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Global Water Demand and Supply Projections *Part 1. A Modeling Approach*

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Abstract: *This paper presents a modeling approach for projections of water demand and supply for domestic, industrial, livestock, and irrigation at the basin or country level in a global scope. Particular emphasis is put on simulating water availability for crops taking into account total renewable water, non-irrigation water demand, water supply infrastructure, and economic and environmental policies at the basin or country level. This paper focuses on concepts and methodology involved in the modeling exercise. Data assessment and results are presented in a companion paper (Rosegrant and Cai, 2002).*

Keywords: *Water demand, water supply, irrigation, global, modeling.*

Introduction

Over the next 30 years, agricultural water demand will increase further due to population growth and changes in the structure of food demand (Hofwegen and Svendsen, 2000), and nonagricultural water uses in industry, households, and environmental and ecological purposes are projected to grow rapidly (Rosegrant and Ringler, 1999). A portion of the growing demand for water will be met through new investments in expanding water supply capacity and improving water management, and some potential exists for the expansion of nontraditional sources of water supply. However, in many arid or semiarid areas – and seasonally in wetter areas – water is no longer abundant, and the high economic and environmental costs of developing new water resources pose limits to supply expansion. Therefore, new supplies may not be sufficient to meet growing demands for agriculture, direct human consumption, industrial, and environmental purposes. As a result, projections of water demand and supply in the future world have been receiving substantial attention in recent years. With irrigated agriculture accounting for about 72 percent of global and 90 percent of developing-country water withdrawal, an understanding of water availability for irrigation in the future is particularly important.

There are many emerging issues in water resources development and management, including the role of storage and inter-basin water transfers given the high financial costs and environmental impacts of large surface reservoirs and transfers; the contribution and limitations of groundwater development and rainfall harvest for rainfed agriculture; the opportunity of water saving and recycling technology and non-conventional sources; and the impact of water demand management with institutional reforms

and application of economic incentives such as water prices, water rights, and markets (Cosgrove and Rijsberman, 2000). It is a significant challenge to address these water development and management issues within an integrated modeling framework that assesses the relationships between water availability and climate variability, water infrastructure development, and water management policies.

This paper, together with a companion paper in this issue, presents such a modeling exercise to assess current and the future global water demand and supply. Concepts and model development are presented in this paper, and results and prospects for global water demand and supply are provided in the second paper (Rosegrant and Cai, 2002).

Global Water Modeling – A Background Review

Over the past ten years, hydrological and meteorological sciences have made great advances in land surface hydrology and in providing knowledge, techniques, and prediction capabilities that are particularly useful in water resource applications. New technologies in remote sensing, radar, and geophysical exploration at multiple scales have been applied in data collection and modeling. Particularly important to global freshwater assessment has been the development of datasets and routing methods for the characterization of water movement over the land surface, at the global scale (Maidment, 1999). Comprehensive global hydrologic databases have been developed [(for example, the climate data series provided by Climate Research Unit (CRU) of the University of East Anglia in England; *Digital Atlas of the World Water Balance* developed at the Center for Research in Water Resources (CRWR) of the University of Texas at Austin; and *World Water and Climate Atlas* developed at the International

Water Management Institute (IWMI)]. On-going research has focused on improving databases, taking into account the impact of land uses and climate changes (IPCC, 2002).

These databases make it possible to evaluate global freshwater supply through global climate models or continental hydrologic models applied to calculate runoff and water storage at the global or continental scale. Such models include Vorosmarty et al. (1996); Miller et al. (1994); Lohmann et al. (1998); Alcamo et al. (1998); and Asante (2000).

Besides global water modeling and assessments, other studies that contribute to water development and management include integrated basin management, field water management, crop water modeling, and system analysis techniques. Integrated basin management has been recognized as an important strategy for managing water uses and dealing with water scarcity at the river basin scale (Batchelor, 1999). The International Water Management Institute (IWMI) has done substantial work in identifying ways of improving productivity of water within basins (Molden et al., 2001) and in modeling natural and man-made processes in river basins (Kite and Droogers, 2001). The International Food Policy Research Institute (IFPRI) has developed integrated basin-wide hydrologic-agronomic-economic models for efficient water allocation and economic water use efficiency analysis (Rosegrant et al., 2000). In order to deal with multiple objectives at the basin level, new problem-solving technologies in the areas of systems analysis, operations research, and decision support systems have emerged and have been applied to deal with the growing complexities in water resources systems (McKinney et al., 1999). These types of detailed basin studies will provide more detailed support for global water resources assessment.

Agricultural water management has also been given priority in water resources research. Soil-plant-atmosphere-research (SPAR) provides a great opportunity to develop databases and modeling tools for crop field water management and crop water modeling. For practical purposes, the set of *Irrigation and Drainage Papers* published by FAO has guided crop field water management widely in the world. Doorenbos and Pruitt (1977) and Allen et al. (1998) provide guidelines for computing crop water requirements; Doorenbos and Kassam (1979) provide an empirical relationship between crop yield response and water stress. These relationships have been widely used, because: (1) the relationship between seasonal crop yield and water is very simple; (2) FAO has the most complete summary of available data for implementation of crop-water relationships; and (3) these data have been widely used for planning, designing, and operating irrigation supply systems and take into account the effect of the different water regimes on crop production (Perry and Narayanamurthy, 1998).

In this paper, we present a modeling exercise that attempts to draw upon these modeling efforts and to integrate available information in water resources, agronomy,

and economics into a consistent framework to analyze 30-year projections of domestic, industrial, livestock, and irrigation water demand and supply for 69 individual or aggregated river basins in the global scope, with consideration of seasonal and inter-annual variability in climate. Concepts related to water demand and supply in different sectors are presented, and a systematic approach is illustrated for water supply simulation given assessments and assumptions on water demand, total renewable water, infrastructure, and water development and management policies.

Methodology

The model is based on a river basin approach. The river basin is a natural unit for integrated water resources planning and management, since water interacts with and influences other natural components such as soil, vegetation, and wildlife. The river basin is the fundamental ecological unit for water, permitting the hydrologically correct assessment of water flows through time and space, including appropriate accounting for consumptive use, withdrawals, return flows, and water use efficiency. The basin perspective captures the trade-offs among competing uses of water, including measurement of externalities, third-party effects, and opportunity costs of water use. Water resources analysis benefits from an integrated basin system including water supply, water demand, and intermediate components.

Figures 1a through 1d present maps of the spatial units used in the modeling exercise, including 9 basins in China, 13 basins in India, 14 basins in the U.S., and 33 aggregated basins in other countries or regions. Due to the data constraints, we currently disaggregate major river basins only for the large countries of China, India, and the United States, which together produce about 60 percent of cereals in the world. Other countries/regions are aggregated as 33 basins, following the spatial element delineation made by Rosegrant et al. (2001) and for the global food production, demand, and trade model.

The year 1995 is treated as the base year in which all demand and supply items are assessed and calibrated. Projections of water demand and supply are made for the 30 years from 1995 to 2025.

Water Demand Assessments and Projections

Water demand is estimated at the river basin scale. Water demands in a basin are aggregated into five sectors, including irrigation, livestock, domestic, and industrial water demand, and environmental and instream flow requirement. Basic definitions of water demand terms used here are given in Box 1.

Irrigation Water Demand

Irrigation water demand is assessed as crop water requirements based on hydrologic and agronomic characteristics. Annual net crop water demand (*NCWD*) in a basin is



Figure 1(a). Impact-water spatial units - 36 countries and regions.

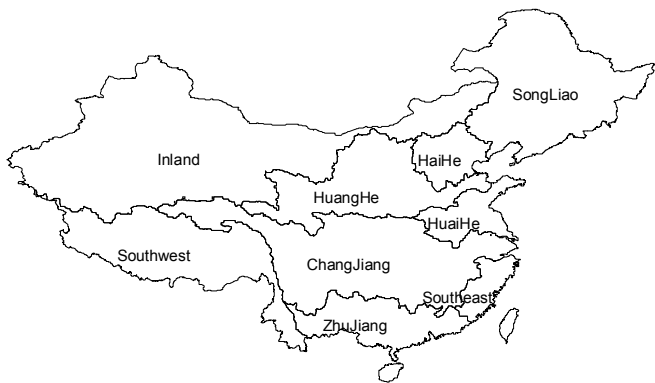


Figure 1(b). Impact-water spatial units - nine major basins in China.



Figure 1(c). Impact-water spatial units - 13 major basins in India.



Figure 1(d). Impact-water spatial units -14 major basins in the U.S.

calculated based on an empirical crop water requirement function (Doorenbos and Pruitt, 1977)

$$NCWD = \sum_{cp} \sum_{ct} kc^{cp,ct} \cdot ET_0^{ct} \cdot A^{cp} \quad (1)$$

in which cp is the index of crops, ct is the index of crop growth stages, ET_0 is the reference evapotranspiration [L], kc is the crop coefficient, and A is the crop area.

Part or all of crop water demand can be satisfied by effective rainfall (PE), which is the rainfall infiltrated into the root zone and available for crop use (USDA 1967). Effective rainfall for crop growth can be increased through rainfall harvesting technology. Then net irrigation water demand ($NIRWD$), with consideration of effective rainfall use and salt leaching requirement, is

$$NIRWD = \sum_{cp} \sum_{st} (kc^{cp,st} \cdot ET_0^{st} - PE^{cp,st}) \cdot AI^{cp} \cdot (1 + LR) \quad (2)$$

in which AI is the irrigated area, and LR is the salt leaching factor, which is characterized by soil salinity and irrigation water salinity.

Total irrigation water demand represented as water depletion ($IRWD$) is calculated as

$$IRWD = NIRWD / BE \quad (3)$$

in which BE is defined as BE . The concept of BE was discussed and various definitions were provided by Molden et al. (2001). In this study, we apply the concept of effective efficiency (Keller et al., 1996) at the river basin scale, taking into account the quantity of the water delivered from and returned to a basin's water supply. Following this concept, the basin efficiency used in this study measures the ratio of beneficial water depletion (crop evapotranspiration and salt leaching) to the total irrigation water depletion at the river basin scale (see Box 2). BE in the base year (1995) is calculated as the ratio of the $NIRWD$ to the total irrigation water depletion estimated from records. BE in future years is assumed to increase at a prescribed rate in a basin, depending on water infrastructure investment and water management improvement in the basin.

Estimation of irrigation water demand then needs extensive hydrologic and agronomic data support. Crop-wise irrigated harvested crop area was assessed by Cai (1999); crop growth periods in different countries or basins are collected from USDA (1998); and the value of kc in crop growth stages is estimated based on Doorenbos and Pruitt (1979) and Allen et al. (1998). A half-degree grid of monthly average ET_0 between 1961 and 1990 in agricultural land is

calculated by using a Taylor method based on global climate datasets (Climate Research Unit (CRU) of the University of East Anglia in England) and GIS coverage of croplands (Alcamo et al., 1998).

The projection of irrigation water demand depends on the changes of irrigated area and cropping patterns, water use efficiency, and rainfall harvest technology. Global climate change can also affect future irrigation water demand through temperature and precipitation change, but is not considered in the current modeling framework.

Livestock Water Demand

Livestock water demand ($LVWD$) in the base year is estimated based on livestock production and water consumptive use per unit of livestock production, including beef, milk, pork, poultry, eggs, sheep and goats, and aquaculture fish production. Consumptive use coefficients for water for livestock are estimated for the United States from Solley et al. (1998), Mancl (1994) and Beckett and Oltjen (1993), and adapted to other developed countries based on FAO (1986). For all of the livestock products except fish, it is assumed that the projection of livestock water demand in each basin, country, or region follows the same growth rate of livestock production. Livestock water demand is determined as a linear function of livestock production, assuming no change in water consumptive use per unit of livestock production. The water demand

Box 1. Definitions of Water Demand Terms

The term "water demand" is often used inconsistently in the literature, referring at times to withdrawal and at times to consumption or depletion. The following definitions are used in this paper.

- *Water Withdrawal*: water removed from a source and used for human needs, some of which may be returned to the original source and reused downstream with changes in the quantity and quality of the water.
- *Water Depletion (or Water Consumption)*: water withdrawn from a source and made unusable for reuse in the same basin, such as through irrecoverable losses, including evapotranspiration, seepage to a saline sink, or contamination.
- *Beneficial Water Depletion*: water depletion that contributes to various benefits of water use. For example, in agriculture, crop evapotranspiration is treated as beneficial water depletion, while pollution sink and seepage in distribution systems that cannot be returned to a source for potential reuse are part of non-beneficial water depletion.
- *Effective Rainfall (PE)*: rainfall that can be effectively used for crop growth, including rainfall intercepted by plant foliage, rainfall that can enter and be stored in the root zone, and artificial rainfall harvested.
- *Basin Efficiency (BE)*: water use efficiency (WUE) assessed at the river basin scale, taking account of return flow reuse. For irrigation, BE measures the ratio of beneficial water depletion to the total irrigation water depletion at the river basin scale.
- *Depletion Coefficient (DC, or Consumption Coefficient)*: ratio of water depletion (consumption) over water withdrawal. The value of $(1-DC)$ indicates the fraction of water returned to water supply system, which can be reused.

Box 2. Definitions of Water Supply Terms

- *Renewable Water (RW)*: renewable water refers to water that can be renewed by the natural cycling of water through the atmosphere and the earth. For one specific region, total renewable water includes *internal renewable water* and *inflow* from other regions. Annual *Internal renewable water* refers to the average annual flow of rivers and recharges of groundwater generated from endogenous precipitation. *Inflow* includes surface and groundwater inflow to the region from other regions.
- *Total Water Availability*: for one region, total water availability is the sum of the *renewable water*, *artificial basin/regional water transfer*, *desalinated water*, *non-renewable groundwater* that is only available for a limited period, and salt water that is only available for limited uses.
- *Maximum Allowable Water Withdrawal (MAWW)*: water withdrawal capacity (surface water diversion capacity and groundwater pumping capacity) available for agricultural and municipal and industrial water uses. It refers to physical capacity and environmental constraints.
- *Realizable Water Withdrawal*: water withdrawal under *Total Water Availability (TWA)* and *Maximum Allowed Water Withdrawal (MAWW)*.
- *Effective Water Supply for Irrigation (EWIR)*: field water supply that can be fully used for crop evapotranspiration. For one region in a specific time period, *effective water supply for irrigation* is subject to *water availability*, *maximum allowed water withdrawal*, *water allocation* between agriculture and municipal and industry sectors, *water quality* (e.g. salt concentration), and *water use efficiency*. For crops, *EWIR* is further subject to crop acreage and crop patterns.

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

Industrial Water Demand

Industrial water demand (*INWD*) in the base year (1995) is assessed based on Shiklomanov (1999) for individual countries and USGS (1998), Gunaratnam (1999, personal communication), and Alcamo (1998, personal communication) for river basins in the U.S., China, and India. For the analysis presented here, the consumptive use of water by the industrial sector is adjusted for the fraction of population living in coastal areas (fraction of people living within 50 km from the coast). For those areas within 50 km from the coast, we assume discharge from municipal and industrial water use system goes to the ocean, and will not be reused for any purposes.

Projection of industrial water demand depends on income (gross domestic production [*GDP*] per capita) and water use technology improvement. A linear relationship between industrial water demand intensity (*IWDI* in m³ of water per \$1,000 *GDP*), *GDP* per capita (*GDPC*), and a time variable (*T*) is estimated by regression based on historical records (Shiklomanov, 1999; World Bank, 2001) and adjusted according to our perspectives on future industrial water demand in different regions and countries.

$$IWDI = \alpha + \beta \cdot GDPC + \gamma \cdot T \quad (4)$$

in which α is the intercept; β is the income coefficient, reflecting how industrial water use intensity changes with *GDPC*; and γ is the time coefficient, mainly reflecting the change of water use technology with technology change. It is found that

$$\alpha > 0, \quad \frac{\partial IWDI}{\partial GDPC} = \beta < 0, \quad \text{and} \\ \frac{\partial IWDI}{\partial T} = \gamma < 0$$

for all basins and countries, which shows that in future years, the industrial water use intensity will reduce with the *GDPC* and *T* ($T=95$ for 1995, 100 for 2000, etc.). The value of α , β , and γ for some selected basins, countries, and regions is presented in Table 1.

Domestic Water Demand

DOWD includes municipal water demand and rural domestic water demand. *DOWD* in the base year is estimated based on the same sources and method as those used for industrial water demand assessment. *DOWD* in future years are projected based on projections of population and income growth. In each country or basin, income elasticities (η) of demand for domestic use are synthesized based on the literature and available estimates. These elasticities of demand measure the propensity to consume water with respect to increases in per capita income. The elasticities

utilized are defined to capture both direct income effects and conservation of domestic water use due to technological and management change. The annual growth rate of *DOWD* ϕ_{dwd} is a function of the growth rate of population (ϕ_{pop}) and that of income (*GDP* per capita, ϕ_{gdpc}), as

$$\phi_{dwd} = \phi_{pop} + \eta \cdot \phi_{gdpc} \quad (5)$$

$$\text{where } \frac{\partial \phi_{dwd}}{\partial \phi_{gdpc}} = \eta < 0$$

implies that per capita domestic water demand will actually decline with income growth, which happens with some developed countries where current per capita domestic water consumption is high; and

$$\frac{\partial \phi_{dwd}}{\partial \phi_{gdpc}} = \eta > 0$$

implies that per capita domestic water demand increase with income growth, which happens in all developing countries. The value of η decreases with time, as can be seen from Table 1, which shows the value of η in some selected years for selected basins, countries, and regions.

Committed Flow for Environmental, Ecological, and Navigational Uses

A rising public awareness concerning the fragility of environmental and ecological systems over the last two decades has caused a demand for committed flow for environmental and ecological maintenance and instream uses such as recreation, hydropower generation, and navigation. Committed flow here is defined as the quantity of water that is reserved for environmental and instream use and unavailable for other uses. In many countries and basins, committed flow is specified through legislative or regulatory processes. In the modeling framework here, committed flow is specified as a percentage of average annual runoff. Data is lacking on this variable for most basins and countries, so an iterative procedure is used to specify this variable where data is lacking. The base value for committed flows is assumed to be 10 percent, and this value is incremented by 20 to 30 percent if navigation requirements are significant (e.g., Yangtze River Basin); by 10 to 15 percent if environmental reservation is significant, as in most developed countries; and by 5 to 10 percent for arid and semi arid regions where ecological requirements, such as salt leaching, are high (e.g., Central Asia). The estimated values for committed flows are then calibrated for the base year relative to basin inflow, outflow, and consumptive use.

Given the lack of reliability and the incompleteness of this data, we also treat this parameter in simulations as a policy variable to test the impact of a range of values. Detailed basin water planning studies are needed to improve the estimation of the committed flow.

Table 1. Parameters for Industrial and Domestic Water Demand Predictions

Basins/Countries/Regions	Parameters for Industrial Water Demand			Domestic Water Demand Elasticity (η)		
	Intercept α	Income coef. β	Time coef. γ	1995–2000	2010–2015	2020–2025
California River Basins	4.127	-8.0E-06	-0.0230	-0.167	-0.245	-0.443
USA	8.701	-8.0E-05	-0.0198	-0.131	-0.144	-0.126
HuangHe Basin	38.262	-8.5E-4	-0.2486	0.676	0.220	0.137
China	34.858	-1.4E-3	-0.1887	0.746	0.328	-0.069
Indus River Basin	13.590	-3.0E-03	-0.0092	0.505	0.509	0.334
India	45.737	-2.0E-02	-0.0365	0.257	0.270	0.120
EC 15 countries	3.526	-4.0E-05	-0.0011	0.102	0.132	0.076
Australia	6.965	-1.2E-05	-0.0360	0.368	-0.076	-0.216
Mexico	14.952	-1.1E-03	-0.0095	0.381	0.071	0.026
Brazil	15.098	-6.9E-04	-0.0311	0.311	0.305	0.114
N SSAfrica	13.954	-1.0E-03	-0.0080	1.331	0.938	0.324
S SSAfrica	6.751	-2.6E-04	-0.0119	1.130	0.592	0.313
Egypt	16.336	-3.9E-03	-0.0039	0.175	0.307	0.020
WANA (excluding Egypt)	10.206	-2.1E-03	-0.0076	0.208	0.151	-0.066
Pakistan	47.939	-1.4E-02	-0.1478	0.550	0.371	-0.022
Indonesia	26.323	-4.5E-03	-0.0331	0.169	0.523	0.290

Demand for Water Withdrawals

Offstream water demand items described above are all expressed in water depletion/consumption. The demand for water withdrawal (*DWW*) is calculated as demand for water depletion (*DWD*) divided by the water depletion coefficient (*DC*, see Box 1)

$$DWW = DWD / DC = (IRWD + INWD + DOWD + LVWD) / DC \quad (6)$$

The value of the water depletion coefficient in the context of the river basin mainly depends on the relative fraction of agricultural and non-agricultural water use (i.e., larger agricultural water use corresponds to a higher value of water depletion coefficient), as well as water conveyance/distribution/recycling systems and pollution discharge and treatment facilities. In the base year, *DC* is calculated by given total water depletion (*WDPT*) and water withdrawal (*WITHD*), and *DC* in the future is projected as a function of the fraction of non-irrigation water use, in which *WDPDO* is domestic water depletion, *WDPIN* is industrial water depletion, and *DWPLV* is livestock water depletion.

$$DC = \rho \cdot \left(\frac{WDPDO + WDPIN + DWPLV}{WDPT} \right)^\psi \quad (7)$$

This regression function is made based on historical non-irrigation water depletion and total water depletion in different basins or countries, resulting in regression coefficients $\rho > 0$ and $\psi < 0$ for all basins and countries.

As a summary, domestic water demand is projected as a function of the growth of population and per capita income; industrial water demand is projected based on income growth and technology improvement; livestock water demand is estimated as a linear function of livestock

production; and irrigation water demand is calculated based on irrigated area, cropping pattern, effective rainfall, and water use efficiency. Water demand projections of these sectors are incorporated into a modeling framework including hydrologic processes and infrastructure representation to determine water supply projections in the next 30 years, which is presented in the following section.

Water Supply Simulation

Basin Aggregation

Definitions of concepts related to water supply are listed in Box 2. Water supply is simulated at the basin scale. For each basin, all surface reservoirs at both the main river and the tributaries are aggregated into an “equivalent basin reservoir,” and all groundwater sources are lumped into a single groundwater source. This aggregation assumes a full water transfer capacity within one basin; that is to say, water in one sub-basin may be used for other sub-basins where needed. Although defined in the model at the basin scale, water demands in the real world are generally located in proximity to water sources, and full water transfer between sub-basins and different water supply systems are often constrained by engineering and hydrological feasibility. To avoid the potential “aggregation fallacy” created by this degree of basin aggregation, we introduce a concept, namely, maximum allowed water withdrawal (*MAWW*), as defined in Box 2. The *MAWW* for a basin depends on several factors, including: (1) the physical capacity of water withdrawal for agricultural, domestic, and industrial uses; (2) instream flow requirements for navigation, hydropower generation, recreation, and environment purposes; (3) source availability; and (4) water demand. Total water withdrawal in a basin is constrained by the *MAWW*, which will prevent water withdrawal beyond the engineering capacity in the basin. While this aggregation is reasonable for modeling on a global scope, it

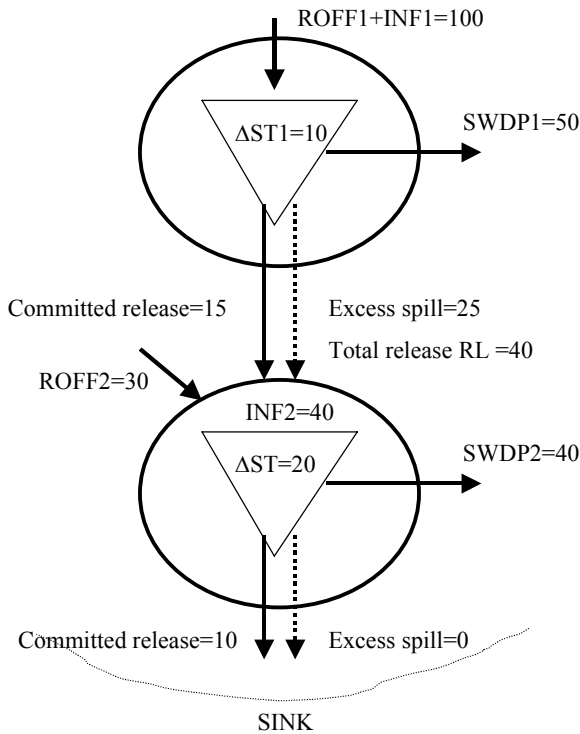


Figure 2. A two-basin diagram of the modeling framework.

may not be suitable for detailed basin studies, in which spatial distribution of water supply and demand are often required to be represented explicitly.

Water Supply Simulation

Assuming minimum environmental and ecological flow requirements as a pre-determined hard constraint in water supply, we focus on the determination of offstream water supply for domestic, industrial, livestock, and irrigation sector. Two steps are undertaken to determine offstream water supply by sector. The first is to determine the total water supply represented as depletion/consumption (WDP) in each month of a year, and the second is to allocate the total to different sectors. Particularly, irrigation water supply is further allocated to different crops in the basin.

To determine the total amount of water available for various offstream uses in a basin, hydrologic processes such as precipitation, evapotranspiration, and runoff will be taken into account to assess total renewable water (TRW). Moreover, anthropogenic impacts will be combined to define the fraction of the total renewable water that can be used. These impacts can be classified into: (1) water demands; (2) flow regulation through storage, flow diversion, and groundwater pumping; (3) water pollution and other water losses (sinks); and (4) water allocation policies, such as committed flows for environmental purposes, or water transfers from agricultural to municipal and industrial uses. Therefore, water supply is calculated based on both hydrologic processes and anthropogenic impacts through the model, including the relationships listed above.

A simple network with a two-basin framework can be used as an example (Figure 2). Water availability in the downstream basin depends on the rainfall drainage in the basin and the inflow from the upstream basin(s). The precipitation-runoff simulation is conducted by an external global hydrologic model (Alcamo et al., 1998) and the runoff ($ROFF$) resulting from the model is taken as a direct input to this modeling framework. Then surface water balance at the basin scale can be represented as

$$ST^t - ST^{t-1} = ROFF^t + INF^t + OS^t - SWDP^t - RL^t - EL^t \quad (8)$$

in which t is the modeling time interval (month); ST is the change of basin reservoir storage; INF is the inflow from other basin(s); OS represents other sources entering water supply system, such as water desalinated; RL is the total release, including the committed instream flow and spill in flooding periods; EL is the evaporation loss (mainly from surface reservoir surface); and $SWDP$ is the total water depletion from surface water sources which is equal to water withdrawal minus return flow. $SWDP$ is determined from this water balance equation, with an upper bound constrained by surface maximum allowed water withdrawal ($SMAWW$) as

$$\sum_t SWDP^t / DC \leq SMAWW \quad (9)$$

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

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

$$\sum_t GWDP^t / DC \leq GMAWW \quad (10)$$

The estimation of the $SMAWW$ and $GMAWW$ in the base year is based on the actual annual water withdrawal and annual groundwater pumping in 1995 (WRI, 2000). Projections of $SMAWW$ and $GMAWW$ are based on assumptions on future surface and ground water development in different countries and regions (Rosegrant and Cai, 2002). In particular, the projection of $GMAWW$ is based on historic pumping and potential groundwater source (measured by groundwater recharge).

A traditional reservoir operation model (see Loucks et al., 1981) is developed, including all of the above relationships of natural water availability, storage regulation, withdrawal capacity, and committed flow requirement. The model is formulated as an optimization model. The model is run for individual years using a time period of a month. The objective is to maximize the reliability of water supply (i.e., ratio of water supply over demand, less or equal to 1.0), as

$$\max \left[\frac{\sum_t (SWDP^t + GWDP^t)}{\sum_t (DOWD + INWD + LVWD + IRWD)} + \omega \cdot \min_t \left(\frac{(11) \quad SWDP^t + GWDP^t}{DOWD + INWD + LVWD + IRWD} \right) \right] \quad (11)$$

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

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

$$\begin{aligned} WDPDO^t &= \min(DOWD^t, SWDP^t + GWDP^t) \\ WDPIN^t &= \min(INWD^t, SWDP^t + GWDP^t - WDPDO^t) \end{aligned} \quad (12a)$$

$$WDPLV^t = \min(LVWD^t, SWDP^t + GWDP^t - WDPDO^t - WDPIN^t), \text{ and} \quad (12b)$$

$$WDIR^t = \min(IRWD^t, SWDP^t + GWDP^t - WDPDO^t - WDPIN^t - WDPLV^t) \quad (12c)$$

Finally, water available for crop evapotranspiration (TET) is calculated by introducing the BE for irrigation systems and discount of salinity leaching requirement, i.e.

$$TET^t = BE \cdot WDIR^t / (1 + LR) \quad (13)$$

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

$$\pi^{cp,t} = \frac{ALLO^{cp,t}}{\sum_{cp} ALLO^{cp,t}} \quad (14)$$

and

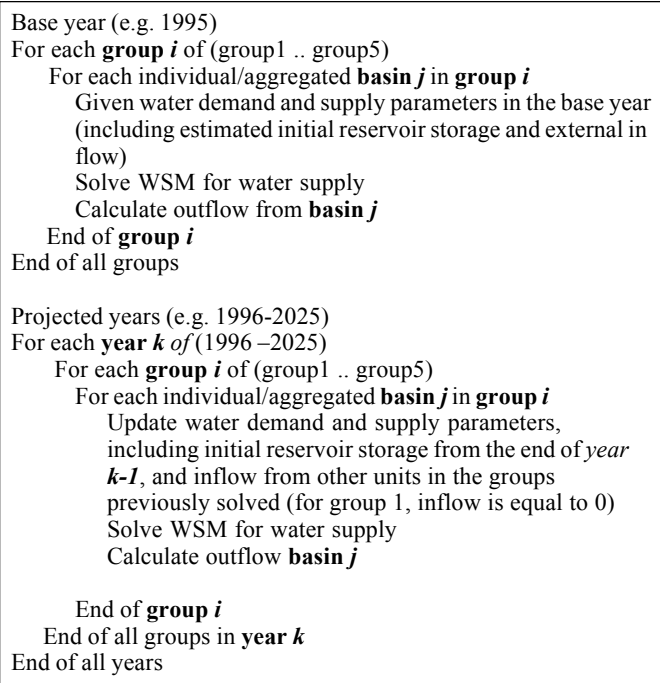


Figure 3. Model implementation procedure.

$$ALLO^{cp} = AI^{cp} \cdot ky^{cp} \cdot [1 - PE^{cp,t} / ETM^{cp,t}] \cdot PC^{cp} \quad (15)$$

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

$$CET^{cp,t} = TET^t \cdot \pi^{cp,t} \quad (16)$$

Thus, irrigation water is allocated based on profitability of the crop, sensitivity to water stress, and irrigation water demand (total demand minus effective rainfall) of the crop. Higher priority is given to the crops with higher profitability, which are more drought sensitive, and/or that require more irrigation water. Water allocation to specific crops makes it possible to estimate the effect on crop production from water stress (Rosegrant and Cai, 2002).

Model Implementation

The model implementation procedure is shown in Figure 3. The model is applied for a monthly water balance within one year. It is run through a series of years by solving individual years in sequence and connecting the outputs from year to year. The time series of climate parameters are derived based on past 30-year historic records, from 1961 to 1990. In addition to a basic scenario that overlays the single historic time series over the 1995 to 2025 projection period, a number of scenarios of hydrologic time series can be generated by changing the sequence of the yearly records. Water supply uncertainty due to various

hydrologic levels can then be identified from the statistics of multiple hydrologic scenarios (Rosegrant and Cai, 2002).

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

Water demand for non-irrigation sectors (*DOWD*, *INWD*, and *LVWD*) is updated year by year by demand projections discussed in an earlier section. Infrastructure is updated by projections of reservoir storage, water use efficiency, and (*MAWW*).

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

In order to trace the flow connection between major international river basins, we classify the 69 basins or aggregated basins (see Figure 1) into five groups according to the flow direction between those basins:

Group 1: without upstream inflow,

Group 2: with upstream inflow only from Group 1,

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

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

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

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

Conclusions

This paper presents a systematic approach to study long-term global water demand and supply projections by

domestic, industrial, livestock, and irrigation sectors. With both water demand and supply calibrated in a base year, water demand for each of these sectors is projected based on empirical relationships including hydrologic, agronomic, and economic parameters that are further discussed in Rosegrant and Cai (2002). Water supply is determined taking account of water demands, total renewable water availability, water supply infrastructure, and economic and environmental policies related to water development and management at the basin, country, or regional level. A modeling framework is developed to solve monthly water supply by sectors in the following 30 years, over 69 individual or aggregated basins in the world, with consideration of seasonal and inter-annual variability in climate. In particular, this modeling exercise integrates pieces of related relationships and information in water resources, agronomy, and economics into a consistent analytical framework, and it also integrates numerous national and international efforts in national and global water resources assessments, as will be made clearer in the companion paper (Rosegrant and Cai, 2002). Moreover, the model is implemented to allow water transfer between basins and water sharing in international river basins.

The purpose of this modeling exercise is to develop a tool for policy analysis in regional and global water resources development and management. Many policy-related water variables are involved in this modeling framework, including potential irrigated area and cropping patterns, maximum allowed water withdrawal for both surface and groundwater, water use efficiency, water storage and inter-basin transfer facility, rainfall harvest technology (i.e., to increase effective rainfall for crops), allocation of water to agricultural and non-agricultural uses, and committed instream flow requirement. In particular, water supply in irrigated agriculture is integrated with irrigation infrastructure, which permits the estimation of the impact of investment on expansion of potential crop area and improvement of irrigation systems.

Obviously, because of the global scope, a number of simplifying assumptions are required compared to detailed basin models. These assumptions are mainly associated with the aggregation of water storage and water supply at the river basin scale. Future work will use more disaggregated spatial representation, including using individual basins to replace those aggregated ones. However, even with the simplified representation in this paper, data requirements are very heavy. Data preparation is discussed in detail in Rosegrant and Cai (2002).

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Terminology

Indices

t	modeling time interval
ct	index of crop growth stages
cp	index of crops

Coefficients in functions

α	intercept in industrial water demand function (Equation 4)
β	income coefficient in industrial water demand function (Equation 4)
γ	time coefficient in industrial water demand function (Equation 4)
η	income elasticity of demand for domestic use (Equation 5)
ϕ_{dwd}	annual growth rate of domestic water demand (Equation 5)
ϕ_{pop}	annual growth rate of population (Equation 5)
ϕ_{gdpc}	annual growth rate of GDP per capital (Equation 5)
ρ, ψ	coefficients in the function of depletion coefficient (Equation 7)
ω	objective weights (Equation 11)
π	fraction of water allocation to crops (Equation 14)

Water demand and supply parameters

A	crop area
AI	irrigated area
BE	basin efficiency
CET	evapotranspiration by crops
DC	water depletion coefficient
$DOWD$	domestic water demand
DWW	demand for water withdrawal
DWD	demand for water depletion
ET_0	reference evapotranspiration
ETM	maximum crop evapotranspiration
EL	evaporation loss (mainly from surface reservoir surface)

GDP	gross domestic production
$GDPC$	per capital gross domestic production
$GMAWW$	groundwater maximum allowed water withdrawal
$GWDP$	total water depletion from groundwater sources
INF	inflow from other basin(s)
$INWD$	industrial water demand
$IRWD$	irrigation water demand
$IWDI$	industrial water use intensity (in m ³ of water per \$1000 GDP)
kc	crop evapotranspiration coefficient
ky	crop yield respond coefficient to water stress
LR	salt leaching factor
$LVWD$	livestock water demand
$NCWD$	net crop water demand
$NIRWD$	net irrigation water demand
OS	other sources entering water supply system
PC	crop price
PE	effective rainfall
RL	release
$ROFF$	runoff generated
ST	basin reservoir storage
$SWDP$	water depletion from surface water sources
$SMAWW$	surface maximum allowed water withdrawal
T	time variable
TET	total crop evapotranspiration
TRW	total renewable water
WDP	total water depletion
$WDPIR$	irrigation water depletion
$WDPDO$	domestic water depletion
$WDPIN$	industrial water depletion
$WDPLV$	livestock water depletion
$WITHD$	water withdrawal