7

Assessment of potential of food supply and demand using the Watersim model

Charlotte de Fraiture

This Report has been produced as part of the Executing Agency Agreement between the African Development Bank and the International Water Management Institute for implementation of the Collaborative Program on "Investments in Agricultural Water Management in Sub Saharan Africa: Diagnosis of Trends and Opportunities."

Final Report
Submitted by International Water Management Institute
August 2005

ACKNOWLEDGEMENTS

This report was prepared as a contribution to the Collaborative Program on "Investments in Agricultural Water Management in Sub Saharan Africa: Diagnosis of Trends and Opportunities." This Program involves collaboration among the African Development Bank (ADB), Food and Agriculture Organization of the United Nations (FAO), International Fund for Agricultural Development (IFAD), International Water Management Institute (IWMI), New Partnership for Africa's Development (NEPAD), and the World Bank. Other supporting partners included the International Livestock Research Institute (ILRI), International Food Policy Research Institute (IFPRI), Comprehensive Assessment of Water Management in Agriculture, and InWent. This particular report was funded by the Comprehensive Assessment of Water Management in Agriculture and is part of IWMI's contribution to the Collaborative Program. Although the report has been reviewed by the members of the Collaborative Partnership Working Group, the author remains responsible for the contents, which do not necessarily reflect the views of the collaborating partners.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

BES	Basin Equivalent Storage
CSE	Consumer Subsidy Equivalent
GDP	Gross Domestic Product
FAOSTAT	FAO's online agriculture database
FPU	Food Producing Units
GAMS	General Algebraic Modeling System
GIS	Geographic Information Systems
GTZ	Gessllschaft fur Technische Zusammenarbeit
ICOLD	International Commission on Large Dams
IFPRI	International Food Policy Research Institute
IPCC	Intergovernmental Panel on Climate Change
IMPACT	International Model for Policy Analysis of Agricultural Commodities and Trade
PODIUM	Policy Dialogue Model
SI	Supplemental Irrigation
SSA	sub-Sahara Africa
SIWI	Stockholm International Water Institute
USDA	United States Department of Agriculture
WATERSIM	Water, Agriculture, Technology Environment and Resources Simulation Model

SUMMARY

At present Sub-Saharan Africa (SSA) is self-sufficient in major staple crops such as cassava, sweet potatoes, other root and tubers, maize and coarse grains (millet, sorghum). Except for rice and wheat, the role of irrigation and trade in food supply is negligible with 98% coming from rainfed agriculture and less than 5% imported from outside SSA. With less than 4% of total harvested area irrigated (most of which is in just three countries), SSA has an extremely low rate of irrigation development compared to other regions. While in a few river basins actual water use is close to the potential, in the majority of the basins, water scarcity is from the lack of water infrastructure rather than physical shortage. Out of the potential irrigated area of 36 million hectares- as estimated by FAO- only 6 million hectares are currently developed, leaving ample scope for expansion.

Food demand will roughly double in the coming 25 years. Based on an exploration of alternative scenarios, this paper argues that most of future food production is likely to come from rainfed agriculture. Despite ample physical potential, irrigation will likely play a very limited role in food supply. First, even if SSA were to double its irrigated area, as suggested by the Commission for Africa, its impact on food supply will remain small (less than 8% of total food production). Because of uneven distribution of water resources and irrigation potential, emphasis on irrigated agriculture implies increased food trade between countries within SSA. Second, it is questionable if irrigated cereal production in SSA – plagued by high marketing costs and limited marketing opportunities - will be able to compete with cheap cereal imports from the USA and Europe. Third, the investment cost of doubling the irrigated area is very high. An estimated 20-35 billion dollars is needed for the construction of irrigation infrastructure, but to make this investment economically viable massive investments in marketing infrastructure are needed (roads, storage, communication).

Without substantial improvements in the productivity of rainfed agriculture, food production will fall short of demand. To keep up with demand, yields of cassava, potato and maize need to be doubled. From a biophysical point of view, water harvesting techniques have proven successful in boosting yields, often up to a two or threefold increase. Literature provides numerous successful examples of traditional and exogenously introduced techniques of improved water management in rainfed areas. Water harvesting techniques work under a variety of settings. This illustrates the need to think in terms of agricultural water management, rather than strictly distinguishing between rainfed versus irrigated agriculture.

However, low adoption rates of water harvesting techniques indicate that upscaling local successes poses major challenges. Low profitability of agriculture and high risks discourage farmers from investing in land and water. A major problem is the lack of domestic market infrastructure, trade barriers to international markets and high marketing costs caused by poor roads. Other barriers include poor governance, institutional disincentives to profitable agriculture (taxes, corruption) and high level of risk discouraging farmers to invest in labour and other inputs.

Assessing actual food production patterns, this paper concludes that in order to achieve food self-sufficiency in the coming 25 years, upgrading existing rainfed agriculture

through better water management – i.e.,,, water harvesting and supplementary irrigation-should be a major part of SSA investment strategy. But without simultaneous improvements in marketing infrastructure (roads, bridges, electricity, communication), these investments may not be effective in enhancing SSA's agricultural sector.

RÉSUMÉ

L'Afrique subsaharienne (ASS) est actuellement autosuffisante pour les principales cultures de base telles que le manioc, la patate douce, d'autres racines et tubercules, le maïs et les céréales secondaires (millet, sorgho). À l'exception du riz et du blé, le rôle de l'irrigation et des échanges commerciaux dans l'approvisionnement en nourriture est négligeable puisque celle-ci provient à 98% de l'agriculture pluviale et que les importations hors ASS représentent moins de 5%. Avec une proportion de la superficie de récolte irriguée inférieure à 4% au total (principalement située dans trois pays seulement), l'Afrique subsaharienne possède un niveau d'irrigation extrêmement faible par rapport à d'autres régions. Alors que la consommation d'eau réelle est proche de son potentiel dans un petit nombre de bassins fluviaux, dans la majorité de ceux-ci, la pénurie en eau est plutôt due au manque d'infrastructures hydriques qu'à une pénurie physique. Sur les 36 millions d'hectares de zone irriguée potentielle – selon les estimations de la FAO – seuls 6 millions sont mis en valeur à l'heure actuelle, ce qui laisse une réelle marge d'expansion.

La demande en nourriture doublera environ au cours des 25 prochaines années. Le présent article s'appuie sur l'analyse de scénarios alternatifs pour affirmer que la majorité de la production alimentaire future proviendra probablement de l'agriculture pluviale. Malgré un potentiel physique amplement suffisant, l'irrigation devrait jouer un rôle marginal dans l'approvisionnement en nourriture. Premièrement, même si l'Afrique subsaharienne venait à doubler la superficie irriguée, comme le suggère la Commission pour l'Afrique, l'impact sur l'approvisionnement en nourriture resterait limité (moins de 8% de la production alimentaire totale). Étant donné la distribution inégale des ressources hydriques et du potentiel d'irrigation, mettre l'accent sur l'agriculture irriguée implique une augmentation des échanges commerciaux alimentaires entre les pays de la zone ASS. Deuxièmement, il convient de se demander si la production céréalière irriguée en ASS – entravée par les coûts élevés liés à la commercialisation et les opportunités limitées en la matière – sera capable de concurrencer les importations céréalières bon marché en provenance d'Europe et des États-Unis. Troisièmement, doubler la surface irriguée représente un coût d'investissement très élevé. La construction d'une infrastructure d'irrigation est estimée à 20-35 milliards de dollars mais des investissements massifs sont nécessaires dans l'infrastructure de commercialisation (routes, stockage, communication) afin de la rendre économiquement viable.

Sans amélioration conséquente de la productivité de l'agriculture pluviale, la production alimentaire ne parviendra pas à satisfaire la demande. Afin de répondre à celle-ci, les rendements du manioc, de la patate douce et du maïs doivent être multipliés par deux. D'un point de vue biophysique, les techniques de récolte de l'eau ont prouvé leur efficacité en termes d'accroissement du rendement, qui, dans bien des cas, double, ou même triple. La littérature spécialisée met en évidence de nombreux exemples réussis de techniques traditionnelles ou introduites de façon exogène pour une meilleure gestion des ressources hydriques dans les zones pluviales. Les techniques de récolte de l'eau fonctionnent dans des configurations différentes. Ce qui illustre à quel point il est nécessaire de réfléchir en termes de gestion des ressources hydriques agricoles, plutôt que d'opposer l'agriculture non-irriguée à l'agriculture irriguée en tant qu'éléments strictement séparés.

Cependant, le faible taux d'adoption des techniques de récolte des eaux indique que la reproduction à l'échelon supérieur des réussites locales pose de sérieux défis. La faible rentabilité de l'agriculture et les risques élevés dissuadent les agriculteurs d'investir dans les ressources hydriques et pédologiques. Le manque d'infrastructure du marché intérieur, les barrières douanières sur les marchés internationaux et le coût important de la commercialisation dû au mauvais réseau routier posent des problèmes majeurs. Une mauvaise gouvernance, des obstacles institutionnels à la rentabilité de l'agriculture (taxes, corruption) et un niveau de risque élevé constituent également des freins qui n'encouragent pas les agriculteurs à investir dans la main d'œuvre et dans d'autres intrants.

Sur la base de l'examen de la structure réelle de la production alimentaire, le présent article conclut qu'en vue de parvenir à l'autosuffisance alimentaire au cours des 25 années à venir, l'amélioration de l'agriculture pluviale agricole grâce à une meilleure gestion des eaux (c.-à-d., récolte de l'eau et irrigation complémentaire) devrait constituer un des principaux piliers de la stratégie d'investissement en ASS. Toutefois, sans amélioration simultanée de l'infrastructure de commercialisation (réseau routier, ponts, électricité, communication), ces investissements pourraient ne pas suffire à dynamiser le secteur agricole de la zone ASS.

INTRODUCTION

7.1 At present the bulk of SSA's food production occurs under rainfed conditions, with irrigation playing a minor role. Compared to other regions in the world, the level of water resources development is low. While actual water use is close to the potential at a few places, irrigation potential has not been realized in the majority of river basins in SSA due to the lack of water infrastructure, leaving ample scope for expansion. At the same time, in order to keep pace with demand, food production needs to be doubled in the coming 25 years.

7.2 This paper addresses the following questions: What is the right mix of investments in irrigated and rainfed agriculture to achieve food self-sufficiency in the next 25 years? Can the shortfall in food supply be met through investments in (formal) irrigated agriculture? What are the implications for international and regional trade? And for water resources development?

7.3 The set-up of the paper is as follows: the second section introduces the model used to analyze these questions. Section three provides details on the actual situation of water and food demand and supply. Next, three options for future food supply are analyzed: baseline, enhancing rainfed production and expansion of irrigated areas. The fifth section presents conclusions.

METHODOLOGY

7.4 To analyze the question of water and food supply and demand in the next 25 years, this paper uses the global model on water and food, Watersim, developed by IWMI and IFPRI. The Watersim model covers 111 economic regions and 125 river basins of the world, of which 40 regions and 18 major river basins are located in the SSA region. The food demand of 16 commodities is estimated as a function of population, per capita consumption and prices of a particular commodity and of competing commodities. Crop production under rainfed and irrigation conditions and the livestock production is a function of crop prices, inputs prices, crop inputs, technology, water availability and climate. Water demands for irrigation, domestic and industrial use are estimated at river basin scale. The irrigation requirement of a river basin is the aggregate of the irrigation demands of food production units in a river basin. Water supply for each river basin is expressed as a function of climate, hydrology, existing infrastructure and water related investments.

7.5 Local prices of commodities are determined by world market prices and the assumption of market clearance at global level. Food production regions are connected to each other in the model through international trade. The international and regional prices of commodities are determined by balancing global production and demand. The regional prices are then fed back into the demand functions, which affect food and water demands.

ACTUAL WATER AND FOOD SUPPLY AND DEMAND

7.6 At present, the bulk of SSA's agricultural production occurs under rainfed conditions with irrigation playing a minor role. Compared to other regions in the world, the level of water resources development is low. While actual water use is close to the potential in a few basins (e.g., Limpopo and Orange), the water scarcity in the majority of the basins is caused by the lack of water infrastructure rather than a physical shortage. With an estimated 6 million hectares under irrigation, only one sixth of the irrigation potential in SSA has been realized.

Food supply and demand

7.7 The main food crops in Sub-Saharan Africa are cassava, sweet potatoes, roots and tubers, coarse grains –such as millet end sorghum, and to a lesser extent maize. Unlike in Asia, cereals such as wheat and rice are less important, accounting for less than 5 percent of the total food demand. The role of trade in food supply is limited, except in the case of rice and wheat. At present, most countries within Sub-Sahara Africa are close to food self-sufficiency in the staple crops mentioned above. SSA imports 9 million tons of wheat (two thirds of the demand) and 5 million tons of rice (corresponding to 40 percent of demand). Food aid, fluctuating between 2 and 3 million tons annually (FAOstat), accounts for less than 3 percent of the total cereal supply, though in some years the percentage of food supply met by aid may go up to 15 percent (as in Ethiopia, in the year 2000).

Table 1: Food demand and supply in SSA for the year 2000

	Demand in million ton	***Production million ton***	***Net trade million ton***	***Percentage of demand imported***
Cassava et al	106.5	106.8	0.3	0.4%
Sweet potatoes	43.8	35.7	-2.1	5.6%
Maize	37.8	32.6	-2.4	6.9%
Other grains	35.0	43.7	-0.1	0.2%
Wheat	13.6	4.6	-9.0	66.2%
Rice	12.0	6.7	-5.3	44.2%

Source: Watersim simulation, based on FAOstat data.
Details by sub-region in annex.

7.8 Most of the agricultural production comes from rainfed areas. Currently, less than 4 percent of the total harvested area is irrigated (6 out of 158 million hectares), with more than 60 percent of the irrigated area in just three countries (South Africa, Sudan and Madagascar). The table below shows that irrigation plays an insignificant role in food production, except for minor crops such as rice and wheat. Irrigated areas provide half of the rice and one third of the wheat production in SSA. But production is concentrated in just a few countries, mainly in Nigeria and Madagascar (55 percent). South Africa and Ethiopia account for three quarters of irrigated wheat.

7.9 These numbers indicate that in general irrigation, trade and food aid play a limited role in food supply. Irrigated food production is concentrated in just a few countries, while most countries are self-sufficient cultivating under rainfed conditions.

Table 2: Percentage of production originating from irrigated areas SSA for the year 2000

	Total production (m ton)	*Percentage from irrigation*
Cassava et al	106.8	0.2%
Sw potatoes	35.7	0.1%
Maize	32.6	4.7%
Other grains	43.7	2.7%
Wheat	4.6	50.8%
Rice	6.7	36.3%

Source: Watersim simulation, based on FAOstat data.
Details by sub-region in annex.

Export crops

7.10 The value of total exports from SSA amounted to US$ 100 billion in 1998-2000, of which agricultural exports accounted for US$ 13 billion, corresponding to 4 percent of GDP. Although SSA exports grew in absolute terms, its share in the world economy declined from 2.56 percent in the early 80s to 1.39 percent by the late 90s, because exports from SSA grew slower than world exports (Diao *et al.* 2003). The study by Diao *et al.* (2003) distinguishes between 'traditional' (cocoa, coffee, cotton, tea, tobacco, sugar) and non-traditional export crops (fruits and vegetables, flowers, livestock, fish).

Traditional export crops

7.11 In dollar terms, traditional export crops accounted for about half of export earnings. Intra-regional trade accounted for 10 percent of total agricultural exports (of which 25 percent was food crops). Traditional exports of all African countries, except South Africa and Malawi, experienced negative demand growth during 1995-99 (Ng and Yeats 2000). Empirical evidence shows that income elasticities of African traditional exports are well below one. Continued reliance on traditional exports will lead to further decline of SSA's share in world exports, unless SSA is able to achieve significant competitive gains (Diao *et al.* 2003). An additional problem in crops such as cotton, sugar, tobacco and cocoa, is price instability. For all traditional exports crops, but particularly cotton, sugar and tobacco, lowering trade barriers in industrial countries would significantly improve the marketing opportunities. Future demand prospects do not appear promising (Diao *et al.* 2003).

Non-traditional export crops

7.12 Non-traditional exports consist of a very diverse category (more than 80 commodities within the fruits and vegetables category). Three quarters of the commodities are traded mostly outside the region, while one quarter has a large intra-regional trade share (but these are mainly processed foods, for which farmers' income share is low). The demand prospects for non-traditional crops are less severe than for traditional export crops. However, non-traditional exports to a large extent cater to niche markets. Even if the success achieved by a few countries can be replicated for other commodities and by other countries, the magnitude of these exports earnings may remain small relative to total trade and income (Diao *et al.* 2003).

7.13 Except for sugarcane, most of the cash crops are grown under rainfed conditions, although the share of production originating from irrigated lands is higher than in food production.

Table 3: Percentage of production originating from irrigated areas SSA for the year 2000

	Total production (m ton)	***Percentage from irrigation***
Fruits	8.8	14.9%
Sugarcane	59.6	49.2%
Cotton	1.26	11.5%
Cocoa	2.0	0.0%
Tea	0.4	4.8%
Coffee	1.0	0.3%

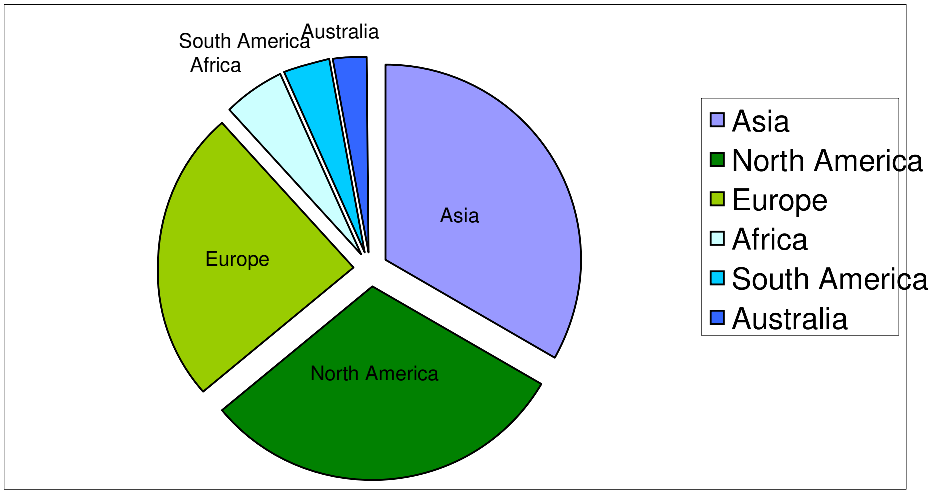
Source: Watersim simulation, based on FAO data.
Details by sub-region in annex.

Water supply and demand in base year

7.14 Compared to other regions of the world, water resources development in SSA is limited. Average per capita storage in SSA amounts to 810 m^3, compared to 3800 m^3 in the USA (based on ICOLD numbers, including storage for other purposes than irrigation). Figure 1 shows the distribution of major dams over the continents. Less than 5 percent of the world's major dams are located in SSA. The distribution of dams among countries in SSA is skewed. Most of storage capacity is concentrated in just a handful of countries (South Africa, Nigeria, Mozambique, Ghana, Zimbabwe, and Ivory Coast), with the majority of countries having limited storage capacity behind dams. Storage is mainly used for hydropower, flood control and navigation and, to a limited extent, for irrigation.

7.15 Total runoff in SSA is estimated at 3770 km3. In the base year (2000), all sectors (i.e., agriculture, domestic use and industry) depleted some 69 km^3, of which 50 km^3 or 74 percent was depleted by the agricultural sector. With less than 2 percent of the available water depleted for human uses, there seems ample scope for further water resources development.

Figure 1: Number of major dams by continent



Source: ICOLD 2004.

7.16 But total numbers mask the very uneven distribution of water resources availability and development within SSA. Compare two extreme cases: the water rich Zambezi basin and the water short Limpopo basin. In the Limpopo basin, more than 53 percent of the annual runoff is depleted mainly by agriculture (2.8 out of 5.3 km3). With 272,000 hectares under irrigation, more than 90 percent of its potential has been realized and further expansion seems limited. In the Zambezi basin on the other hand, less than 3 percent of the annual runoff is depleted and with 251,000 hectares irrigated, only 2 irrigated of the potential has been developed (Table 4 and Figure 2).

Table 4: Irrigation potential and actual development in major basins in SSA (2000)

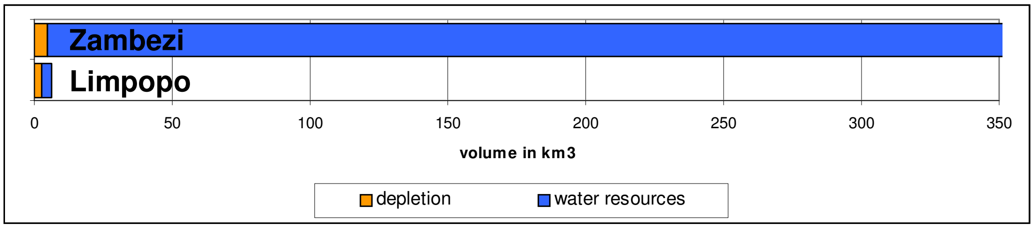
Basin	**Irrigation potential* (m ha)**	**Irrigated area** (m ha)**	**Percentage of potential realized**	**Depletion in km^3****	**Percentage of total water resources ****
Lake Chad	1.16	0.15	13%	1.1	12%
Senegal	0.42	0.13	31%	2.9	19%
East African Coast		0.23		2.6	1%
Volta		0.24		5.3	6%
Zambezi	3.16	0.25	8%	3.8	1%
Limpopo	0.30	0.27	90%	2.8	53%
Orange	0.39	0.37	95%	2.5	40%
Horn of Africa		0.46		9.2	11%
Niger	1.68	0.64	38%	11.9	5%
Madagascar	1.50	0.94	63%	7.8	2%
Total SSA	36	6.2	16%	69	2%

* based on FAO (1997) ** from Watersim database

Data by country given in annex.

Basins are categorized as physical water scarce if more than 40 percent of the water resources are depleted (Alcamo *et al*, Seckler *et al*).

Figure 2: Annual runoff and depletion in the Zambezi and Limpopo basin



Source: From Watersim database.

7.17 Within international basins, water availability and use is often unevenly distributed between countries. Consider, for example, the substantial variation in water use between the four countries in the Limpopo basin (Botswana, South Africa, Zimbabwe and Mozambique). The flow diagram in Figure 3 and data in Table 5, which provide details on water flows and use, indicate that within basin boundaries Zimbabwe and South-Africa deplete between 50-60 percent of available water (i.e., internally generated runoff plus inflow from upstream). According to most definitions, this percentage implies physical water scarcity. Botswana and Zimbabwe use a relatively small percentage of the available water resources. But increased water use by Botswana would directly affect South Africa's supply downstream. Except for Mozambique, the potential for further development of water resources in the Limpopo that increases water depletion seems limited.

Figure 3: Water flows and use in the Limpopo basin

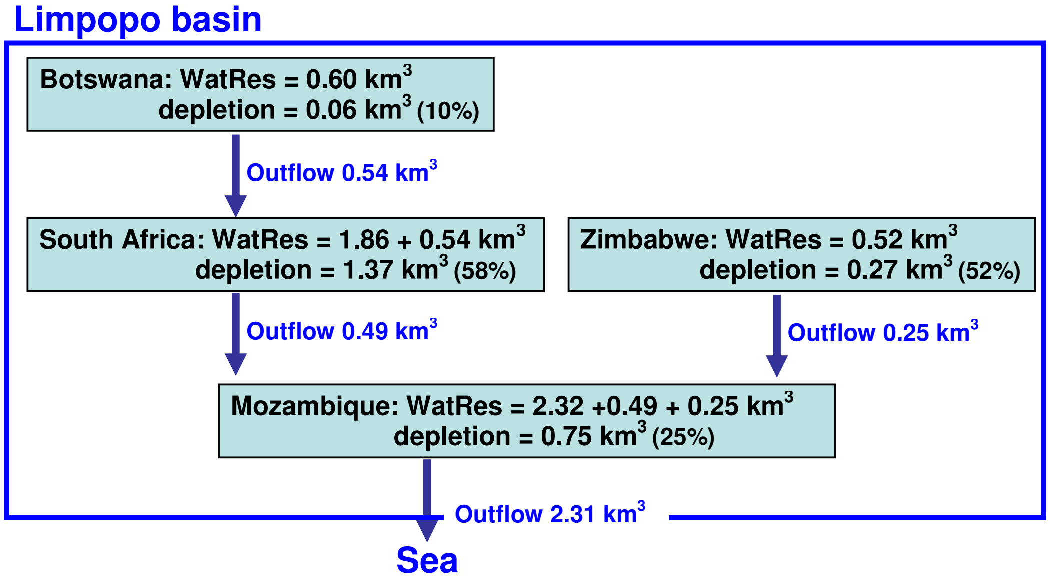


Table 5: Water balance in Limpopo basin

Country within basin boundary	***internally generated runoff***	***Inflow from upstream***	***Depletive demand***	***Depletive Supply***	***Ratio supply over demand***	***Total Diversions***	***Consumptive fraction***
Botswana	0.601	0	0.060	0.060	1	0.143	0.42
Zimbabwe	0.538	0	0.309	0.221	0.72	0.448	0.49
South Africa	1.857	0.537	1.785	1.273	0.71	2.418	0.53
Mozambique	2.322	1.550	0.599	0.599	1	1.366	0.44
Total	5.328	0	2.753	2.153	0.78	4.375	0.49

Source: Watersim simulation.

7.18 Summarizing, at present the bulk of SSA's agricultural production occurs under rainfed conditions with irrigation playing a minor role (except for wheat, rice and sugarcane). Compared to other regions in the world, the level of water resources development is low. While actual water use is close to the potential in a few basins (Limpopo and Orange), water scarcity in the majority of the basins is caused by the lack of water infrastructure rather than an actual physical shortage. With an estimated 6 million hectares under irrigation, only one sixth of the irrigation potential in SSA has been realized.

FUTURE WATER AND FOOD DEMAND AND SUPPLY

Baseline

Food demand

7.19 The main drivers behind future food demand are population growth and changes in diet, as a result of urbanization and improved living standards. Under the baseline scenario, population and per capita income will grow by 3.2 percent and 3.1 percent respectively (refer to the annex for details). In a baseline scenario where major trends in population growth and GDP improvements continue, food demand will roughly double.

Table 6: Food commodity demand in SSA

	Demand 2000 million ton	***Demand 2025 million ton***	***Percentage increase***
Cassava & other roots & tubers	106.5	196.8	85%
Sweet potatoes	43.8	82.4	88%
Maize	37.8	75.4	99%
Other grains	35.0	78.6	125%
Wheat	13.6	24.8	82%
Rice	12.0	22.5	87%

Source: Watersim simulation.

Includes demand for food, feed and other uses.
Details by sub-region in annex.

Table 7: Livestock product and feed demand million tons total SSA

	2000	*2025*
Beef	3.2	6.9
Egg	1.3	2.4
Milk	19.2	40.0
Pork	0.7	1.4
Sheep	1.4	2.4
Cassava for feed	16.5	29.7
Maize for feed	6.0	10.5
Meals for feed	4.0	7.6
Other grains feed	1.6	3.0

Source: Watersim simulation.

7.20 High income growth will generate strong domestic demand for meat and cereals, with more growth in demand for rice and wheat than for maize. Although cereal demand for feed is responsive to incomes, its impact on overall cereal demand in SSA is limited because feed ratios are low (i.e., most livestock is fed with grass, fodder and crop residues). Simultaneous productivity growth in cereals and livestock offer more potential for major impacts on food consumption. With reduced marketing costs and improved market access, domestic demand for agricultural products need not constrain agricultural growth. The key to stimulating food demand is reducing transaction costs through investments in marketing infrastructure (roads, bridges, ports, storage facilities, electricity etc.) and development of market institutions (Kherallah *et al.* 2002). More productivity in agriculture will have a limited impact on real income (Diao *et al.* 2003).

Potential demand for exports crops

7.21 Traditional agricultural exports (coffee, cocoa, cotton and sugar) suffer from declining terms of trade and price instability. Moreover, low productivity and problems with maintaining quality have led to declining market shares of SSA countries. Under a ‘business as usual’ scenario, future demand prospects do not appear promising. Lowering marketing costs (by building roads and storage facilities) will improve opportunities for intra-regional trade. Lowering trade barriers in industrial countries would significantly improve the marketing opportunities for all traditional exports crops, but particularly cotton, sugar and tobacco (Diao *et al.* 2003).

7.22 Demand prospects for non-traditional crops (fruits and vegetables) are less severe but they are to a large extent targeted to niche markets. Even if the success achieved by a few countries can be replicated for other commodities and by other countries, the magnitude of these export earnings may remain small relative to total trade and income (Diao *et al.* 2003).

7.23 A high growth of traditional agricultural exports will have relatively small effect on income growth, even under optimistic demand scenarios. First, for most SSA countries, the traditional export sectors accounts for a small share of total agricultural GDP. Second, it is expected that world market prices will remain low; (the situation may be different if world market prices improve). Growth in the agricultural sector alone will not significantly improve GDP. Only in combination with growth in non-agricultural sectors will agricultural growth produce substantial gains in income (Diao *et al.* 2003).

Food supply

7.24 Under an optimistic baseline scenario, where trends in area expansion and yield improvements continue, areas under rainfed conditions will grow by 18 percent from 157 to 193 million hectares, while yield will increase by 70 percent. Irrigated areas will grow by 30 percent from 6.1 to 7.8 million hectares, while irrigated yields will improve by 35 percent. Most of the crop production will take place under rainfed conditions.

7.25 By and large, agricultural production in SSA countries will be able to keep up with demand increases in main staples (roots and tubers). SSA as a whole will be self-sufficient in major staple crops. And the majority of the countries will be close to self-sufficient in tuber crops with less than 5 percent of the production traded within SSA (Table 8 and annex).

Table 8: Food supply in 2025, baseline

	Percentage met from irrigated	***Percentage met from rainfed***	***Percentage met from trade****
Cassava & other roots & tubers	0.1%	100%	0%
Sweet potatoes	0.1%	100%	0%
Maize	3%	69%	29%
Other grains	2%	88%	10%
Wheat	17%	21%	62%
Rice	23%	49%	28%

Source: Watersim simulation.
* Imports from outside SSA, details by sub-region in annex.

7.26 The production of maize will fall short of demand by 22 million tons, with Ethiopia, Nigeria and Tanzania being the main importers. Because of changes in diet as a result of urbanization, wheat demand will outpace production by 15 million tons. While South Africa will export a minor quantity (0.5 million tons), nearly all wheat has to be imported from outside SSA, mainly from the USA, with Nigeria the biggest importer (3.6 million tons). Under a 'business as usual' scenario, SSA will import 6.4 million tons of rice, mainly to Senegal, South Africa and Nigeria.

7.27 Potential cereal trade opportunities, especially intra-regional trade, are quite small given the current African production structure. Without improving competitiveness (reducing both production and marketing costs), it would be hard to increase intra-regional trade and reduce imports of cheap foreign sources of rice, wheat, maize and other grains (Diao *et al.* 2003).

7.28 Under a baseline scenario, SSA will remain an importer of grains. Given the fast growing population and food demand, can SSA be food self-sufficient in the coming 25 years? Where will the additional food come from?

‘Rainfed scenario’: improved productivity in rainfed areas

7.29 In sub-Saharan Africa, over 60 percent of the population depends on rainfed agriculture, which generates between 30 to 40 percent of those countries’ gross domestic products (World Bank 1997, Rockström *et al.* 2003, Wani *et al*. 2003). Agricultural productivity is generally very low. Investing in upgrading rainfed systems can reduce poverty, malnutrition and environmental degradation. Rockström *et al.* (2003) argue that by reducing the risk of short dry spells during the growing season, it is possible to double or even quadruple cereal yields in SSA. What does this mean for food supply in SSA? Table 9 gives the results of a scenario, in which rainfed yields are doubled, while the area expands as in the baseline scenario (by 18 percent).

Table 9: Scenario double rainfed yields by 2025

	Irrigated area ***M ha***	***Irrigated yield*** ***Ton/ha***	***Rainfed area*** ***M ha***	***Rainfed yield*** ***Ton/ha***	***Production (m ton)***	***Percentage of demand imported***
Cassava	0.03	8.6	17.4	12.6	209.1	0%
Maize	0.66	3.1	26.5	2.7	73.6	2%
Other grains	0.68	1.9	52.8	1.4	75.2	4%
Rice	2.22	2.3	8.2	1.4	16.6	26%
Wheat	1.09	3.8	2.2	2.6	9.9	60%

Source: Watersim simulation.
Details by sub-region in annex.

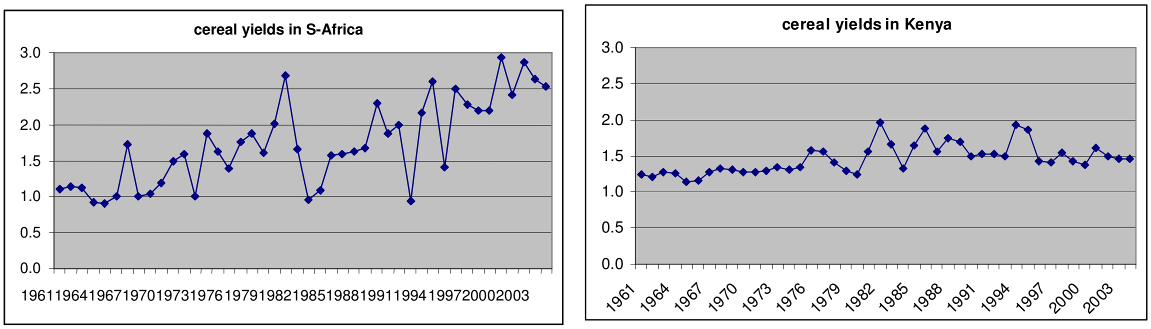
7.30 By doubling productivity of rainfed systems, SSA as a whole would be close to self-sufficient in tubers, maize and other grains, but would still need to import considerable amounts of wheat (mainly from the USA and Europe) and rice (from South-East Asia). It seems unlikely that SSA farmers will be able to compete with cheap grain imports, unless the USA and Europe abolish subsidies and SSA reduces marketing costs (i.e., through improved road network). Even so, to meet wheat demand, productivity needs to be more than quadrupled.

7.31 Although SSA as a whole will be close to food self-sufficiency in major staples, this scenario will lead to a slight increase in trade among SSA countries. Now less than 2 percent of the total maize production in SSA is traded. But because of differences in yield potential, the ‘rainfed’ scenario implies that 8 percent of the total maize production will be traded, with South Africa the biggest exporter and Democratic Republic of Congo, Tanzania, Ethiopia and Zambia the main importers. Likewise, at present, less than 1 percent of the other grain produce is traded internally. In the ‘rainfed’ scenario, this will increase to 6 percent, with Nigeria the biggest exporter and Niger and Sudan the main importers.

Upgrading rainfed agriculture

7.32 Relying on rainfed agriculture poses substantial risks to farmers because of unreliable rain and temporal and spatial variations at country level[1]. Harvests are always at risk, because of frequent short dry spells during the growing season, which reduce the volume of yields. They also have an indirect impact on cultivation as farmers are less likely to invest in inputs and land management due to the high risk of crop failure. No overall estimates on losses because of drought and short dry spells are available. But yield figures show an enormous year to year variation, especially in southern Africa, less so in East Africa, which is – at least partly -- related to unreliable rainfall.

Figure 4: Fluctuating cereal yields in South Africa and Kenya



Source: FAOstat database.

7.33 Preliminary estimates from the Watersim model indicate that yield reduction due to water stress in maize cultivation could be up to 47 percent (Angola, Zimbabwe, South Africa), with an overall average for SSA of 32 percent. This implies that by eliminating water shortage during dry spells, productivity may be improved by nearly one third, without counting the impact of improved input as a result of decreased risks.

7.34 Rockstöm *et al.* (2003) argue that mitigating the risk of these dry spells through soil and water conservation, water harvesting techniques and small scale irrigation can double or even quadruple productivity in drought-prone tropical regions.

7.35 Water harvesting is a *spatial* intervention defined as the process of concentrating rainfall as runoff from a larger area for use in a smaller target area. The process is distinguished from irrigation by three key features: first, the “catchment” area is contiguous and small; second, the application to the target area is essentially uncontrolled —the objective is simply to capture as much water as possible and store it within reach of the plant(s), in the soil profile of a cultivated area or in some type of reservoir; third, water harvesting can be used to concentrate rainfall for purposes other than crop production (Oweis *et al.* 1999). Supplemental irrigation (SI) is a *temporal* intervention defined as the application of a limited

---

[1] The overall production in SSA is reasonably stable, because fluctuations in individual countries cancel out.

amount of water to the crop, when rainfall fails to provide sufficient water for plant growth to increase and stabilize yields. The additional amount of water alone is inadequate for crop production. Hence, the essential characteristic of SI is the supplemental nature of rainfall and irrigation (Oweis *et al.* 1999).

7.36 Water harvesting and supplementary irrigation techniques are well known and have been used in many Sub-Saharan countries. Many examples of traditional and exogenously introduced systems are described in literature. Examples include: *tabia's* in Tunisia (Nasri *et al.* 2004 and Ouessar *et al.* 2004), earth ponds and cisterns in Jordan (Alkhaddar 2003 and Jabarin 2003), *guimelther* in Cameroon (Fonteh and Nji 2002), sloped maize fields in Tanzania (Hatibu *et al*. 2003 and Gowing *et al*. 2003), farm ponds in Burkina Faso (Fox and Rockström 2003), intercropping and silt traps in Ethiopia (Abdelkdair and Schultz 2005, Zigta and Waters-Bayer 2001, Pender and Gebremedhin 2004), small ponds in Burkina Faso and Kenya (Fox *et al*. 2001), trench and water pan technologies in Kenya (Lagat *et al*. 2003), infiltration pits in Zimbabwe (Magube, 2004), *majaluba* in Tanzania (Senkondo *et al*. 2000; and van Dijk and Ahmed, year unknown), traditional techniques in Uganda (Zaman, 2003), Syria (Salkini and Ansell 1992), Sudan (El Sammani and Dabloub 1996) and Malawi (Mangisoni and Phiri 1996)[2].

7.37 Without exception, these studies report a positive impact on yields, even up to a two or threefold increase. From a biophysical point of view, water harvesting has proven successful in a variety of settings. Further, the studies that addressed economic aspects of rain water harvesting report positive cost benefit analyses (among others Kunze 2000, Sekondo *et al.* 2000 and Matabazi *et al.* 2004). Note that these studies may give a biased (optimistic) picture as successful cases have a larger probability of being reported and published than failures.

7.38 Many scholars have pointed to its potential in boosting food production and alleviating rural poverty. However, scaling up local successes in water harvesting poses major challenges and the adoption rate of traditional and non-traditional techniques is low. Holden *et al.* (2004) describe how farmers dismantled exogenously introduced soil and water conservation structures in Ethiopia, as they reduced the effective cropping area without increasing yields in the short run and the fertile soil collected behind the structures could be used elsewhere to increase short term production. Others point to high initial labour costs and lack of short term benefits.

7.39 The problems of adoption seem to relate to the socio-economic setting, low profitability and high risks of agriculture in general, rather than to bio-physical problems inherent to the techniques themselves. These problems plague the irrigation sector as well as rainfed agriculture (see discussion below).

7.40 What does the 'rainfed' scenario mean for water resources? Water harvesting and small scale irrigation techniques augment the quantity of evapotranspiration. In the extreme – and unlikely -- case that all short dry spells are eliminated and actual evapotranspiration would equal potential evapotranspiration, an additional 360 km^3 would be evaporated according to preliminary estimates from the

---

[2] Mati et al. (forthcoming, 2005) provides an overview of these technologies as used in eastern and southern Africa.

Watersim model (Table 10). The increase in evapotranspiration is most likely to have an impact on river discharge and groundwater recharge downstream. No studies are available to quantify this claim.

Table 10: Potential and actual evapotranspiration for SSA (average year)

Crop	*ET pot (km3)*	*ET act (km3)*	*Yield reduction*
Cassava	92	57	30%
Maize	138	82	32%
Other grain	243	139	28%
all crops	***890***	***540***	

Source: Watersim simulation.

7.41 This illustrates the need to think in terms of agricultural water management, rather than distinguishing strictly between rainfed versus irrigated agriculture (Rockström *et al*. 2003). Major gains in productivity can be made by upgrading existing rainfed agriculture by making water supply to crops more reliable. Low-cost approaches such as treadle pumps, water bags, and water harvesting can provide the key to unlocking rainfed potential and reducing poverty on marginal rainfed lands (Molden and de Fraiture 2004; and SIWI and IWMI 2004; see also Van Koppen et al. 2005).

Role of formal irrigation in food supply

7.42 With less than 4 percent of total harvested area irrigated (most of which is in just three countries), SSA has a very low rate of irrigation development compared to other regions. While in a few basins actual water use is close to the potential, in the majority of basins water scarcity is due to the lack of water infrastructure rather than a physical shortage. Out of the potential of 36 million hectares (as assessed by FAO, 1997), only 6 million hectares are currently under formal irrigation, leaving ample scope for expansion. How far can irrigation play a role in food production? What will be the implications for water use and trade?

7.43 At present, wheat and rice are the main irrigated food crops. As demand will roughly double in the coming 25 years, an additional 22 million tons of wheat and 16 million tons of rice will be needed as compared to 2000 production levels. Presently, wheat and rice production and demand are concentrated in a few countries. Three countries (Ethiopia, Nigeria and South Africa) account for more than 60 percent of the total demand. Ethiopia and South Africa produce 80 percent of the total wheat in SSA, but due to high domestic demand still need to import. Nigeria imports more than 95 percent of its wheat. The production of rice is equally skewed. Madagascar and Nigeria produce 55 percent of SSA's total rice; in Madagascar this is mainly under irrigated conditions.

7.44 The Commission for Africa (2005) recommends doubling the area under irrigation by 2015. Doubling the area under formal irrigation – potential allowing – leads to an additional 4.2 million hectares. Assuming that additional new areas will be planted with rice and wheat and yields will grow at the same rate as in the 'business as usual' scenario, SSA can be self-sufficient in rice but still needs to import 10 million tons of wheat. Because of differences in irrigation potential, rice and wheat demand trade in this scenario will play an increasingly important role. South Africa, with its limited scope for further irrigation development, would be a big importer, as will Nigeria, where wheat demand is high but production potential low. Sudan – with a large scope of irrigated area expansion – would be an exporter of wheat.

Table 11: Wheat and rice production after doubling formal irrigated area

	Irrigated area (m ha)	***Irrigated yield (ton/ha)***	***Rainfed area (m ha)***	***Rainfed yield (ton/ha)***	***Production (m ton)***
Wheat	2.2	3.75	2.2	2.33	13.4
Rice	4.4	2.39	8.2	1.34	21.5

Source: Watersim simulation.
* Details by sub-region in annex.

7.45 This scenario has significant implications for water use, including the need for additional water infrastructure and trade between SSA countries. Table 12 shows the expansion of irrigated areas and irrigation water depletion in major basins.

Table 12: Irrigated area and irrigation water depletion by basin

Basin	***Irri area 2000***	***Irri area 2025***	***depletion 2000***	***depletion 2025***
Lake Chad	0.05	0.10	0.58	1.10
Senegal	0.13	0.32	2.11	4.93
East African Coast	0.23	0.46	0.73	1.39
Volta	0.24	0.52	4.21	8.67
Zambezi	0.25	0.51	3.18	6.16
Limpopo	0.27	0.30	2.14	2.26
Orange	0.39	0.42	2.12	2.32
Horn of Africa	0.46	0.90	5.52	9.80
Niger	0.64	1.20	7.96	13.93
Madagascar	0.94	1.50	7.32	11.84
South African Coast	0.95	1.45	4.32	6.26
Total SSA	**6.20**	**10.40**	**50.80**	**84.70**

Source: Watersim simulation.

7.46 The additional *depletion* for irrigation required in this scenario amounts to 34 km^3, corresponding with some 90 km^3 of additional water *withdrawals*[3]. Water and land resources are available, but this requires substantial investments in infrastructure. The Commission for Africa (2005) estimates 20 billion dollars are needed for infrastructure development, including roads and irrigation. Compared to others, this estimate seems low. At 5,000 to 8,000 US$ per hectare (Rosegrant

---

[3] Water withdrawals are higher than depletion of return flows (refer to Molden 1997 for terminology)

and Perez 1997), 4.2 million hectares will require an investment of 20-35 billion dollars, just for irrigation infrastructure. Adding the essential investments for roads and marketing infrastructure, without which irrigation will not be viable, the cost per hectare can be as much as 18,000 US$ per hectare (Rosegrant *et al.* 2005), corresponding to 75 billion total.

7.47 Scenario results indicate that irrigation will likely play a very limited role in food supply. First, even by doubling the irrigated area under cereals, its share in food production remains small. Less than 8 percent will originate from irrigation. Second, this scenario is not very plausible from an economic point of view. With high marketing costs and limited marketing opportunities within SSA, it is unlikely that irrigated wheat will be able to compete with cheap cereal imports from US and Europe. Third, investment costs to double the irrigated area are very high.

7.48 Irrigated agriculture may play a bigger role in the production of commercial crops (mainly sugar and cotton). But, as Diao *et al.* (2003) show, without additional policy changes (both in industrial as well as SSA countries) and massive investments in infrastructure, marketing opportunities remain limited. Further, without economic growth in non-agricultural sectors, the overall impact of investments in agriculture on income will be very limited.

Potential use of groundwater for irrigation

7.49 The lack of statistics on availability and use prohibits a systematic picture of groundwater potential in SSA. Recent analyses suggest that hydrogeology in SSA generally limits groundwater irrigation to small areas with limited yields. Use is therefore generally limited to small scale applications for small gardens, livestock, and domestic water supply (Giordano forthcoming). With less than 1.5% of the rural households using groundwater for crop production, the role of groundwater in the agricultural economy is very small (Giordano forthcoming). Although groundwater irrigation can yield high returns regionally and locally –especially in the livestock sector-, it is unlikely to account for a large share of crop production in Sub-Saharan Africa. Groundwater aquifers in much of the region are fragmented and discontinuous, and with slow recharge. In many cases, the water may be over 100 meters deep and therefore costly to extract (FAO 1986, Rosegrant and Perez 1997). Groundwater may play a role in supplementary irrigation locally, where aquifers are shallow.

CONCLUSIONS

7.50.1 SSA is currently self-sufficient in major staple crops such as cassava, sweet potatoes, other root and tubers, maize and coarse grains (millet, sorghum). Except for rice and wheat, the role of irrigation and trade in food supply is negligible with 98 percent coming from rainfed agriculture and less than 5 percent imported from outside SSA. With less than 4 percent of total harvested area irrigated (most of which is in just three countries), SSA has an extremely low rate of irrigation development compared to other regions. Of the potential irrigation area of 36 million hectares – as estimated by FAO – only 6 million hectares are currently developed, leaving ample scope for expansion. Yet it seems unlikely that irrigation will play a major role in food production in the coming decades, mainly because of the high costs involved.

7.51 By doubling productivity of rainfed systems, SSA as a whole would be close to self-sufficient in tubers, maize and other grains, but it still needs to import considerable amounts of wheat. It seems unlikely that SSA farmers will be able to compete with cheap grain imports, unless the USA and Europe abolish subsidies and SSA reduces marketing costs (i.e., by improving road networks). Even so, to meet the demand for wheat, productivity needs to be more than quadrupled. Although SSA as a whole will be close to food self-sufficiency in major crops, this scenario will lead to an increase in trade among SSA countries.

7.52 Actual yields in rainfed areas are low partly because of unreliable rainfall (i.e., short dry spells that reduce yields and pose a risk to farmers, who are less inclined to invest in inputs as a result). The physical potential to increase yields by better water management in rainfed areas (water harvesting and small scale supplementary irrigation) is high. Literature provides numerous examples of success stories. However, low adoption rates of water harvesting techniques indicate that upscaling local successes poses major challenges. Physical and technological potential does not seem the major constraint here.

Irrigation or rainfed: A discussion on potential

7.53 There is no easy answer to the question whether investments in agriculture should focus on irrigation or upgrading rainfed agriculture. From a physical and technical point of view, both hold considerable potential. Rather than assessing the physical potential, the question is why this potential is not being realized.

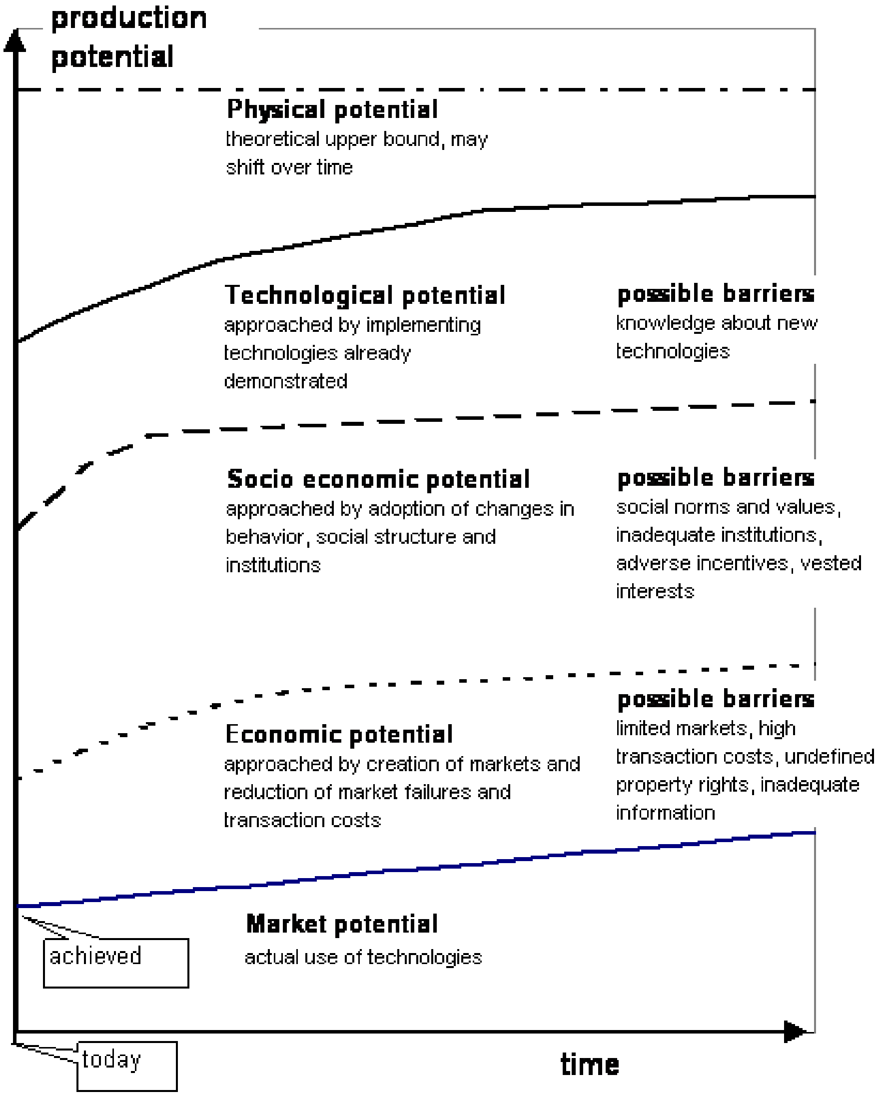
7.54 The IPCC (2001) developed a framework to analyze the potential of lowering the emission of green house gasses by adopting environmentally friendly techniques, which may be helpful for the discussion here. The framework distinguishes between five types of potential (Figure 5). The physical potential provides the theoretical upper bound, which may shift over time due to technological breakthroughs. The physical irrigation potential is bounded by availability of land and water resources. The physical potential of rainwater harvesting techniques is bounded by the total quantity and variability of rain and soil properties. In practice, the upper bound is given by the technological potential, which is realized if all available best techniques were adopted by all farmers. At the lower end of the spectrum lies the market potential, which corresponds with the actual use of available techniques. The gap between market potential and technological potential is caused by barriers – defined as any obstacle to reaching a potential that can be overcome by a policy, program, or measure. Two broad categories of barriers are distinguished: economic and socio-economic. The economic potential is approached if markets are ubiquitous and functioning optimally, and transaction costs are minimized. The socio-economic potential is approached if all institutional and cultural barriers are removed. Note that the economic and socio-economic potential can fall anywhere between the market and technological potential, not necessarily in the order depicted in the figure.

7.55 In both irrigated and rainfed agriculture in SSA, there is a big gap between market and technological potential. The diffusion of techniques that enhance land and water productivity (such as water harvesting and irrigation) is hampered by several barriers. A major problem is the lack of domestic market infrastructure, trade barriers to international markets and high marketing costs caused by poor roads (Diao *et al.* 2003, Rosegrant *et al.* 2001, Rosegrant and Perez 1997, Moussa 2002, Oweis *et al*. 1999, IAC 2003). Other barriers include poor governance, disincentives for profitable agriculture (taxes, rent seeking, land tenure arrangements) and high level of risk discouraging farmers to invest in labor and other inputs (Rockström 2004).

7.56 While the potential of irrigated agriculture to increase and stabilize production is greater than that of upgrading rainfed, the barriers to realizing this potential seem much higher. First, it requires an enormous public investment. While donors have recently agreed to increase grants to Africa (Commission for Africa 2005), institutional strength and absorptive capacity may prove insufficient for a rapid irrigated area expansion. Second, because the practice of irrigated agriculture is not widespread, knowledge and ability to – communally – manage irrigation schemes may be insufficient at farmer group level.

7.57 Without investments in rural infrastructure, the possibilities of scaling up local successes in rainfed and irrigated agriculture remain uncertain.

Figure 5: Analytical frame work of potential



Source: adapted from IPCC, 2001.
Note that economic and socio-economic potentials may lie anywhere between market and technological potential.

REFERENCES

Abdelkdair, A. and R.C. Schultz. 2005. Water harvesting in a ‘runoff-catchment’ agroforestry system in the dry lands of Ethiopia. *Agroforestry Systems* 63(3): 291-298.

Alkhaddar. 2003. Water harvesting in Jordan using earth ponds. *Waterlines* 22(2): 19-21.

AQUASTAT: http://www.fao.org/ag/agl/aglw/aquastat/main/index.stm

Commission for Africa 2005. *Our common interest.* Report of the Commission for Africa. March 2005. Internet [accessed 505]. http://213.225.14043/english/report/introduction.html

Diao, X., P.; Dorosh, and Rahman, S.M. 2003. *Market opportunities for African agriculture: An examination of demand-side constraints on agricultural growth.* DSGD Discussion paper no.1. Washington DC: International Food Policy Research Institute

El Sammani, M.O. and Dabloud, S.M.A. 1996. Making the most of local knowledge: water harvesting in the Red Sea Hills of Northern Sudan. In *Sustaining the soil: Indigenous soil and water conservation in Africa*. Eds. C. Reij, I. Scoones and C. Toulman. Earthscan London

FAO (Food and Agricultural Organization). 1986. *Irrigation in Africa South of the Sahara*. Investment Centre Technical Paper Number 5. Rome: FAO.

FAO (Food and Agricultural Organization). 1997. *Irrigation potential in Africa: A basin approach*. Land and water Bulletin no. 4. FAO Land and Water Development Division

FAO (Food and Agricultural Organization). 2002. *World agriculture: towards 2015/2030*. Summary report. http://www.fao.org/documents/show_cdr.asp?url_file=docrep/004/y3557e/y3557e00.htm

FAOSTAT: http://faostat.fao.org/

Fonteh, M.F and Nji, A. 2002. Potential and constraints to the adoption of water harvesting technologies in traditional economies. *Discovery and Innovation* 14 (3-4): 202-214

Fox, P.; Rockström, J. and.Barron, J. 2001. Risk analysis and economic viability of water harvesting for supplemental irrigation in semi-arid Burkina Faso and Kenya. *Agricultural Systems* 83(3): 231-250.

Fox, P. and Rockström, J. 2003. Supplemental irrigation for dry-spell mitigation of rainfed agriculture in the Sahel. *Agricultural Water Management* 61(1): 29-50.

Giordano, M. forthcoming. Agricultural groundwater use and rural livelihoods in Sub-Saharan Africa: A first-cut assessment. Accepted for publication in: *Hydrogeology*

Gowing, J.W, Young, M.D.; Hatibu, N.; Mahoo, H.F.; Rwehumbiza, F. and Mzirai, O.B. 2003. Developing improved dryland cropping systems for maize in semi-arid Tanzania. Part 2: Use of a model to extrapolate and add value to experimental results. *Experimental Agriculture* 39(3): 293-306.

Hatibu, N. 2003. Rainwater management: Strategies for improving water availability and productivity in semi-arid and arid areas. *Issues of water management in Agriculture: Compilation of essays*. Comprehensive Assessment.

Hatibu, N.; Young, M.D.; Gowing, J.W.; Mahoo H.F and Mizrai, O.B. 2003. Developing improved dryland cropping systems for maize in semi-arid Tanzania. Part 1: Experimental evidence for the benefits of rainwater harvesting. *Experimental agriculture* 39(3): 279-292.

Holden, S.; Shiferaw, B. and Pender, J.. 2004. Non-farm income, Household welfare and sustainable land management in a less-favoured area in Ethiopian highlands. Discussion paper D-06/2004. Department of Economics and Resource Management. Agricultural University of Norway.

International Commission On Large Dams (ICOLD). 2003. World registry of dams. http://icold-cigb.org

Intergovernmental Panel on Climate Change (IPCC). 2001. Climate change 2001: Mitigation. Technical summary. A Report of Working Group III of the Intergovernmental Panel on Climate Change

InterAcademy Council (IAC). 2003. Realizing the promise and potential of African agriculture. http:///www.interacademycouncil.net/report

Islam, S, Saleh, A.F., and Bhuiyan, S.I... 1998. Agro-hydrologic and economic analyses of on-farm reservoirs for drought alleviation in rainfed ricelands of North-West Bangladesh. *Rural and environmental engineering* 35(8): 15-26.

Jabarin. 2003. The economics of water harvesting techniques in the arid zones of Jordan. *Agricultural Sciences* 30(3): 364-3723.

Kherallah, M,; Delgado, C.; Gabre-Madhin, E.; Minot, N. and Johnson, M.. 2002. *Reforming agricultural markets in Africa.* Baltimore: Baltimore, MD: John Hopkins University Press.

Kunze, D., 2000. Economic assessment of water harvesting techniques: A demonstration of various methods. *Quarterly Journal of International Agriculture* 39 (1): 69-91.

Lagat, J.K.; Ithinji, G. K. and Buigut, S.K.. 2003. Determinants of the adoption of water harvesting technologies in the marginal areas of Nakuru District, Kenya: The case of trench and water pan technologies. *Eastern Africa Journal of Rural Development* 19(1): 24-32.

Mangisoni, J.H. and Phiri, G. S. 1996. New perspectives on local conservation techniques: a case study from Malawi. In *Sustaining the soil: indigenous soil and water conservation in Africa,* eds. Reij, C.; Scoones, I. and Toulman, C. London: Earthscan.

Mati, B., de Lange, M., Penning de Vries, F., Merrey, D. J., and Bossio, D. Forthcoming 2005. An overview of adaptable technologies and approaches in rainfed agriculture in Eastern Africa. Unpublished paper being revised for publication as IWMI Working Paper. Pretoria, South Africa: IWMI.

Molden, D. 1997. Accounting for water use and productivity. SWIM Paper 1. Colombo, Sri Lanka: International Irrigation Management Institute.

Molden, D. and de Fraiture, C. 2004. Investing for Water for Food, Ecosystems and Livelihoods. Blue Paper Discussion Draft. Colombo, Sri Lanka: International Irrigation Management Institute. Available from: http://www.iwmi.cgiar.org/assessment/FILES/pdf/BluePaper.pdf

Moussa, S. Z. 2002. Technology transfer for agriculture growth in Africa
Economic Research Papers no 72. African Development Bank. Cote d'Ivoire.

Mugabe, F.T. 2004. Evaluation of the benefits of infiltration pits on soil moisture in semi-arid Zimbabwe. *Journal of Agronomy* 3(3): 188-190.

Mutabazi, K.D.; Sekondo, E. E.; Tumbo, D.S.; Mbilinyi, B.P.; Mahoo, H. F. and Hatibu, N. 2004. Economics of rainwater harvesting for crop enterprises in semi-arid areas: The case of Makanya watershed in Pangani River Basin, Tanzania.

Nasri, S., Albergel, J, Cudennec, C. and Berndtsson, R. 2004. Hydrological processes in macrocatchment water harvesting in the arid region of Tunesia: The traditional system of Tabias. *Hydrological Science Journal* 4(2): 261-272.

Ng, F. and A. Yeats. 2000. *On the recent trade performance of Sub-Saharan African countries: Cause for hope or more of the same?* Washington DC: World Bank.

Ouessar, M.; Sghaier, M.; Mahdi, N.; Abdelli, F.; de Graaff, J.; Chaieb, H.; Yahyoui, H. and Gabriels, D.. 2004. An integral approach for impact assessment of water harvesting techniques in dry areas: The case of oued Oum Zessar watershed, Tunesia. *Environmental Monitoring and Assessment* 99(1/3): 127-140.

Oweis, T.; Hachum, A. and Kijne, J. 1999. *Water harvesting and supplementary irrigation for improved water use efficiency in dry areas.* SWIM Paper 7. Colombo: International Water Management Institute.

Pender, J. and Gebrmedhin, B. 2004 Impacts of policies in dryland agriculture: Evidence from northern Ethiopia. In *Challenges and strategies for dryland agriculture*, ed. Rao, . CSSA special publication 32. American Society of Agronomy and Crop Science of America.

Rockström. J. 2004. Making the best of climatic variability: Options for upgrading rainfed farming in water scarce regions. *Water Science and Technology* 49(7): 151-156.

Rockström, J.; Barron, P. and Fox, P. 2003. Water productivity in rainfed agriculture: Challenges and opportunities for smallholder farmers in drought-prone tropical agroecosystems. In Water productivity in agriculture: Limits and opportunities for improvement, eds. Kijne, J. W.; Barker, R.; and Molden. D. Colombo: CABI.

Rosegrant, M. and N.D. Perez. 1997. *Water resources development in Africa: A review and synthesis of issues, potentials and strategies for the future*. EPTD Discussion paper no. 28. Washington DC: International Food Policy Research Institute.

Rosegrant, M.; Cline, S., Li, W.; Sulser, T.; and Valmonte-Santos, R. 2005. *Looking ahead: Long-term prospects for Africa's agricultural development and food security.* 2020 Discussion Paper. Washington DC: International Food Policy Research Institute.

Salkini, A.B. and Ansell, D. 1992. *Agro-economic impact of supplemental irrigation on rainfed wheat production under the Mediterranean environment of Syria.* International conference on supplementary irrigation and drought water management. Vol 1.

Senkondo, E.M.M,; Msangi, A.S.K.; Xavery, P.; Lazaro, E.A. and Hatibu, N., 2000. Profitability of rainwater harvesting for agricultural production in selected semi-arid areas of Tanzania. *Journal of Applied Irrigation Science* 39(1): pp 65-81.

Stockholm International Water Institute (SIWI) and International Water Management Institute (IWMI). 2004. Water – More nutrition per drop. http://www.siwi.org/downloads/More_Nutrition_Per_Drop.pdf

Van Dijk, J. and Ahmed, M.H. unknown year. Opportunities for expanding water harvesting in Sub-Saharan Africa: The case of the teras of Kassala, Tanzania IIED GATEKEEPER SERIES No. 40.

Van Koppen, B., Safilios-Rothschild, C., Namara, R. 2005. Reducing poverty through investments in agricultural water management. 2 parts. Report to African Development Bank under the Collaborative Program on Trends and Opportunities for Investments in Agricultural Water Management in sub-Saharan Africa. Pretoria, South Africa: IWMI.

Wani, S. P.; Pathak, P.; Sreedevi, T. K.; Singh, H. P. and Singh, P. 2003. Efficient management of rainwater for increased crop productivity and groundwater recharge in Asia. In Water productivity in agriculture: Limits and opportunities for improvement, eds. Kijne, J. W.; Barker, R. and Molden. D. Colombo: CABI.

World Bank. 1997. World development Report 1997. Washington DC: World Bank.

Zaman, A. 2003. Farmer-managed small-scale irrigation systems for sustainable crop production in Uganda, East-Africa. *Journal of Food, Agriculture and Environment* 1(3/4): 312-315

ANNEX 1: TABLES

Yields and areas, FOOD CROPS, BASELINE

Sub-region*	Irrigated area in million hectares	Rainfed area in million hectares	Irrigated yield in ton per ha	Rainfed yield in ton per ha	Total production in million ton	% from irrigated
Central	0.00	3.24	0.00	7.77	25.14	0%
Eastern	0.03	3.20	8.84	8.31	26.82	1%
Gulf of guine	0.00	6.99	0.00	7.34	51.37	0%
Madagscar	0.00	0.38	0.00	7.03	2.68	0%
Safrica	0.00	0.00	0.00	0.00	0.00	0%
Sudano-sahel	0.00	0.12	0.00	6.26	0.77	0%
total SSA	***0.03***	***13.93***	***8.84***	***7.65***	***106.78***	***0%***

Cassava and other roots & tubers

*follows region definitions as in FAO demand study

Maize

Sub-region	Irrigated area in million hectares	Rainfed area in million hectares	Irrigated yield in ton per ha	Rainfed yield in ton per ha	Total production in million ton	% from irrigatedi
Central	0.00	2.60	0.00	0.96	2.50	0%
Eastern	0.11	10.55	2.12	1.43	15.34	2%
gulf of guine	0.02	5.86	2.70	1.20	7.10	1%
madagscar	0.00	0.19	0.00	0.91	0.18	0%
Safrica	0.36	3.20	3.50	2.49	9.21	14%
Sudano-sahel	0.11	1.02	1.27	1.15	1.31	10%
total SSA	***0.60***	***23.43***	***2.81***	***1.45***	***35.65***	***5%***

Rice

Sub-region	Irrigated area in million hectares	Rainfed area in million hectares	Irrigated yield in ton per ha	Rainfed yield in ton per ha	Total production in million ton	% from irrigatedi
Central	0.04	0.46	1.56	0.50	0.29	19%
Eastern	0.12	0.67	1.86	0.80	0.77	30%
gulf of guine	0.07	3.11	2.16	0.93	3.03	5%
madagscar	0.90	0.30	1.48	1.16	1.67	79%
Safrica	0.00	0.00	1.96	0.00	0.00	100%
Sudano-sahel	0.37	0.28	1.83	0.81	0.90	75%
total SSA	***1.49***	***4.82***	***1.63***	***0.88***	***6.65***	***36%***

Wheat

Sub-region	Irrigated area in million hectares	Rainfed area in million hectares	Irrigated yield in ton per ha	Rainfed yield in ton per ha	Total production in million ton	% from irrigatedi
central	0.00	0.02	0.00	0.80	0.01	0.00
eastern	0.06	1.33	5.71	1.25	2.01	0.17
gulf of guine	0.02	0.03	2.39	1.13	0.07	0.58
madagscar	0.00	0.00	0.00	2.47	0.01	0.00
safrica	0.63	0.21	2.97	1.46	2.17	0.86
sudano-sahel	0.13	0.03	1.90	1.18	0.28	0.89
total SSA	***0.84***	***1.62***	***2.99***	***1.28***	***4.56***	***0.55***

Yields and areas, BASELINE (continued)

Other grains

Sub-region	Irrigated area in million hectares	Rainfed area in million hectares	Irrigated yield in ton per ha	Rainfed yield in ton per ha	Total production in million ton	% from irrigatedi
central	0.00	0.94	0.00	0.76	0.72	0.00
eastern	0.04	5.83	1.48	0.97	5.70	0.01
gulf of guine	0.00	13.57	0.00	1.04	14.04	0.00
madagscar	0.00	0.00	0.00	0.50	0.00	0.00
safrica	0.03	0.24	2.54	1.64	0.47	0.17
sudano-sahel	0.51	22.03	1.41	0.49	11.59	0.06
total SSA	***0.59***	***42.61***	***1.48***	***0.74***	***32.52***	***0.03***

Potatoes

Sub-region	Irrigated area in million hectares	Rainfed area in million hectares	Irrigated yield in ton per ha	Rainfed yield in ton per ha	Total production in million ton	% from irrigatedi
central	0.00	0.06	0.00	4.49	0.25	0.00
eastern	0.00	0.62	0.00	9.19	5.66	0.00
gulf of guine	0.03	0.10	7.29	3.89	0.59	0.36
madagscar	0.00	0.05	0.00	5.94	0.29	0.00
safrica	0.01	0.04	37.65	27.63	1.64	0.28
sudano-sahel	0.01	0.00	7.84	6.98	0.08	0.66
total SSA	***0.05***	***0.86***	***14.96***	***9.02***	***8.51***	***0.08***

Sweet potatoes

Sub-region	Irrigated area in million hectares	Rainfed area in million hectares	Irrigated yield in ton per ha	Rainfed yield in ton per ha	Total production in million ton	% from irrigatedi
central	0.00	0.32	0.00	5.52	1.75	0.00
eastern	0.00	1.43	0.00	4.26	6.09	0.00
gulf of guine	0.00	3.77	0.00	9.21	34.69	0.00
madagscar	0.00	0.09	0.00	5.70	0.52	0.00
safrica	0.00	0.01	4.48	3.30	0.04	0.23
sudano-sahel	0.00	0.13	15.70	4.93	0.66	0.05
total SSA	***0.00***	***5.74***	***10.09***	***7.61***	***43.73***	***0.00***

Yields and areas, CASH CROPS, BASELINE

Sugar

Sub-region	Irrigated area in million hectares	Rainfed area in million hectares	Irrigated yield in ton per ha	Rainfed yield in ton per ha	Total production in million ton	% from irrigatedi
central	0.20	18.77	0.01	33.16	4.04	0.09
eastern	0.15	18.58	0.21	93.68	22.52	0.88
gulf of guine	0.04	18.50	0.02	31.82	1.41	0.48
islands	0.04	26.99	0.03	39.90	2.19	0.54
safrica	0.32	69.02	0.00	0.00	22.09	0.00
sudano	0.00	0.00	0.13	55.90	7.38	1.00
total	***0.74***	***40.78***	***0.40***	***72.55***	***59.62***	***0.49***

Cotton

Sub-region	Irrigated area in million hectares	Rainfed area in million hectares	Irrigated yield in ton per ha	Rainfed yield in ton per ha	Total production in million ton	% from irrigatedi
central	0.38	0.31	0.00	0.00	0.12	0.00
eastern	1.08	0.18	0.19	0.49	0.28	0.32
gulf of guine	1.13	0.34	0.00	0.00	0.38	0.00
islands	0.02	0.60	0.00	0.00	0.01	0.00
safrica	0.06	0.51	0.01	0.16	0.03	0.04
sudano	1.04	0.36	0.14	0.38	0.43	0.12
total	***3.70***	***0.30***	***0.34***	***0.43***	***1.26***	***0.12***

Fruits

Sub-region	Irrigated area in million hectares	Rainfed area in million hectares	Irrigated yield in ton per ha	Rainfed yield in ton per ha	Total production in million ton	% from irrigatedi
central	0.10	0.07	0.01	0.00	1.07	1%
eastern	0.22	0.03	0.01	0.00	1.70	4%
gulf of guine	0.57	0.00	0.00	0.00	0.57	0%
islands	0.09	0.00	0.00	0.00	0.09	0%
sudano	0.09	1.53	0.13	0.00	1.76	69%
total	***1.07***	***0.14***	***0.15***	***0.00***	***8.77***	***14.8%***

Production, demand and trade, BASELINE

Cassava and other roots & tubers

sub region	demand 2000 (m ton)	production 2000 (m ton)	net trade 2000 (m ton)	demand 2025 (m ton)	production 2025 (m ton)	net trade 2025 (m ton)
Central	25.417	25.141	-0.276	58.26	56.178	-2.082
Eastern	26.602	26.865	0.263	51.741	52.09	0.349
gulf of guine	50.865	51.368	0.503	79.728	94.593	14.865
Madagscar	2.667	2.678	0.011	5.219	4.672	-0.547
Safrica	0.076	0	-0.076	0.082	0	-0.082
sudano-sahel	0.732	0.773	0.041	1.595	1.561	-0.034
total SSA	***106.36***	***106.83***	***0.47***	***196.63***	***209.09***	***12.47***

Maize

Central	2.694	2.503	-0.191	8.003	4.917	-3.086
Eastern	17.553	15.337	-2.216	39.341	25.634	-13.707
gulf of guine	7.096	7.100	0.004	14.452	11.129	-3.323
Islands	0.176	0.176	0.000	0.457	0.297	-0.160
Safrica	8.988	9.203	0.215	9.642	9.398	-0.244
Sudano	1.228	1.314	0.086	3.346	2.046	-1.300
total SSA	***37.74***	***35.63***	***-2.10***	***75.24***	***53.42***	***-21.82***

Rice

Central	0.667	0.287	-0.38	1.412	0.894	-0.518
Eastern	1.553	0.766	-0.787	2.83	1.646	-1.184
gulf of guine	5.19	3.03	-2.16	9.364	8.13	-1.234
Islands	1.914	1.665	-0.249	3.65	3.325	-0.325
Safrica	0.571	0.002	-0.569	0.724	0.003	-0.721
Sudano	2.009	0.899	-1.11	4.267	1.92	-2.347
total SSA	***11.9***	***6.65***	***-5.26***	***22.25***	***15.92***	***-6.33***

Wheat

Central	1.242	0.013	-1.229	3.107	0.038	-3.069
Eastern	4.831	2.010	-2.821	9.294	5.107	-4.187
gulf of guine	2.789	0.074	-2.715	5.159	0.199	-4.960
Islands	0.111	0.010	-0.101	0.236	0.025	-0.211
Safrica	2.757	2.167	-0.590	2.967	3.445	0.478
Sudano	1.872	0.281	-1.591	4.045	0.498	-3.547
total SSA	***13.60***	***4.56***	***-9.05***	***24.81***	***9.31***	***-15.50***

Production, demand and trade, BASELINE (cont)

Other grains

sub region	demand 2000 (m ton)	production 2000 (m ton)	net trade 2000 (m ton)	demand 2025 (m ton)	production 2025 (m ton)	net trade 2025 (m ton)
Central	0.866	0.716	-0.150	2.065	2.013	-0.052
Eastern	6.452	5.699	-0.753	14.257	13.032	-1.225
gulf of guine	14.376	14.048	-0.328	29.825	29.638	-0.187
Islands	0.007	0.001	-0.006	0.010	0.003	-0.007
Safrica	0.900	0.468	-0.432	0.948	0.580	-0.368
Sudano	12.323	11.590	-0.733	31.378	25.307	-6.071
total SSA	***34.92***	***32.52***	***-2.40***	***78.48***	***70.57***	***-7.91***

Potatoes

central	0.301	0.247	-0.054	0.596	0.728	0.132
eastern	5.130	5.659	0.529	9.701	14.150	4.449
gulf of guine	0.599	0.590	-0.009	0.865	1.094	0.229
islands	0.291	0.291	0.000	0.482	0.633	0.151
safrica	1.629	1.646	0.017	1.634	2.178	0.544
sudano	0.138	0.083	-0.055	0.266	0.155	-0.111
total SSA	***8.09***	***8.52***	***0.43***	***13.54***	***18.94***	***5.39***

Sweet potatoes

central	1.747	1.746	-0.001	4.019	4.270	0.251
eastern	6.131	6.086	-0.045	16.130	12.537	-3.593
Gulf of guine	34.724	34.683	-0.041	59.622	69.001	9.379
islands	0.520	0.518	-0.002	1.068	0.946	-0.122
safrica	0.036	0.039	0.003	0.037	0.045	0.008
sudano	0.649	0.656	0.007	1.477	1.337	-0.140
total SSA	***43.81***	***43.73***	***-0.08***	***82.35***	***88.14***	***5.78***

Irrigated area potential and realized in thousand hectares

Country	Potential	Realized	Percentage
Angola	3700	40	1%
Benin	322	14	4%
Botswana	13	1	8%
Burkina Faso	165	72	44%
Burundi	215	93	43%
Cameroon	290	36	12%
Central African Republic	1900	0	0%
Chad	335	22	7%
Congo, Dem Republic of	7000	10	0%
Congo, Republic of	400	0	0%
Côte d'Ivoire	475	155	33%
Eritrea	187.5	18	10%
Ethiopia	2700	204	8%
Gabon	440	8	2%
Ghana	1900	14	1%
Guinea	520	12	2%
Guinea-Bissau	281.3	31	11%
Kenya	353.1	64	18%
Lesotho	12.5	0	0%
Liberia	600	3	1%
Madagascar	1517	935	62%
Malawi	161.9	36	22%
Mali	566	292	52%
Mauritania	250	34	14%
Mozambique	3702	60	2%
Namibia	47.3	35	74%
Niger	270	69	26%
Nigeria	2331	262	11%
Rwanda	165	5	3%
Senegal	409	60	15%
Sierra Leone	807	25	3%
Somalia	240	168	70%
South Africa	1445	1456	101%
Sudan	2784	1324	48%
Swaziland	90	62	69%
Tanzania, United Rep of	2132	120	6%
Togo	180	7	4%
Uganda	90	13	14%
Zambia	523	47	9%
Zimbabwe	365.6	225	62%

Population and per capita income

Sub-region	population 2000 (million)	population 2025 (million)	annual population growth	per capita income 2000 (US$/cap)	per capita income 2025 (US$/cap)	annual income growth
Central	84.49	149.08	0.02	840.00	1868.00	0.03
Eastern	227.20	351.77	0.02	303.00	484.00	0.02
Gulf of guinea	160.60	258.18	0.02	309.00	427.00	0.01
Madagscar	15.97	29.03	0.02	252.00	320.00	0.01
Safrica	44.00	41.22	0.00	4148.00	7849.00	0.03
sudano-sahel	98.32	183.29	0.03	239.00	343.00	0.02
total ssa	***647.78***	***1036.46***	**1.90%**	***637***	***960***	***1.70%***

ANNEX 2: PROJECT TERMS OF REFERENCE

The primary objective of this component is to study the alternative options for alleviating poverty and contributing to food and water security for the sub-Saharan African countries. Specifically the following questions will be explored using the integrated global water-food model being developed by IWMI and IFPRI.

- The potential contribution of rainfed agriculture in the food supply and water demand equation
- The options of regional and international trade and their impact on food security in SSA region
- Implications for water and food policies, prices and also options of investments under different water supply and demand scenarios

Methodology and activities:
The global model on water and food accounting-WATERSIM (Water, Agriculture, Technology Environment and Resources Simulation Model) being developed by IWMI and IFPRI will be used for addressing the specific objectives of the study. The WATERSIM, covers 111 economic regions and 125 river basins of the world. Of which 40 economic regions and 18 river basins cover SSA region.

The food demand of 16 commodities for economic regions is estimated as a function of population, per capita consumption and prices of a commodity and the prices of competing commodities. The crop production under rainfed and irrigation conditions and the livestock production for each region is also estimated. The production function (including yield and area functions) for each crop is expressed as a function of a combination of variables from crop prices, inputs prices, labour, technology, irrigation water, water availability, investments, climate, potential yield etc. The local prices of the commodities are determined by the world market prices and the assumption of market clearance at global level.

The water demands for the irrigation, domestic, industrial sectors, for livestock and for the environment sector are estimated at river basin scale. The irrigation requirement of a river basin is the aggregate of the irrigation demands of food production units which fall in a river basin. The choice of technology, management variables, efficiencies are part of the assessment of water demand. The water supply for each river basin is expressed as a function of climate, hydrology, existing infrastructure, water related investments.

The food production regions are connected to each other in the model through international trade. The international and the regional prices of commodities are determined by balancing the global production and demand. The regional prices are then feed back into the demand functions which affect the food and water demand.

The model will be used to develop alternative water and food supply and demand scenarios with specific policy options related to sub-Saharan Africa. The alternative scenarios will specifically look at the available options including investments in irrigated and rainfed agriculture, trade (regional and international) for food security and poverty alleviation in the sub-Saharan African countries.

Outputs:
This component will provide three alternative future scenarios of water supply and demand for SSA and their policy implications for different countries.

1. Business as usual scenario, where present trends of investment in water related development continues in to the future,
2. More irrigation scenario, where increased investment is expected than at present, and

3. A scenario of more rainfed yield and more trade between regions within SSA or more trade with regions outside the SSS.

ANNEX 3: WATERSIM MODEL DESCRIPTION

Broadly-speaking the model consists of two integrated modules (figure 1): the ‘food demand and supply’ module, which is adapted from IMPACT developed by IFPRI (Rosegrant *et al.,* 2001); and the ‘water supply and demand’ module which uses a water balance based on the Water Accounting framework (Molden 1997) underlying PODIUM (Fraiture et al. 2000 and 2003) combined with elements from the IMPACT-WATER model (Cai and Rosegrant, 2002).

Spatial and temporal scale

Spatial units

To model hydrology adequately, it makes most sense to choose a river basin as basic spatial unit. When it comes to food policy analysis, administrative boundaries should be used -since trade and policy happen at national level, not at river-basin scale. WATERSIM takes a hybrid approach to its spatial units of analysis. Firstly, the world is divided into 125 major river basins of various sizes with the goal of achieving accuracy with regard to the basins most important to irrigated agriculture. Next, the world is divided into 115 economic regions including mostly single nations with a few regional groupings of nations. The food module uses the economic regions as basic modelling unit, while the water module runs at river basin scale. The interaction between food and water modules is facilitated by intersecting basins and regions into 282 sub-basins or Food Producing Units (FPU’s). The hydrological processes are modelled at basin scale by summing up relevant parameters and variables over the FPU’s that belong to one basin. Similarly, economic processes are modelled at regional scale by summing up relevant variables over the FPU’s belonging to one region.

Temporal scale

Economic processes are modelled at an annual time step, while hydrological and climate variables are modelled at a monthly time-step. Crop related variables are either determined by month (crop evapotranspiration) or by season (crop yield, area). The food supply and demand module runs at region level on a yearly time-step. The water supply and demand module runs at sub-basin level at a monthly time-step. For area and yield computations the relevant parameters and variables are aggregated over the months of the growing season.

The year 2000 is taken as base. Projections are made for the year 2025, but the model allows for shorter or longer projections as well.

Food module[4]

The food module is a partial-equilibrium agricultural production and trade model, that simulates global food production, consumption and trade levels consistent with

---

[4] largely based on IMPACT work, documented in Rosegrant, Agcaoili-Sombilla and Perez (1995); Rosegrant, Meijer and Cline (2002); and Rosegrant, Cai and Cline (2002).

observed technologies, input prices and water available for crop production. The model incorporates 32 food commodities – including all cereals, soybeans, roots and tubers, meats (including beef, pig meat, sheep and goat, and poultry), milk, eggs, oils, meals, fruits, sugarcane, sugar beet, cotton, eight fish commodities, fish oil, and fish meal. Despite its primary focus on the agricultural sector, the structure of the food module considers income growth in both the agricultural and non-agricultural sectors. It permits long-term projections of food prices, supply, demand and commodity trade.

The food supply and demand relationships respond to regional economic conditions and world food prices through a system of supply and demand elasticities, that translate price signals into food production and consumption levels. These elasticities are embedded in a system of non-linear equations representing the underlying behavioural and technological characteristics of each region. The supply and demand relationships include regional income and population levels, among other important socio-economic variables – such as agricultural technology. By iterative adjustment of the world prices, the solution algorithm of the food module finds the price levels at which the aggregate agricultural supply and demand levels for the world are equalized – thereby achieving a global partial equilibrium in food consumption and production. Consequently, food commodity prices are endogenous to the model.

Crop supply functions

Domestic crop production is determined by the area and yield response functions, formulated separately for production under irrigated and rainfed conditions. Harvested area is specified as a response to the crop's own price, the prices of other competing crops, the projected rate of an exogenous (non-price) growth trend, and water. 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 non-agricultural uses. Yield is a function of the commodity price, the prices of labour and capital, water, and a projected non-price exogenous trend factor. The trend factor reflects productivity growth driven by technology improvements, including crop management research, conventional plant breeding, wide-crossing and hybridization breeding, and biotechnology and transgenic breeding. Other sources of growth considered include private sector agricultural research and development, agricultural extension and education, markets, infrastructure, irrigation, and water. Annual production of crop commodity is estimated as the product of its area and yield. If water availability falls below a certain threshold, crop area and yield are reduced. This production response mechanism to water availability provides the essential link between the food and water modules.

Livestock supply functions

Livestock production is modelled similarly to crop production except that livestock yield reflects only the effects of expected developments in technology. 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. Total production is calculated by multiplying the slaughtered number of animals by the yield per head.

Demand functions

Domestic demand for a commodity is the sum of its demand for food, feed, and other uses. Food demand is a function of commodity price, prices of other competing commodities, per capita income, and total population. Per capita income and population increase annually according to region-specific growth rates. Feed demand is a derived demand determined by the changes in livestock production, feed ratios, and own- and cross-price effects. The feed demand equations incorporate a technology parameter reflecting improvements in feeding efficiencies. The demand for other uses is estimated as a proportion of food and feed demand.

Prices

World prices for food are endogenous to the system of equations that represent the underlying food production and consumption relationships[5]. Domestic prices are a function of world prices, and are expressed in terms of the local regional currencies, through exchange rates, and are further adjusted by the effect of regional price policy regimes and market characteristics. The effects are expressed in terms of the producer subsidy equivalent (PSE), the consumer subsidy equivalent (CSE), and the marketing margin (MI). The PSE and CSE 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. The marketing margin (MI) reflects other factors such as transport and marketing costs or product quality differences. To calculate producer prices, the world price is reduced by the MI value and increased by the PSE value, whereas the consumer prices are obtained by adding the MI value to the world price and reducing it by the CSE value. All the PSE, CSE and MI values are expressed as percentages of the world price.

International linkage through trade

In the global food module, regions are linked through food commodity trade, which is the difference between domestic production and demand for each region. Regions with positive trade balances in a commodity are net exporters of that good, while those with negative balances are net commodity importers. The specification of commodity trade within the food module is non-spatial, i.e.,, it does not permit a separate identification of importing and exporting regions of a particular commodity, nor the analysis of explicit spatial trade patterns and flows.

At the global aggregate level, the food module reaches an equilibrium in which net trade equals zero. The world price of a commodity is the equilibrating mechanism. When an exogenous shock is introduced in the model, the world price will adjust such that each adjustment is successively passed back to the effective producer and consumer prices via the price transmission equations. Changes in domestic prices subsequently affect commodity supply and demand, necessitating their iterative readjustments until world supply and demand balance, and the world net trade balance, again, equals zero.

Water module

The methodology adopted in the water demand and supply module is based on water balance at basin level using the concepts of the water accounting framework (Molden 1997) relating water demand to available water supply. Water demand for human purposes, besides environmental and in-stream purposes, is derived from four sectors -agriculture, domestic sector, industry and livestock. At sub-basin level, water availability is simulated using a water balance approach, considering internally generated runoff, inflow from other units, groundwater contributions existing infrastructure and management practices. Sub-basins are connected in such a way that outflow from

---

[5] Based on earlier work by Agcaoili, Oga and Rosegrant (1993); Oga and Gehlar (1993).

upstream becomes inflow into the lower sub-basin. When supply falls short of demand, the shortages are distributed over months, sectors and crops using an optimization model and allocation rules.

Agricultural water demand

WATERSIM differentiates between depletion and total diversions. Water depletion is defined as a use or removal of water from a basin that renders it unavailable for further use (Molden 1997). Water is depleted by four processes: evaporation, flows to sinks, pollution and incorporation into a product (for example, water taken up by crops incorporated into plant tissues). Total depletive demand consists of depletion in four sectors: irrigated agriculture, industry, domestic use and livestock.

Depletive water demand in agriculture is a function of the irrigated area, cropping pattern, crop water requirements, effective precipitation and effective efficiency. Crop water requirements are determined at a 0.1 x 0.1 degree global grid using cropping pattern information from AQUASTAT[6] crop coefficients taken from FAO (Allen et al. 1998, Doorenbos and Kassam 1979) and reference evaporation data from the IWMI-water-and-climate atlas[7]. The effective precipitation, defined as that part of the rainfall that is beneficially used by crops, is computed according to the SCS method (USDA 1967), using data on total precipitation from the CRU TS 2.0 dataset (Mitchell et al. 2003) determined at a 0.5 x 0.5 degree level of spatial resolution on the global grid.

The Effective Efficiency (EE) - indicating how efficient *depleted* water has been utilized - is computed from the amount of water beneficially used by the intended process divided by the total amount of freshwater depleted during the process of conveying and applying water (Keller and Keller,1995). The upper limit of EE is 100% but in practice this is never reached due to prohibitively high costs to achieve this. Volumetric water pricing may induce improvements in EE. To facilitate this option in the model, EE is formulated as a function of water price in some scenarios, though in the baseline scenario this option is not used.

Monthly water balance at sub-basin level

The total inflow into a sub-basin consists of internally generated runoff, groundwater recharge, inflow from inter-basin transfer and other sources such as desalinization. The total inflow is stored in the basin, or if the inflow is greater than the existing storage capacity, spills to a lower basin or sink. The storage capacity in the sub-basin is simulated by the Basin Equivalent Storage (BES), reflecting the maximum amount of controllable surface and groundwater available for use at one point in time. It is equal to the real storage (surface and groundwater) plus the ‘storage’ equivalent to the sum of water lifting, gravity diversion, and other forms of water diversion from the water system, discounted for the internal return flows. The BES is a function of investment in infrastructure. Groundwater is function of natural recharge from precipitation and seepage from irrigation fields and canals.

The amount of water available for different uses depends on the basin equivalent storage, water management and the amount of monthly inflow. As long as available storage is small in comparison to inflow, additional storage capacity will increase the amount of available water, up to a certain limit where the amount of inflow becomes the

---

[6] http://www.fao.org/ag/agl/aglw/aquastat/main/index.stm
[7] http://www.iwmi.cgiar.org/WAtlas/atlas.htm

limiting factor. For example, in the Colorado basin where in dry years all potentially utilizable water is depleted or committed to downstream uses, a new dam would merely change the distribution of available water over the basin without augmenting its quantity. Where reservoirs account for big part of the storage, reservoir operational rules impact water availability. For example, if reservoirs are filled at the beginning of the rainy season, inflow from rainstorms cannot be captured and flows out without being made available for later use.

Water in the reservoirs is either stored for later use or released. While part of the release is depleted or transferred out of the basin as part of inter basin transfer scheme, the remainder flows out as return flow to a lower sub-basin or sink.

Optimizing water supply according demand

Supply is matched to demand adopting an optimization approach, described in Cai and Rosegrant (2002), with the objective to maximize the ratio of depletive supply over demand. The optimization formulation assumes a rational water management with perfect foresight, in which water is allocated in accordance to demand. The optimal allocation is constrained by physical limits, operational rules and environmental concerns which may be different in the various scenarios.

With growing agricultural and industrial development, balancing the needs of aquatic ecosystems and human uses is becoming critical in many water basins. To assess that balance WATERSIM uses in-stream environmental water requirements, expressed as percentage of the total river flow, derived from Smakhtin et al. (2004). Policies on meeting environmental water requirements can be entered as hard constraints, in which environmental requirements are always met. But they can also be treated as soft constraints to simulate a more realistic situation in which a certain degree of environmental damage is tolerated in extreme water short periods.

The result from the optimization procedure is a monthly estimate of the total amount of water actually available for depletion.

Allocation rules to sectors and crops

If water available for depletion falls short of demand, WATERSIM uses different allocation rules to distribute the shortage over the sectors, depending on the scenario. In the base line scenario the industrial and domestic sectors will take preference over agriculture. If the amount of water available for depletion is insufficient to cover industrial and domestic demands, the domestic sector will get priority. Alternatively, water shortage, if occurring, can be distributed over the sectors proportional to demand or priority can be given to the agricultural sector.

The allocation of irrigation water to crops is based on the profitability of the crop, sensitivity to water stress and net irrigation demand. Higher priority is given to crops with higher profitability, higher drought sensitivity and higher irrigation water requirements.

Yield and area reduction due to water stress

Water shortages, occurring in irrigated or rainfed agriculture, reduce crop yields and harvested areas. When irrigation water is scarce farmers have the choice of reducing the water layer on the field, or reduce the cropped area to increase the water layer on the remaining area. The model simulates the reduction in areas and yields using the formulation developed by FAO (Doorenbos and Kassam 1979), while considering this trade-off between reduction in area and water layer.

Integration of water and food modules

The basic assumption in the food module is that each year the world market for agricultural commodities clears, i.e.,, production equals demand plus change in stocks. The water module is based on a water balance approach, i.e.,, inflow equals outflow plus change in basin storage. Both modules are connected through two variables: 1) agricultural area, which determines food supply and water demand; 2) crop price which determines food demand and crop profitability which in turn affects water allocation. The food module estimates food production (area and yield) as a function of socio-economic driving forces. Where water limits agricultural production, the model accounts for the effects of water stress through a reduction factor for area and yields, in both irrigated and rainfed agriculture. Updated areas and yields are then fed back into the food module and the market equilibrium recalculated. The model iterates between the water and food modules until market equilibrium and water balance is reached

Model implementation

The modelling approach followed here is very data intensive with information derived from a variety of sources. Where possible, GIS techniques are used to format the data into the right spatial resolution. The model is calibrated on data for the base year 2000 and, where available, for the year 1995[8]. The base line projections are chosen such that growth rates in the coming 25 years are consistent with the trends observed in the past 40 years (1961-2000 data, mainly taken from FAOSTAT[9]). This implies that the baseline projection reflects the Business-as-Usual scenario, continuing past trends. While the model is solved in GAMS, input and output files are in Excel format to facilitate easy analysis of modelling results. It takes about 6 to 7 hours to solve one scenario on a high-end PC (3.4 Hz CPU).

References

Agcaoili, M.C., K. Oga and M.W. Rosegrant. 1993. Structure and Operation of the International Food Policy and Trade Simulation (IFPTSIM) Model. Paper presented at the Second Workshop of the Research Project on Projections and Policy Implications of Medium- and Long-Term Rice Supply and Demand. International Rice Research Institute, Los Baños, Philippines.

Allen, R.G., L.S. Pereira, D. Raes and M. Smith. 1998. Crop evapotranspiration, guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56.

Cai, X. and M. Rosegrant. 2002. Global water demand and supply projections. Part 1: A modeling approach. Water International 27(3): 159-169.

---

[8] Previous models IMPACT-water (IFPRI) and Podium (IWMI) use 1995 as base year. Direct comparison of modeling results is not always possible due to differences in spatial units and definitions of terms

[9] http://faostat.fao.org/default.jsp

Fraiture, C., X. Cai, M.Rosegrant, D. Molden and U.Amarasinghe. 2003. Addressing the unanswered questions in global water policy: a methodology framework. Irrigation and Drainage 52(1): 21-30.

Fraiture, C. de, D. Molden, U. Amarasinghe and I. Makin. 2001. Podium: Projecting global water supply and demand for food production in 2025. Physics and Chemistry of the Earth (B. Hydrology Oceans and Atmosphere) 26(11/12): 869-876

Keller, A. and J. Keller. 1995. Effective efficiency: A water use concept for allocating freshwater resources. Water Resources and Irrigation Division (Discussion Paper 22). Arlington, Va, USA: Winrock International.

Mitchell, T.D., Carter, T.R., Jones, P.D., Hulme,M., New, M., 2003: A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: the observed record (1901-2000) and 16 scenarios (2001-2100). Journal of Climate: submitted.

Molden, David. 1997. Accounting for water use and productivity. SWIM Paper 1. Colombo, Sri Lanka: International Irrigation Management Institute.

Oga, K. and C. Gehlar. 1993. The International Food Policy Simulation (IFPSIM) Model: Documentation and Applications. Mimeo. International Food Policy Research Institute, Washington, D.C.

Rosegrant, M.W., M. Agcaoili-Sombilla, and N.D. Perez. 1995. Global Food Projections to 2020: Implications for Investment. 2020 Vision for Food, Agriculture and the Environment Discussion Paper No.5. International Food Policy Research Institute, Washington, D.C.

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

Rosegrant, M.W., S. Meijer, and S.A. Cline. 2002. International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model Description. International Food Policy Research Institute, Washington, D.C. <http://www.ifpri.org/themes/impact/impactmodel.pdf>

Rosegrant, M., X. Cai, S. Cline. 2002. World Water and Food to 2025. Dealing with scarcity. Washington DC: International Food Policy Research Institute.

Smakthin, V., C. Revenga, P. Döll. 2004. Taking into account environmental water requirements in global-scale water resources assessments. Comprehensive Assessment Research Report no.2. Colombo, Sri Lanka: International Water Management Institute.

USDA (United States Department of Agriculture).1967. Irrigation water requirements. Technical release No. 21. Engineering Division, Soil Conservation Service (SCS)