

Project Report

PODIUMSIM and WATERSIM Models

Project report of the IWMI/IFPRI Component of the Country Policy Support Studies Program

International Water Management Institute

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PODIUMSIM and WATERSIM- IWMI/IFPRI Component of the Country Policy Support Studies Program

Background

The PODIUM, the Policy Dialogue Model, designed in Microsoft Excel environment, is a user friendly interactive scenario generating tool for scientists and policy makers (www.iwmi.org). Having published its first major report in assessing the future water supply and demand of world's major countries (Seckler et al 1998), the International Water Management Institute (IWMI), has refined the data and methodology of the assessment and developed a new model PODIUM. It explores the technical, social and economic aspects of alternative scenarios of future water demand and supply at country level.

The participants in many consultations and workshops viewed PODIUM as a useful scenario generating tool. Scientist and policy makers of various countries used the PODIUM model for generating alternative scenarios of water supply and demand in their national consultations leading to the 2nd World Water Forum in Hague. IWMI has used PODIUM for developing three scenarios for the World Water Council's Vision program (IWMI 200, Rijsberman 2000). However, some limitations of the first version of the PODIUM were also highlighted in these meetings. The model considers only one crop, the cereals, for food and water demand assessment. And the model does not have the capacity to estimate food demand supply and water demand for individual crops, even within the cereals category. Further, the model also does not capture the spatial variations of water supply and demand, especially for large countries such as India and China.

The PODIUM, upgraded through the Country Policy Support Program (CPSP) of the International Commission and Irrigation and Drainage (ICID), addresses the limitations of the model and the concerns of various users. The Country Policy Support Program of the ICID contributes to identifying effective options for water management to the achievement of an acceptable food security level and sustainable rural development, primarily in China and India. As part of the CPSP, the IWMI and the International Food Policy Research Institute (IFPRI) were to

1. improve the PODIUM model to handle country specific issues at sub-national level and
2. integrate PODIUM and IMPACT to better address the hydrologic and economic issues for developing scenarios.

The upgraded PODIUM model is PODIUMSIM and the integration of PODIUM and IMPACT-Water is WATERSIM. This report provides the details of upgrading PODIUM model and the process of integration with IMPACT Water. The next section gives the details of PODIUMSIM model. The third section gives an account of the extent to which PODIUM and the IMPACT are integrated at present. And the last section highlights the capacity building through the IWMI/IFPRI component.

2. PODIUMSIM for CPSP

PODIUM to PODIUMSIM – Upgrades

The PODIUMSim retains the four major components of the PODIUM: Consumption, Production, Water Demand and Water supply. However, substantial improvements exist both at spatial and temporal scale within individual components. The table 1 shows the differences-the temporal and spatial scales at which the scenarios can be developed for different components. A notable improvement in PODIUMSIM is the introduction of sub-national units to capture the spatial variation of water supply and demand. At temporal scale, the irrigation water needs are now assessed at monthly time periods and then aggregates to obtain seasonal and annual agriculture water requirements.

Table 1. Spatial and temporal scale improvements of different components

Component	PODIUM		PODIUMSIM	
	Spatial scale	Temporal scale	Spatial scale	Temporal scale
Consumption	National	Annual	National	Annual
Production	National	Seasonal	River basin	Seasonal
Water Demand				
Irrigation	National	Seasonal	River Basin	Monthly
Domestic	National	Annual	River Basin	Annual
Industrial	National	Annual	River basin	Annual
Environment	-	-	River basin	Annual/Monthly
Water Supply	National	Annual	River Basin	Annual

Crop consumption estimation

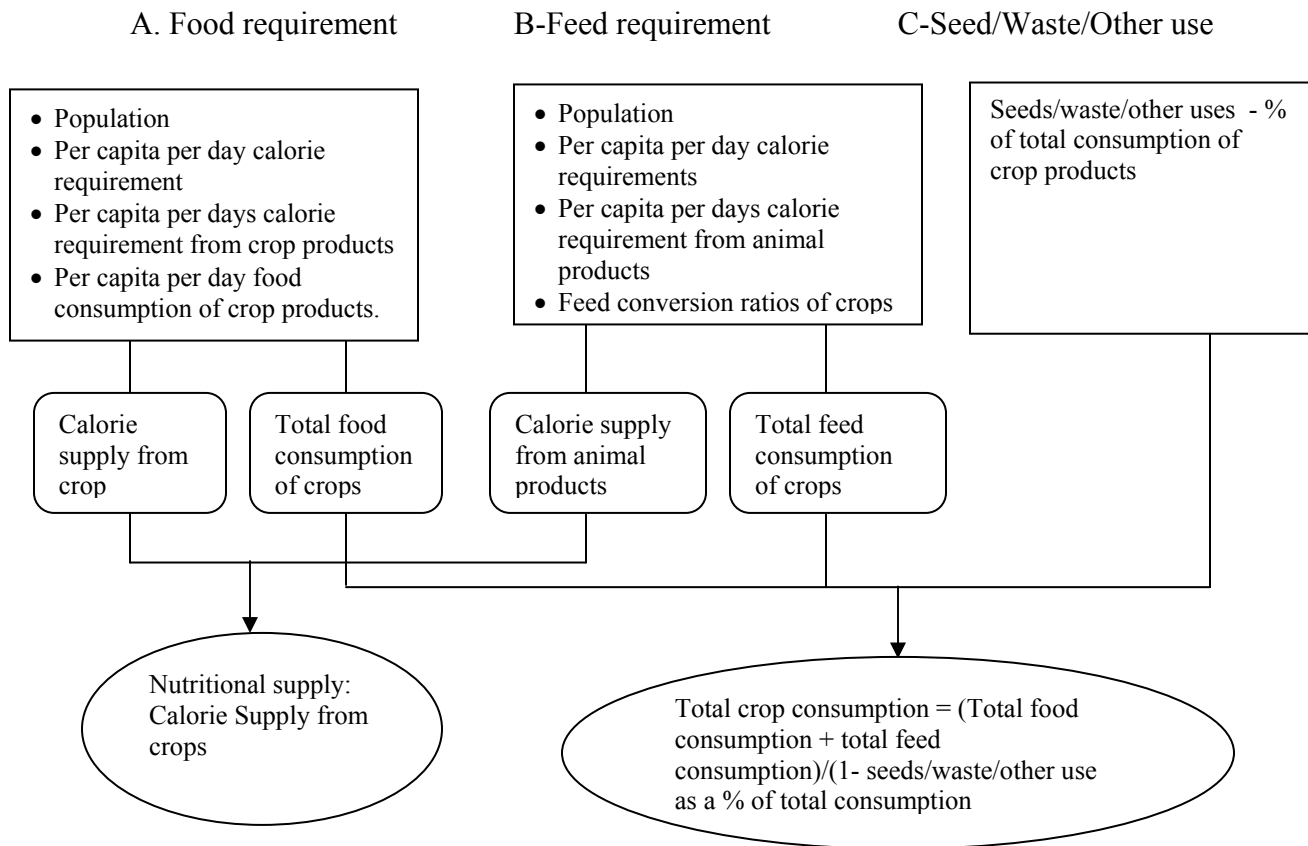
The major improvement in the consumption component is that details of consumption patterns of 11 crop categories are now available for both rural and urban sectors (Table 2)

Table 2. Drivers of the consumption component

Drivers	PODIUM	PODIUMSIM
Population	National	National (Rural & Urban)
Total calorie supply/person/day	National	National (Rural & Urban)
% Calorie supply from Grains	National	National (Rural & Urban)
% calorie supply from oil crops	-	National (Rural & Urban)
% calorie supply from fruits and vegetables	-	National (Rural & Urban)
% calorie supply from animal products	National	National (Rural & Urban)
Per capita food consumption of	Cereals	10 crop categories (rice, wheat, maize, other cereals, pulses, oil crops, roots and tubers, vegetables, fruits, sugar)
Feed conversion factors (i.e., kg of feed for a unit a animal product)	Cereals	10 crop categories
Seeds/Waste/Other uses	Cereals	10 crops (9 crop categories and cotton)

This component first estimates the food requirement, the feed requirements and the seeds/waste/other uses separately for 10 crop categories and then aggregate to obtain grain, non-grain and total crop requirement. The figure 1 shows the flow diagram of estimation of crop requirements for a given level of nutritional requirements.

Figure 1. Flow diagram of consumption component



Food requirement: The major drivers of food requirement estimation are

- population growth
- per person daily calorie requirement growth
- composition of daily calorie supply changes, i.e., changes in the daily calorie supply from grains, oil crops, fruits and vegetables and other crop products as a percent of total calorie supply and
- the changes in daily consumption of crop products such as rice, wheat, maize, other cereals, pulses, oil crops, roots and tubers, vegetables, sugar, fruits.

The growth or changes of the drivers satisfies the constraint that the absolute difference of calorie requirement and calorie supply, i.e., |calorie requirement – calorie supply from crop consumption|, of crop categories of grains, oil crops, fruits/vegetables and other crops should be less than 5 kcal. The food requirement of i^{th} crop or crop category is estimated as

Food consumption of i^{th} crop = Total population \times Consumption/pc/day of i^{th} crop \times 365

Feed requirement: The major drivers of feed requirement estimation are

- population growth
- total calorie requirement growth,
- growth in per person calorie supply from animal products in the total and
- the changes in feed conversion ratios, i.e., the quantity of different crop products for supplying the required calorie supply from animal crop products.

The feed consumption of i^{th} crop or crop category is estimates as

Feed consumption of i^{th} crop = Total population \times animal products calorie supply/pc/day
 $\times 365 \times$ feed conversion ratio of crop i

Seeds/Waste/Other uses: The quantity of seeds/waste and other uses of crop as a percentage of total crop consumption is a driver of estimating total crop requirement.

Total requirement of crop i :

Total consumption of crop i = (Food consumption of crop i + Feed consumption of crop i)
 $/ (1 - (\text{seeds/waste/other use of crop } i \text{ as \% of total consumption}))$.

In addition to the food crops, we estimate the annual requirement of cotton (lint equivalent).

Grain, non-grain and all crop requirements: The total crop requirements of grains, non-grains and all crops of the scenario year are shown as the aggregate value of crop products based on base year export prices. The base year export prices are used only as a means of aggregating the quantity of different crop products. Let R_{ti} and P_{0i} are the total quantity of consumption of crop i in year t and the base year unit export prices of crop i . Then

Grain crop requirement = $\sum R_{ti} \times P_{0i}$, $i \in$ (Rice-milled equivalent, wheat, maize, other cereals, pulses)

Non-grain crop requirement = $\sum R_{ti} \times P_{0i}$, $i \in$ (oil crops, roots and tubers, vegetables, sugar, fruits, cotton)

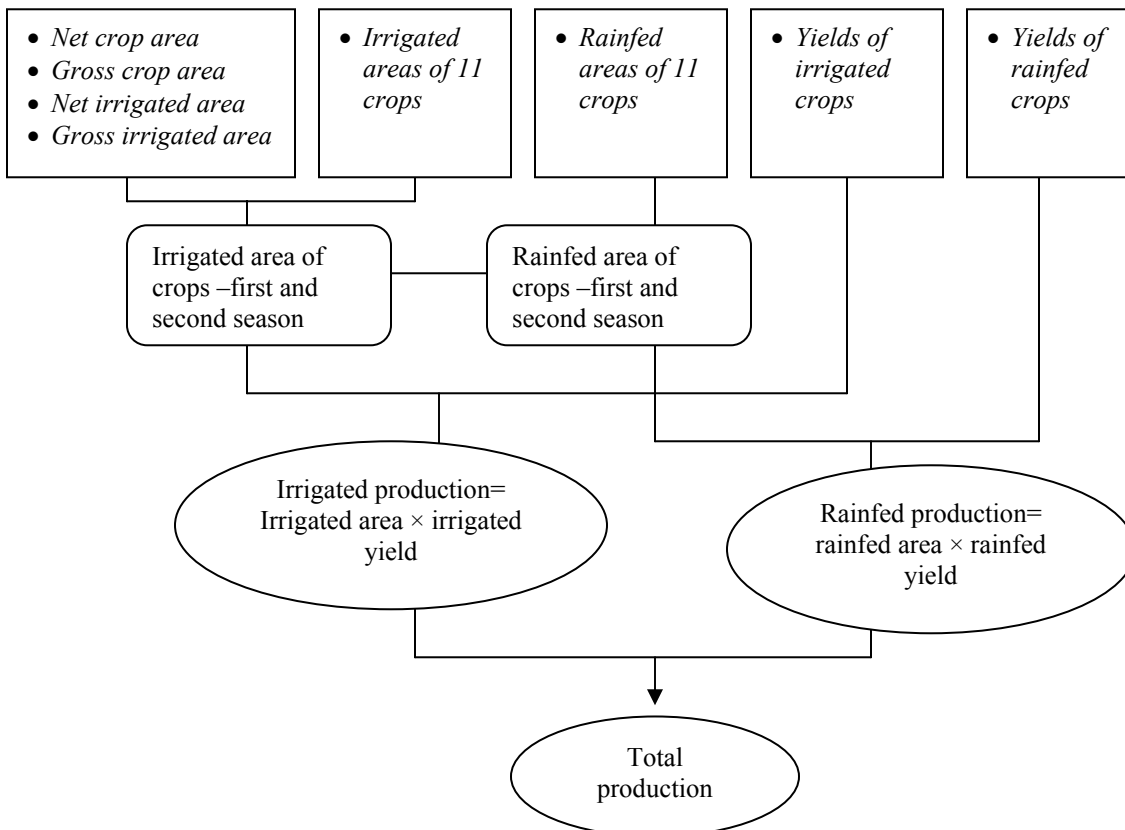
Crop production estimation

The major improvement of this component of PODIUMSIM is its capacity to capture the spatial variability of production potentials of several crop categories. The model estimates crop production at river basin level for 11 crop categories in both irrigation and rain fed condition. Table 3 shows the major drivers.

Table 3. Major drivers of crop production component

Drivers	PODIUM	PODIUMSIM
Net irrigated area	National	River basin
Gross irrigated area	National	River basin
Irrigated crop area	Cereals at national level for two season	11 crop categories at river basin level for two seasons
Rainfed crop area	Cereals at national level annually	11 crop categories at river basin level for two seasons
Irrigated crop yield	Cereals at national level for two season	11 crop categories at river basin level for two seasons
Rainfed crop yields	Cereals at national level annually	11 crop categories at river basin level for two seasons

Figure 2. Flow chart of crop production estimation



First, the growth of net and gross crop area and net and gross irrigated are specified. This gives the changes of total crop areas under irrigated and rainfed conditions for two seasons and cropping intensities.

*Overall cropping intensity = gross crop area/ net crop area, and
Irrigated cropping intensity = gross irrigated area/ net irrigated area.*

Second the seasonal irrigated cropping patterns, i.e., the irrigated crops areas are specified. The changes in irrigated crop areas in the two seasons satisfy the following constraints:

*First-season total irrigated crop area \leq net irrigated area
Change in first season irrigated crop area \geq change in net irrigated area
Change second season irrigated area = change in gross irrigated area – change in first season irrigated area.*

Third, the seasonal rainfed cropping patterns, i.e., rainfed crop areas, are specified. Changes in rainfed crop areas satisfy the following constraints.

*First-season total rainfed crop area \leq net crop area - net irrigated area
Change in first season rainfed crop area \geq changes in (net crop area – net irrigated area)
Change in second season rainfed area = changes in (gross crop area – gross irrigated area)-changes in first season rainfed crop area*

Fourth, the growth of irrigated and rainfed crop yields are specified. The crop production of i^{th} crop is

Total production-crop_i = \sum area-crop_{ij} \times yield-crop_{ij} j \in (first season, second season).

Agriculture water requirement estimation

PODIUMSIM has substantial improvements in irrigation water requirement estimation. It now captures the variation of crop water requirements temporally by monthly estimations and spatially by river basins level estimations. Table 4 shows the key drivers and the upgrades of PODIUMSIM over the PODIUM model.

Table 4. Drivers of crop water requirement estimation

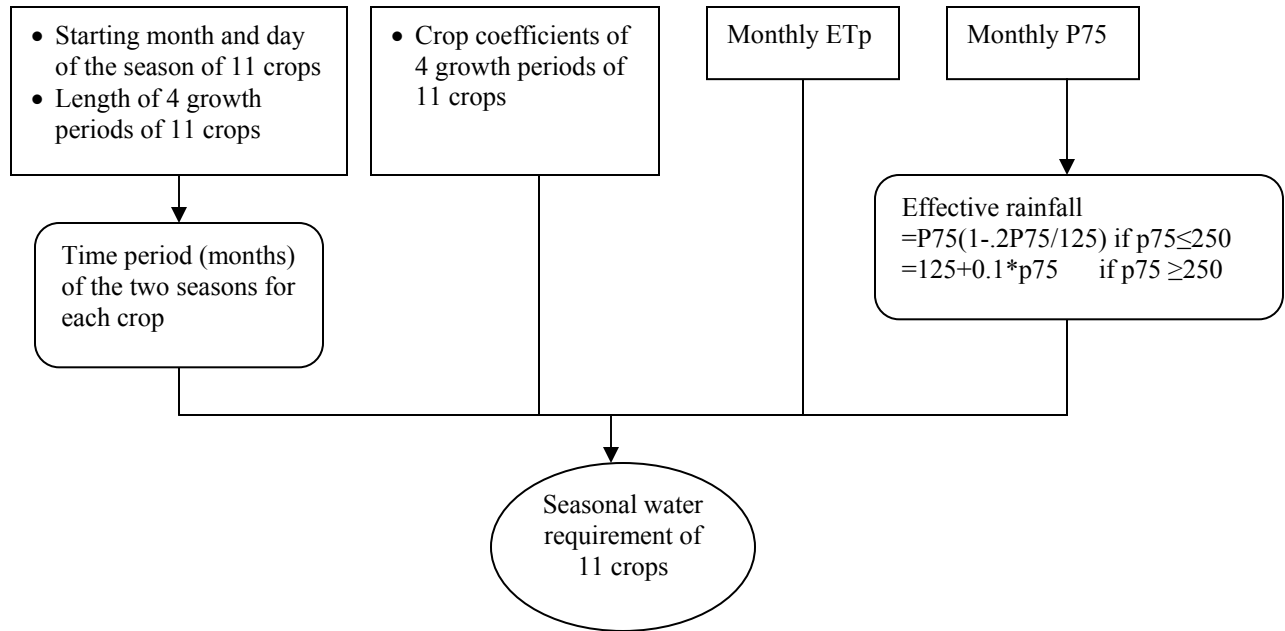
Drivers	PODIUM	PODIUMSIM
P75 (75 percent exceedence probability rainfall)	Two seasons at national level	Monthly at river basin level
ETp (potential evapo-transpiration)	Two seasons at national level	Monthly at river basin level
Crop calendar – Starting date of the season	Starting month of two seasons for cereals at national level	Starting month and day of two seasons for 11 crop categories at river basin level
Length (number of days) of crop growth periods	Number of months in two seasons at national level	Number of days in four growth periods for each seasons at river basin level
Crop coefficients	For cereals in two seasons at national level	For 11 crop categories, in four crop growth periods in each season at river basin level
Crop area	Seasonal irrigated area at national level	Irrigated area of 11 crops in two seasons at river basin level
Groundwater irrigated area	-	Seasonally at river basin level
Percolation requirement for paddy	Seasonal at national level	Seasonal at river basin level
Project efficiency-surface irrigation	Seasonally at national level	Seasonally at river basin level
Project efficiency-Ground water irrigation	-	Seasonally at river basin level

Crop Water Requirement: First the model estimates crop water requirement for each crop (figure 3). First it determines the time (months) of the growth periods using the starting date (month and day) of the season and the length of the growth periods and also the effective rainfall for each month using P75. Next it estimates the crop water requirement for each growth period using effective rainfall, Etp and crop coefficients. The seasonal crop water requirement of each crop is given by

$$Water\ req\ of\ Crop^l = \sum_{i \in growth\ periods} \sum_{j_i \in months} \max[(Effe.\ rain_{ij_i} - Crop\ coeff_{ij_i}^l \times ETP_{ij_i}), 0] \times \frac{d_{ij_i}^l}{n_{ij_i}^l}$$

where $k \in 11$ crops (rice, wheat, maize, other cereals, pulses, oil crops, vegetables, fruits, sugar, cotton), $i \in$ four growth periods (initial, development, middle and late), $j_i \in j^{th}$ months in i^{th} crop growth period, $d_{ij_i}^l$ = number of days of j^{th} months in i^{th} crop growth period of crop k , and n_{j_i} = number of days of j_i^{th} month.

Figure 3. Flow chart of estimating crop water requirement



Irrigation water requirement: Next the model estimates irrigation water requirement of the river basin. Let

IA_{ij} – irrigated area of i^{th} crop in j^{th} season

CWR_{ij} - crop water requirement of i^{th} crop in j^{th} season

PER_j – Percolation requirement for paddy in j^{th} season

$GWIA_j$ – Groundwater irrigated area as a percent of total irrigated area in j^{th} season

SEP_j - Surface project irrigation efficiency paddy in j^{th} season

$SEOC_j$ - Surface project irrigation efficiency other crops in j^{th} season

GE_j - Ground water project irrigation efficiency in j^{th} season

PER_j - Percolation requirement for paddy in j^{th} season

Then the annual irrigation requirement is

$$\begin{aligned}
 \text{Irrigation water requirement} = & \sum_{j=1}^2 (1 - GWIA_j) \left(\frac{CWR_j^{\text{paddy}} + PER_j + \frac{\sum_{i \in \text{other crops}} CWR_{ij}}{SEOC_j}}{SEP_j} \right) \\
 & + \sum_{j=1}^2 GWIA_j \left(\frac{CWR_j^{\text{paddy}} + PER_j + \frac{\sum_{i \in \text{other crops}} CWR_{ij}}{SEOC_j}}{GE_j} \right)
 \end{aligned}$$

Domestic and industrial water requirement estimation

The domestic water requirement includes water requirements for humans and livestock. The drivers of estimating domestic human and livestock water requirements and industrial water requirements are shown in table 5.

Table5. Drivers of Domestic and Industrial water requirement assessment

Drivers	PODIUM	PODIUMSIM
Urban and Rural population	National level	River basins
Daily per person withdrawals for urban and rural sectors	National level	River basins
Percent urban and rural population with pipe water supply	National level	River basins
# of animals (cattle, goats, pigs and others)	-	River basins
Daily per animal water requirement	-	River basins
Total industrial water requirements	National	River basins

The domestic water requirement humans and livestock are estimated by

$$\text{Domestic water requirement for humans} = \sum_{i=Urban,Rural} \left(\begin{array}{l} \text{Population}_i \times \% \text{ pop. with pipe water supply}_i \times \\ \text{Per capita daily requirement}_i \times 365 \end{array} \right)$$

$$\text{Livestock water requirement} = \sum_{i \in (cattles, goats, pigs)} \left(\begin{array}{l} \text{Number of animal} \times \text{Daily water requirement} \\ \text{per animal} \times 365 \end{array} \right)$$

The growth of total industrial water requirement is taken as a driver in future industrial water requirement assessment.

Environmental flow requirement estimation

The environmental flow requirement module, a new component in the PODIUMSIM, incorporates scenarios of annual river flow requirements that need to be met from the potentially utilizable water resources. It operates at river basin level and has two options: it can either directly enter the annual environmental flow requirements or can estimate from the monthly environmental flow requirements. The drivers of this component are given in table 6.

Table 6. Drivers of environmental flow requirement assessment

Drivers	PODIUMSIM
Annual river flow requirement	Annual values at river basin level
Monthly renewable surface water resources	Monthly at river basin level
Potentially utilizable water resources	Monthly at river basin level
% of minimum flow requirement to be met from potentially utilizable water resources	Monthly at river basin level

In the case of estimation from monthly flows, first we observe that for each month all or part of the minimum flow requirement can be met from the un-utilizable part of the renewable surface water resources (RSWR). Second, all or part of the minimum flow requirement that cannot be met from un-utilizable RSWR has to be met by the potentially utilizable surface water resources (PUWR). The model keeps this portion of PUWR as a driver for determining environmental flow requirement scenarios. Let

MFR_i – Minimum flow requirement of i^{th} month

$RSWR_i$ - Renewable surface water resources of i^{th} month

$PUWR_i$ – Potentially utilizable water resources of i^{th} month

$PCTMFR_i$ – Percent of minimum flow requirement to be met from $PUWR_i$

The environmental flow requirement is estimated as

$$Environmental\ flow\ requirement = \sum_{i=1}^{12} Max(RSWR_i - PUWR_i - MFR_i, 0) \times \%MFR_i$$

The PODIUMSIM model consider that the estimated environmental water requirement has to be deducted from the potentially utilizable water supply for estimating potentially available water supply for other sectors of water use.

Utilizable water resources estimation

This component estimates the potentially available water resources for agriculture, domestic and industrial sectors of water use. Table 7 shows the drivers and improvements in the PODIUMSIM model.

Table 7. Drivers of potentially utilizable water resources assessment

Drivers		PODIUM	PODIUMSIM
Potentially utilizable surface water resources		Annually at country level	Annually at river basin level
Potentially utilizable groundwater resources		Annually at country level	Annually at river basin level
Water transfers in		Annually at country level	Annually at river basin level
Water transfers out		Annually at country level	Annually at river basin level
Environmental water requirement	water	-	Annually at river basin level

The potentially available water resources is

$$\begin{aligned}
 \text{Available water resources} = & \text{Potentially Utilizable surface and ground water resources} \\
 & + \text{Water transfers in} - \text{water transfers out} + \\
 & + \text{Environmental water requirement}
 \end{aligned}$$

Accounting of utilizable water resources

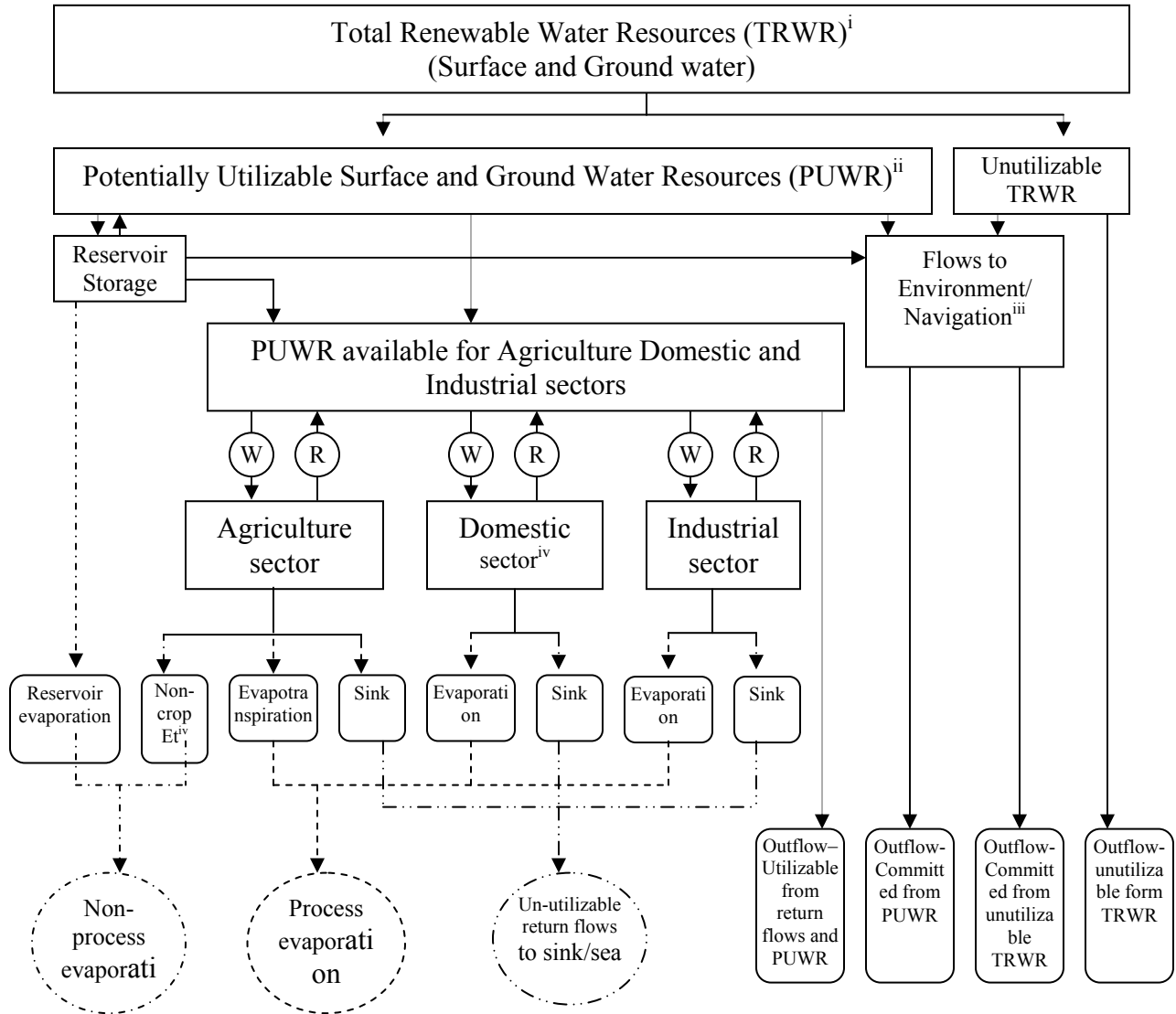
The PODIUMSIM model estimate water accounting for potentially utilizable water resources of river basins. Part of the potentially utilizable water resources is developed and used in different sectors of water use. Of the water diversions to agriculture, domestic and industrial sectors, the model estimates

1. process evaporation (evapotranspiration in irrigation and consumptive use in domestic and industrial sectors)
2. balance flows, i.e., the difference between withdrawals and process evaporation
3. return flows to surface water supply
4. recharge to ground water supply
5. non-process evaporation, i.e., flows to swamps in irrigation,
6. un-utilizable flows to the sea or a sink and
7. utilizable flows to sea from the surface return flows and groundwater recharge.

The total process evaporation of the three sectors is given by

$$\text{Total process evaporation} = \left\{ \begin{array}{l} \sum_{i \in \text{allcrops}} (\text{water req } crop_i \times \text{area } crop_i) + \\ \text{Domestic water withdrawals} \times \text{consumptive use factor}^{Dom} + \\ \text{Industrial water withdrawals} \times \text{consumptive use factor}^{Ind} \end{array} \right.$$

Figure 4. Flow diagram of water accounting



⊙ (W) - Withdrawals, ⊙ (R) - Return flows to surface/Groundwater Recharge

- i. TRWR – Total Renewable Water Resources
- ii. PUWR – Potentially Utilizable Water Resources
- iii. Parts of the environment and navigation flows are met from unutilizable TRWR and the other parts are met by PUWR
- iv. Domestic sector includes livestock sector water needs.
- v. Non crop ET is the evaporation and transpiration from the swamps, bare fields, and tress and other crops which the water withdrawals are not intended for.

Balance flow (BF) of each sector is defined as the difference between water withdrawals and process evapotranspiration. The return flows to surface and recharge to groundwater in each sector are estimated as

$$\text{Return flows to surface water} = \begin{cases} \text{Balanceflow}^{irri} \times \% \text{ balance flows to surafce}^{irri} + \\ \text{Balanceflow}^{Dom} \times \% \text{ balance flows to surafce}^{Dom} + \\ \text{Balanceflow}^{Ind} \times \% \text{ balance flows to surafce}^{Ind} \end{cases}$$

$$\text{Ground water recharge} = \begin{cases} \text{Balanceflow}^{irri} \times \% \text{ balanceflow recharge to groundwater}^{irri} + \\ \text{Balanceflow}^{Dom} \times \% \text{ balanceflow recharge to groundwater}^{Dom} + \\ \text{Balanceflow}^{Ind} \times \% \text{ balanceflow recharge to groundwater}^{Ind} \end{cases}$$

The non-process evaporation is estimated as

$$\text{Total non process evaporation} = \begin{cases} \text{Balance flow of irrigation} \times \% \text{BF to swamps} + \\ \text{Reervoir storage capacity} \times \% \text{ evaporation from surface} \end{cases}$$

The un-utilizable flows to sea or sink is estimated as

$$\text{Un utilizable flows to sea} = \begin{cases} \text{Balance flow}^{irri} \times \% \text{ unutilizable of balance flow}^{irri} \\ \text{Balance flow}^{Dom} \times \% \text{ unutilizable of balance flow}^{Dom} \\ \text{Balance flow}^{Ind} \times \% \text{ unutilizable of balance flow}^{Ind} \end{cases}$$

The utilizable flows to sea from the surface return flows and groundwater recharge are estimated as

$$\text{Utilizable return flows to sea} = \begin{cases} \text{Return flows to surface} \times \% \text{return flows to sea} + \\ \text{Ground water recharge} \times \% \text{ground water recharge to sea} \end{cases}$$

The primary water supply is defined as

$$\text{Primary water supply} = \text{Process evaporation} + \text{Non process evaporation} + \\ \text{un utilizable flows to sea} + \text{utilizable returnflows to sea}$$

The total depletion of the primary water supply is

$$\text{Total depletion} = \text{Process evaporation} + \text{Non process evaporation} + \text{un utilizable flows to sea}$$

Three indicators of the extent of water development and use in the basin is given by

$$\text{Degree of development} = \frac{\text{Primary water supply}}{\text{PUWR} - \text{environmental flows from PUWR}}$$

$$\text{Depletion fraction} = \frac{\text{Total depletion}}{\text{Primary water supply}} \text{ and}$$

$$\text{Groundf water abstraction ratio} = \frac{\text{Total ground water withdrawals}}{\text{Total available groundwater supply}}$$

PODIUMSIM Model applications and publications

The upgraded model, PODIUMSIM, is adapted to India and China at river basin level. The model considers 19 river basins for India and 9 river basins for China. The adapted versions for the two countries PODIUMSIM India and PODIUMSIM China, the data and the model brochure are available in the ICID and IWMI web sites (www.icid.org and www.iwmi.cgiar.org/tools/podiumsim.html). A draft research report, “Water Supply and Demand Variation across river basin India” available in the ICID web site, is published as IWMI Research Report 83 (Amarasinghe et al, 2005). Another draft report highlighting the water supply and demand of Chinese river basins were also prepared (see annex A).

2. 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.

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 on income.

Funding and progress

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 ran 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). All water related variables are determined at water basin level, while economic variables are simulated at nation level.

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

year	<i>Consumption in million tons</i>		<i>Change %</i>
	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%

In total, cereal demand increases from 190 million tons in 2000 to 256 million tons in 2025. The increase is mainly caused by population growth, but also by changes in diets (refer to section below). At present India is self-sufficient or minor exporter of its major food grains. But if current trends and growth rates persist, by the year 2025 India will have to import some of its food commodities such as wheat, maize, other coarse grains and dairy products (table 2).

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	70.9	4.88	104.98	91.03	-13.95	13%
Rice	83.76	87.75	3.99	126.87	127.09	0.22	0%
Maize	12.21	12.06	-0.15	20.31	14.44	-5.87	29%
Other grains	19.03	19.76	0.73	30.61	23.84	-6.77	22%
Poultry meat	1.05	1.05	0	3.37	2.65	-0.72	21%
Eggs	1.83	1.76	-0.07	4.07	3.32	-0.75	18%
Milk	81.65	80.18	-1.47	188.66	174.59	-14.07	7%

Tables 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

	<i>Rain fed area (m ha)</i>	<i>Irrigated area (m ha)</i>	<i>Rain fed yield (t/ha)</i>	<i>Irrigated yield (t/ha)</i>	<i>% production from irrigated</i>
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**

	<i>Rain fed area (m ha)</i>	<i>Irrigated area (m ha)</i>	<i>Rain fed yield (t/ha)</i>	<i>Irrigated yield (t/ha)</i>	<i>% production from irrigated</i>
Wheat	4.43	23.78	1.87	3.48	91%
Rice	21.35	24.87	2.13	3.28	64%
Maize	4.94	1.19	2.04	3.70	30%
Other grains	21.62	0.67	1.05	1.60	5%
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).

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 1.6 billion hectares of which roughly 40% is irrigated. Under the baseline scenario, the total harvested area increases slightly (by 5%). The irrigated area grows by 10 million hectare (or 15%) as some rain fed lands are brought under irrigation.

According to the Business as Usual scenario cereal demand rises by 100 million tons in the period 2000-2025. Production will increase by 66 million tons while imports will have to rise by to 34 million tons. Under the baseline most of the additional cereal production originates from an increase in irrigated yield (46%), while part of it comes from an increase in rain fed yield (32%) and irrigated area (22%).

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

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

	Agricul- tural	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)

	Agricul- tural	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

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 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 scenarios¹ were compared: one Business-as-Usual, a pessimistic and optimistic scenario. Table 7 provides the assumptions on population and income per capita for the

Scenario	<i>Population (in million)</i>		<i>Income per capita (in US\$ per year)</i>	
	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

base year 2000 and projection for 2025.

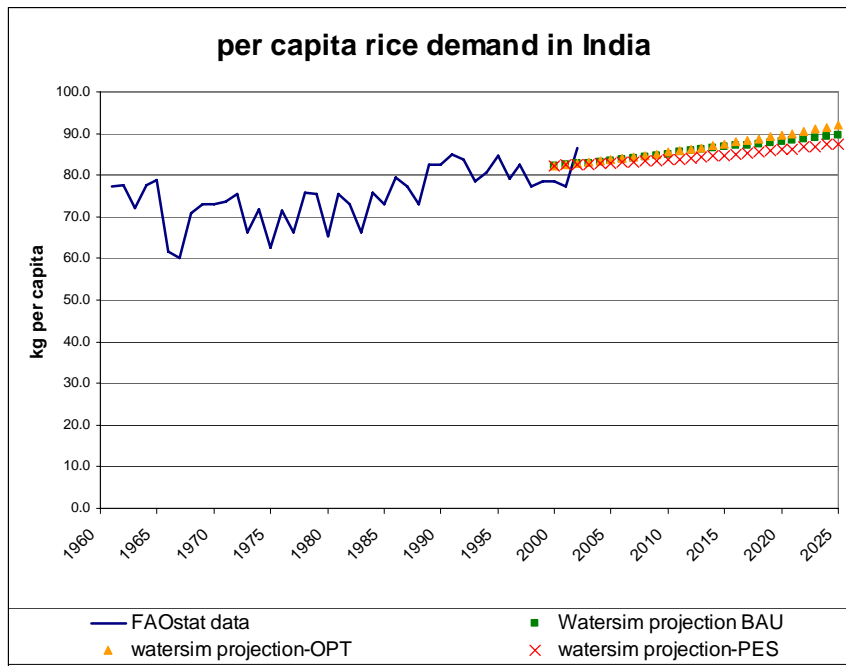
Table 7: Income and population of India under different scenarios

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

¹ Based on Millennium Ecosystem Assessment scenarios.

The results in figure 2, 3 and 4 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.

Figure 2: per capita rice demand in India under different socio-economic scenarios



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

Figure 3: per capita wheat demand in India under different socio-economic scenarios

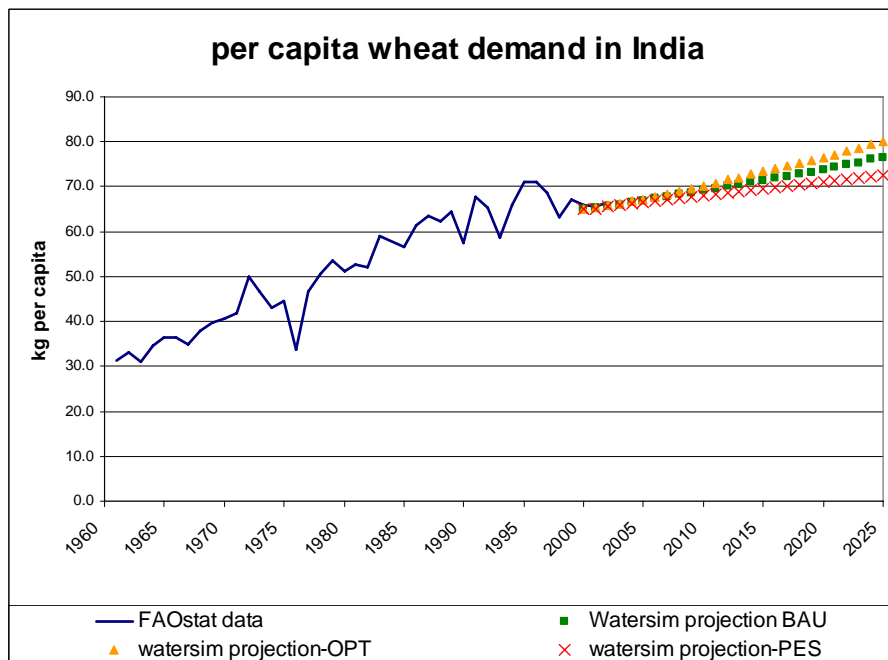
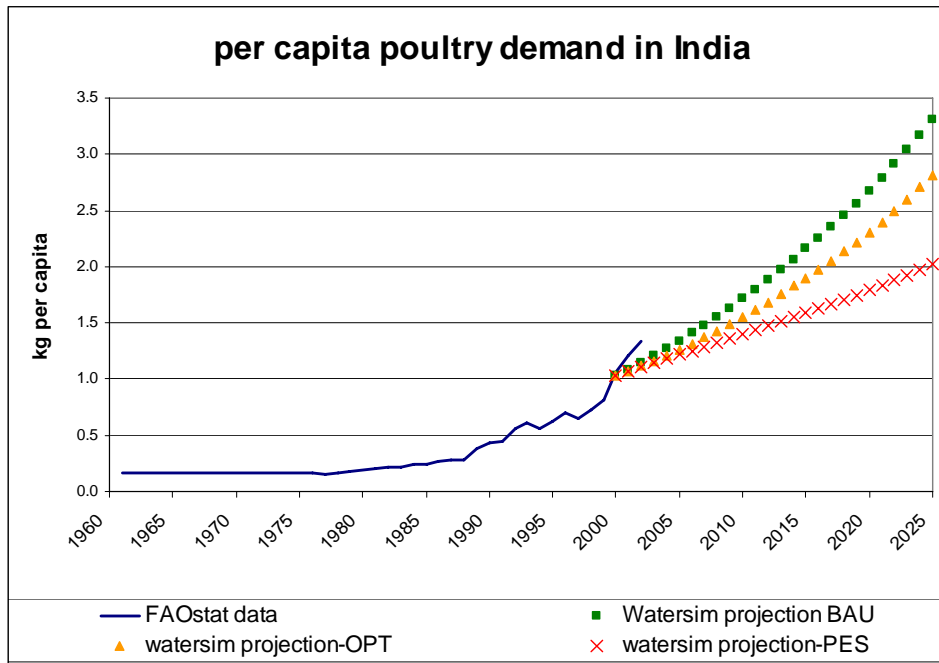


Figure 4: per capita poultry meat demand in India under different socio-economic scenarios



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. 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.

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)

	<i>Agricultural</i>	<i>Industrial</i>	<i>Domestic</i>	<i>Total</i>	<i>Per capita (m³/cap/yr)</i>
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 350 m³/cap/yr while in the pessimistic it is 301 m³/cap/yr.

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; and the ‘water supply and demand’ module which uses a water balance based on the Water Accounting framework underlying PODIUM combined with elements from the IMPACT-WATER.

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, region and globe until the conditions of economic equilibrium and hydrologic water balance are met.

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:

$$AI_{yrc} = \alpha i_{yrc} \times (PS_{yrc})^{\epsilon_{rec}} \times \prod_{c \neq p} (PS_{yrc})^{\epsilon_{rep}} \times (1 + gAI_{yrc}) + \Delta AI_{yrc} \quad (1)$$

$$AR_{yrc} = \alpha r_{yrc} \times (PS_{yrc})^{\epsilon_{rec}} \times \prod_{c \neq p} (PS_{yrc})^{\epsilon_{rep}} \times (1 + gAR_{yrc}) + \Delta AR_{yrc} \quad (2)$$

Yield response:

$$YI_{yrc} = \beta i_{yrc} \times (PS_{yrc})^{\gamma_{rec}} \times \prod_s (PF_{yrc})^{\gamma_{res}} \times (1 + gYI_{yrc}) + \Delta YI_{yrc} \quad (3)$$

$$YR_{yrc} = \beta r_{yrc} \times (PS_{yrc})^{\gamma_{rec}} \times \prod_s (PF_{yrc})^{\gamma_{res}} \times (1 + gYR_{yrc}) + \Delta YR_{yrc} \quad (4)$$

Production:

$$QS_{yrc} = AI_{yrc} \cdot YI_{yrc} + AR_{yrc} \cdot YR_{yrc} \quad (5)$$

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	
ai	=	irrigated area intercept	
ar	=	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:

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

Yield:

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

Production:

$$QS_{yrk} = AL_{yrk} \times YL_{yrk} \quad (8)$$

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:

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

where

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

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

Demand for feed:

$$QL_{yrf} = \beta_{yrf} \times \sum_k (QS_{yrk} \times FR_{yrfk}) \times (PI_{yrf})^{\gamma_{rf}} \times \prod_{f \neq g} (PI_{yrf})^{\gamma_{fg}} \times (1 + FE_{yrf}) \quad (12)$$

Demand for other uses:

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

Total demand:

$$QD_{yri} = QF_{yri} + QL_{yri} + QE_{yri} \quad (14)$$

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:

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

Consumer prices:

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

Intermediate (feed) prices:

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

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:

$$QT_{yri} = QS_{yri} - QD_{yri} - STC_{yri} \quad (18)$$

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.

$$\text{World market clearing condition: } \sum_r QT_{yri} = 0; \quad (19)$$

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. 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.

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:

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

where: $DDTo$ = monthly depletive demand - total (km³)
 DDA = monthly depletive demand - irrigated agriculture (km³)
 DDI = monthly depletive demand - industry (km³)
 DDM = monthly depletive demand - municipal use (km³)
 y = year index
 m = month
 u = food producing unit (FPU)

Depletive demand in irrigated agriculture:

Irrigation water depletion in agriculture is estimated from:

$$DDA_{ymu} = \sum_c \left(\frac{AI_{yrc} \cdot (ETa_{ymuc} - PE_{ymuc})}{EE_{yu}} \right) \cdot 100 \quad (21)$$

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 (equations 73-76). To initialize the model at the first iteration of each year, ETa is approximated by the potential evaporation from:

$$ETp_{ymuc} = kc_{mc} \cdot ET0_{ymuc} \quad (22)$$

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:

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

where PR = total precipitation (mm)

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

$$cf = 1.0 \quad \text{if } Da = 75\text{mm}, \quad (24a)$$

$$cf = 0.133 + 0.201 \cdot \ln(Da) \quad \text{if } Da < 75\text{mm per application, and} \quad (24b)$$

$$cf = 0.946 + 0.00073 \cdot Da \quad \text{if } Da > 75\text{mm per application.} \quad (24c)$$

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 $PR < 12.5\text{mm}$, $PE = PR$.

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

$$PE'_{ymuc} = \lambda_{ymuc} \cdot PE_{ymuc} \quad (25)$$

where PE' = corrected effective precipitation
 λ = correction factor to account for water harvesting methods ($\lambda \geq 1$)

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:

$$EE'_{yu} = EE_{yu} \cdot (RWP_{yu})^{\omega_u} \quad (26)$$

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

$$DDI_{ymu} = f(\text{population, } GDP_{ind}, \text{waterprice, environmental regulations etc.}) \quad (27)$$

Depletive demand in domestic uses

$$DDM_{ymu} = f(\text{population, investments, income, waterprice etc.}) \quad (28)$$

Monthly water balance at sub-basin level

The total inflow (TW) into a FPU consists of internally generated runoff (RO), groundwater recharge (GW), inflow from inter-basin transfer (IBT) and other sources such as desalinization (OS).

Total water flowing into basin:

$$TW_{ymu} = RO_{ymu} + INF_{ymu} + GW_{ymu} + IBT_{ymu} + OS_{ymu} \quad (29)$$

where TW = total water flowing into basin (km³)
 RO = internally generated runoff (km³)
 INF = inflow from upstream basin (km³)
 GW = groundwater source (km³)
 IBT = water from inter-basin transfer (km³)
 OS = water from other sources (f.e. desalinization) (km³)
 y = year; m = month; u = FPU

Groundwater is function of natural recharge from precipitation and seepage from irrigation fields and canals

$$GW = f(PR) \quad (30)$$

$$GW = f(AI) \quad (31)$$

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:

$$SP_{ymu} = ST_{y,m-1,u} + TW_{ymu} - BES_{yu} \quad \text{if } SP_{ymu} > 0 \quad (32a)$$

$$SP_{ymu} = 0 \quad \text{if } SP_{ymu} \leq 0 \quad (32b)$$

where SP = monthly spill (km³)
 ST_{m-1} = water stored from previous month (km³)
 BES = basin equivalent storage capacity (km³)

The Basin Equivalent Storage (BES) reflects the maximum amount of controllable blue water 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. A challenge in this set-up is to develop a suitable methodology to determine the BES. The Primary Water Supply (PWS) estimates in PODIUM may be a good starting point.

The BES is a function of investment in infrastructure:

$$BES_{yu} = f(\text{investment}) \quad (33)$$

The amount of water available for different uses (AW) depends on the basin equivalent storage, reservoir operation and the amount of annual 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 reservoir storage accounts for big part of the BES, 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.

The amount of water available for different uses is computed from:

$$AW_{ymu} = ST_{y,m-1,u} + TW_{ymu} - SP_{ymu} - EL_{ymu} \quad (34)$$

where AW = available water (km³)
 EL = evaporation from reservoirs (km³)

Available water is either stored or released:

$$AW_{ymu} = ST_{ymu} - REL_{ymu} \quad (35)$$

where ST = amount of water stored (km³)
 REL = release (km³)

Part of the release is depleted or transferred out of the basin as part of inter basin transfer scheme. The remainder flows out of the basin:

$$REL_{ymu} = DEPL_{ymu} + OF_{ymu} + IBTo_{ymu} \quad (36)$$

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

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:

$$\max \left[\frac{\sum_m DEPL_{ymu}}{\sum_m DDTo_{ymu}} + w \cdot \min_m \left(\frac{DEPL_{ymu}}{DDTo_{ymu}} \right) \right] \quad (37)$$

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:

$$OF_{ymu} + SP_{ymu} \geq CF_{ymu} \quad (38)$$

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:

$$REL_{ymu} \leq BES_{yu} \quad (39)$$

Actual depletion is never greater than demand

$$0 \leq \frac{DEPL_{ymu}}{DDTo_{ymu}} \leq 1 \quad (40)$$

Operational constraints

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

$$ST_{ymu} \geq \text{certain amount} \quad (41a)$$

or: $ST_{ymu} \geq x\% \text{ of } BES$ (41b)

Environmental flow requirements

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

$$EFR_{mu} \leq OF_{ymu} + SP_{ymu} \quad (42)$$

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.

$$DEPL_{ymu} = DSA_{ymu} + DSI_{ymu} + DSM_{ymu} \quad (43)$$

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:

$$DSA_{ymu} = DEPL_{ymu} - DSI_{ymu} - DSM_{ymu} \quad \text{if } DSA > 0 \quad (44a)$$

$$DSA_{ymu} = 0 \quad \text{if } DSA \leq 0 \quad (44b)$$

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

$$DSI_{ymu} = DEPL_{ymu} - DSM_{ymu} \quad \text{if } DSI > 0 \quad (45a)$$

$$DSI_{ymu} = 0 \quad \text{if } DSI \leq 0 \quad (45b)$$

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

$$DSA_{ymu} = DDA_{ymu} - \frac{DDA_{ymu}}{DDTo_{ymu}} \cdot (DDTo_{ymu} - DEPL_{ymu}) \quad (46a)$$

$$DSI_{ymu} = DDI_{ymu} - \frac{DDI_{ymu}}{DDTo_{ymu}} \cdot (DDTo_{ymu} - DEPL_{ymu}) \quad (46b)$$

$$DSM_{ymu} = DDM_{ymu} - \frac{DDM_{ymu}}{DDTo_{ymu}} \cdot (DDTo_{ymu} - DEPL_{ymu}) \quad (46c)$$

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:

$$\pi_{ymuc} = \frac{ALLO_{ymuc}}{\sum_i ALLO_{ymuc}} \quad (47)$$

$$ALLO_{ymuc} = ky_c \cdot \left(1 - \frac{PE_{ymuc}}{ETp_{ymuc}} \right) \cdot PS_{yuc} \quad (48)$$

Allocation to individual crops is then:

$$DSAC_{ymuc} = \pi_c \cdot DSA_{ymu} \quad (49)$$

The amount of beneficial depletion by each crop is then:

$$BAC_{ymuc} = EE_{ymu} \cdot DSAC_{ymuc} \quad (50)$$

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)
 $m \in$ 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:

$$WL_{ymuc} = \frac{BAC_{ymuc}}{AI_{yuc}} + PE_{ymuc} \quad (51)$$

where WL = water layer on the field before area reduction (mm)
 $m \in$ 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:

$$\Delta AI_{yuc} = 0, \quad \text{if } \frac{\sum_m WL_{ymuc}}{AI_{yuc}} > E^*_{ymuc} \quad \text{otherwise} \quad (52)$$

$$\Delta AI_{yuc} = AI_{yuc} \cdot \left[1 - \left(\frac{\sum_m WL_{ymuc}}{\sum_m ETp_{ymuc}} / E^*_{ymuc} \right) \right] \quad (53)$$

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:

$$ETa_{ymuc} = \frac{BAC_{ymuc}}{(AI_{yuc} - \Delta AI_{yuc})} + PE_{ymuc} \quad (54)$$

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:

$$\Delta YI_{yuc} = YI_{yuc} \cdot ky_{yuc} \cdot \left(1 - \frac{\sum_m ETa_{ymuc}}{\sum_m ETp_{ymuc}} \right) \cdot \left[\frac{\min_m (ETa_{ymuc} / ETp_{ymuc})}{(ETa_{ymuc} / ETp_{ymuc})} \right]^\tau \quad (55)$$

where ΔYI = reduction in 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:

$$ETa_{ymuc} = PE_{ymuc} \quad (56)$$

In rain fed areas farmers don't have the choice to reduce area to maintain water layer, but they may lose 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:

$$\Delta AC_{yuc} = AR_{yuc} \cdot \left[1 - \left(ky_c \cdot \left(1 - \frac{\sum_m ETa_{ymuc}}{\sum_m ETp_{ymuc}} / E^*_{yuc} \right) \right)^\rho \right] \quad (57)$$

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:

$$\Delta YR_{yuc} = YR_{yuc} \cdot ky_c \cdot \left(1 - \frac{\sum_m ETa_{ymuc}}{\sum_m ETp_{ymuc}} \right) \cdot \left[\frac{\min_m (ETa_{ymuc} / ETp_{ymuc})}{(ETa_{ymuc} / ETp_{ymuc})} \right]^\tau \quad (58)$$

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.

3. Capacity Building

The IWMI/IFPRI component of CPSP has contributed to two PhD studies.

1. Dr. Liao Yongsong of Chinese Center for Agricultural Policy has completed his PhD studies under the PODIUMSIM model development component.
2. Dr. Charlotte De Fraiture of IWMI has completed her PhD studies under the WATERSIM model development component.

In addition to supporting PhD studies, IWMI has also conducted several model development or orientation workshops and supported attendance of several conferences during the project period. This list is given below.

Workshop Name	Venue and Date	Number of Participants
Training workshop for PODIUMSIM for participants of India, China and Pakistan	Colombo, Sri Lanka November 2001	5 (2 India, 1 China, 1 Pakistan)
PODIUMSIM India model revision	Colombo, Sri Lanka May 2002	2 (2 from India)
Presentations at 52 nd ICID Congress in Canada by Mr. A.K. Shukla of Central Water Commission	Montreal, Canada, August 2002	3 (1 from India, 2 from Sri Lanka)
PODIUMSIM China- Orientation workshop	Beijing, China January 2003	6 (all Chinese participants)
PODIUMSIM China model revision	Colombo, Sri Lanka March 2003	1 Chinese participant
PODIUMSIM India and China - Orientation workshop	Delhi, India November 2003	10 (2 from IWMI, 4 each from India and China)
India National Consultation	Delhi, India November 2003	2 (From IWMI)
IWMI / ICID Scenario Development Orientation Workshop for India & China	Moscow, Russia September 2004	22 (11 from India, 6 from China, 1 from Malaysia and 4 from IWMI)

The IWMI/ICID Scenario Development orientation workshop held in Moscow, Russia was attended by several Policy makers/Researchers from India, China and Malaysia. The workshop proceedings are published in the ICID website (www.icid.org).

Annex A. Water Supply and Demand of China River Basins

