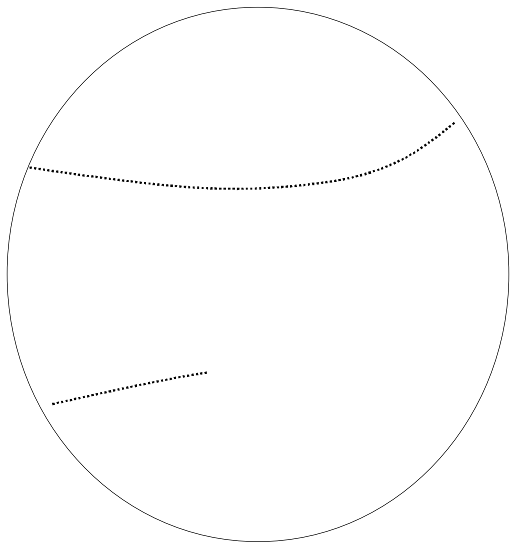

Figure 5: The coupling of HRUs, FPUs and countries for integrated food production, demand and trade modeling in the Nile region. Note one FPU can include one or more than HRUs and one country can include one or more than FPUs.

3.4. Other concerns on model choices

There are two other concerns on the model choice. One is related to the participation of national and local partners and the other is related to the knowledge right. It would be more effective for training and capacity building and then the further development of the project to have the active participation of national and local partners even in the data compilation and model development stage. The possible role of local partners in data compilation will be discussed in the following data requirement section. The role in model development can be active in the model extensions, for example, the development of FPU in each country associated as 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 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 to use the model when using an existing model like IMPACT-WATER. 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 and has been always been run by IFPRI staff and has never been opened to the public. There will be no problem for IMPACT-WATER to be coupled with the 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 RAPT 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 rather than using an existing one. **The model can be a reduced version of IMPACT-WATER, but with 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.**

4. Data Requirements

With respect to additional data needed to enhance the agriculture related modules in the NBI-DSS, upon request by RATP, WRPM 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) land cover and crop area map; 2) more realistic estimate of crop ET based on remote sensing data; and 3) some socio-economic data including water supply coverage, cost of infrastructure, crop prices, poverty, water productivity, etc. Figure 6 shows three categories of data, covered by WRPM Work Package 2, the new data compilation effort by RATP, and the joint effort of the two programs. All these categories 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 available the best data on all aspects of agriculture.

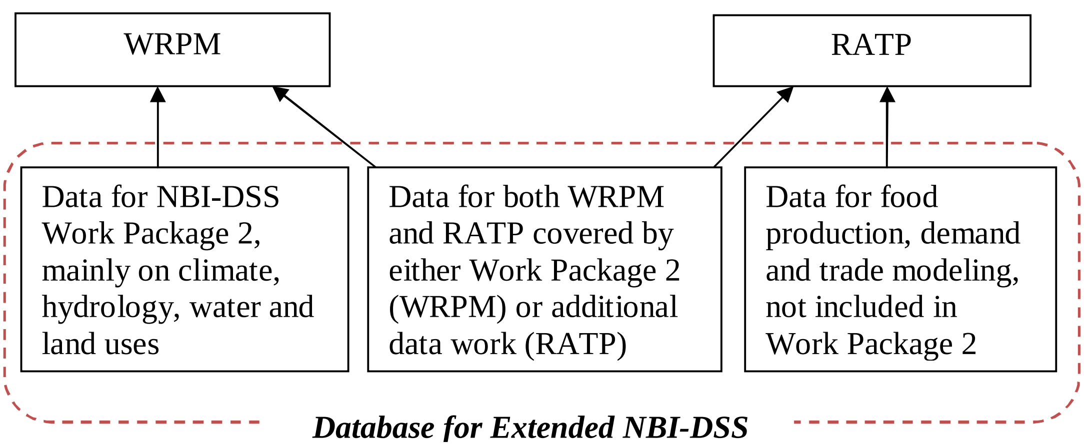

Figure 6: Data components for the extended NBI-DSS

This section follows the existing work and discusses the additional data requirements for food production, demand and trade modeling, starting from existing data sources.

4.1. Existing data sources

The question is: to what extend 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? Several ongoing and recently finished projects focus on 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 socio-economic 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).

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. It is possible that the studies done by the ENIDS project is extended to upper stream Nile Basin countries through RATP.

FAO Nile develops the baseline and projections of water use and productivity in the Nile Basin region and explores basin wide agricultural development options by 2030. The outputs of the project include geo-referenced (GIS) information products integrating physical and socio-economic data for water resources management in the Basin. The products include agricultural water productivity case studies, basin wide survey of agricultural water use, scenarios of demand for agricultural production and 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 irrigated agriculture baseline and 2030 projection in *sub-Saharan Africa*, which includes some Nile Basin countries (see details in Appendix B).

However, there is 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, one of the major components (probably the most important component) is *not* ready to release to any NBI programs at this moment (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 under proper coordination among the projects may still take a big effort, which however should be much easier than collecting the primary data items if without those data development projects.

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 and the results should be available to the public soon (T. Tang, personnel communication).

4.2. Data requirements for agriculture production models

Table 1 shows the data items required for crop production modeling, including the potential sources and methods to collect and compile 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.

A key issue for the crop production modeling is to simulate irrigated and rainfed crops separately. The existing irrigated and rainfed crop area and yield in different countries or regions within the NB is the required data set. Also the projections of such split items will be important to assess the role of rainfed and irrigated agriculture in future of the Nile Basin. FAO (2003) has such data at the country level based on an 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 be a reference for the future work. 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 data at finer spatial scale and in more recent years.

4.3. 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 need a separate consultancy project but rather having the selected model developer 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 at least part 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.

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 by a joint work of international consultants and local partners.

Table 1: Data requirements for crop production models

Data Items	Sources	Notes
1. Crop land map: irrigated and rainfed area in a baseline year (e.g., 2008), considering both food and non-food crops. Soil and landscape and climate attributes should be established with the crop land coverage	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 Country and regional agricultural statistics	General method – integration of remote sensing and field survey data with verification by country partners International database and previous project outputs should be used as a basis International consultants take lead Land productivity should be assessed using the soil, landscape and climate attributes
2. Irrigated and rainfed crop yield in a baseline year	FAO Nile and other FAO estimate in 1997, IWMI PODIUM Country and regional agricultural statistics	General method: Given gross area and yield by crop and precipitation and crop ET (potential and actual, see next item), split irrigated and rainfed crop area and yield can be estimated by a systematic method developed by Cai et al. (2007) and the result should be verified by local partners International consultants take lead

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	General method: 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. International consultants take lead
4. Agricultural inputs additional to water including fertilizer, pesticides, labor, machinery, seed etc.	FAO statistics: FAOSTAT Country and regional agricultural statistics	Country partners take lead
5. Infrastructures: water use efficiency and effective rainfall use ratio fraction	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
6. Water productivity, virtual water trade	Challenge Program of Water and Food (CPWF), CGIAR, Basin Focus Project for Nile, http://cpwfbfp.pbworks.com/	Compiling existing data
7. 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

<table>
<tr><th>Data Items</th><th>Sources</th><th>Notes</th></tr>
<tr><td>1.Population: current and future</td><td>UN and national population survey and projection</td><td rowspan="6">Data collection only 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.</td></tr>
<tr><td>2. Nutrition demand: current and future</td><td>IFPRI, FAO (FAO Nile)</td></tr>
<tr><td>3. Food trade (by different crop types) between NB countries</td><td>FAO Nile, national records</td></tr>
<tr><td>4. Food trade (by different crop types) between NB countries and the rest of the world</td><td>IFPRI, FAO</td></tr>
<tr><td>5. Crop prices- producers and consumers prices in the baseline year</td><td>IFPRI, FAO</td></tr>
<tr><td>6. Commodity pattern based on nutrition demand</td><td>IFPRI, FAO, national documents</td></tr>
<tr><td>7. Self-sufficiency: baseline and benchmarks</td><td>National planning reports</td><td rowspan="2">Assessment based on existing international and national work is needed. International consultant should take lead with collaboration from national partners</td></tr>
<tr><td>8. Trends and national policies on food trade</td><td>IFPRI, national planning reports</td></tr>
</table>

5. Term of References (TOR) and Roadmap of Activities

5.1. Term of References (TOR)

The ***overall goal*** of this project is to *strengthen the capacity of NBI to support the development of an economically viable agriculture in the Nile Basin that uses water resources in a sustainable and efficient manner*. It is in this context that the NBI-DSS and RATP have common interests in developing a DSS that will integrate agriculture into the basin strategic water resource planning and management. The NBI-DSS Concept and Development Plan will provide information and decision support for land and water management that will be directly used for assessing the food security vision of the Nile Basin region. Meanwhile, RATP will build on other related NBI projects and other sources to compile relevant data and develop additional modules for agricultural production and water use analysis. The additional data and modules will make the NBI-DSS more appropriate for supporting knowledge-based water resource management for more productive and sustainable agriculture in the Nile Basin.

The RAPT effort will focus on agricultural productivity, trade, efficient water and land use, and capacity building and **Specific activities** include:

- Assess the present and future food demand & supply and their effect on the changes in land and water use.
- Assess the potential of and tradeoff between irrigated and rainfed agricultural expansion and the impact on the basin water balance and environment, and development alternative plans for agriculture development in different areas considering both irrigation development and rainfed agricultural enhancement.
- Develop options to improve productivity levels under irrigated and rain-fed systems through the various possibilities of improving water use efficiency, enhancing rainfall harvests and building centralized flow and storage regulation projects.
- Evaluate the impact of droughts and floods impact on food production particularly in the content of climate variability and climate change.
- Understand the impact of other development sectors (urban, industrial, and ecological) on the agricultural sector and develop options for mitigating the possible conflicts.
- Address opportunities and challenges for agriculture markets to promote Nile Basin regional trade and associated virtual water trade in relation to water use in rainfed and irrigated agriculture; evaluate the cost of promoting regional trade; assess the national and transboundary benefits and impacts of agriculture development with a large focus on the regional activities related to trade, productivity, and transboundary impacts than national activities.
- Building capacity to support more productive and economically sustainable agriculture in the Basin through promoting regional trade, considering the role of the countries, NBI, economic communities, and other regional organizations working in the agriculture sector. This will require developing a shared-vision method to involve the stakeholders in all stages of the agricultural planning such as developing alternative plans, determining the final plan, and evaluating the consequences of the realization of the chosen plan.

5.1. Roadmap of activities

Undertaking the project activities will follow the principles as below:

- Coordinate with the work packages underlying the NBI-DSS Concept and Development Plan, including the coordination of modeling and data compilation efforts as discussed in sections 3 and 4, with special monitoring on the timing of the DSS work packages and additional work for the agricultural extension.
- Take advantage of previous and ongoing project outputs for data collection, as discussed in section 4.2.
- Give equal weight to rainfed agriculture and irrigated agriculture.
- Use a set of data that is sufficient for the project purposes but will stay with the time and fund availability.
- Use a set of models that will be effective to address all the issues and questions related to agricultural development, as well as other questions to be addressed by the DSS, as discussed in section 4. The choice of the models should also:
    - be consistent with the data availability
    - be coupled well with other DSS modules
    - go with the project time and fund limitation
    - support training and capacity building and stakeholder participation
    - stay with NBI-DSS (e.g., model accessibility), be easy to run and support future project development

Following these principles and the discussion on data and model requirement (Section 3 and 4), a particular roadmap of activities is recommended as below:

- Develop a regional model that integrates food production, demand and trade in a consistent manner. The model should assess food production at the level of food production units (FPUs, i.e., one country will be divided into multiple FPUs) and food demand and trade at the country level (covering all countries in the Nile region).

- The food production component should simulate irrigated and rainfed crops separately; the area and yield should be a function of both water and non-water inputs such as labor, machinery, fertilizer and pesticides, and seed (agricultural research). The food production component should be coupled with the hydrologic and water resources simulation model (to be developed under Work Package 2 of NBI-DSS) by taking water and land availability by time and space from the ND-DSS as inputs (Figure 7).

- The trade component of the model should simulate the intra-regional trade between the countries in the region, as well as the inter-regional trade between the Nile region and the rest of the world. The intra-regional trade can be depicted by a trade-scenario model at the country level (section 3.3) and the inter-regional trade (between countries in the Nile region and the rest of the world) can be depicted by the regional model (Figure 7).

- Water demand from municipal and industrial and ecological sectors (non-agricultural) will be assessed by an external module and be coupled with the water and land availability component shown in Figure 7.

- The feedback impacts from agricultural economics (production and demand and trade) to hydrology should be examined.

- The integrated food production, demand and trade model should be a partial equilibrium model with focus on the countries in the Nile region. The development of such a model can take advantage of existing models, for example but not necessarily, IFPRI's IMPACT-WATER model and FAO's trade-scenario model for the sub-Saharan Africa. The model can be a reduced version of these models, but with more detailed depiction on the Nile region and simpler depiction on the rest of the world (Figure 3). This new model will belong to the NBI after the project is finished.

- The model should be provided to RATP and NBI-DSS group and it should be incorporated into the NBI-DSS and tightly connected stay with other models (Section 3.3).

- The model and relevant analysis should be supported by the data items as suggested in Tables 1 and 2, as well as those proposed in Work Package 2 of NBI-DSS. The data items for crop production (Table 1) may need a separate consultant from the model development consultant; however the food demand and trade data may stay with the model development consultant.

- The data collection and compilation should consider the existing sources and follow the methods given in Tables 1 and 2. In particular, ongoing NBI projects and local partners should be combined in the data work.

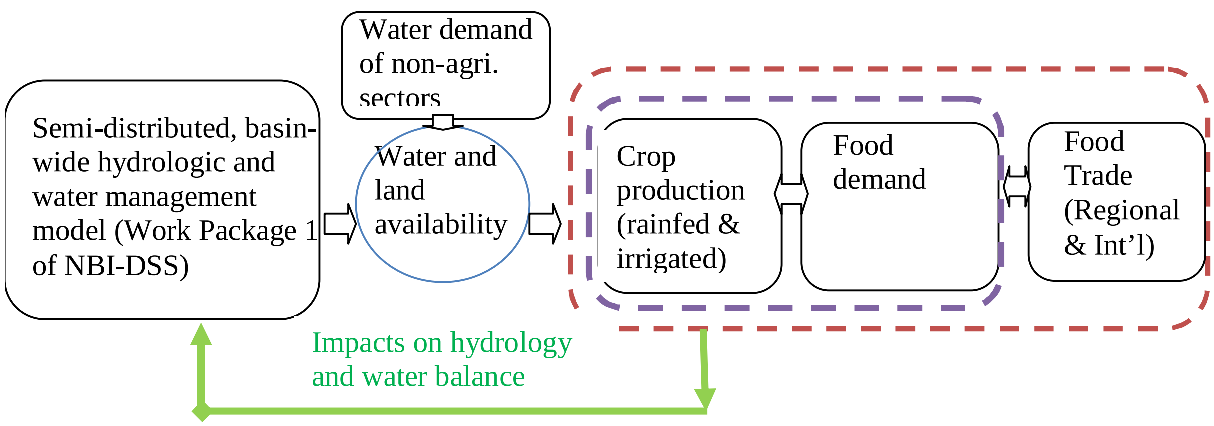

Figure 7: Model components for the extended NBI-DSS

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Appendices

A. An introduction of 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.

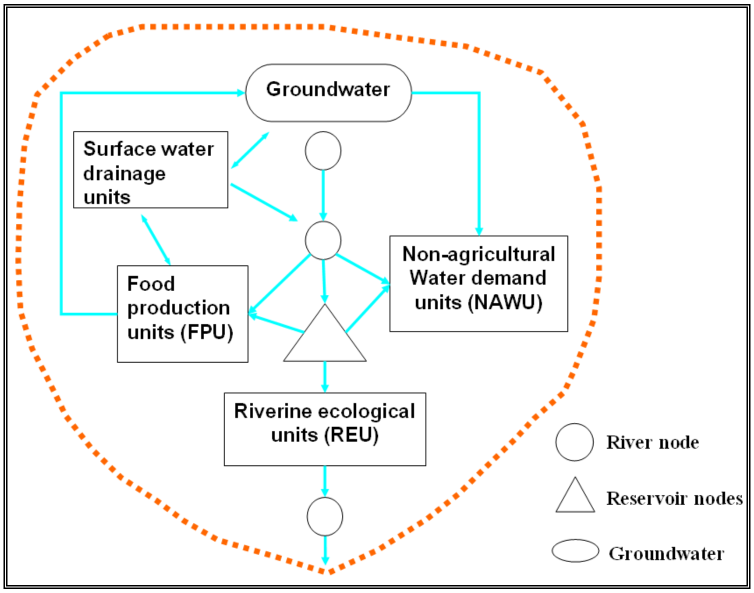


Figure A0-1: Network Representation of IMPACT-WATER

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).

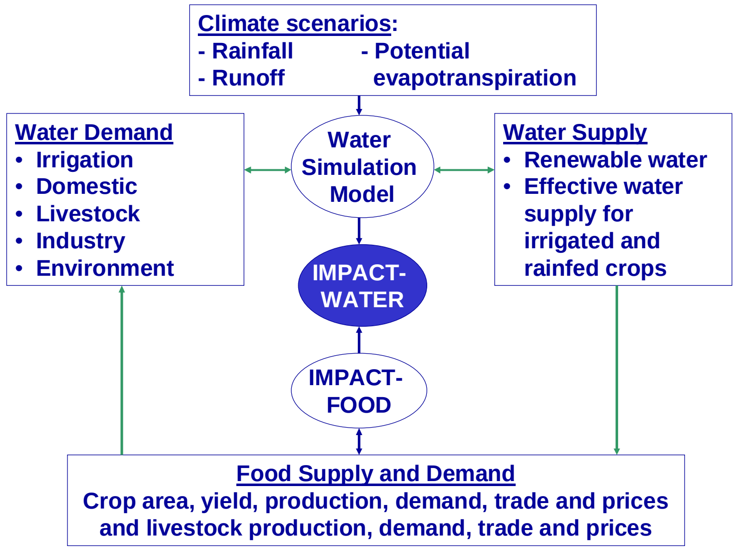


Figure A0-2: Coupled Water and Food Model: IMPACT-WATER

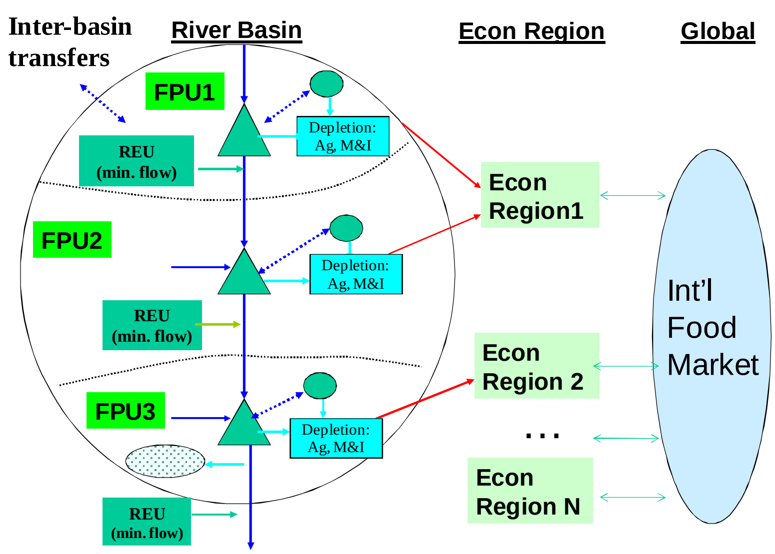


Figure A0-3: Coupling Water and Food Model Crossing Scales

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:

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

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

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

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.

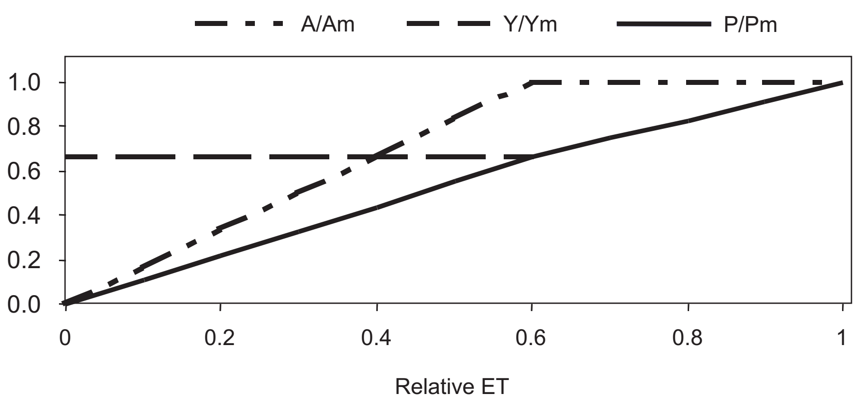
Actual crop evapotranspiration includes irrigation water which can be used for crop evapotranspiration (*NIW*) and effective rainfall (*PE*),

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

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:

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

where

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

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

Demand for feed:

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

Demand for other uses:

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

Total demand:

$$QD_{tni} = QF_{tni} + QL_{tni} + QE_{tni}; \tag{16}$$

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:

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

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:

$$NMAL_t = MAL_t \times POP5_t, \tag{23}$$

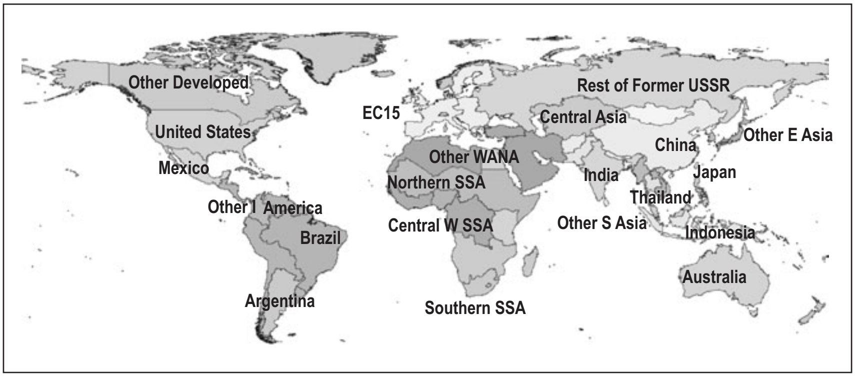
where *NMAL* = number of malnourished children, and
POP5 = number of children 0-5 years old in the population.

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



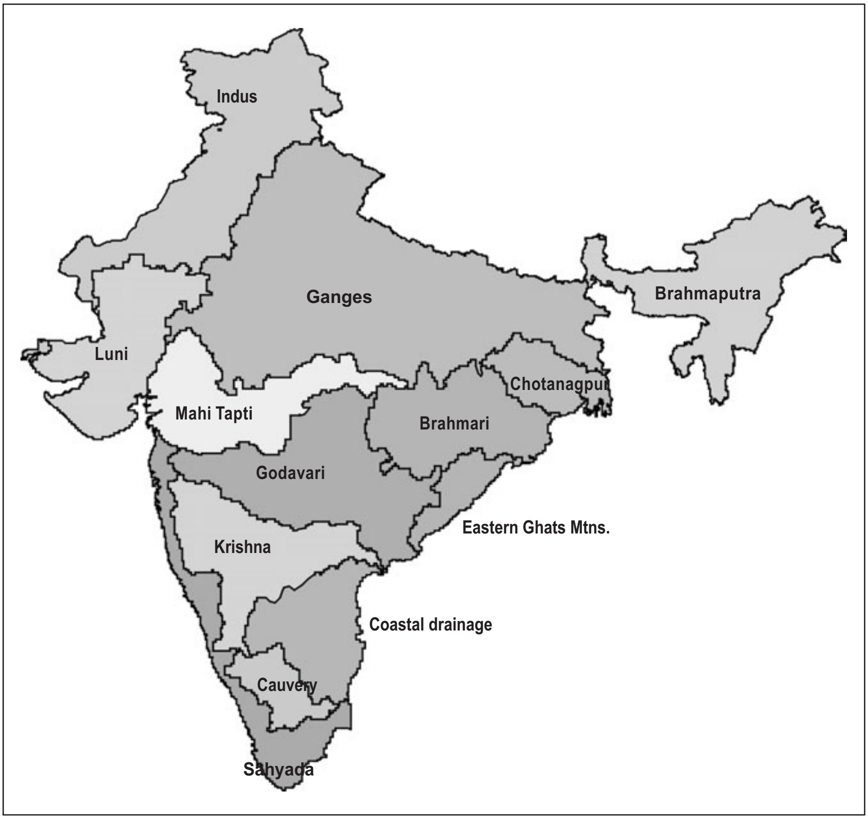
Source : Authors' assessments.

(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):

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

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:

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

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:

$$IRWD = NIRWD / BE \tag{26}$$

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 $\alpha > 0$, $\partial IWDI / \partial GDPC = \beta < 0$, and $\partial IWDI / \partial T =$ 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):

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

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:

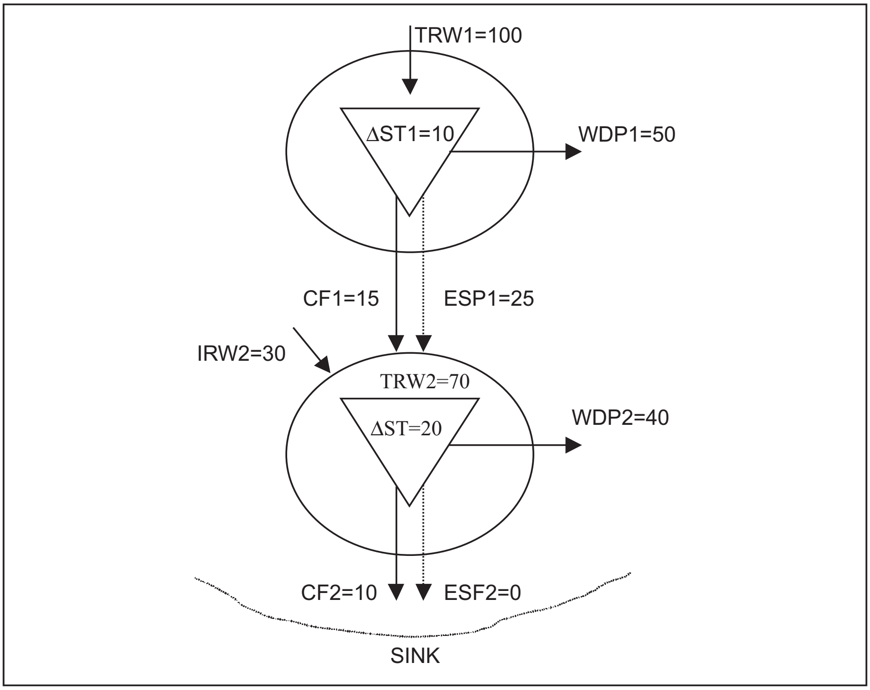
$$ST^{t} - ST^{t-1} = ROFF^{t} + INF^{t} + OS^{t} - SWDP^{t} - RL^{t} - EL^{t} \qquad (33)$$

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*):

$$\sum_t GWDP^t / DC \leq GMAWW \tag{35}$$

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

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

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:

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

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 (SM_0), 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.

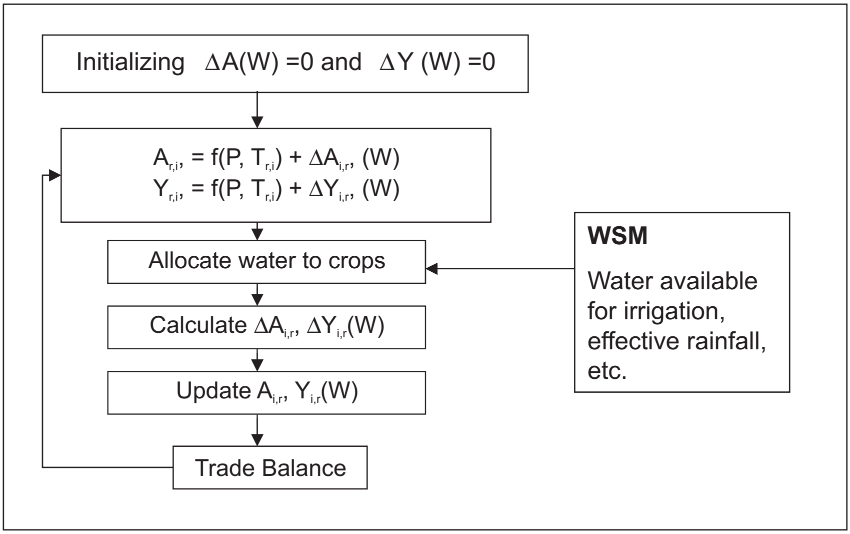
Group 1, without any inflow, is first solved; and then group 2, with inflow from one or more basins of group 1, and so on. One group is ready to be solved with inflows from all the groups that have flow release to basins in the current group. The implementation of this spatial connection allows the model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

Recommendations from the study:

- 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.