WATERSIM for CPSP

I. Introduction

Background

Water availability for agriculture - the major user worldwide – is considered to be one of the most critical factors for food security in many regions of the world. The role of water availability for irrigated agriculture and food supplies has been receiving substantial attention in recent years. In some arid and semiarid regions in the world, water scarcity has already become a severe constraint on food production.

During the World Water Forum in The Hague (2000) and Japan (2003) and following debates, many –sometimes strongly opposing- views were presented on future developments in water, food and the environment. To provide an objective and scientifically sound basis to these debates, the International Water Management Institute (IWMI) and International Food Policy Research Institute (IFPRI) embarked on a joint modeling exercise, resulting in the Watersim model. Watersim (Water, Agriculture, Technology, Environment and Resources Simulation Model) explores the impact of water and food related policies on water scarcity, food production, food security and environment. The Watersim model builds on IMPACT-WATER, an economic and water simulation model developed by IFPRI and PODIUM, an agro-hydrological model developed by IWMI.

Specific modeling objectives include:

1. To better understand the key linkages between water, food security, and environment.
2. To develop an integrated analytical tool for exploring various scenarios to address key questions for food water, food, and environmental security.
3. To perform analysis with key stakeholders to explore strategic decisions on alternative water and food development paths.

While many measures to alleviate water scarcity are within the water sector, it is increasingly recognized that many drivers, policies and institutions outside the water sector have large and real implications on how water is being allocated and used. Important drivers for water use include population and income growth, urbanization, trade and other macroeconomic policies, environmental regulations and climate policy. While some of these processes and trends, especially those at global level, may prove difficult to influence directly, it is important to understand their linkages with water issues to analyze the relative impact of various policies in the agricultural and water sectors on water and food security.

The strong linkages between economic trends, agricultural policies and water use call for an integrated and multidisciplinary modeling approach. The WATERSIM model is a suitable tool to explore the impacts of water and food related policies on global and regional water demand and supply, food production and the environment.

Importance to CPSP

Designed as a global water and food model, Watersim fulfils an important aspect of basin and national studies in providing the global setting in which processes at basin and country level take place. The global context works in two directions: 1) the global economy influences local prices, policies and investment in infrastructure which impact on water use at basin or country level; 2) conversely, policies and water availability at basin level impact agricultural production which in turn may impact trade flows and world market prices. The latter aspect is important in the context of India and China, both big producers and consumers. For example, a decrease in India's production due to water scarcity, may cause a considerable demand for grains at world market prices which in turn may lead to an increase in world market prices. A drop of 10% in grain production in India would lead to an increase of global trade of 7%. Though global production capacity is sufficient to handle this drop it will have consequences for world market prices.

The global economic context is linked to local water use at basin scale in many ways. For example, low world market prices for food commodities may render local investments in water development projects less favorable from an economic point of view. This may impact local food security in the longer run. Or, developments in crop technology through international research efforts may boost yields and water productivity, reducing water use. Furthermore, the liberalization of world markets for agricultural commodities, as discussed in the latest WTO rounds, will impact local agricultural economy by creating new opportunities or damaging existing markets. Since agriculture is the main water user in many countries, the local agricultural economy and water use are intrinsically linked.

While PODIUMsim is an important tool in the CPSP, WATERSIM is an important complementary model that provides the economic and global context. In a globalizing world, the link between global water and food models, such as WATERSIM, and basin level analysis, such as done by PODIUMsim, will become increasingly important. The next chapter will provide an example for India to show how Watersim provides results that are complementary to existing models, by highlighting the impact of socio-economic scenarios of income.

Funding and progress

The IWMI-IFPRI global modeling project is funded by the Dutch Government though the Comprehensive Assessment, total 1 million US$ over a three year period (2002-2004). The funding provided by ICID under the CPSP consists of part of the overall funding of the project (150 k). The first phase of the joint IWMI-IFPRI modeling project runs through December 2004. The progress described below concerns the overall project.

After extensive discussion between researchers from IWMI and IFPRI, the overall model structure has been finalized (see technical annex). The model is coded in GAMS, a scientific programming language. Global datasets were obtained from a variety of sources (among others, IWMI water atlas, FAOstat, Aquastat, University of East Anglia, University of Kassel, Millenium Ecosystem Assessment, USDA and GRDC).

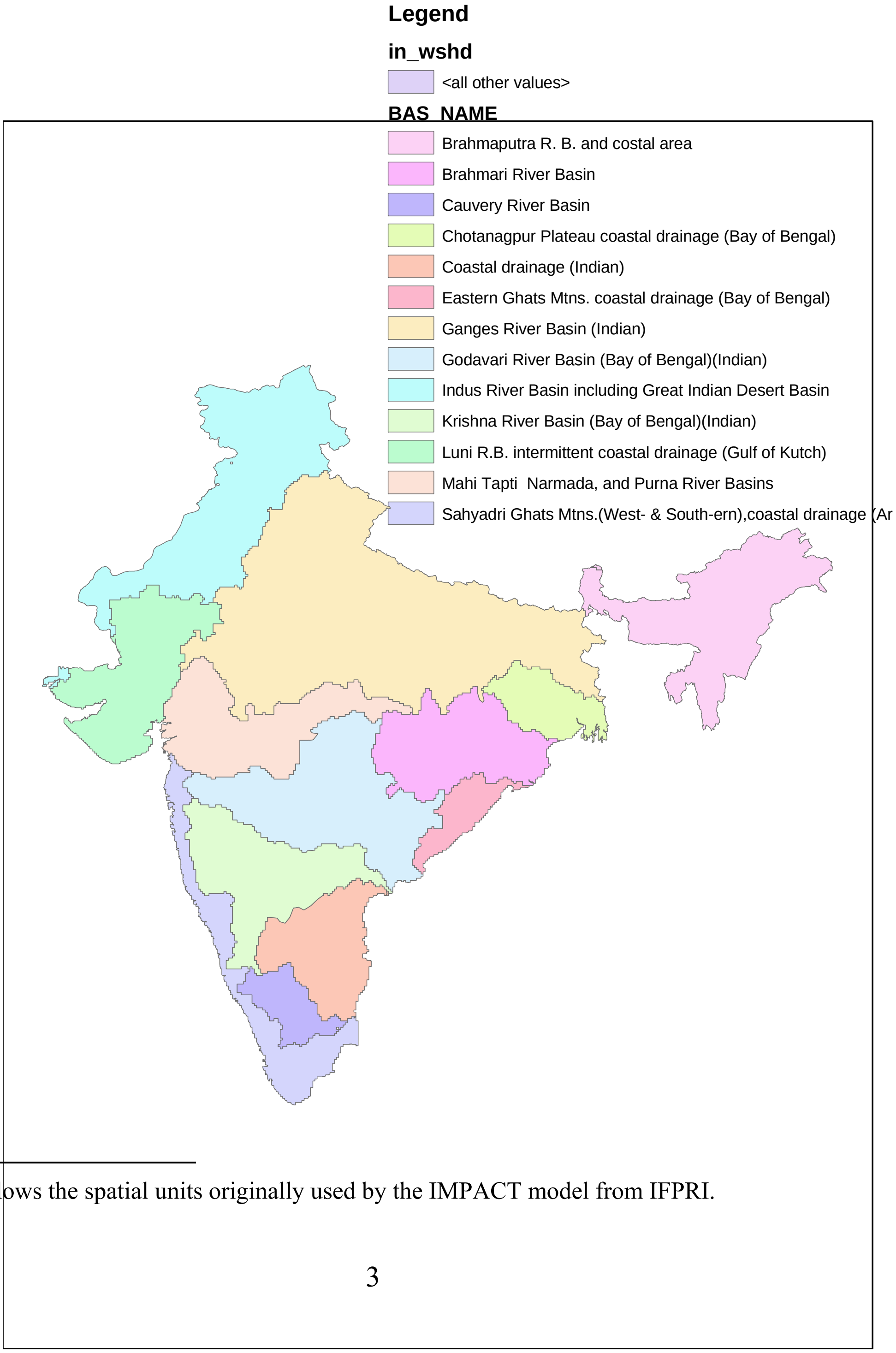
The model is now ready for scenario analysis and will be used in the Comprehensive Assessment and the International Assessment on Agriculture, Science, Technology and

Development (IAASTD). To show the usefulness of the Watersim model to the CPSP some scenarios and preliminary results for India will be presented in the next sections.

II. Applications of the Watersim model to India

A. Baseline for India

To account for spatial variation in water availability, the Watersim model uses India's 14 major river basins as spatial units (figure 1)[1]. All water related variables are determined at water basin level, while economic variables are simulated at nation level.



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[1] The model follows the spatial units originally used by the IMPACT model from IFPRI.

Tables 1 and 2 show the baseline water and food demand for the year 2000 and projections for 2025 under a Business as Usual scenario.

Table 1: Baseline commodity demand for India

	Consumption in million tons		*Change*
year	***2000***	***2025***	*%*
Wheat	66.02	104.98	59%
Rice	83.76	126.87	51%
Maize	12.21	20.32	66%
Other grain	19.03	30.61	61%
Poultry meat	1.05	3.37	221%
Eggs	1.83	4.07	122%
Milk	81.65	188.66	131%

Table 2: Production and demand of selected commodities, India (in million tons)

	2000, base year			2025, Business as Usual			
	Demand	Production	net trade	Demand	Production	Net trade	% of consumption
Wheat	66.02	70.04	4.88	104.98	95.02	-9.96	9%
Rice	83.76	87.75	3.99	126.87	127.11	0.24	0%
Maize	12.21	12.06	-0.15	20.31	20.16	-0.15	1%
Other grains	19.03	19.76	0.73	30.61	27.94	-2.66	9%
Poultry meat	1.05	1.05	0	3.37	3.15	-0.22	6%
Eggs	1.83	1.76	-0.07	4.07	3.32	-0.75	14%
Milk	81.65	80.18	-1.47	188.66	186.98	-1.68	1%

In total, cereal demand increases from 190 million tons in 2000 to 283 million tons in 2025. The growth is mainly a result of population growth and, to a lesser extent, changes in diets (refer to section below). At present India is self-sufficient or minor exporter of its major food grains. Under a business as usual scenario where current trends and growth rates persist, by the year 2025 India will be 95% self-sufficient in grains. Some minor quantities of its food commodities such as wheat, other coarse grains and dairy products need to be imported (table 2).

At present some 63% of the cereal production originates from irrigated areas (mostly under small groundwater pumps), but it varies by crop. Wheat and rice are mostly produced under irrigated conditions while maize and other grains are grown in rain fed areas. It is estimated that the total harvested area amounts to 167 million hectares of which roughly 40% is irrigated. Under the baseline scenario, the total harvested area increases slightly (by 5%). The harvested irrigated area grows by 10 million hectare (or 15%) as some rain fed lands are brought under irrigation and cropping intensity on existing lands is increasing.

Table 3 provides yields and areas of cereal crops for the base year (2000). Table 4 provides this for the year 2025 under a Business as Usual scenario.

Table 3: Yield and areas of selected commodities, India, base year 2000

	Rain fed area (m ha)	*Irrigated area (m ha)*	*Rain fed yield (t/ha)*	*Irrigated yield (t/ha)*	*% production from irrigated*
Wheat	5.68	21.51	1.80	2.80	85%
Rice	21.92	21.43	1.52	2.54	62%
Maize	5.38	1.18	1.53	3.24	32%
Other grains	22.84	0.66	0.83	1.37	5%
Total area (all crops)	92.14	74.81			

Table 4: Yield and areas of selected commodities, India, 2025, Business as Usual**

	Rain fed area (m ha)	*Irrigated area (m ha)*	*Rain fed yield (t/ha)*	*Irrigated yield (t/ha)*	*% production from irrigated*
Wheat	4.42	23.76	1.90	3.64	91%
Rice	21.35	24.87	2.13	3.28	64%
Maize	5.30	1.80	2.50	3.80	34%
Other grains	21.54	0.67	1.24	1.80	4%
Total area (all crops)	89.72	85.36			

** Business as Usual scenario presented here is based on the irrigated area growth rates as presented by IWMI-base case scenario (Seckler et al. 2000). Irrigated area growth is therefore slightly higher than presented by IMPACT-water (Rosegrant et al 2002).

Figures 2, 3, 4 and 5 compare the yields and areas as projected by Watersim with the observed trends from 1961-2000 (from FAOstat).

Figure 2: wheat area and yield 1961-2025

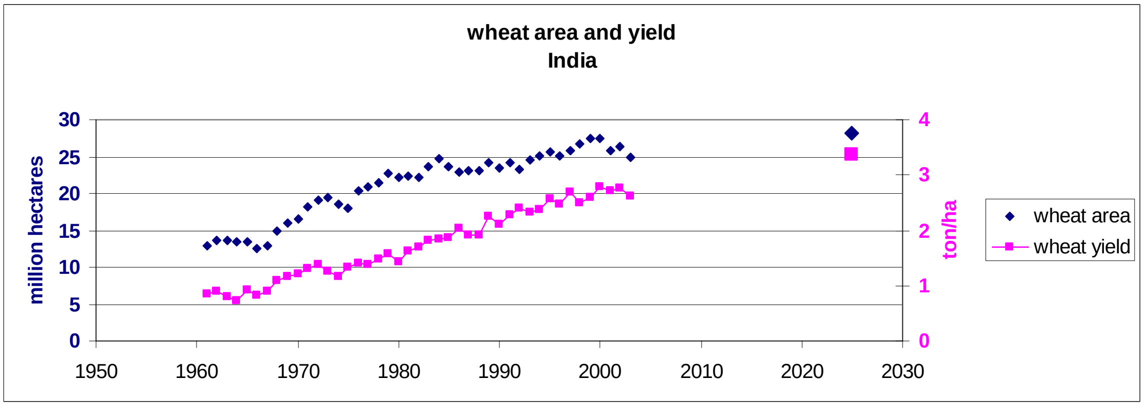


Figure 3: Rice area and yield 1961-2025

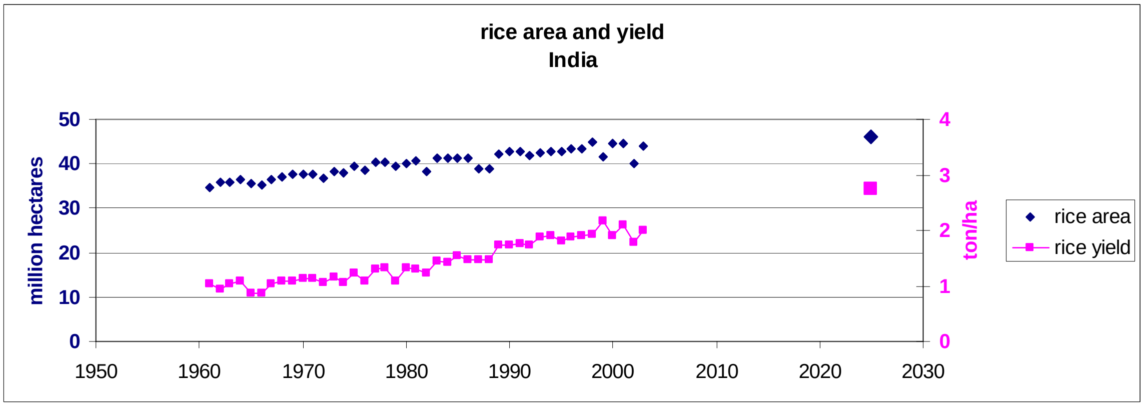


Figure 4: maize area and yield

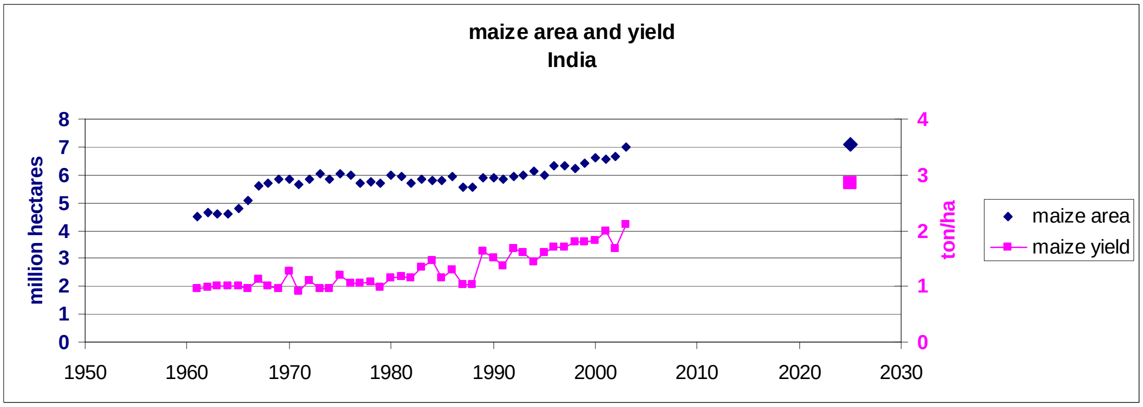
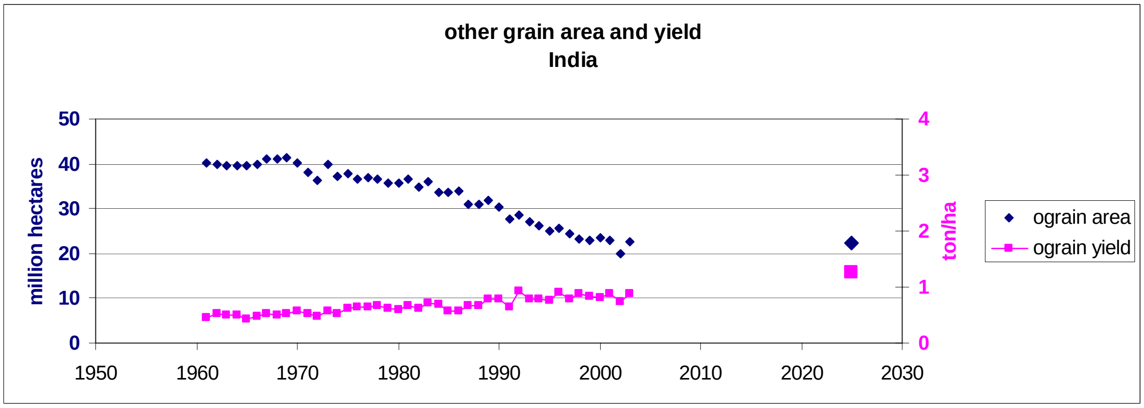


Figure 5: other grains area and yield



Water depletion in agriculture by basin is provided in table 5 and 6.

Table 5: Water depletion in the base year 2000 (in km3)

	Agricultural	Domestic	Industrial	Total
Brahmaputra	3.42	0.95	0.39	4.76
Chotanagpur	1.29	1.08	0.38	2.75
Lancang_Jiang	4.75	0.02	0.01	4.78
Eastern Ghats	6.07	0.34	0.13	6.54
Cauvery	6.52	0.55	0.21	7.28
Sahyadri Ghats	6.27	1.94	0.71	8.92
Godavari	16.27	1.54	0.59	18.40
Brahmari	16.44	0.92	0.37	17.73
Mahi-Tapti	16.72	1.16	0.45	18.33
Luni	22.14	0.61	0.23	22.98
India_East Coast	22.38	0.72	0.26	23.36
Krishna	23.15	1.82	0.71	25.68
Indus	64.29	1.38	0.54	66.21
Ganges	129.38	8.24	3.24	140.86
Total India	***339.09***	***21.29***	***8.22***	***368.60***

Table 6: Water depletion in 2025, Business as Usual (in km3)

	Agricultural	Domestic	Industrial	Total
Brahmaputra	3.89	1.88	0.75	6.52
Chotanagpur	1.44	2.14	0.73	4.31
Lancang_Jiang	5.40	0.04	0.02	5.46
Eastern Ghats	6.82	0.67	0.25	7.74
Cauvery	7.34	1.09	0.41	8.83
Sahyadri Ghats	6.97	3.84	1.37	12.18
Godavari	18.59	3.05	1.14	22.78
Brahmari	18.82	1.82	0.72	21.35
Mahi-Tapti	18.76	2.29	0.87	21.92
Luni	25.03	1.21	0.44	26.68
India_East Coast	25.75	1.42	0.50	27.68
Krishna	26.45	3.60	1.37	31.42
Indus	72.22	2.73	1.04	75.99
Ganges	145.51	16.29	6.27	168.07
Total India	***383.01***	***42.06***	***15.90***	***440.95***

Prices

Production depends, among others, on the agricultural policies in place that provide price incentives to farmers to produce a certain crop. Domestic prices are a function of world prices, adjusted by the effect of price policies and expressed in terms of the producer subsidy equivalent (PSE), the consumer subsidy equivalent (CSE), and the marketing margin (MI). 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. MI reflects other factors such as transport and marketing costs. In the model, PSE, CSE, and MI are expressed as percentages of the world price. To calculate producer prices, the world price is reduced by the MI value and increased by the PSE value. Consumer prices are obtained by adding the MI value to the world price and reducing it by the CSE value. Refer to the annex for more details on formulas. Table 3 provides the assumptions on crop prices and subsidies for the base year.

Table 7: variables on prices for the base year

	PSE	CSE	MI	PP	PC
Wheat	-0.19	0.19	0.30	71	131
Rice	0.18	-0.09	0.30	171	292
Maize	-0.02	0.02	0.30	64	118
Other grains	-0.02	0.02	0.30	53	97
Poultry meat	-0.41	0.20	0.30	509	1281
Eggs	-0.11	0.11	0.30	440	816
Milk	0	0	0.30	1541	2861

PSE: Produces Subsidy Equivalent. Negative values indicate tax
CSE: Consumer Subsidy Equivalent. Negative values indicate tax
MI: Marketing Margin
PP: producer price in US$/ton
PC: consumer price in US$/ton

Projections on food and water demand depend on many assumptions. In the previous section a Business as Usual scenario was presented assuming that historic trends over the last 30 years continue more or less unchanged. But what will happen if trends change? In the following section one important aspect of water and food demand will be highlighted. namely, the impact of income change on changes of diets and therefore water demand.

B. Changes in diets and associated water demands due to income changes

One of the strengths of the Watersim model is its integration of water and food and economic aspects and its ability to link global and regional scales. Because over 90% of the total water demand comes from agriculture, there is a strong link between food and water demand. Food demand depends on the total population growth and on consumer preferences, which in turn depend on urbanization and per capita income growth.

Rising incomes throughout much of Asia over the last three decades led not only to increasing consumption of staple cereals, but also to a shift in consumption patterns among cereal crops and away from cereals towards livestock products and high-value crops. Wheat and feed grains increasingly emerged as particularly important cereal crops in a region traditionally dominated by rice consumption. Consumption of high-value crops (such as vegetables, fruit, sugar and oils) also increased substantially. Both rising incomes and structural changes to consumption patterns will continue to drive trends in food –and hence agricultural water- demand in Asia over the next decades. Rapid urbanization is perhaps the most important ongoing structural shift affecting food consumption, with historical evidence from China indicating that consumption of grains, edible oils and vegetables is higher in rural areas, while consumption of meat, fish and dairy products is higher in urban areas (Huang and Bouis 1996). Because water requirements to produce high-value crops and meats and oils are generally higher than of cereals water use per kilocalorie consumed will increase over time.

To show changes in diets as a result of income changes and urbanization in India three scenarios[2] were compared: one Business-as-Usual, a pessimistic and optimistic scenario. Table 7 provides the assumptions on population and income per capita for the base year 2000 and projection for 2025.

Table 7: Income and population of India under different scenarios

	Population (in million)		*Income per capita (in US$ per year)*	
Scenario	**2000**	**2025**	**2000**	**2025**
BAU	1017.38	1372.76	464.38	1255.87
OPT	1017.38	1284.53	464.38	1542.47
PES	1017.38	1472.27	464.38	932.22

BAU = Business as Usual, OPT = Optimistic, PES = Pessimistic

The results in figure 6, 7 and 8 show how income affects per capita demand of three selected commodities. The solid blue line reflects the historic trend over 1961 to 2003, based on FAOstat data. The dotted lines give the projections made by the Watersim model for the three scenarios.

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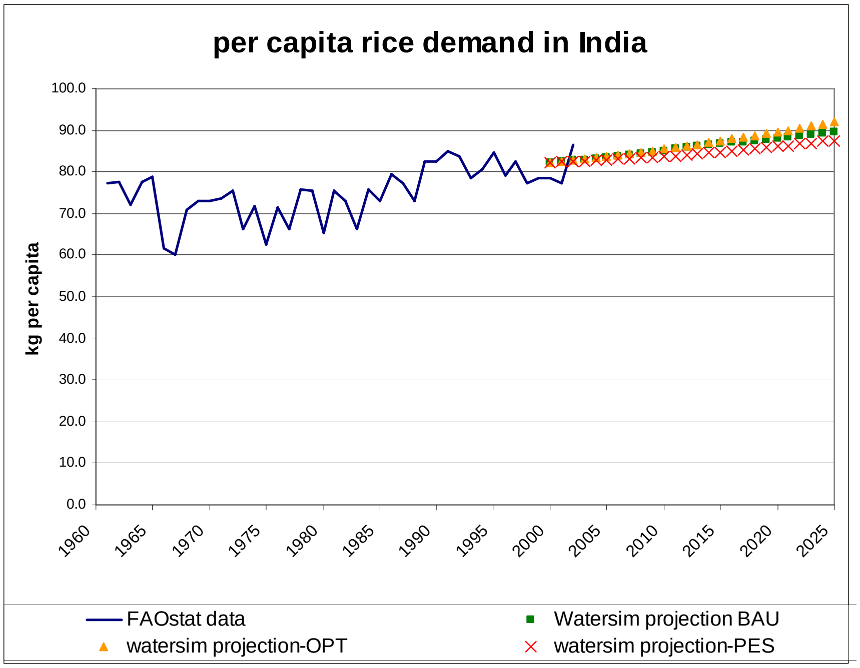
[2] Based on Millennium Ecosystem Assessment scenarios.

Figure 6: per capita rice demand in India under different socio-economic scenarios



BAU = Business as Usual, OPT = Optimistic, PES = Pessimistic

Figure 7: per capita wheat demand in India under different socio-economic scenarios

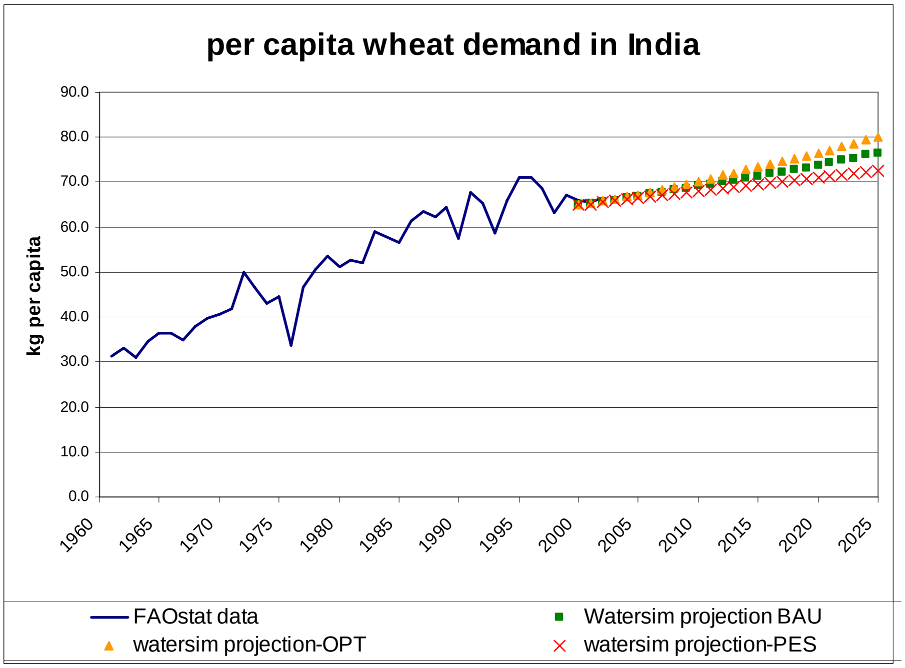
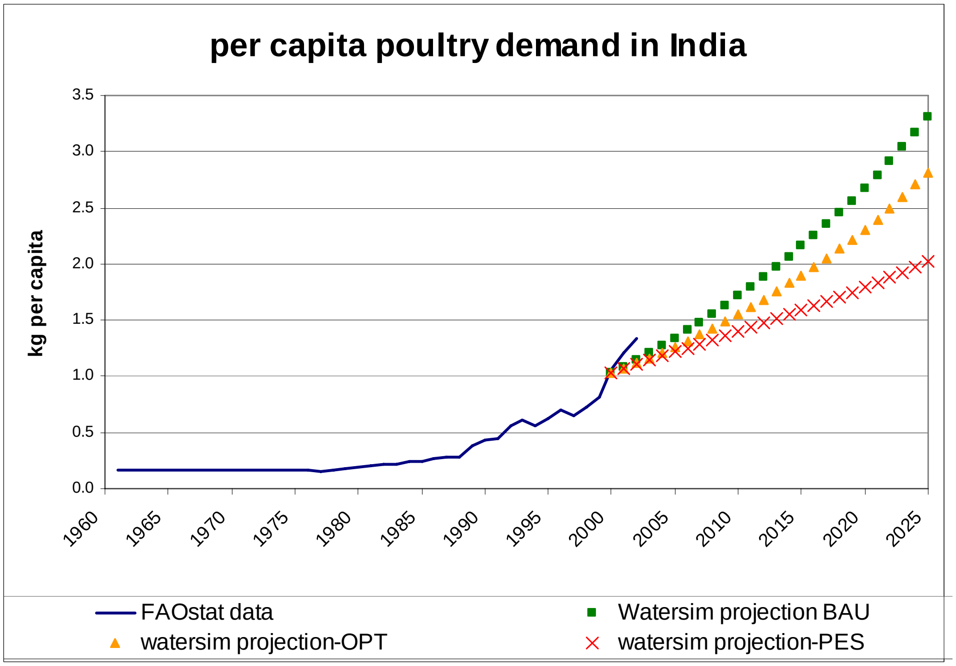


Figure 8: per capita poultry meat demand in India under different socio-economic scenarios



BAU = Business as Usual, OPT = Optimistic, PES = Pessimistic

Over the years per capita rice demand increased slightly and all three scenarios foresee a further small increase. Per capita rice demand is relatively insensitive to changes in income. Evidence from Thailand indicate that per capita rice demand starts to *decrease* above a certain income level and degree of urbanization as people switch to food stuffs that are easier to prepare. While in Thailand (with a per capita income of US$ 2830 per year) this peak level is reached, in India (with a per capita income of US$ 465 per year) rice demand still rises with income. Per capita wheat demand in India is more sensitive to income (people start eating bread products as result of urbanization and changing life styles). However, the impact of incomes on poultry meat and milk products is most noticeable. Per capita consumption in a pessimistic income scenario is nearly half of that in an optimistic income scenario. Due to religious considerations and consumer preferences beef demand is negligible.

Since the water demands per commodity are quite different, this results in different water demands. Also, since industrial and domestic demand on income, total depletion is different for the three scenarios (table 8).

Table 8: Water depletion for three different socio-economic scenarios (km3)

	Agricultural	*Industrial*	*Domestic*	*Total*	*Per capita (m3/cap/yr)*
BAU	383.01	15.90	42.06	440.97	321
OPT	370.36	22.88	56.14	449.38	350
PES	395.70	8.21	38.89	442.80	301

Note that under the optimistic income scenario the agricultural water use is lower than under the pessimistic scenario despite higher per capita food demand, because the population is lower. Per capita water depletion in the optimistic income scenario is .. while in the pessimistic it is ..

These figures show the importance of income and urbanization trends on food demand and associated water depletion. Watersim, combining economics as well as water use aspects, is a suitable tool to explore the sensitivity of these trends.

ANNEX: DETAILED MODEL DESCRIPTION

Broadly speaking the model consists of two integrated modules: the 'food demand and supply' module, which is adapted from IMPACT (Rosegrant, Cai and Cline 2002); 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) combined with elements from the IMPACT-WATER (Cai and Rosegrant 2002). It improves on Podium by incorporating economic and market forces into the food model. It improves on IMPACT-water by a better spatial resolution, a better interaction between water and food module and an enhanced water balance module.
The model estimates food demand as a function of population, income and food prices. Crop production depends on economic variables such as crop prices, inputs and subsidies on one hand and climate, crop technology, production mode (rain fed versus irrigated) and water availability on the other. Irrigation water demand is a function of the food production requirement and management practices, but constrained by the amount of available water.

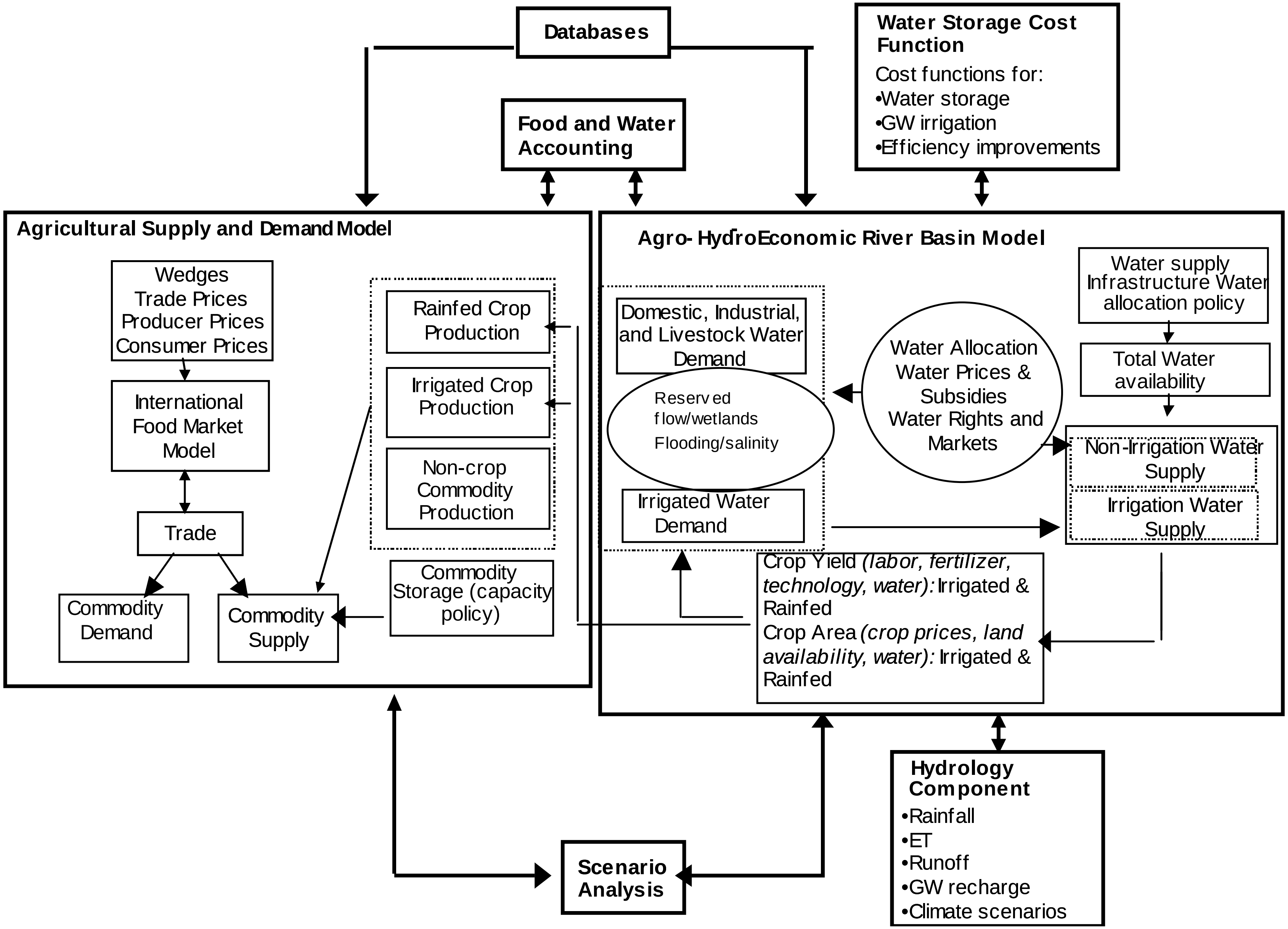
Water demand for irrigation, domestic purposes, industrial sectors, livestock and the environment are estimated at basin scale. Water supply for each basin is expressed as a function of climate, hydrology and infrastructure. At basin level, hydrologic components (water supply, usage and outflow) must balance. At the global level food demand and supply are leveled out by international trade and changes in commodity stocks. The model iterates between basin, country and globe until the conditions of economic equilibrium and hydrologic water balance are met.

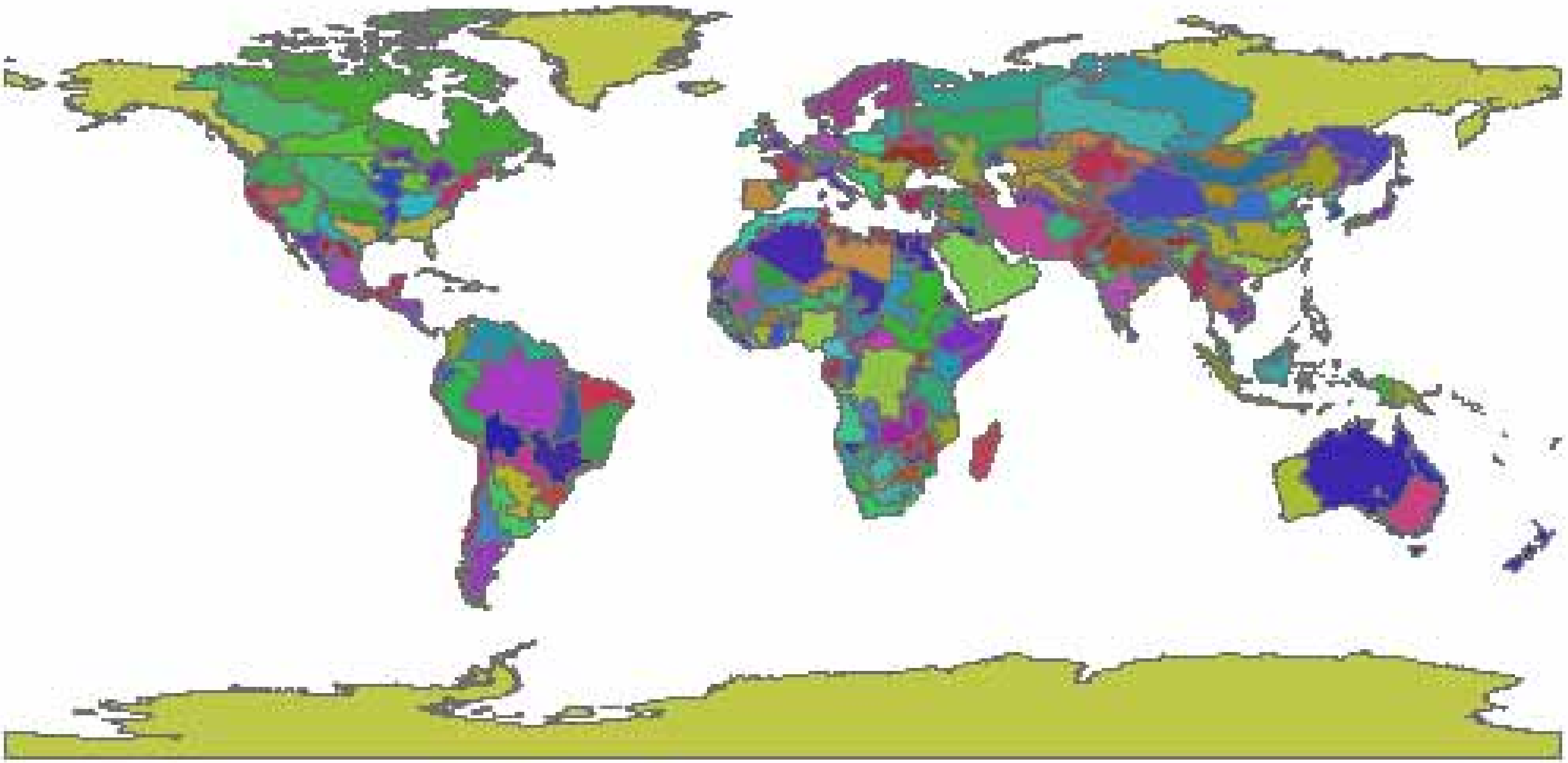
Spatial scale

In order to adequately model hydrology, it makes most sense to use river basin as basic spatial unit. When it comes to food policy analysis, administrative boundaries should be used (trade and policy making happens at national level, not at river basins scale). Therefore, WATERSIM takes a hybrid approach to its spatial unit of modeling. 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. Finally the river basins were intersected with the economic regions to produce 282 Food Producing Units (FPUs).

The hydrological processes are modeled at basin scale by summing up relevant parameters and variables over the FPU's that belong to one basin. Similarly economic processes are modeled at regional scale by summing up the variables over the FPU's belonging to one country.

Figure 1: Schematic Diagram of WATERSIM Model





Temporal scale

The baseline year is 2000. Projections are made for the year 2025.
Economic processes are modeled at an annual time step, while hydrological and climate variables are modeled at a monthly time-step. Crop related variables are either determined by month (crop ET) or by season (yield, area). More specifically, the food supply and demand module runs at region level on a yearly time-step.
Water supply and demand runs at FPU level at a monthly time-step. For the area and yield computations the relevant parameters and variables are summed over the months of the growing season.

1 Food supply and demand module

The food supply and demand module offers a methodology for analyzing baseline and alternative scenarios for global food demand, supply, trade, income and population. The food module covers 32 commodities including all cereals, soybeans, roots and tubers, meats (including beef, pig meat, sheep and goat, and poultry), milk, eggs, oils, oilcakes and meals, tropical and subtropical fruits, temperate fruits, sugarcane, sugar beet, eight fish commodities, fish oil, and fish meal. The food module is specified as a set of regional equations, which determine supply, demand, and prices for agricultural commodities. Regional agricultural demand and supply are linked through trade.

The food module uses a system of supply and demand elasticities incorporated into a series of linear and nonlinear equations to approximate the underlying production and demand functions. World agricultural commodity prices are determined annually at levels that clear international markets. Demand is a function of prices, income, and population growth. Growth in crop production in each region is determined by crop prices and the rate of productivity growth. Future productivity growth is estimated by its component sources, including crop management research, conventional plant breeding, wide-crossing and hybridization breeding, and biotechnology and transgenic breeding. Other sources of growth considered include private sector agricultural research and development, agricultural extension and education, markets, infrastructure, and irrigation.

Crop supply functions

Domestic crop production is determined by the area and yield response functions, formulated separately for production under irrigated and rain fed conditions. Harvested area is specified as a response to the crop's own price, the prices of other competing crops, the projected rate of exogenous (non-price) growth trend in harvested area, and water (equation 1 and 2). The projected exogenous trend in harvested area captures changes in area resulting from factors other than direct crop price effects, such as expansion through population pressure and contraction from soil degradation or conversion of land to nonagricultural uses. Yield is a function of the commodity price, the prices of labor and capital, water, and a projected 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 (equation 3 and 4). Annual production of crop commodity *c* in region *r* is then estimated as the product of its area and yield (equation 5).

Irrigated area response:

$$AI_{yrc} = \alpha i_{yrc} \times (PS_{yrc})^{\varepsilon_{rcc}} \times \prod_{c \neq p} (PS_{yrp})^{\varepsilon_{rcp}} \times (1 + gAI_{yrc}) + \Delta AI_{yrc} \tag{1}$$

$$AR_{yrc} = \alpha r_{yrc} \times (PS_{yrc})^{\varepsilon_{rcc}} \times \prod_{c \neq p} (PS_{yrp})^{\varepsilon_{rcp}} \times (1 + gAR_{yrc}) + \Delta AR_{yrc} \tag{2}$$

Yield response:

$$YI_{yrc} = \beta i_{yrc} \times (PS_{yrc})^{\gamma_{rcc}} \times \prod_{s} (PF_{yrs})^{\gamma_{rcs}} \times (1 + gYI_{yrc}) + \Delta YI_{yrc} \tag{3}$$

$$YR_{yrc} = \beta r_{yrc} \times (PS_{yrc})^{\gamma_{rcc}} \times \prod_{s} (PF_{yrs})^{\gamma_{rcs}} \times (1 + gYR_{yrc}) + \Delta YR_{yrc} \tag{4}$$

Production:

$$QS_{yrc} = AI_{yrc} . YI_{yrc} + AR_{yrc} . YR_{yrc} \tag{5}$$

where AI = irrigated cropped area (M ha)
AR = rain fed cropped area (M ha)
YI = irrigated crop yield (ton/ha)
YR = rain fed crop yield (ton/ha)
QS = quantity produced (M ton)
PS = effective producer price (US$/ton)
PF = price of factor or input *k* (labor, fertilizer) (US$/ton)
c,p = commodity indices: crops
s = inputs such as labor and capital
r = spatial unit: region
y = time step: year
gAI = growth rate of irrigated crop area (%)
gAR = growth rate of rain fed crop area (%)
gYI = growth rate of irrigated crop area (%)
gYR = growth rate of rain fed crop yield (%)
ε = area price elasticity
γ = yield price elasticity
αi = irrigated area intercept
αr = rain fed area intercept
βi = irrigated yield intercept
βr = rain fed yield intercept
ΔAI = irrigated crop area reduction due to water stress (M ha)
ΔAR = rain fed crop area reduction due to water stress (M ha)
ΔYI = irrigated yield reduction due to water stress (ton/ha)
ΔYR = rain fed yield reduction due to water stress (ton/ha)

The determination of the crop area and yield reduction due to water stress is endogenous to the model and described under ‘water supply and demand module’. The model is initialized by setting the reductions to zero (i.e. assuming no water limitations). The areas and yields are updated accounting for water stress in subsequent model iterations.

Livestock supply functions

Livestock production is modeled similarly to crop production except that livestock yield reflects only the effects of expected developments in technology (equation 6). Total livestock slaughter is a function of the livestock’s own price and the price of competing commodities, the prices of intermediate (feed) inputs, and a trend variable reflecting growth in the livestock slaughtered (equation 7). Total production is calculated by multiplying the slaughtered number of animals by the yield per head (equation 8).

Number slaughtered:

$$AL_{yrk} = \alpha_{yrk} \times (PS_{yrk})^{\varepsilon_{rkk}} \times \prod_{k \neq l} (PS_{yrl})^{\varepsilon_{rkl}} \times \prod (PI_{yrf})^{\gamma_{rkf}} \times (1 + gAL_{yrk}) \tag{6}$$

Yield:

$$YL_{yrk} = (1 + gLY_{yrk}) \times YL_{y-1,rk} \tag{7}$$

Production:

$$QS_{yrk} = AL_{yrk} \times YL_{yrk} \tag{8}$$

where AL = number of slaughtered livestock ('000)
YL = livestock product yield per head (ton)
PI = price of intermediate (feed) inputs (US\$/ton)
k, l = commodity indices specific for livestock
f = commodity index specific for feed crops
gAL = growth rate of number of slaughtered livestock (%)
gYL = growth rate of livestock yield (%)
α = intercept of number of slaughtered livestock
ε = price elasticity of number of slaughtered livestock
γ = feed price elasticity

Demand functions

Domestic demand for a commodity is the sum of its demand for food, feed, and other uses (equation 14). Food demand is a function of the price of the commodity and the prices of other competing commodities, per capita income, and total population (equation 9). Per capita income and population increase annually according to region-specific population and income growth rates as shown in equations 10 and 11. Feed demand is a derived demand determined by the changes in livestock production, feed ratios, and own- and cross-price effects of feed crops (equation 12). The equation also incorporates a technology parameter that indicates improvements in feeding efficiencies. The demand for other uses is estimated as a proportion of food and feed demand (equation 13). Note that total demand for that livestock consist only of food demand.

Demand for food:

$$QF_{yri} = \alpha_{yri} \times (PD_{yri})^{\varepsilon_{rii}} \times \prod_{i \neq j} (PD_{yrj})^{\varepsilon_{rij}} \times (INC_{yr})^{\eta_{ri}} \times POP_{yr} \tag{9}$$

where

$$INC_{yr} = INC_{y-1,r} \times (1 + gINC_{yr}) \tag{10}$$

$$POP_{yr} = POP_{y-1,r} \times (1 + gPOP_{yr}) \tag{11}$$

Demand for feed:

$$QL_{yrf} = \beta_{yrf} \times \sum_{k} (QS_{yrk} \times FR_{yrfk}) \times (PI_{yrf})^{\gamma_{rf}} \times \prod_{f \neq g} (PI_{yrf})^{\gamma_{rfg}} \times (1 + FE_{yrf}) \tag{12}$$

Demand for other uses:

$$QE_{yri} = QE_{y-1,ri} \times \frac{(QF_{yri} + QL_{yri})}{(QF_{y-1,ri} + QL_{y-1,ri})} \tag{13}$$

Total demand:

$$QD_{yri} = QF_{yri} + QL_{yri} + QE_{yri} \tag{14}$$

where QD = total demand (M ton)
QF = demand for food (M ton)
QL = derived demand for feed (M ton)
QE = demand for other uses (M ton)
PD = effective consumer price (US\$/ton)
INC = per capita income (US\$/cap)
POP = total population (million)
FR = feed ratio
FE = feed efficiency improvement (%)
i,j = commodity indices specific for all commodities
k,l = commodity index specific for livestock
f,g = commodity indices specific for feed crops
$gINC$ = income growth rate (%)
$gPOP$ = population growth rate (%)
ε = price elasticity of food demand
γ = price elasticity of feed demand
η = income elasticity of food demand
α = food demand intercept
β = feed demand intercept

Prices

Prices are endogenous in the system of equations for food. Domestic prices are a function of world prices, adjusted by the effect of price policies and expressed in terms of the producer subsidy equivalent (PSE), the consumer subsidy equivalent (CSE), and the marketing margin (MI). 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. MI reflects other factors such as transport and marketing costs. In the model, PSE, CSE, and MI are expressed as percentages of the world price. To calculate producer prices, the world price is reduced by the MI value and increased by the PSE value (equation 15). Consumer prices are obtained by adding the MI value to the world price and reducing it by the CSE value (equation 16). The MI of the intermediate prices is smaller because wholesale instead of retail prices are used, but intermediate prices (reflecting feed prices) are otherwise calculated the same as consumer prices (equation 17).

Producer prices:

$$PS_{yni} = [PW_{yi}\ (1 - MI_{yri})](1 + PSE_{yri}) \tag{15}$$

Consumer prices:

$$PD_{yri} = [PW_{yi}\ (1 + MI_{yri})](1 - CSE_{yri}) \tag{16}$$

Intermediate (feed) prices:

$$PI_{yri} = [PW_{yi}\ (1 + 0.5\, MI_{yri})](1 - CSE_{yri}) \tag{17}$$

where PW = world price of the commodity (US$/ton)
MI = marketing margin (%)
PSE = producer subsidy equivalent (%)
CSE = consumer subsidy equivalent (%)

The Trading Price (PT) is defined as
PT = XR.PW with XR = exchange rate

International linkage through trade

Regional production and demand are linked through trade. Commodity trade by region is the difference between domestic production and demand (equation 35). Regions with positive trade are net exporters, while those with negative values are net importers. This specification does not permit a separate identification of both importing and exporting regions of a particular commodity.

Net trade:

$$QT_{yri} = QS_{yri} - QD_{yri} - STC_{yri} \tag{18}$$

where QT = volume of trade (M ton)

At global level net trade equals zero (equation 36). The world price (PW) of a commodity is the equilibrating mechanism such that when an exogenous shock is introduced in the model, PW will adjust and each adjustment is passed back to the effective producer (PS) and consumer (PD) prices via the price transmission equations (equations 15−17). Changes in domestic prices subsequently affect commodity supply and demand, necessitating their iterative readjustments until world supply and demand balance, and world net trade again equals zero.

World market clearing condition: $\sum_{r} QT_{yri} = 0;$ (19)

2 Water demand and supply module

The methodology adopted in the water balance module is based on the water accounting philosophy underlying PODIUM and the reservoir formulation employed in IMPACT-WATER. It relates water demand derived from agricultural, domestic and industrial sectors to available water supply determined by internally generated runoff, inflow from other units, groundwater contributions and existing infrastructure. When supply falls short of demand, the shortages are distributed over months, sectors and crops using a reservoir optimization model and allocation rules. Area and yield reductions resulting from water shortages are fed back into the 'food supply and demand' module. Both modules are iterated until both the economic equilibrium and water balance conditions are met. The water demand and supply module runs at a monthly time-step[3]. Area and yield reductions due to water stress are determined at a seasonal scale.

This module deals with 'blue water' resources. Soil water components (evapotranspiration from rain fed and water requirements in irrigated agriculture met by effective precipitation) are determined exogenously from the model. Hydrologic changes due to land use changes are not taken into account in this version (these will be incorporated in the next version of the model.

Depletive water demand - total

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 three sectors: irrigated agriculture, industry and domestic use:

Total depletive demand:

$$DDTo_{ymu} = DDA_{ymu} + DDI_{ymu} + DDM_{ymu} \qquad (20)$$

---

[3] In India crops are grown in two seasons (Rabi and Khariff). Running the model at a monthly time step takes care of the seasonal differences.

where: $DDTo$ = monthly depletive demand - total (km^3)
DDA = monthly depletive demand - irrigated agriculture (km^3)
DDI = monthly depletive demand - industry (km^3)
DDM = monthly depletive demand - municipal use (km^3)
y = year index
m = month
u = food producing unit (FPU)

Depletive demand in irrigated agriculture:

Irrigation water depletion in agriculture is estimated from:

$$DDA_{ymu} = \sum_{c} \left(\frac{AI_{yrc}.(ETa_{ymuc} - PE_{ymuc})}{EE_{yu}} \right).100 \tag{21}$$

where: AI = irrigated crop area (Mha)
ETa = actual crop evapotranspiration (mm)
PE = effective precipitation (mm)
EE = effective efficiency (%)
c = crop

The irrigated crop area is determined by the ‘food supply and demand’ module. The quantification of the actual evapotranspiration is endogenous to the model. To initialize the model at the first iteration of each year, ETa is approximated by the potential evaporation from:

$$ETp_{ymuc} = kc_{mc}.ET0_{ymuc} \tag{22}$$

where ETp = potential evapotranspiration (mm)
kc = crop factor
ET0 = reference evapotranspiration
m $\in$ cropping period

ETp is determined at a 0.5 x 0.5 degree global grid using cropping pattern data from FAOstat, kc data from FAO and ET0 coverages from Kassel University and the IWMI atlas. ETp is then averaged over the grid cells falling within the FPU.

The effective precipitation is determined at a 0.5 x 0.5 degree global grid, using data on total precipitation from the CRU TS 2.0 dataset (Mitchell 2002). Effective precipitation is computed according to the SCS (USDA 1967) method:

$$PE_{ymuc} = cf \cdot \left(1.253PR^{0.824} - 2.935\right) \cdot 10^{(0.001ETp_{ymuc})} \tag{23}$$

where PR = total precipitation (mm)

cf is the correction factor depending on the depth of water application (Da):

$$cf = 1.0 \qquad \text{if } Da = 75\text{mm}, \tag{24a}$$
$$cf = 0.133 + 0.201*\ln(Da) \qquad \text{if } Da<75\text{mm per application, and} \tag{24b}$$
$$cf = 0.946 + 0.00073*Da \qquad \text{if } Da>75\text{mm per application.} \tag{24c}$$

Da is 75mm to 100mm for irrigated land and 150mm to 200mm for rain fed agriculture or rain fed land. If the above results in *PE* greater than *ETp* or *PR*, *PE* equals the minimum of *ETp* or *PR*. When *PR*<12.5mm, *PE=PR*.

To account for increased effective precipitation through water harvesting methods, the model applies a correction factor, λ, with λ ≥ 1.

$$PE'_{ymuc} = \lambda_{ymuc} . PE_{ymuc} \tag{25}$$

where PE' = corrected effective precipitation
λ = correction factor to account for water harvesting methods (λ ≥ 1)

The Effective Efficiency (EE), according to the definition given by Keller, Keller and Seckler (1996), is 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. It indicates how efficient *depleted* water has been utilized. The upper limit of Effective Efficiency is 100% but in practice this is never reached due to prohibitively high costs to achieve this. Very little information is available on EE. Estimates from PODIUM and IMPACT-WATER are used.

Volumetric water pricing may induce improvements in Effective Efficiency. To facilitate this option in the model, EE is a function of water price in some scenarios:

$$EE'_{yu} = EE_{yu} . (RWP_{yu})^{\varpi_u} \tag{26}$$

where EE' = improved effective efficiency
RWP = relative water price (for example 1.3 means an increase of 30%)
ω = price elasticity for effective efficiency improvement

Depletive demand in industry

Water demand in each of the industrial sectors– namely manufacturing, energy and agro-industry – is represented by the following equation:

$$DDI_{ymu} = dmi_{mu} \,.\, itcp_{yu} \,.\, (INC^{\alpha\iota})_{yu} . (WP^{\beta\iota})_{yu} . \, (e^{\gamma\iota . T})_{u} \tag{27}$$

where DDI = industrial depletive demand (km^3)
itcp = intercept (-)
INC = per capita income (US$/cap)
$\alpha\iota$ = income elasticity for industrial water demand (-)
$\beta\iota$ = industrial water price elasticity (-)
$\gamma\iota$ = time trend coefficient industrial water demand (-)
T = year (-)
dmi = factor to distribute yearly industrial demand over months

The elasticities with respect to per capita GDP and water price are specific to each region and industrial sector, and are synthesized from empirical literature and original estimates. The trend in industrial water demand is simulated under a variety of growth scenarios with respect to population and per capita income.

Depletive demand in domestic sector:

Water demand in the domestic sector, including both urban and rural residential uses, is calculated on the basis of income and population growth rates. Following Rosegrant *et al.* (2002) domestic demand is projected using the following growth rate:

$$gDDM_{yu} = gPOP_{yu} + \eta d_{yu} \cdot gINC_{yu} \,. \tag{28a}$$

gDDM = growth rate municipal water demand (%)
gPOP = population growth (%)
gINC = per capita income growth (%)
ηd = elasticity term domestic water demand (-)

This linear relationship combines the growth rates for population and GDP through an elasticity term. The relationship between demand and population and income growth rates was found by regression analysis on time-series data obtained from Shiklamanov (1999) and World Bank (1998). The domestic depletive demand for each period is then calculated by:

$$DDM_{ymu} = dmm_{mu} . (1 + gDDM_{yu}) . DDM_{y-1,mu} \tag{28b}$$

where *DDM* = depletive demand in municipal sector (km^3)

dmm = factor to distribute yearly municipal demand over months

Monthly water balance at sub-basin level

The schematic water balance is given in figure 2. The methodology adopted in the water balance at basin level follows the water accounting framework (Molden 1997).

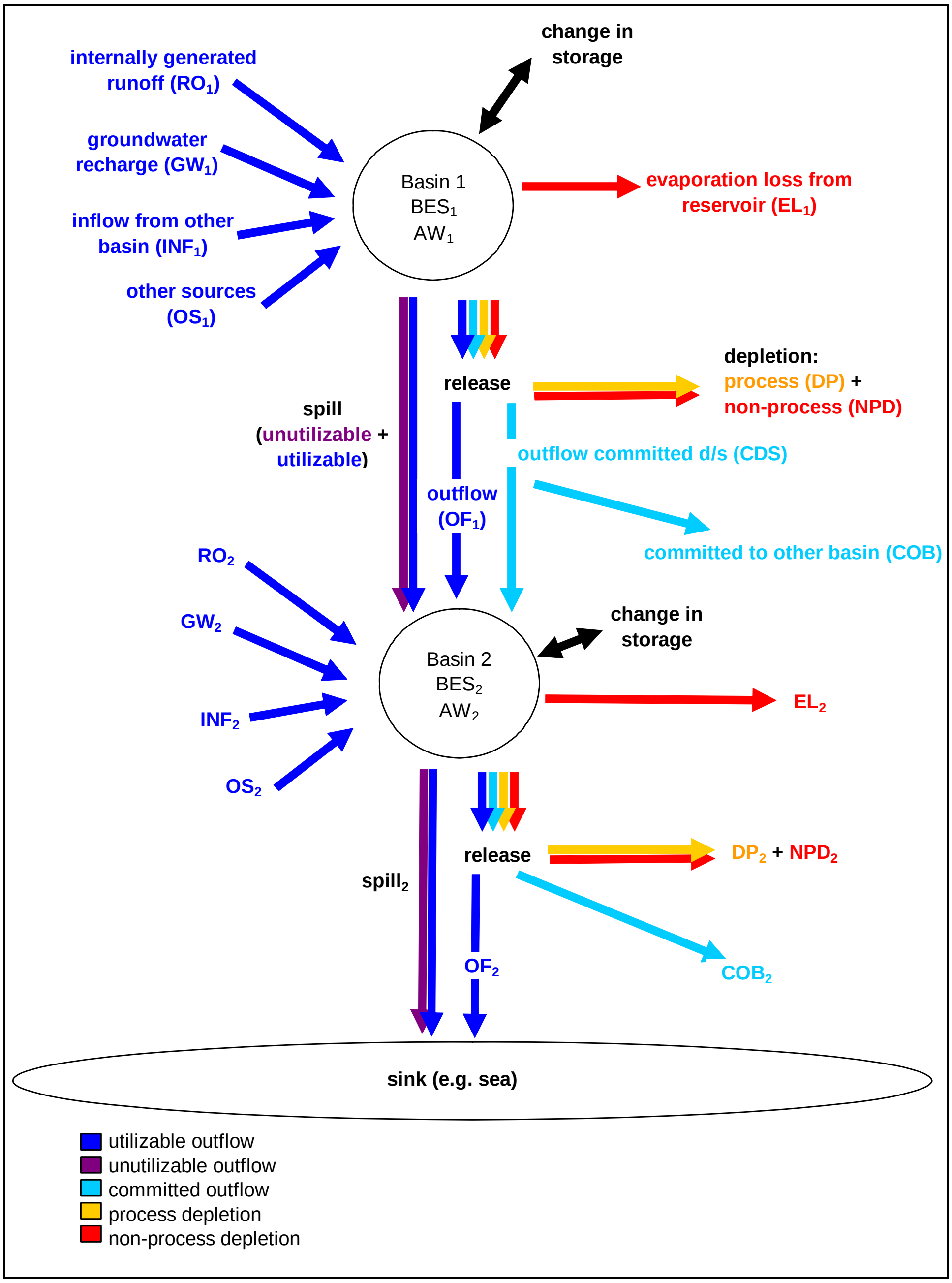


Figure 2: Water balance schematic

Total water resources in an upstream basin consist of surface and groundwater resources plus water from other sources (such as desalinization and water imports in tankers).

$$TWS_{ymb} = SI_{ymb} + GI_{ymb} + OS_{ymb} \tag{29}$$

where: *TWS* = total water resources (km^3)
SI = surface water inflow, i.e. internally generated runoff (km^3)
GI = natural groundwater recharge (km^3)
OS = water from other sources (km^3)
b = basin index (-)

The water balance at sub-basin level is estimated for both groundwater and surface water. The interaction between groundwater and surface water is simulated by the 'interflow', also referred to as 'overlap'. Interflow is the amount of water that can either be added to surface water or to groundwater depending on the interacting status of surface and ground water flows. Generally, when groundwater is over-pumped (more than recharge), part of surface water will become interflow and be added groundwater (this is the recharge process); when surface water is over-withdrawn, part of groundwater will become interflow and be added to surface water (this is the process of discharge).

The surface water balance thus becomes:

$$\begin{aligned} STs_{yum} - STs_{yu,m-1} = ISTs_{yum} + SI_{yum} + INF_{yum} + IBTi_{yum} + IW_{yum} - \\ EL_{yum} - SP_{yum} - REL_{yum} - IBTo_{yum} \end{aligned} \tag{30}$$

with: *STs* = surface water storage at the end of the month (km^3)
ISTs = surface water storage at beginning of the month (km^3)
INF = inflow from an upstream (sub-)basin (km^3)
IBTi = inflow from interbasin transfer (km^3)
IBTo = outflow for interbasin transfer (km^3)
REL = release for human uses (surface water) (km^3)
PM = pumping for human uses (groundwater) (km^3)
EL = evaporation from reservoirs and open water bodies (km^3)
IW = interflow ('overlap' between surface and groundwater) (km^3)
where $IW > 0$ represents "discharge" and $IW < 0$ represents "recharge".

The groundwater balance thus becomes:

$$\begin{aligned} STgw_{yum} - STgw_{yu,m-1} = ISTgw_{yum} + GI_{yum} + RIF_{yum} - \\ PM_{yum} - IW_{yum} \end{aligned} \tag{31}$$

STgw = groundwater storage at the end of the month (km^3)
ISTgw = groundwater storage at end of the month (km^3)
RIF = recharge to groundwater from irrigated fields (km^3)

The interflow is estimated as (derivation by Cai (2004):

$$IW_{yum} = IW_{yu,m-1} \cdot \exp[-\alpha \cdot \Delta t] + \left(GI_{ymu} + RIF_{ymu} - PM_{ymu}\right) \cdot \left(1 - \exp[-\alpha \cdot \Delta t]\right) \qquad (32)$$

where: α = base flow recession constant (-)
Δt = monthly time step (-)

The base flow recession constant is a direct index of groundwater flow response to changes in recharge (Smedema and Rycroft, 1983). Values vary from 0.1-0.3 for land with slow response to recharge to 0.9-1.0 for land with a rapid response. Although the base flow recession constant may be calculated, the best estimates are obtained by analyzing measured stream flow during periods of no recharge in the watershed. Note that in this equation *IW* could be negative if pumping is greater than the recharge.

Percolation from standing water in paddy fields, canals and reservoirs contributes to groundwater recharge of shallow aquifers that may be pumped later in the season. Man-made recharge from irrigated fields (*RIF*) –as opposed to natural recharge from precipitation (*GI*) – is estimated from:

$$RIF_{ymu} = \sum_{c} ETA_{ymuc} \cdot AI_{yuc} \cdot \frac{1 - \varepsilon_{yuc}}{\varepsilon_{yuc}} \cdot \rho_c \qquad (33)$$

where: *RIF* = recharge from irrigation fields (km^3)
ETA = actual evaporation (mm)
AI = irrigated area (m ha)
ε = depleted fraction (%)
ρ = recharge coefficient (-)

Depleted fraction (or irrigation efficiency) is defined as the ratio of the amount of water depleted over withdrawals. The recharge coefficient indicates what part of the return flow from irrigated areas percolates to groundwater. This factor is usually high for paddy fields (NIRE)

Water is either stored in the (sub-) basin for later use or -if the inflow is greater than the existing storage capacity- spills into a lower sub-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.

If the surface water inflow is greater than the existing storage capacity, water spills to a lower basin or sink. If groundwater recharge exceeds the groundwater storage capacity, the excess is added to the surface water balance through the interflow term.

$$SP_{ymu} = ST_{y,m-1,u} + TW_{ymu} - BES_{yu} \qquad \text{if } SP_{ymu} > 0 \qquad (34a)$$

$$SP_{ymu} = 0 \qquad \text{if } SP_{ymu} \leq 0 \qquad (34b)$$

where: BES = basin equivalent storage capacity (km^3)

BES is a function of investment in infrastructure:

$$BES_{yu} = f(investment) \qquad (35)$$

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 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.

Releases and pumping are limited by the amount of water stored in the basin. To ensure withdrawals are smaller than the amount of water stored, the following conditions are added:

$$REL_{ymu} \leq STs_{ymu} \qquad (36a)$$

$$PM_{ymu} \leq STgw_{ymu} \qquad (36b)$$

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 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:

$$REL_{ymu} + PM_{ymu} = DEPL_{ymu} + OF_{ymu} + IBTo_{ymu} \tag{37}$$

where OF = outflow from release (return flow) (km^3)
$DEPL$ = actually depleted (km^3)
$IBTo$ = transferred to a basin, other than downstream (km^3)

The depleted fraction is defined as the ratio of depletion over water released:

$$DF_{ymu} = \frac{DEPL_{ymu}}{REL_{ymu} + PM_{ymu}} \tag{38}$$

where DF = depleted fraction (-)

In this formulation the depleted fraction is not a fixed constant determined exogenously from the model (like in most models the irrigation efficiency). An endogenous variable bounded by a set upper limit, the depleted fraction varies with water availability: in wet months it can be low, while in dry months with high water demand it will hit the upper boundary.

Optimizing water supply according demand

Supply is matched to demand adopting an optimization approach commonly used in reservoir models (Rosegrant, Cai and Cline 2002). The objective is to maximize the ratio of depletive supply over demand. The amount of water depletive supply (*DEPL*) is determined by solving:

$$\max\left[\frac{\sum_{m} DEPL_{ymu}}{\sum_{m} DDTo_{ymu}} + w.\min_{m}\left(\frac{DEPL_{ymu}}{DDTo_{ymu}}\right)\right] \tag{39}$$

where w = weight to ensure distribution over the months according to demand

Constraints

The optimization formulation assumes a rational water management with perfect foresight, in which water is allocated in accordance to demand. The optimal allocation will be constrained by physical limits, operational rules and environmental concerns. These may be different in the various scenarios. The following sets of constraints are considered: committed flow, physical constraints, operational constraints and environmental requirements.

Committed flows

Committed outflow is that part of outflow that is committed to other uses. For example, water may be reserved for use by downstream countries, or other downstream uses that have a right to water. Committed flows are met by the outflow from release plus spill.

Committed flow downstream:

$$OF_{ymu} + SP_{ymu} \geq CF_{ymu} \tag{40}$$

where CF = flow committed downstream

Physical constraints

For consistency the following physical constraints need to be added.

Monthly release cannot be greater than storage capacity:

$$REL_{ymu} \leq BES_{yu} \tag{41}$$

Actual depletion is never greater than demand

$$0 \leq \frac{DEPL_{ymu}}{DDTo_{ymu}} \leq 1 \tag{42}$$

Operational constraints

For example, the generation of hydropower may require a minimum amount of water stored at a certain month:

$$ST_{ymu} \geq certain\ amount \tag{43a}$$

or: $$ST_{ymu} \geq x\%\ of\ BES \tag{43b}$$

Environmental flow requirements

Environmental flow requirements can be added to the model as hard constraint, in which the requirements are always met:

$$EFR_{mu} \leq OF_{ymu} + SP_{ymu} \tag{44}$$

where EFR = environmental flow requirements (km^3)

Allocation to sectors

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

$$DEPL_{ymu} = DSA_{ymu} + DSI_{ymu} + DSM_{ymu} \tag{45}$$

where DSA = monthly depletive supply to agriculture
DSI = monthly depletive supply to agriculture
DSM = monthly depletive supply to agriculture

The next step is to allocate this amount over the different sectors and crops. In most scenarios the industrial and domestic sectors will take preference over agriculture[4]:

$$DSA_{ymu} = DEPL_{ymu} - DSI_{ymu} - DSM_{ymu} \qquad \text{if DSA} > 0 \tag{46a}$$

$$DSA_{ymu} = 0 \qquad \text{if DSA} \leq 0 \tag{46b}$$

If the amount available for depletion is insufficient to cover industrial and domestic demands, the domestic sector will get priority:

$$DSI_{ymu} = DEPL_{ymu} - DSM_{ymu} \qquad \text{if DSI} > 0 \tag{47a}$$

$$DSI_{ymu} = 0 \qquad \text{if DSI} \leq 0 \tag{47b}$$

Alternatively, water shortage, if occurring, can be distributed over the sectors proportional to demand:

$$DSA_{ymu} = DDA_{ymu} - \frac{DDA_{ymu}}{DDTo_{ymu}}.(DDTo_{ymu} - DEPL_{ymu}) \tag{48a}$$

$$DSI_{ymu} = DDI_{ymu} - \frac{DDI_{ymu}}{DDTo_{ymu}}.(DDTo_{ymu} - DEPL_{ymu}) \tag{48b}$$

$$DSM_{ymu} = DDM_{ymu} - \frac{DDM_{ymu}}{DDTo_{ymu}}.(DDTo_{ymu} - DEPL_{ymu}) \tag{48c}$$

Or any other allocation mechanism defined by a scenario.

Allocation to crops

The allocation over 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.
The allocation fraction is given by:

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[4] For India, the National Water Policy (2002) provides the Irrigation sector second priority in allocation after drinking water in planning and operation of water resources systems. The priority is as follows:

- Drinking water
- Irrigation
- Hydro-power
- Ecology
- Agro-industries and non-agricultural industries
- Navigation and other uses

These priorities are followed in the simulations for India

$$\pi_{ymuc} = \frac{ALLO_{ymuc}}{\sum_{i} ALLO_{ymuc}} \tag{49}$$

$$ALLO_{ymuc} = ky_c . \left(1 - \frac{PE_{ymuc}}{ETp_{ymuc}} \right) . PS_{yuc} \tag{50}$$

Allocation to individual crops is then:

$$DSAC_{ymuc} = \pi_c . DSA_{ymu} \tag{51}$$

The amount of beneficial depletion by each crop is then:

$$BAC_{ymuc} = EE_{ymu} . DSAC_{ymuc} \tag{52}$$

where π = allocation fraction (%)
ky = crop yield response to water factor FAO (-)
PS = producer price -from IMPACT run (US$/ton)
DSAC = amount of irrigation water depletion supplied to crop i (km^3)
BAC = amount of beneficial irrigation depletion by crop *c* (km^3)
m ∈ cropping period

Yield and area reduction due to water stress, irrigated crops

The minimum water layer on the cropped area on a monthly basis is:

$$WL_{ymuc} = \frac{BAC_{ymuc}}{AI_{yuc}} + PE_{ymuc} \tag{53}$$

where WL = water layer on the field before area reduction (mm)
m ∈ cropping period

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. To simulate this trade-off between area and water layer, the parameter E* is introduced. This behavioral parameter expresses the threshold level of relative evapotranspiration below which farmers will reduce crop area rather than imposing additional water stress on existing area. The reduction in area is thus:

$$\Delta AI_{yuc} = 0, \qquad if \; \frac{\sum_{m} WL_{ymuc}}{AI_{yuc}} > E^{*}_{ymuc} \qquad otherwise \tag{54}$$

$$\Delta AI_{yuc} = AI_{yuc} \cdot \left[1 - \left(\frac{\sum_{m} WL_{ymuc}}{\sum_{m} ETp_{ymuc}} / E^{*}_{ymuc} \right) \right] \tag{55}$$

where ΔAI = reduction in irrigated area due to water stress
$m \in$ cropping period

When E* equals one all adjustments to water shortage are realized through area reduction while crop yields are maintained. The parameter E* depends on the sensitivity of crops to water stress. For crops that are highly sensitive to drought E* will approach a value of one, i.e. water shortages are handled by leaving a portion of the land fallow while maintaining yields on the remaining area. For relatively drought resistant crops the threshold for area reduction may be much lower. For these crops, maximization of production and return will require spreading the water over as broad an area as possible to maintain production while reducing crop yields.
Likewise, in areas with many small subsistence farmers the level of E* will be lower than in areas with large commercial farms. Small subsistence farmers may not have the option to reduce areas.

Accounting for the area reduction, the actual evapotranspiration (ETa) becomes:

$$ETa_{ymuc} = \frac{BAC_{ymuc}}{(AI_{yuc} - \Delta AI_{yuc})} + PE_{ymuc} \tag{56}$$

The yield reduction due to water stress is based on seasonal water availability (that is, seasonal ETa). An additional term is added to "penalize" yield if water availability in some months during the crop growth is lower than the seasonal level:

$$\Delta YI_{yuc} = YI_{yuc} \cdot ky_{yuc} \cdot \left(1 - \frac{\sum_{m} ETa_{ymuc}}{\sum_{m} ETp_{ymuc}} \right) \cdot \left[\frac{\min_{m}\left(ETa_{ymuc} / ETp_{ymuc} \right)}{(ETa_{ymuc} / ETp_{ymuc})} \right]^{\tau} \tag{57}$$

where ΔYI = reduction if irrigated yield due to water stress
τ = coefficient to characterize penalty item
$m \in$ cropping period

τ should be estimated based on local water application in crop growth stages and crop yield.

Yield and area reduction due to water stress, rain fed crops

In rain fed areas the actual evapotranspiration equals the effective precipitation:

$$ETa_{ymuc} = PE_{ymuc} \tag{58}$$

In rain fed areas farmers don't have the choice to reduce area to maintain water layer, but they may loose part of the harvested area due to drought. The parameter E* in rain fed areas indicates the threshold level below which a farmer decides to give up part of the area because of drought damage. Equation 79 captures the effect of severe drought on the harvested rain fed area:

$$\Delta AC_{yuc} = AR_{yuc} \cdot \left[1 - \left(ky_c \cdot (1 - \frac{\sum_m ETa_{ymuc}}{\sum_m ETp_{ymuc}} / E^*_{yuc}) \right)^{\rho} \right] \tag{59}$$

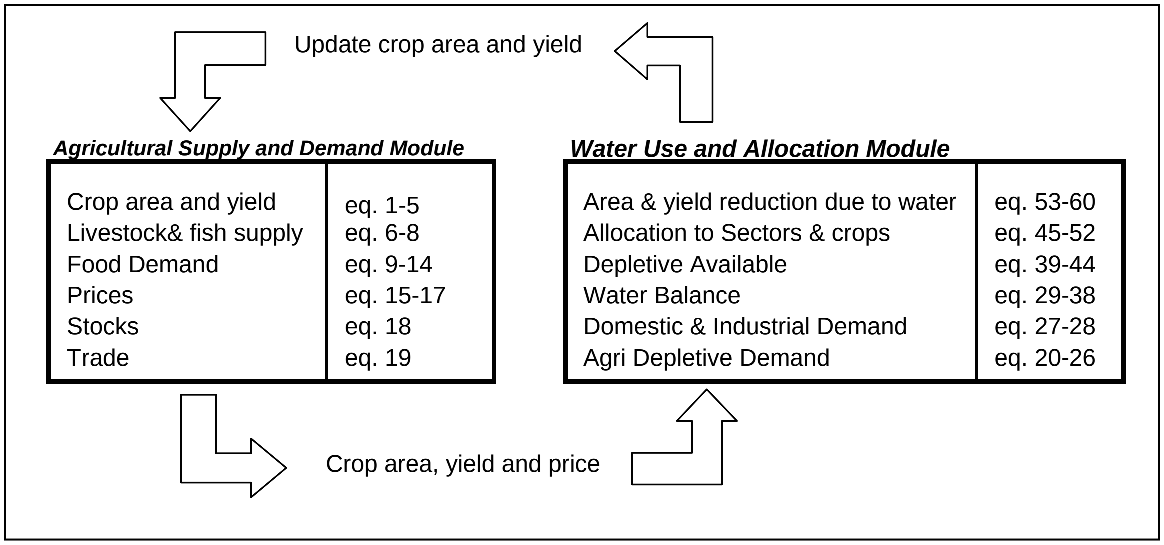
The value of E* for rain fed crops will be much lower than for irrigated crops.

The reduction in rain fed yield is estimated by:

$$\Delta YR_{yuc} = YR_{yuc} \cdot ky_c \cdot \left(1 - \frac{\sum_m ETa_{ymuc}}{\sum_m ETp_{ymuc}} \right) \cdot \left[\frac{\min_m \left(ETa_{ymuc} / ETp_{ymuc} \right)}{(ETa_{ymuc} / ETp_{ymuc})} \right]^{\tau} \tag{60}$$

3 Linkage water and food modules

The food module estimates food production (area and yield) as a function of socio-economic driving forces. The water module assesses the impact of irrigation water availability on areas and crop yields. 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 rain fed 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.



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