# *MIT Joint Program on the Science and Policy of Global Change*

# Modeling the Global Water Resource System in an Integrated Assessment Modeling Framework: IGSM-WRS

*Kenneth Strzepek, Adam Schlosser, William Farmer, Sirein Awadalla,*
*Jonathan Baker, Mark Rosegrant, and Xiang Gao*

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The MIT Joint Program on the Science and Policy of Global Change is an organization for research, independent policy analysis, and public education in global environmental change. It seeks to provide leadership in understanding scientific, economic, and ecological aspects of this difficult issue, and combining them into policy assessments that serve the needs of ongoing national and international discussions. To this end, the Program brings together an interdisciplinary group from two established research centers at MIT: the Center for Global Change Science (CGCS) and the Center for Energy and Environmental Policy Research (CEEPR). These two centers bridge many key areas of the needed intellectual work, and additional essential areas are covered by other MIT departments, by collaboration with the Ecosystems Center of the Marine Biology Laboratory (MBL) at Woods Hole, and by short- and long-term visitors to the Program. The Program involves sponsorship and active participation by industry, government, and non-profit organizations.

To inform processes of policy development and implementation, climate change research needs to focus on improving the prediction of those variables that are most relevant to economic, social, and environmental effects. In turn, the greenhouse gas and atmospheric aerosol assumptions underlying climate analysis need to be related to the economic, technological, and political forces that drive emissions, and to the results of international agreements and mitigation. Further, assessments of possible societal and ecosystem impacts, and analysis of mitigation strategies, need to be based on realistic evaluation of the uncertainties of climate science.

This report is one of a series intended to communicate research results and improve public understanding of climate issues, thereby contributing to informed debate about the climate issue, the uncertainties, and the economic and social implications of policy alternatives. Titles in the Report Series to date are listed on the inside back cover.

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# Modeling the Global Water Resource System in an Integrated Assessment Modeling Framework: IGSM-WRS

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## Abstract

*The availability of water resources affects energy, agricultural and environmental systems, which are linked together as well as to climate via the water cycle. As such, watersheds and river basins are directly impacted by local and regional climate variations and change. In turn, these managed systems provide direct inputs to the global economy that serve and promote public health, agricultural and energy production, ecosystem surfaces and infrastructure. We have enhanced the Integrated Global System Model (IGSM) framework capabilities to model effects on the managed water-resource systems of the influence of potential climate change and associated shifts in hydrologic variation and extremes (i.e. non-stationarity in the hydro-climate system), and how we may be able to adapt to these impacts. A key component of this enhancement is the linkage of the Water Resources System (WRS) into the IGSM framework. WRS is a global river basin scale model of water resources management and agricultural (rain-fed and irrigated crops and livestock) and aquatic environmental systems. In particular, WRS will provide the capability within the IGSM framework to explore allocation of water among irrigation, hydropower, urban/industrial, and in-stream uses and investigate how society might adapt water resources due to shifts in hydro-climate variations and extremes. This paper presents the overall design of WRS, its linkages to the land system and economic models of the IGSM, and results of test bed runs of WRS components to address issues of temporal and spatial scales in these linkages.*

## Contents

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## 1. INTRODUCTION

The MIT Integrated Global System Model (IGSM) (Sokolov *et al.*, 2007) is designed for analyzing the global environmental changes that may result from anthropogenic causes, quantifying the uncertainties associated with the projected changes, and assessing the costs and environmental effectiveness of proposed policies to mitigate climate risk. The Water Resource System (WRS) component of the IGSM is designed to model the managed aspect of the hydrologic cycle. The integrated water resources management framework can be divided into three sub-systems: 1) water supply, the collection, storage and diversion of natural surface and groundwater, 2) water demand, the withdrawal and consumption of water for economic, social, and environmental uses and 3) the supply/demand balance at a river basin scale. WRS models all three sub-systems.

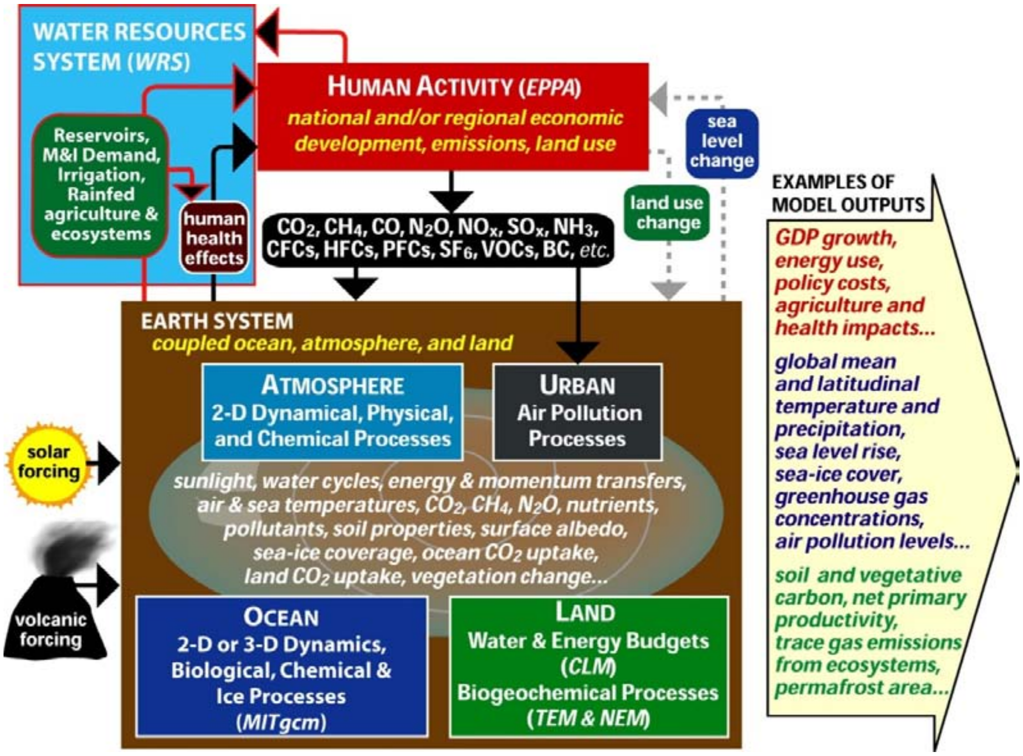

**Figure 1.** IGSM-WRS Framework.

WRS is the synthesis of two lines of research on global water systems, one led by Kenneth Strzepek at the University of Colorado (CU) focusing on the impacts of climate change upon hydrological systems, and a second led by Mark Rosegrant, of the International Food Policy

Research Institute, focusing on global food and agricultural systems. **Figure 1** illustrates the position of WRS within the IGSM framework. The natural surface and ground water is modeled by the Global Land System component (GLS) (Schlosser *et al.,* 2007) of the IGSM. The economic and social demand for water is driven by inputs from the Emissions Prediction and Policy Analysis model (EPPA) (Paltsev *et al.,* 2007), which is the part of the MIT IGSM that represents the human systems. EPPA is a recursive-dynamic multi-regional general equilibrium model of the world economy. It is designed to develop projections of economic growth and anthropogenic emissions of greenhouse related gases and aerosols. Environmental demands are driven by inputs from the Land System and the Terrestrial Ecosystem Model (TEM) of GLS. The output of WRS provides information to EPPA on water-related impacts on economic (agricultural, industrial and energy) production.

Work at CU began with a national-level assessment of water resources supply-demand balances for the UN Comprehensive Fresh Water Assessment (Raskin *et al.*, 1997). This national-level analysis was extended and incorporated in Stockholm Environment Institute's (SEI) Polestar model (Raskin *et al.*, 1998) and commissioned by the World Water Council to perform an analysis of the global water situation in 2025 for the World Water Vision 2000 (Gangopadhyay *et al.*, 2001, Cosgrove and Rijsberman, 2000). Over this period the CU contingent continued to develop tools that could analyze the impacts of climate change on future water supply and demand.

The recognition that the long-term change in water demand and availability, particularly a rapidly-increasing, non-agricultural demand for water, would impact agricultural production and demand, food security and trade led to a renewed effort on the part of IFPRI and partner collaborators to make more explicit linkages between food production and water availability within an integrated modeling framework. The result of this research has led to the development of the IMPACT-WATER model, which integrates the global partial-equilibrium agricultural sector model, IMPACT, with a water simulation module (WSM) that balances water availability and demands within various economic sectors, at the global and regional scale.

The IMPACT-WATER framework allows exploration of the relationship between water availability and food demand considering trade at a variety of spatial scales – ranging from river basins, to countries and more aggregated regions, to the global level. Water supply and demand and crop production are first assessed at the river-basin scale. Crop production is then summed to the national level, where food demand and trade are modeled. While the primary IMPACT model divided the world into 36 countries and regions, the IMPACT-WATER model uses a finer disaggregation of 281 "food-producing units" – which represent the spatial intersection of 115 economic regions and 126 river basins. This finer spatial scale recognizes the significance of regional climatic and hydrologic variations, which are not captured in more aggregate units. **Figure 2** displays these food-producing units (FPUs). Of the countries represented within the IMPACT-WATER model, China, India and the United States, producing an aggregate 60% of the world's cereal grains, have the highest level of sub-national disaggregation and are divided into 9, 13 and 14 major river basins, respectively. Other regions considered by IMPACT are considered within the remaining basins. A general overview of the countries/ regions, commodities, and the definitions of the river basins are given in Appendices A, B, C respectively.

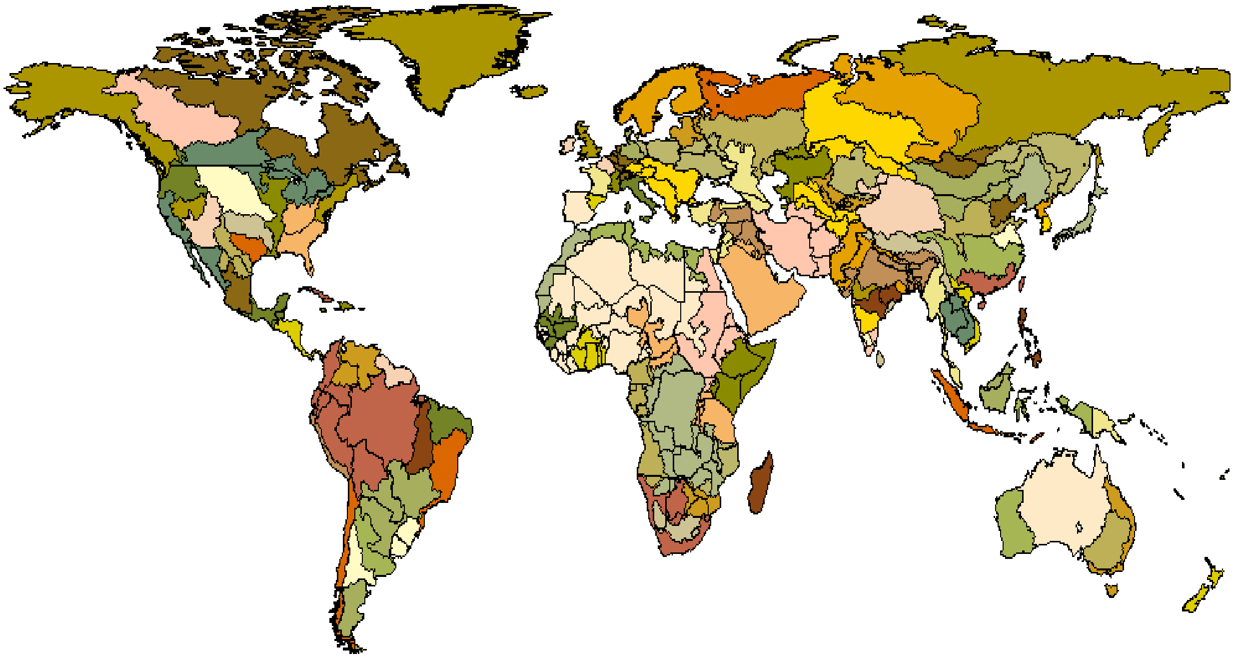

**Figure 2.** IMPACT-WATER 281 food-producing units (FPUs).

Policy analyses based on alternative scenarios analyzed with IMPACT-WATER were published by IFPRI (Rosegrant, Cai and Cline, 2002). The North American Commission for Environmental Cooperation also used IMPACT_WATER to make policy evaluations (Rosegrant, Runge and Cai, 2000), looking at implications of NAFTA on water use and agricultural production in North America. IMPACT-WATER is also currently being used for a World Bank report on the role of agriculture to achieve the Millennium Development Goals as well as in a small effort by the US EPA aimed at assessing the role of greenhouse gas mitigation for rice production in China.

## 2. MODELING FRAMEWORK

The WRS module is a set of water supply and demand models set within a river basin framework. A core model, the Water Simulation System (WSS), simulates the water supply and demand balance. WRS can be run in a stand-alone mode with runoff supplied by a global hydrologic model and socio-economic growth parameters supplied exogenously to the model.

**Figure 3** shows the IGSM-WRS configuration. As can be seen, WRS receives runoff from the land surface model of the IGSM. Runoff is estimated by the biogeophysics package of the Community Land Model (CLM). Socio-economic drivers for water demand are provided from the EPPA model. Water demand is modeled in the WRS for agricultural, environmental, municipal and industrial uses. CliCrop, a joint University of Colorado/MIT-JP crop-yield model is being implemented to replace the standard IMPACT-Water crop-yield model component. Non-crop water demands are calculated from a model driven by GDP/capita and assumptions about technology change over time. These components are described in more detail below.

By sector, WRS estimates the impacts of water supply on economic production potential. This data is then sent to EPPA. CliCrop estimates rain-fed crop yields, while irrigated yields are modeled with irrigation demands from CliCrop and the water availability in WSS. These changes in yields are fed to EPPA, where they are a parameter in the agriculture sector production function. WRS also provides a simple estimation of impacts from water stress on industrial production and hydroelectric energy production, which feeds into EPPA's production functions for water-intensive industrial sectors and hydroelectric energy. A detailed river-basin-level energy model that will provide detailed estimations of impacts on thermal electric generation as well as impacts on hydropower generation is under development for the next version of WRS.

WRS and EPPA do not have the same spatial and temporal scales. The sectoral economic impacts are estimated by WRS on an annual time step at the food producing unit (FPU) level. These results are aggregated to the 16 EPPA regions and then averaged over for the five-year periods that make up EPPA's time step. These regional estimates of water impacts become parameters for the supply curves in the dynamic, economy-wide computable general equilibrium (CGE) model that is solved every five years.

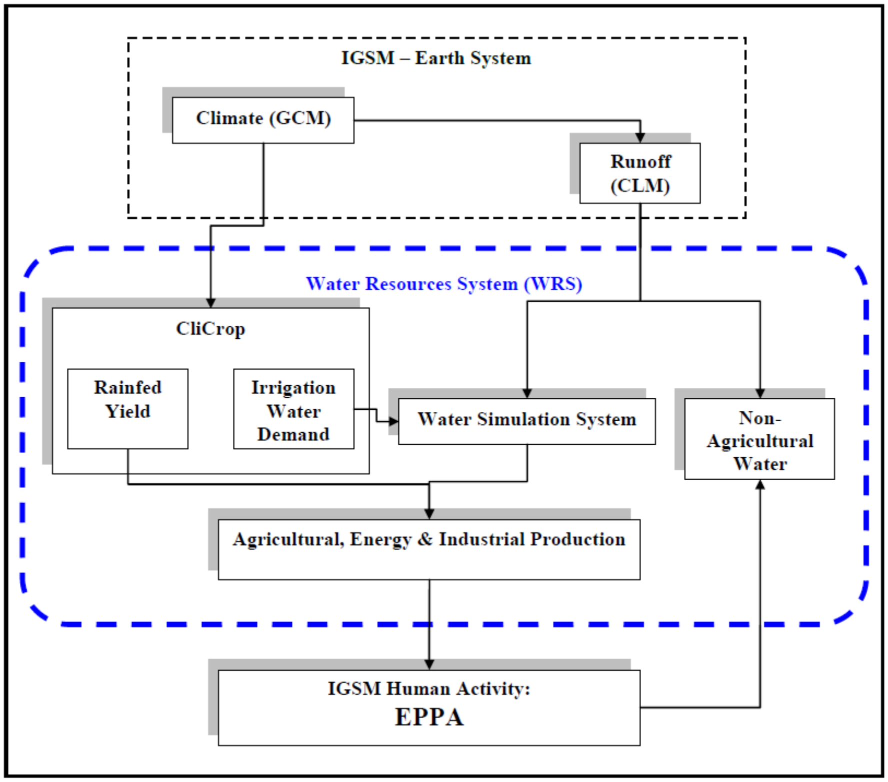

**Figure 3.** WRS Framework.

## 2.1 Water Supply

### *2.1.1 Hydrologic Cycle and Hydrology*

The Community Land Model (CLM) (Oleson *et al.*, 2004), the land surface model of ISGM, models the hydrologic cycle over land and interactions with the atmosphere via precipitation, water and energy fluxes as well as with ocean via the discharge of runoff from the land surface (**Figure 4a**). These interactions are directly linked to the biogeophysics of the land surface and soil zone, affecting regional temperature, precipitation and runoff.

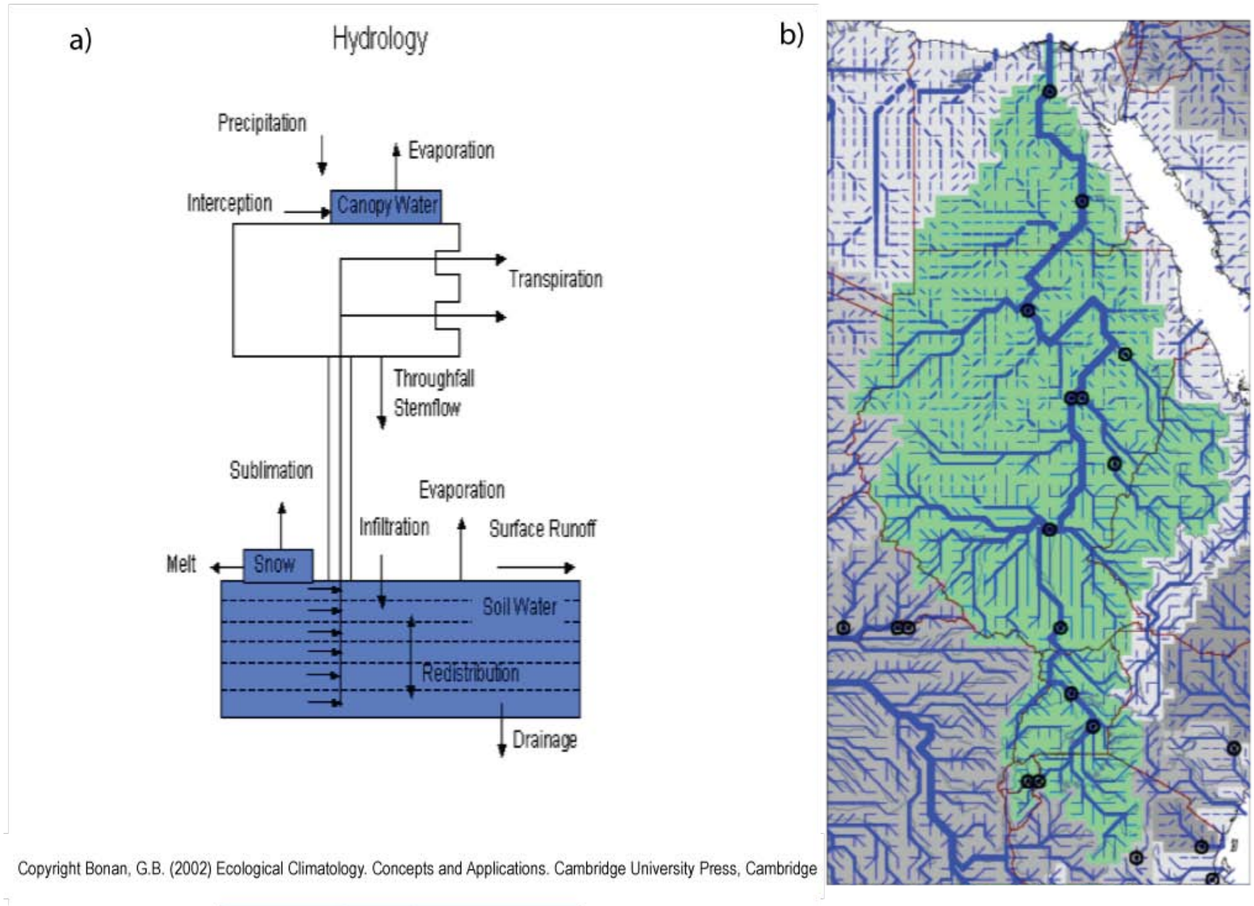

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**Figure 4.** Schematics of (a) the CLM hydrology indicating all the flows and storages of liquid and frozen water that are explicitly tracked through the soil/vegetation column and, (b) an example of the RTM network describing the Nile River basin.

### *2.1.2 River Routing*

Total runoff (surface and sub-surface runoff) is routed downstream to oceans using a river transport model (RTM). The gridded runoff from CLM/ RTM is aggregated to the FPU level and directed as input to WRS.

## 2.2 Agricultural Production Systems

### *2.2.1 Rain-fed Crop Yields*

CliCrop is a generic crop model used to calculate the effect of daily precipitation on crop yields and irrigation water demands (Fant, 2008). It is driven by water-stress and therefore explicitly models the soil water balance in the root zone. It can model 36 crop types by calculating daily crop water demand and root water uptake to provide an estimate of crop yield via state-dependent stress metrics. These metrics represent the controls of crop productivity through the four primary stages of crop growth: seeding, developmental, mid-, and late season. It models both rain-fed and irrigated crop production response to soil moisture from precipitation and irrigation. The model was developed in response to the lack of availability of computationally-efficient, daily crop models. It avoids the use of simple monthly crop yield models, which use monthly average rainfall and temperature to produce crop outputs. These monthly models do not capture the potentially important effects of daily variations in precipitation and temperature, which greatly impact crop development. For example, most of the IPCC GCMs predict that total annual precipitation will decrease in Africa, but rain will be more intense and therefore less frequent

Currently CliCrop is able to produce predicted changes in crop yields due to climate change for both rainfed and irrigated agriculture, as well as changes in irrigation demand. Since CliCrop was developed to study effects of agriculture on a global or continent scale, it can be used at a variety of scales, from field level to the scale of agro-ecological zones.

The inputs into CliCrop are weather (temperature and precipitation), soil parameters (field capacity, wilting point, saturated hydraulic conductivity, and saturation capacity), and crop growth and water use characteristic as needed for the FAO CROPWAT model (planting date, crop growth stage length, rooting depth, consumptive use coefficient) (FAO, 2010). The daily distributions of the precipitation and temperature can be derived from any global daily climate dataset (*e.g.* historic, AR4 GCM or the MIT-IGSM). All of the required soil parameters are extracted from the FAO Soils Database (FAO-UNESCO, 2005). Rain-fed crops yields are based on the FAO 33 water-stress method (Doorenbos and Kassam, 1986) with crop water supply based on actual root water extraction from the soil based on precipitation-supplied water.

### *2.2.2 Irrigated Crop Yields*

The same inputs are required and the same soil moisture accounting is used for modeling irrigated crops. The difference is that precipitation is supplemented by irrigation supply. Data must be supplied with the on-farm irrigation efficiency, a measure of how much water applied to the field actually infiltrates to the root zone. These efficiencies are related to irrigation technology (*e.g.* flood irrigation: 50%; drip irrigation: 90%). Irrigated yields are based on the FAO 33 water-stress method, as with rain-fed yields (Doorenbos and Kassam, 1986).

## 2.3 Water Demand

The Water Demand is calculated in WRS differently for each of the agricultural and non-agricultural sectors. These demands grown over time related to population and economic variables supplied by EPPA. The sections below provide a description of the water demands projected for each of the major water use sectors.

### *2.3.1 Irrigation Demand*

As discussed above, CliCrop is a soil water accounting system that tracks water applied to the field via precipitation or irrigation, its infiltration, uptake by roots and transpiration by the crop. It uses the *potential* evapotranspiration (the optimal crop water demand) to estimate the *actual* crop evapotranspiration based on soil water availability.  CliCrop then calculates the irrigation water demand by determining the "on-farm water requirement." The "on-farm water requirement" is the amount of water that must be applied on the field to make up any precipitation deficit, the difference between actual and potential evapotranspiration based solely on soil water that infiltrates from rainfall. Irrigation demand is function of the irrigation technology (on-farm efficiency), the soil parameters (field capacity, wilting point, saturated hydraulic conductivity, and saturation capacity) and the temporal delivery of irrigation water. This value is determined as depth per unit area of crop.

The amount of water diverted from a reservoir or river for irrigation must be based on both the cropped area being irrigated and the irrigation demand per unit area. The volumetric, total water demand is the product of the cropped area and the depth per unit area. However this is not the total irrigation demanded from the reservoir water supply. Losses in irrigation delivery systems must be accounted for in the water demanded. The efficiency of the delivery system is known as the conveyance efficiency, and WRS must supply irrigation water from each basin reservoir that is based on the on-farm irrigation demand and this term. The conveyance efficiency is a function of the design, operation and lining material of the canal system from water supply to farm.

### *2.3.2 Municipal Demand*

Municipal water demand, as defined here, encompasses both domestic and commercial uses. Increases in municipal water use, which will be driven by both rising populations and per capita incomes, will vary widely across countries. As noted by Cole (2004) and others, a nation's per capita GDP is a strong determinant of its per capita municipal water use. As per capita incomes rise in poorer nations, the level of service moves from systems such as rainwater catchments, truck-supplied water, or public standpipes, to plumbing systems where water is delivered directly to households. Gleick (1996) observes that at the lowest levels of service, individuals may only consume an average of 10 liters of water per day, whereas, at the highest levels, people may consume between 150 and 400 liters per day. The path of the per capita water use to per capita GDP relationship over time depends on the development path of the particular nation; countries with more equitable distributions of resources (*i.e.*, lower Gini coefficients) will spread advancements in water service more widely, which will lead to more rapid increases in average per capita water use.

Once the majority of a population has ready access to water (*e.g.*, developed nations), household (and commercial) consumption of water flattens with respect to incomes, and begins to fall with further increases in per capita income as developed nations introduce or require water efficiency measures (*e.g.*, water saving showerheads and toilets). As a result, over the last few decades OECD nations have had constant or falling per capita municipal water use as per capita GDPs have increased (**Figure 5**).

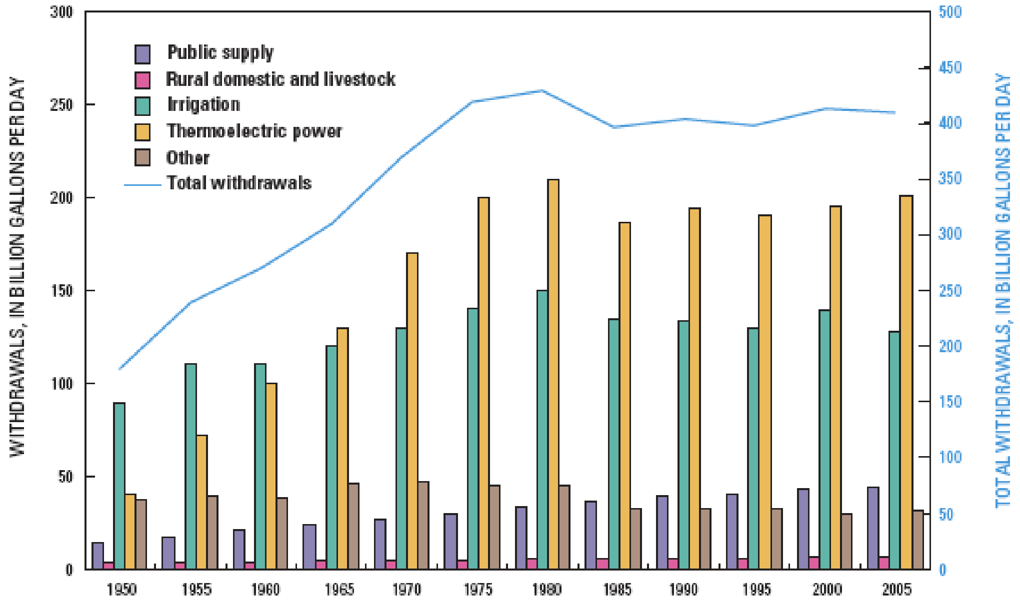

**Figure 5.** Trends in US water use, by category, 1950 to 2005. (USGS, 2009.)

This trend has prompted Cole (2004) to inquire whether municipal water use follows an environmental Kuznets curve, where per capita water initially rises with incomes, and then falls, as nations grow wealthier. Indeed, as seen in **Table 1**, European water withdrawals generally increased through the 1970s and declined between 1980 and 1995. Given that GDP and population were generally rising through this period, the trend in per capita use relative to per capita GDP would be considerably lower.

**Table 1.** Trend in total European Water Withdrawals. Krinner *et al.*, 1999.

| Country | Mean Annual Change in Withdrawals (%) | | Country | Mean Annual Change in Withdrawals (%) | |
|---|---|---|---|---|---|
| | 1970-80 | 1980-95 | | 1970-80 | 1980-95 |
| Austria | | 0.2 | Norway | -1.6 | |
| Belgium | -0.5 | | Portugal | | 1 |
| Denmark | | -1.9 | Spain | 5 | -1.2 |
| Finland | 1.2 | -2.9 | Sweden | 0.1 | -2.7 |
| France | 4.1 | 1.1 | United Kingdom | 0.2 | -1.5 |
| Germany | 2.9 | 0.8 | Estonia | | 0.5 |
| Greece | 5 | | Hungary | 4.9 | 1.9 |
| Italy | 3 | 0 | Poland | 3.4 | -1.1 |
| Netherlands | 1.1 | -1.5 | | | |

Developing nations where incomes are rising rapidly, such as China or India, will experience dramatic increases in municipal water use as levels of water service become more advanced. In nations where populations are also rising, these effects will be further magnified. World Bank projections of municipal water use over time for OECD and non-OECD countries are included in **Figure 6**. OECD municipal demand is projected to increase only 10 percent (162 to 178 billion $m^3$) through 2050, as compared to the over 100 percent increase forecast in non-OECD countries (from 257 to 536 billion $m^3$).

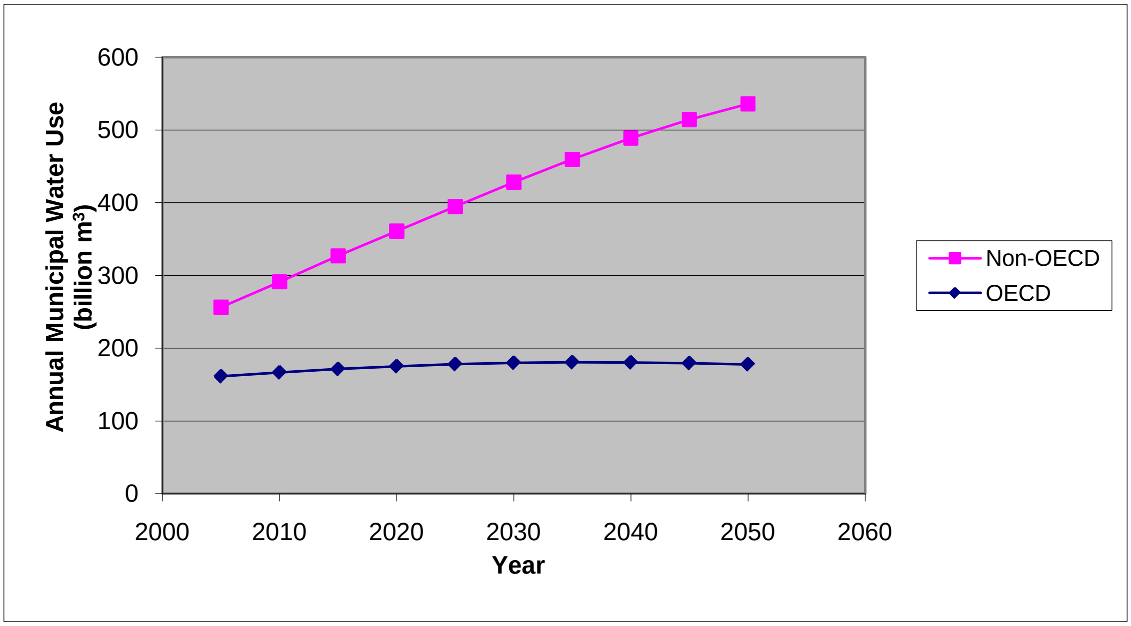

**Figure 6.** Total projected municipal water use, 2005 to 2050. Hughes *et al.*, 2010

### *2.3.3 Industrial Demand*

Industrial water demand includes water use for manufacturing, energy generation, and other industrial activities. Similar to municipal demand, per capita industrial water use tends to rise rapidly as a nation industrializes, and then fall as countries move toward more service-based industries. As a result, the most important determinant of future industrial water use is the stage of a country's development.

A related factor affecting future industrial water use is whether the country adopts water-conserving technologies. If regulations on water use are imposed that require conservation technologies, or if water prices cause industrial water use to become more costly than conservation, water use will tend to decline. This trend is typified in the construction of new energy generation capacity in developing and developed countries: new power plants in developing countries generally use water for thermoelectric cooling, whereas new facilities in developed nations often use air cooling condensers to avoid excess water use and thermal pollution. In some instances, developed nations transfer lower water use technology to developing nations and thus allow those nations to "leapfrog" past the period during their development paths with highest per capita industrial water use.

These patterns can be observed in **Figure 7**, which shows World Bank projections of total OECD and non-OECD industrial water use between 2005 and 2050. Note that total OECD industrial water use declines, and non-OECD use increases only slightly after peaking during the 2030s. The World Bank projections assume that leapfrogging occurs to facilitate reductions in developing nations' industrial use.

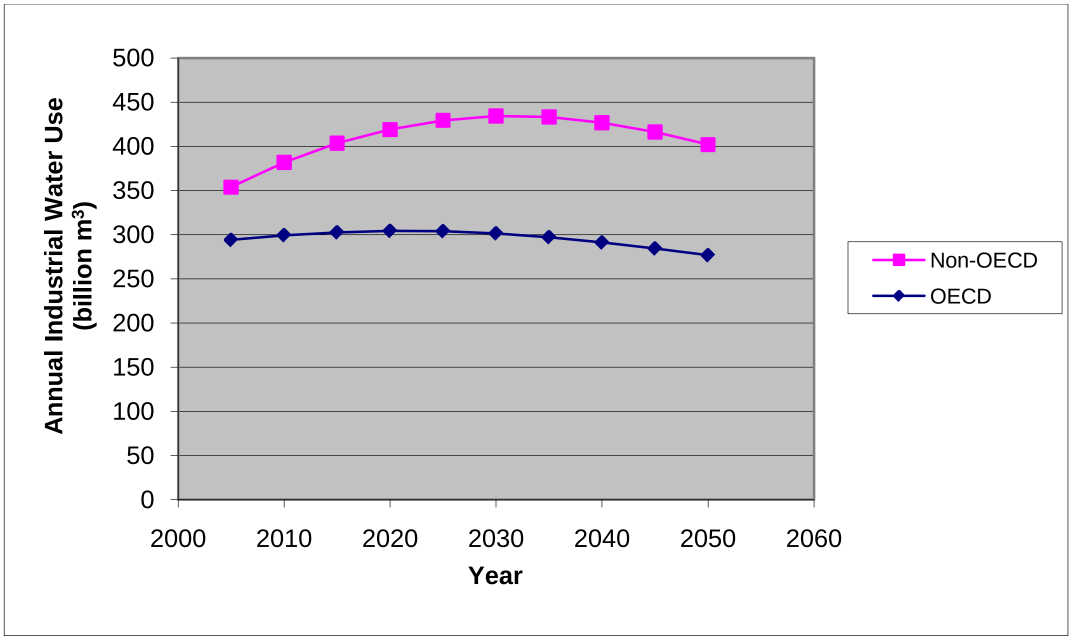

**Figure 7.** Total projected industrial water use, 2005 to 2050.

### *2.3.4 Electrical Energy Demand*

Water withdrawals for thermal electric cooling accounted for 49 percent of all water withdrawal in the United States in 2005 (Kenny *et al.*, 2009). Any change in electrical energy generation policy and technologies has the potential to have a major impact on the management of local and regional water resources.

A model was developed that estimates water withdrawals and consumption for thermal electric cooling and non-thermal process water initialized to 2006 using DOE Energy Information Agency. The model calculates water demand for each generating technology at the county level. The model makes use of USGS estimates of water withdrawals for four types of water-generating technology combinations: OTF- Fresh water used in once-through cooling; OTS -Saline water used in once-through cooling; CCF- Fresh water used in recirculation cooling; CCS - Saline water used in recirculation cooling, assuming that the distribution of water source and cooling technology remains constant over time. Environmental management policies that may lead to changes in water source or cooling technologies can also be modeled. Concentrated solar power and geothermal power plants can be assumed to use either dry or wet cooling, depending upon the assumed cooling technology employed. Further, it is assumed that hydropower plants require no additional water for cooling, but may use water for other noncooling operations. The model was calibrated to a 2006 base dataset consisting of water use data and electricity generation at the county level.

The United States Geological Survey (Kenny *et al.*, 2009) reports national water withdrawals used for thermo-electric cooling in 2005 at the county level by water type and cooling technology. USGS estimates less than 3% of water withdrawals for once-through cooling and over 60% of water withdrawals for recirculation cooling are consumptive. The model uses these percentages to calculate consumptive use based on withdrawals.

Non-thermal renewable electricity technologies do not require water for cooling but do require water for operation (*e.g.* photovoltaic plants needs water for cleaning the collectors and concentrated solar plants may need water to clean the mirrors). Macknick (2010) provides estimates of operational water consumption for most of electric generation technology with an emphasis on renewable technologies.

### *2.3.5 Environmental Flow Requirements*

Environmental Flow Requirements (EFRs) refer to minimum flows allocated for the maintenance of aquatic ecosystem services. EFRs can also be viewed as a sector or a user, similar to the domestic or industrial demands defined above; this demand, however, is for floodplain maintenance, fish migration, cycling of organic matter, maintenance of water quality, or other ecological services (Smakhtin, 2008). Although these demands are increasingly being viewed as crucial, they are often not included in traditional accounting determinations of how close basins are to full diversion of mean annual flow.

Falkenmark and Rockström (2006) differentiate between the ‘blue water’ in lakes, rivers, and aquifers that is available for human withdrawal, and the ‘green water’ in soil moisture that is used by terrestrial ecosystems, including agricultural systems, as seen in **Figure 8**. Excessive blue water withdrawals can lower water tables and affect the availability of green water, thus potentially impairing terrestrial ecosystem function.

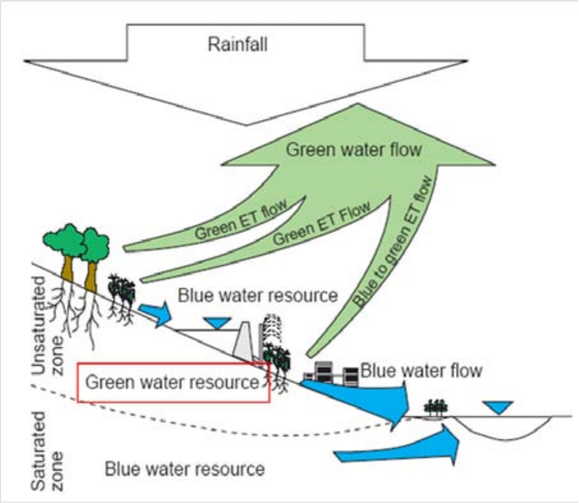

**Figure 8.** A representation of blue and green water. Falkenmark and Rockström, 2006.

As the understanding of ecosystem health has shifted from maintaining minimum flows to ensuring that the timing and magnitude of flows is appropriate to assure ecosystem health, quantifying EFRs within individual river basins has grown more complex. Smakhtin (2004a) notes that EFRs have two components: low flow requirements (LFRs) and high flow requirements (HFRs). LFRs are minimum flow requirements needed to sustain ecosystems, whereas HFRs are necessary for floodplain and stream channel maintenance.

Smakhtin suggests that Q90 flows (*i.e.*, flows that are exceeded 90 percent of the time) are sufficient to maintain riparian health in ‘fair’ condition, and are generally a reasonable assessment of EFRs. He contrasts these with Q50 flows (*i.e.*, median flows), which maintain the riparian system in ‘natural’ condition (*i.e.*, negligible modification of habitat) and Q75 flows, which maintain the system in ‘good’ condition (*i.e.*, largely intact biodiversity and habitats despite development). Depending on the shape of a river’s hydrograph, Q90 flows may be exceedingly low (*e.g.*, if greater than 10 percent of flows are zero, Q90 flows will be zero). In these instances, Smakhtin suggests that HFRs be imposed that impose requirements at the high end of the hydrograph. Specifically, if Q90 flows are less than 10 percent of mean annual flow (MARs), HFRs are 20 percent. For Q90 flows greater than 30 percent of MARs, no additional HFRs are necessary. Where Q90 flows are from 10 to 20 percent of MARs and 20 to 30 percent of MARs, HFRs are 15 percent and 7 percent, respectively. **Figure 9** presents a map of a water stress indictor (WSI) for the world’s river basins with Q90 flow and HFRs included. WSI is a ratio of the total annual water withdrawal to the mean annual runoff of a river basin. Note the number of stressed basins, particularly in the Middle East, central Asia, and southern Europe.

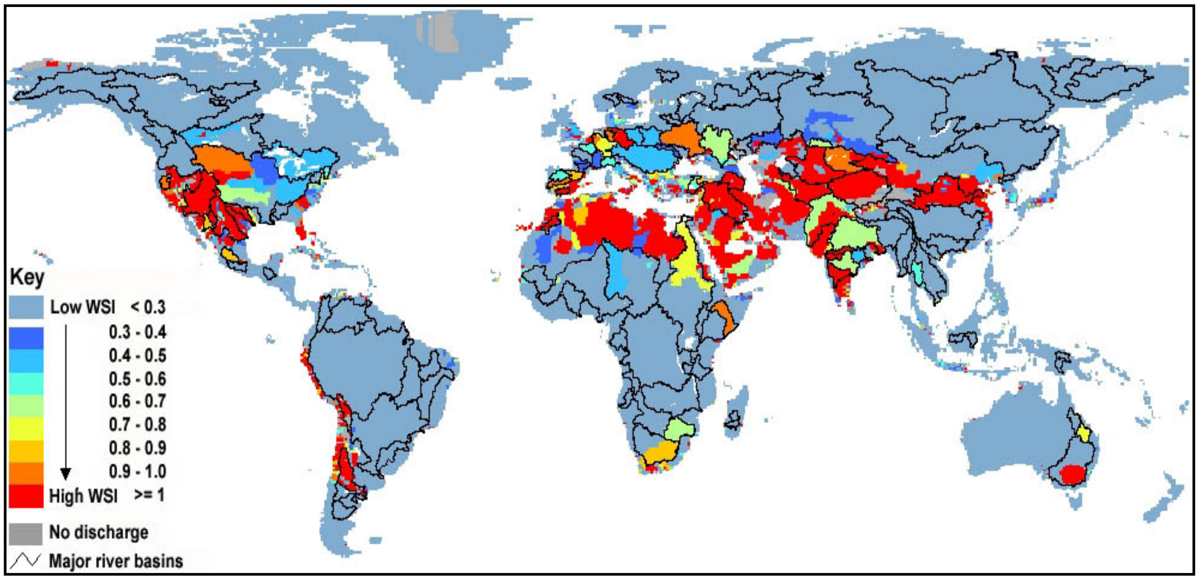

**Figure 9.** Water stress, with environmental flows, in the world's basins from Smakhtin *et al*., 2004b.

## 2.4 Water Management System

Assuming minimum environmental and ecological flow requirements impose a predetermined hard constraint in water supply, we focus on the determination of off-stream water supply for domestic, industrial, livestock, and irrigation sectors. Two steps are undertaken to determine off-stream water supply by sectors. The first is to determine the total water supply represented as depletion/consumption (WDP) in each month of a year; and the second is to allocate that 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 off-stream uses in a basin, hydrologic processes, such as precipitation, evapotranspiration, and runoff are taken into account to assess total renewable water (TRW). Moreover, anthropogenic impacts are combined to define the fraction of the total renewable water that can be used. These impacts can be classified into (1) water demands; (2) flow regulation through storage, flow diversion, and groundwater pumping; (3) water pollution and other water losses (sinks); and (4) water allocation policies, such as committed flows for environmental purposes, or water transfers from agricultural to municipal and industrial uses. Therefore, water supply is calculated based on both hydrologic processes and anthropogenic impacts through the model, including the relationships listed above.

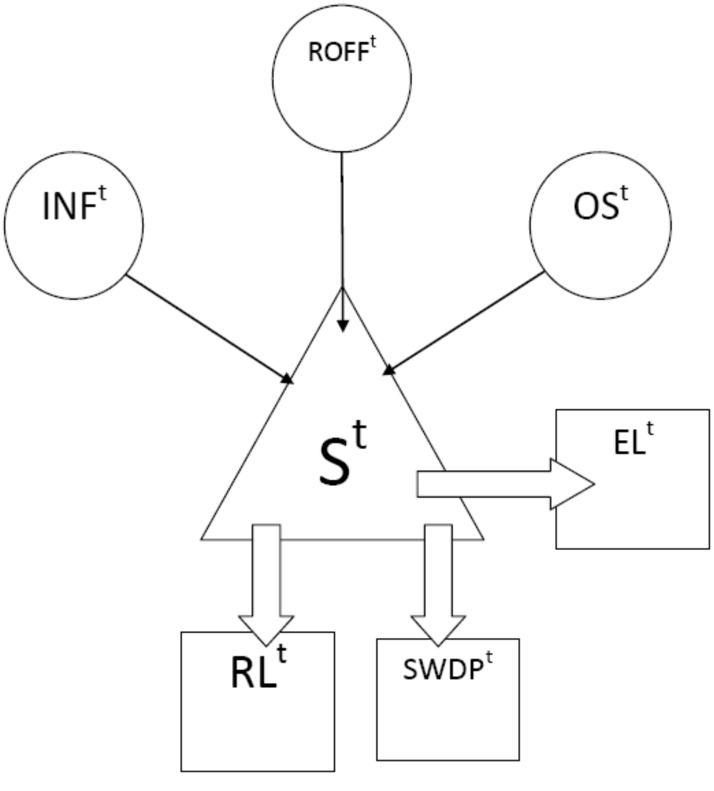

**Figure 10.** River Basin Water Supply-Demand Balance.

A simple river basin supply-demand balance is shown schematically in **Figure 10**. Water availability in the basin depends on the runoff from the basin and the inflow from the upstream basin(s). Then surface water balance at the basin scale can be represented as:

$$ST^t - ST^{t-1} = ROFF^t + INF^t + OS^t - SWDP^t - RL^t - EL^t \tag{1}$$

in which t is the modeling time interval; ST is the basin reservoir storage; INF is the inflow from other basin(s); OS represents other sources entering water supply system, such as water desalinized; RL is the total release, including the committed in-stream 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 its upper bound (normalized by direct consumption, DC) constrained by surface maximum allowed water withdrawal (SMAWW) as:

$$\sum_t SWDP^t / DC \le SMAWW \tag{2}$$

Other constraints related to the items in Equation 1 include that flow release (*RL*) must be equal or greater than the committed in-stream flow. Monthly reservoir evaporation is calculated based on reservoir surface area and climate characteristics.

Depletion from groundwater (GWDP) is constrained in a similar fashion to that of *SWDP* by maximum allowed water withdrawal from groundwater (GMAWW):

$$\sum_t GWDP^t / DC \le GMAWW \tag{3}$$

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

A traditional reservoir operation model is incorporated, including all of the above relationships of natural water availability, storage regulation, withdrawal capacity, and committed flow requirements. The model is formulated as an optimization model. The model is run for individual years with one month as the time step. The objective is to maximize the reliability of water supply (that is, ratio of water supply over demand, less or equal to 1.0), as:

$$\max \left[ \begin{array}{l} \dfrac{\sum_t (SWDP^t + GWDP^t)}{\sum_t \left(DOWD^t + INWD^t + LVWD^t + IRWD^t\right)} + \\ \omega \cdot \min_t \left( \dfrac{SWDP^t + GWDP^t}{DOWD^t + INWD^t + LVWD^t + IRWD^t} \right) \end{array} \right] \tag{4}$$

and, as can be seen, the objective function also drives the water application according to the water demand in crop growth stages (months) by maximizing the minimum ratio among time periods (12 months). The weight item $\omega$ 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 the constraints described above, the next step is to determine the water supply available for different sectors. Assuming domestic water demand is satisfied first, priority is then given to industrial and livestock water demand, whereas irrigation water supply is the residual claimant. Monthly non-irrigation water demands are calculated based on their annual value multiplied by monthly distribution coefficients. Water supply represented as depletion for different sectors is calculated as:

$$WDPDO^t = \min\ (DOWD^t,\ SWDP^t + GWDP^t), \tag{5}$$

$$WDPIN^t = \min\ (INWD^t,\ SWDP^t + GWDP^t - WDPDO^t), \tag{6}$$

$$WDPLV^t = \min\ (LVWD^t,\ SWDP^t + GWDP^t - WDPDO^t - WDPIN^t), \tag{7}$$

$$WDIR^t = \min(IRWD^t,\ SWDP^t + GWDP^t - WDPDO^t - WDPIN^t - WDPLV^t), \tag{8}$$

where WDPDO is domestic water supply, WDPIN is the industrial water supply, WDPLV is the livestock water supply, and WDIR is irrigation water supply.

Finally, total water available for irrigated crop evapotranspiration (*TNIW*) is calculated by introducing the basin efficiency (*BE*) for irrigation systems and discounting the salinity leaching requirements (*LR*), as:

$$TNIW^t = BE \cdot WDIR^t / (1 + LR). \tag{9}$$

*TNIW* can be further allocated to crops according to crop irrigation water demand, yield response to water stress (*ky*), and average crop price (*PC*) for each of the major crops considered in a basin, including rice, wheat, maize, other grains, soybeans, potato, sweet potato, and roots and tubers.

The allocation fraction is defined as:

$$\pi^{i,t} = \frac{ALLO^{i,t}}{\sum_{cp} ALLO^{i,t}} \text{ and,} \tag{10}$$

$$ALLO^i = AI^i \cdot ky^i \cdot \left[1 - PE^{i,t} / ETM^{i,t}\right] \cdot PC^i \tag{11}$$

where *AI* is the irrigated area for a given crop (*i*), $ETM^{i,t} = ET_0^{i,t} \cdot kc^{i,t}$, is the maximum crop evapotranspiration scaled by the crop coefficient, *kc*, to the potential rate, $ET_0$; $\pi$ is a scaled number in the range of (0,1) and the sum of $\pi$ over all crops is set to equal 1. The effective water supply allocated to each crop (*NIW*) is then calculated by:

$$NIW^{i,t} = TNIW^t \cdot \pi^{i,t} \tag{12}$$

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.

## 3. TESTBEDS FOR MODEL IMPLEMENTATION

A set of three tests of IGSM/WRS modeling component have been completed and are presented below. The tests are (1) runoff modeling using CLM, (2) spatial scale implication on CliCrop crop yield modeling and (3) thermal electric cooling water modeling.

### 3.1 CLM: Runoff modeling

A critical issue in the linkage between the natural and managed hydrologic systems will be the ability of the modeled system to faithfully represent the naturalized hydrograph of the world's major watersheds. By doing so, the management scheme of WRS is provided a robust baseline of surface-water availability in the river basin. Within the structure of the IGSM, this linkage is established by CLM's simulation of runoff at every grid point and then the routing of that runoff through the network of river basins by WRS. Given this, an evaluation of CLM's ability to represent the naturalized state of river flow (or basin runoff) is desirable. Therefore, we have evaluated CLM's simulated runoff obtained at various grid resolutions, and under different atmospheric forcings, against observations at 99 basins that span the contiguous United States.

The U.S. Geological Survey gages, measures and organizes stream runoff data such that the continental U.S. is composed of 18 main river catchments; these are then divided into 99 sub-basins, which are divided further. This particular analysis uses runoff data from the 4-digit Hydrologic Unit Code (HUC)[1], which identifies the 99 sub-basins. The important distinction of this data is that it represents measurements of the naturalized streamflow (aggregated runoff) for all the basins considered. Runoff data from sub-basins is available at a monthly time step and includes the following time periods:

a. Measurement of sub-basins did not begin simultaneously, some were measured starting as early as 1897, while others were as late as 1961.
b. The data ends in the mid 1970's: 4 sub-basins' measurements ended before 1976; remaining 95 were measured through 1976, with 54 of them ending in 1977.

As described in Schlosser *et al.*, (2007), total runoff (surface and sub-surface runoff) are provided in the IGSM through the Community Land Model (CLM). For this evaluation, we calculated runoff values by forcing CLM (Version 3.5) (Oleson *et al.*, 2004) with three separate meteorological forcing data sets: NCEP Corrected by CRU (NCC, Ngo-Duc *et al.*, 2005), Climate Analysis Section (CAS), (Qian *et al*., 2006), and the Global Offline Land Data (GOLD), Dirmeyer and Tan, 2001). CLM uses these forcing datasets to generate runoff rates (as well as other biogeophysical states and fluxes – as depicted by Figure 4) at 3 spatial resolutions, 0.5°x0.5°, 1°x1° and 2°x2.5° and at the respective time steps for each forcing dataset, yielding 9

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[1] From USGS website at http://nhd.usgs.gov/data.html

runoff datasets, denoted herein as: NCC05, NCC1, NCC2, CAS05, CAS1, CAS2, GOLD05, GOLD1 and GOLD2.

For each sub-basin, USGS provides monthly runoff averaged over its entire time period of measurement, as well as the average annual runoff for the sub-basin. To compare CLM's generated runoff to that measured by USGS the 9 CLM datasets were first processed in the following way:

1. Multi-daily runoff values were aggregated to yield monthly time steps.
2. Using the map provided by USGS for identifying the 99 unique sub-basins, GIS mapping software was used to overlay the 9 global CLM datasets and extract runoff for each sub-basin, thus yielding 9 CLM runoff datasets within the US for each sub-basin.

After these initial steps, a period was chosen for averaging the CLM monthly and annual data. This period should overlap datasets being compared and should include the largest segment of this data. This period was chosen to be 1949-1976 for the following reasons:

1. 6 of CLM's 9 datasets began by 1949.
2. USGS runoff measurements began before 1948 for 97 out of 99 sub-basins.
3. 1976 was chosen as the ending year as all 9 CLM datasets are covered through that year, and 95 out of 99 sub-basins' natural measurement cover that year.
4. For 3 NCC datasets and 3 CAS datasets, data was extracted for the years 1949-1976, and average monthly and annual runoff were computed from this 28-year period.
5. For 3 GOLD datasets, data was extracted for the years 1958-1976, and average monthly and annual runoff were computed from this 19-year period.

Based on this analysis, the 9 CLM datasets were compared to the measured USGS dataset for 99 sub-basins. **Figures 11** and **12** compare average annual sub-basin discharge (taken as the average across all months during period of analysis). The figures show that for most sub-basins, CLM runoff compares favorably to measured data. The figures also show that this is equally true across the 3 types of forcing data (NCC, CAS, and GOLD) and across their 3 resolutions. Similar seasonal results are presented for NCC in the northern hemisphere winter (DJF) and summer (JJA) in **Figure 13**. Similar to the annual results, CLM is able to reproduce the overall aspects of observed inter-basin variations of runoff. Some discrepancies exist in CLM's ability to reproduce observations at sub-basins with the highest JJA runoff rates. Yet these represent a small fraction of the total number of basins (and flow), and the CLM simulation captures the much stronger peak observed in DJF for the basin very well.

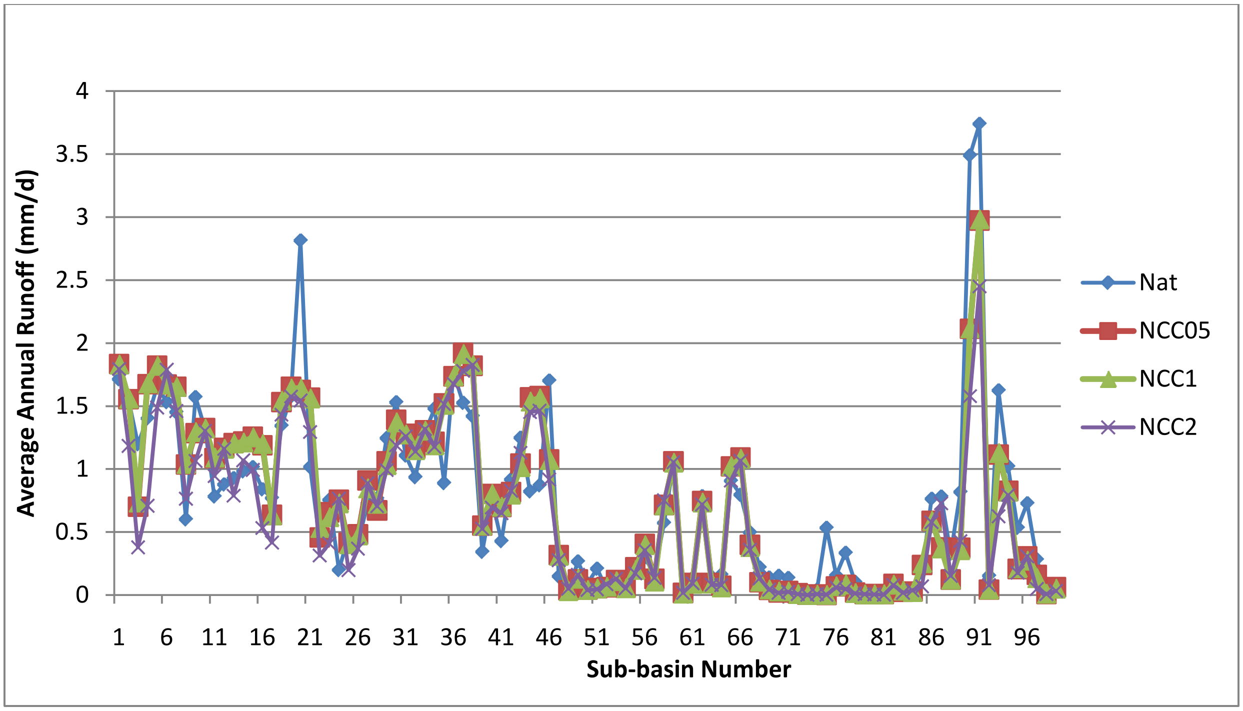

**Figure 11.** Comparison of NCC05, NCC1 and NCC2 to measured Natural Runoff (Nat) for the 99 U.S. sub-basins.

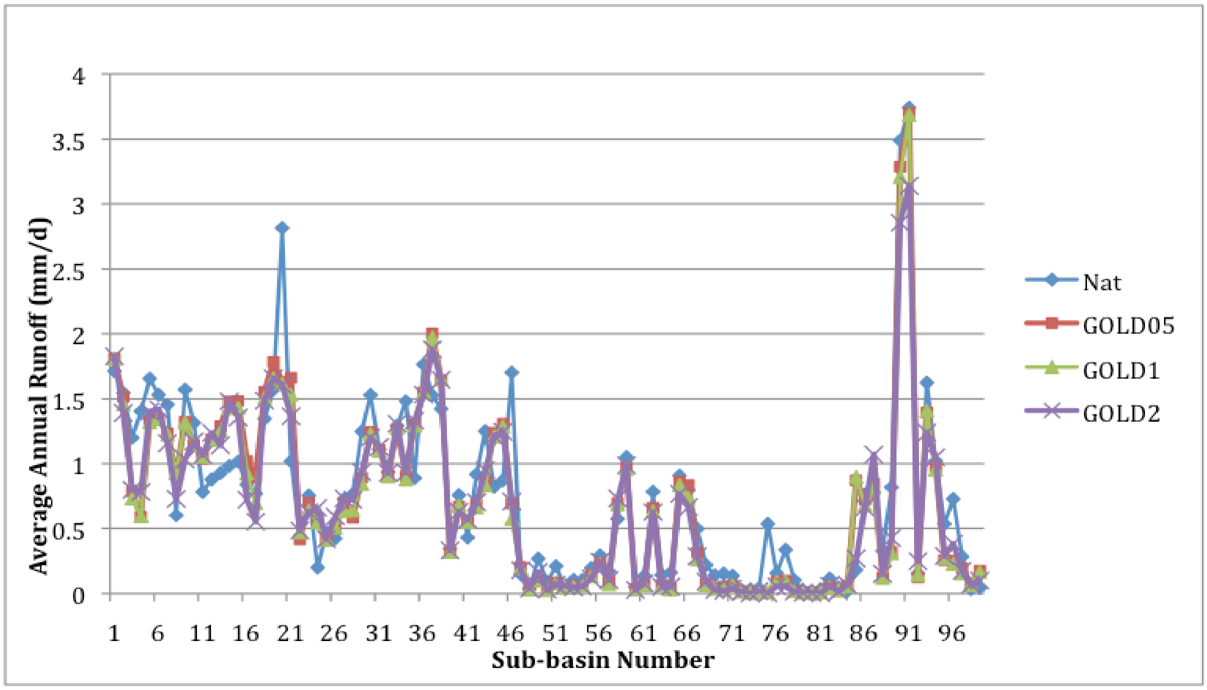

**Figure 12.** Comparison of GODL05, GOLD1 and GOLD2 to measured Natural Runoff (Nat) for the 99 U.S. sub-basins.

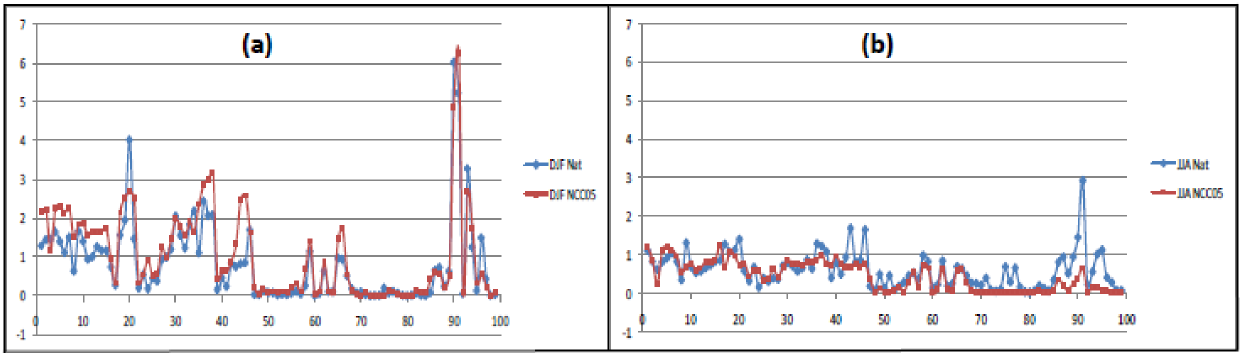

**Figure 13**. Seasonal comparison of NCC05 to measured Natural Runoff for the 99 U.S. sub-basins for (a) DJF and (b) JJA means. Units are in mm/day.

To obtain a more quantitative evaluation of CLM's runoff, a correlation, *R*, between each of the 9 simulations and measured natural runoff (Nat) were computed for each of the 99 basins. The correlation coefficient for each sub-basin, $R_b$, was calculated from the average monthly values of simulated data against its counterpart of measured data. $R_b$ was then averaged across the 99 sub-basins for each of the 9 datasets, to give $R_U$ (a national, unweighted aggregate correlation). Further, the $R_b$ correlation coefficients were weighted by each sub-basin's annual flow and then averaged accordingly across all sub-basins for each of the 9 datasets to give $R_W$ (a national aggregate correlation, weighted by the sub-basin flow). **Table 2** and **Figure 14** summarize the results of this correlation analyses. For Figure 14, the $R_b$ correlation coefficients (obtained from the NCC05 simulation) are color-coded by significance levels (based on 10 degrees of freedom for 12 monthly points); *R* values 0.82 and higher are significant at the 0.0005 level; *R* values starting at .70 are significant at the .005 significance level; *R* values starting at 0.65 correspond to a 0.01 significance level; *R* values starting at 0.57 correspond to the 0.025 significance level; *R* values starting at 0.49 correspond to the 0.05 significance level; and *R* values at 0.39 correspond to the .10 significance level. The remaining shading of sub-basins denotes those that have lower, but positive and negative *R* values.

Across all simulations performed with CLM, the difference between $R_U$ and $R_W$ (Table 2) indicate that the $R_b$ correlations are higher at a majority of basins with higher discharge. This result is further illustrated by Figure 14, showing most of the significant correlations occurring in higher flow basins in the eastern half of the U.S. and west coast basins. The insignificant correlations are, for the most part, confined to the driest sub-basins. The effect of different spatial resolutions and forcing data do not impact this characterization of CLM's performance.

**Table 2.** Unweighted ($R_U$) and weighted ($R_W$) correlation coefficients between simulated and observed runoff, aggregated over the 99 U.S. Basins. Results are shown for each of the CLM simulations performed in this study.

| | CAS05 | CAS1 | CAS2 | GOLD05 | GOLD1 | GOLD2 | NCC05 | NCC1 | NCC2 |
|---|---|---|---|---|---|---|---|---|---|
| $R_U$ | 0.47 | 0.46 | 0.46 | 0.42 | 0.41 | 0.41 | 0.52 | 0.51 | 0.49 |
| $R_W$ | 0.77 | 0.77 | 0.77 | 0.74 | 0.75 | 0.75 | 0.79 | 0.79 | 0.76 |

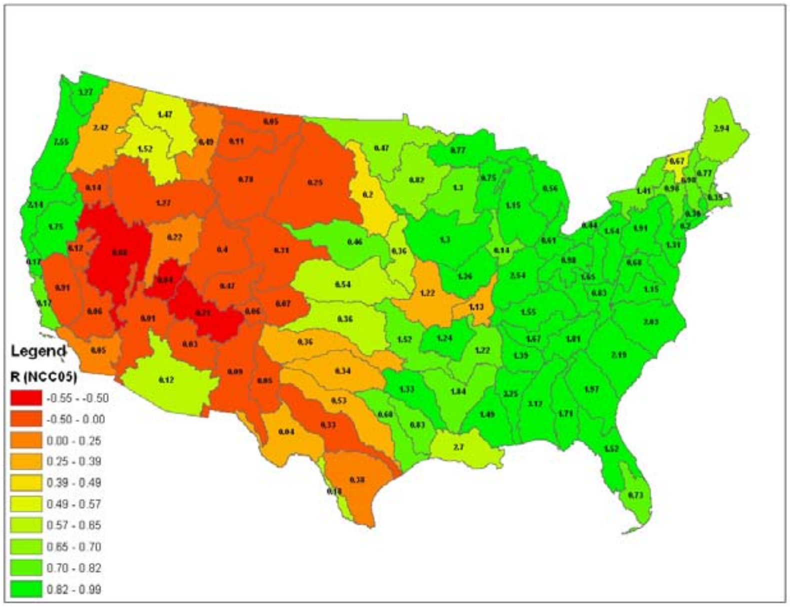

**Figure 14.** NCC05 correlation coefficients of sub-basins. Values on map are percent flow of each sub-basin with respect to total U.S. flow.

### 3.2 Spatial and Temporal Issues In Crop Modeling

The purpose of this exercise is to determine the coarsest resolution at which the outputs of a daily soil-water model of crop yield can be trusted. For the purpose of this exercise the model evaluated was CliCrop, as it will be a main component of WRS. As discussed, climate inputs needed are daily temperature, temperature range, and precipitation.

To review, CliCrop is capable of running at any resolution in which data is available, though run time increases as the resolution becomes finer. For the sake of coupling this detailed crop model to larger models such as the IGSM framework at MIT, it is important to show that the validated results from a half-degree-square resolution are valid when all inputs are aggregated to the level of larger models and frameworks.

In order to validate CliCrop as a multi-scale model, it was run globally for three separate crops at three resolutions. The model was run for grain: Maize, Sorghum and Spring Wheat. It was run at half-degree-square (0.5°x0.5°), one-degree-square (1°x1°) and two-degree-square (2°x2°) resolutions for 10 years. Results were then aggregated to the two-degree-square resolution and compared.

The analysis will demonstrate that, even when all inputs are aggregated to the two-degree-square resolution, the model is able to statistically duplicate the results of finer resolutions.

### ***3.2.1 Methods***

The model was run for Maize, Sorghum and Spring Wheat for half-degree-square, one-degree-square and two-degree-square resolutions. Each run modeled ten years of weather conditions from 1997 through 2006. Additionally, each run was done over the gridded globe at cells reported to contain the given crop.

It is important to identify the gridded inputs into CliCrop along with their native resolutions in order to understand the issues of mosaic aggregation. Inputs include:

- Daily mean, minimum and maximum surface temperature as well as daily precipitation, retrieved from the NASA POWER database with a native resolution of one-degree-square (Stackhouse *et al*., 2010).
- Soil data, available at a native, spatial resolution of five arc-minutes (FAO-UNESCO, 2005).
- Data on planting dates, as provided by SAGE at the University of Wisconsin (Sacks *et al.*, 2010). This data was available regionally. The data, after being gridded, was then extrapolated to cover regions that lacked data.
- The crop locations were provided at a five-minute resolution from IFPRI (You *et al.*, 2006).

CliCrop outputs gridded crop yield factors and irrigation demands. The output grid is the designated input grid.

Once the model was run, the outputs were collected and aggregated to two-degree-square grids by finding the mean result over a given number of cells. For the half-degree-square resolution, 16 cells were averaged to each two-degree-square cell; for one-degree, four cells.

The first and last year of each simulation was dropped to avoid results from partial growing seasons. (This occurs when a planting date is late in the year.)

After this filtering, the remaining results were eight years of yield and irrigation demand in a two-degree-square grid of the globe excluding Antarctica. These results were then subjected to paired t-tests over each year and the averages.

First, a paired t-test was used to compare the eight years in each cell at each resolution. This amounted to a paired t-test of the eight years in each cell, resulting in a rejection or lack thereof in each cell. In a cell where the eight years were not statistically equal a binary 1 was noted for the cell. These zeroes and ones were averaged, giving the fraction of cell in which the eight years were not statistically similar.

Then, the eight years were averaged. These averages were then compared with a paired t-test. The result of this global comparison was a single rejection of the null hypothesis or lack thereof.

### ***3.2.2 Results***

Firstly, the aggregation from finer to coarser grids resulted in significant decreases in run time. **Table 3**, below, details the run time of each run. By aggregating the input data from half-degree to two-degree the run time was reduced by an average of 89.16% compared to the half-degree resolution across the three crops. For the on-degree resolution, run time was reduced by some 69.73%.

**Table 3.** Run times, in minutes, of each crop at each resolution.

| Resolution | 0.5 | 1 | 2 |
|---|---|---|---|
| Maize | 3778.4 | 1107.0 | 490.3 |
| Sorghum | 2277.1 | 697.7 | 222.6 |
| Wheat | 2917.8 | 900.8 | 284.6 |

Note: Maize was actually run on a slightly slower processor.

When maize yields were compared within a cell, year-by-year, the majority of cells showed no statistical difference among all resolution comparisons, as seen in **Table 4**, along with values for sorghum and spring wheat. It is intuitive that the larger the jump from fine to coarse resolution, the higher the fraction of failures. For Maize some 87.22% of two-degree results match the aggregated half-degree results.

**Table 4.** Fraction of cells in which the paired eight years of the given crop yields were not statistically similar.

| Resolution Comparison | 0.5° to 1° | 0.5° to 2° | 1° to 2° |
|---|---|---|---|
| Maize | 0.0260 | 0.1278 | 0.1068 |
| Sorghum | 0.0259 | 0.1544 | 0.1412 |
| Wheat | 0.0168 | 0.1378 | 0.1206 |

**Table 5** displays the p-values of t-tests run on average yields, cell-by-cell. A higher p-value means a stronger relationship. While the p-value for the two-degree to half-degree resolution appears much lower than all others, it remains significant at the 0.05 significance level. In fact, all null-hypotheses could not be rejected in these comparisons.

**Table 5.** p-values of t-Test on average crop yields across the globe.

| Resolution Comparison | 0.5° to 1° | 0.5° to 2° | 1° to 2° |
|---|---|---|---|
| Maize | 0.7966 | 0.0794 | 0.1345 |
| Sorghum | 0.8514 | 0.1929 | 0.2666 |
| Wheat | 0.7185 | 0.0553 | 0.1198 |

Note: A p-value less than 0.05 will reject the null hypothesis of equality.

When averaging over all the crops, only 12.29% of cells, year-by-year, rejected the null hypothesis when one-degree was compared to two-degree. For the one- to half-degree comparison, only 2.29% were rejected and 14% were rejected in the half- to two-degree comparison.

The average p-value across the three crops for the comparison between one-degree and half-degree was about 0.7888, for the comparison between one-degree and two-degree it was 0.1736 and for half-degree to two-degree, 0.1092. All of these values fail to reject the null hypothesis of similarity at a 0.05 significance level.

Results were similar for irrigation demands, as seen in **Tables 6** and **7**. The fraction of rejections across all crops in the year-by-year comparison was 21.63% for one to two, 10.01% for one to half and 23.63% for half to two. The average p-values were 0.1498 for one to two, 0.8530 for one to half and 0.1032 for half to two. Again, all of these tests yield no significant differences.

**Table 6.** Fraction of cells in which the paired eight years of the given crop irrigation demands that were not statistically similar.

| Resolution Comparison | 0.5° to 1° | 0.5° to 2° | 1° to 2° |
|---|---:|---:|---:|
| Maize | 0.1001 | 0.2497 | 0.2165 |
| Sorghum | 0.0976 | 0.2340 | 0.2191 |
| Wheat | 0.1025 | 0.2251 | 0.2132 |

**Table 7.** P-values of t-Test on average crop irrigation demands across the globe.

| Resolution Comparison | 0.5° to 1° | 0.5° to 2° | 1° to 2° |
|---|---:|---:|---:|
| Maize | 0.8672 | 0.0729 | 0.1045 |
| Sorghum | 0.8988 | 0.1195 | 0.1530 |
| Wheat | 0.7931 | 0.1173 | 0.1918 |

Note: A p-value less than 0.05 will reject the null hypothesis of equality.

### *3.2.3 Discussion and Conclusion*

The results demonstrate that accuracy is only marginally degraded when moving from half-degree to two-degree resolutions. Even on a year-by-year basis, the majority of cells yield similar results. This suggests that reduction in run time gained from moving to the two-degree resolution is far worth the degradation of accuracy.

The advantages of the two-degree resolution are more than just efficiency. Many GCMs and MIT's IGSM run at a resolution much closer to two-degree than to half-degree. This ability to run a crop model at a near-native resolution may reduce the uncertainty associated with disaggregating GCM and IGSM outputs.

Further exercises should look at the value of aggregating to irregularly-shaped geographic areas, such as countries or river basins. These results suggest that quasi-quadrilateral regions might be most valuable. These explorations will be continued in future exercises.

## 3.3 Environment and Electric Cooling Demands

### *3.3.1 Energy Demand*

The U.S. National Renewable Energy Laboratory (NREL) is leading a study of renewable electricity futures for the U.S. Department of Energy (DOE.) The Renewable Electricity Futures Study (REFS) has generated a set of scenarios for 80% renewable electricity generation by 2050 (Ref80). NREL has provided MIT with four scenarios of electricity generation for 2050: a baseline and a Ref80 scenario for both Low and High Energy demand. These scenarios are generated using the Regional Energy Deployment System (ReEDS), which forecasts generation capacity and electricity generation for a suite of generating technologies at 134 geographic regions called Power Control Authority (PCA) regions. The technologies represent renewable and non-renewable as well as thermal (requiring cooling water) and non-thermal generation.

### *3.3.2 Results and Implications*

Currently 90% of withdrawals are once through with one-third using saline water. **Figures 15** and **16** provide a summary of the results of the model. The Baseline scenario for low demand suggests a 5 percent decrease in total withdrawals because some (but not a significant amount of) non-thermal generation comes online. In contrast, the high demand Baseline scenario shows a 39% increase in withdrawals since thermal generation capacity must increase to meet the high demand. The Ref80 scenarios show dramatic decreases in water withdrawals from current conditions with a 42% reduction for the low demand scenario and a 23% reduction for the high demand scenario. Figure 16 shows that consumption predominates in the eastern part of the USA. Finally, there is a significant drop in saline coastal withdrawals and consumption as the large coastal nuclear plants are retired.

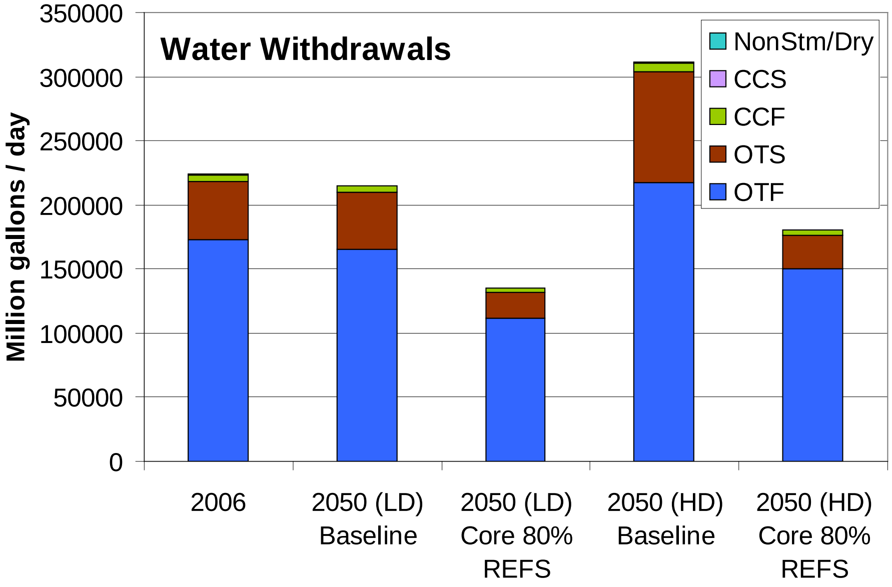

**Figure 15.** Total water withdrawals for base low demand 2006 (BLD2006), base low demand 2050 (BLD2050) and core low demand 2050 (CLD2050).

Under the high demand Baseline scenario, total national water withdrawals would increase by 20%. Given increased competition for water and recent environmental policy on thermal pollution this result seems unfeasible. A dramatic shift from once-through to closed-cycled cooling would be required at a substantial cost. Under the 2050 Ref80 scenarios, for both low and high demand, the water withdrawals and consumptions are reduced from the Baseline by 40% and 46 % respectively. This would suggest an additional positive environmental externality to the high renewal benefit. However, the large increase in non-thermal renewable technology in the arid Southwest may lead to local water conflict hotspots where the demands for process and cleaning water is greater than local water resource or if a concentrated solar plant or geothermal plant plans to run wet rather than dry.

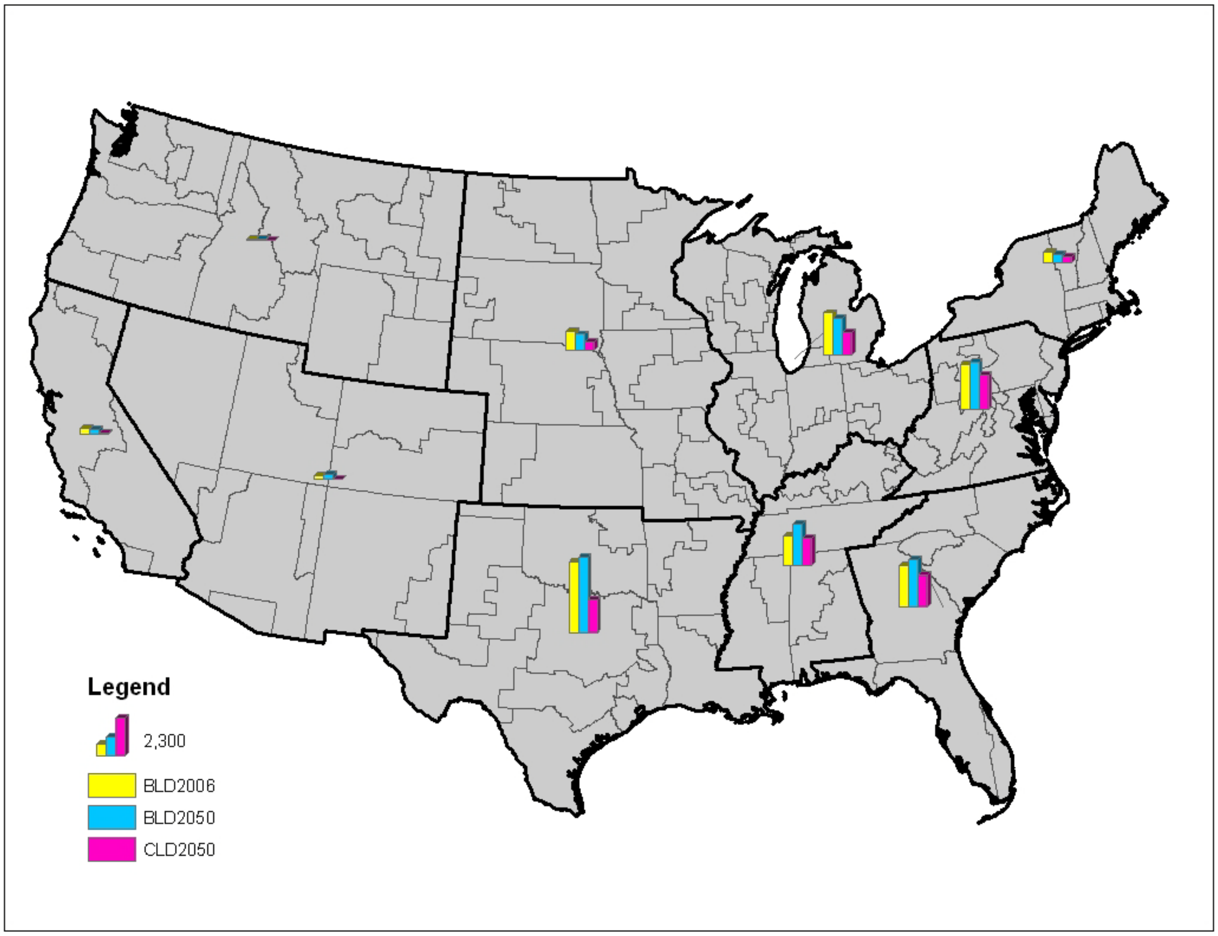

**Figure 16.** Total water consumption for base low demand 2006 (BLD2006), base low demand 2050 (BLD2050) and core low demand 2050 (CLD2050).

## 4. LINKAGE WITH EPPA

EPPA is capable of providing inputs to WRS. EPPA runs for 16 large-scale regions of the globe at a 5-year time step. The outputs of EPPA that are of direct use in WRS are listed in **Table 8.** WRS is driven by estimate of economic, population, technological and capital growth at 5-year increments so there is a perfect temporal fit between EPPA and WRS. However WRS operated at 115 economic regions so that a mapping of EPPA's 16 regions to WRS's 115 was required. Further refinement of this mapping is in progress.

**Table 8.** EPPA to WRS Linkages.

| EPPA Regional Outputs to WRS | WRS Input at FPU level |
|---|---|
| • 5 yearly GDP/cap<br>• 5 yearly Pop<br>• 5 yearly Energy demand<br>• 5 yearly Ag demand | • For Municipal Water Demand<br>o GDP/cap<br>o Pop<br>• For Industrial Water Demand<br>o GDP/cap<br>o Pop<br>• Hydropower<br>o Energy Growth (%)<br>• Crop Growth<br>o Rainfed<br>o Irrigation<br>• Reservoir Volume<br>o Endogenous |

WRS provide inputs to EPPA on the impact of climate change on the assumed economic production of the agricultural and energy sectors. Enhancement under development will provide estimates of flood damage to fixed capital in the public infrastructure capital and private capital. **Table 9** outlines the WRS to EPPA linkages.

**Table 9.** WRS to EPPA Linkages.

| EPPA Inputs from WRS | WRS Outputs to EPPA |
|---|---|
| • 5 year average Water Limited AG production relative to 2000 (ala TEM)<br>• 5 yearly average Hydropower energy production relative to 2000<br>• Capital Costs for Water Investments | • 5 year average Water Limited AG production relative to 2000 (ala TEM)<br>• 5 yearly average Hydropower energy production relative to 2000<br>• Capital Costs for Water Investments |

A great deal of effort has gone into how to model the impacts of year to year variability in agricultural production, especially rain-fed crops at the 5 year time step of EPPA. There is a great difference in farmer welfare of 5 years of 60 percent production as opposed to two years of 100 percent followed by two years of drought with 0 percent production and a fifth year of 100 percent. Both average to 60 percent over the five year, but yet the impact on the farmer and the investment decisions that will be made will be totally different. Temporal aggregation is a major area of the research on the WRS- EPPA linkage.

Spatial aggregation of production is straight forward as crops are modeled at a high level of spatial aggregation to capture soil and climate and water resources heterogeneity and then aggregated to the economic regions. This avoids any non-linear impacts of climate on crop growth.

The trade-off of computing time and appropriate temporal and spatial scales of WRS and EPPA and their linkage with the other components of the IGSM is an on-going area of research.

## 5. NEXT STEPS AND FUTURE RESEARCH

This report has outlined the basic structure, important components and the proposed information flow of the Water Resource System within the Integrated Global System Modeling framework. There are a number of issues that remain related to the spatial and temporal scales of modeling within WRS, including the level of aggregation of agricultural, energy and industrial sectors within the EPPA model to best model impact and adaptations to climate change at a global scale. A list of next steps in the development of an enhanced IGSM-WRS follows.

1. Modeling the water demand for irrigated food crops, paddy rice, pastures, and bio-fuels should be attempted to model water allocation and implication of productions of these sectors to regional water scarcity.
2. As wetlands are one of the most valuable water resources components from a biodiversity and ecosystems services perspective, an explicit wetlands model should be developed to link CLM and WRS.
3. The WRS-IGSM linkage will be vetted for the continental United States at the U.S. Water Resource Council’s 99 Sub-basin Assessment Regions focusing on rain-fed and irrigated agricultural production as well as thermal electric and hydropower production.
4. A multi-temporal and multi-scale flooding model capable of modeling the impacts of flooding on public and private infrastructure should be developed for WRS.
5. The thermal electric cooling water model should be extended to link capital investment decisions on cooling technology and net plant energy output. A model of impacts of cooling intake water and air temperatures on technical performance of plants as well as regulatory impacts on cooling options should be developed.
6. Hydropower and reservoir operation is a key element of the WRS system; continued development of modeling techniques within WRS to improve of accuracy of modeling a collection of individual hydropower plants as a single virtual hydropower plant for each river basin should be undertaken.

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## APPENDIX A: IMPACT COUNTRIES/REGIONS

| | | |
|---|---|---|
| Adriatic | Afghanistan | Algeria |
| Alps | Angola | Argentina |
| Australia | Baltic | Bangladesh |
| Belgium-Luxembourg | Benin | Bhutan |
| Botswana | Brazil | British Isles |
| Burkina-Faso | Burundi | Cameroon |
| Canada | Caribbean-Central | Caucasus |
| Central-African | Central-Europe | Central So.Am |
| Chad | Chile | China |
| Colombia | Congo | Cyprus |
| Djibouti | Ecuador | Egypt |
| Equatorial-Guinea | Eritrea | Ethiopia |
| France | Gabon | Gambia |
| Germany | Ghana | Guinea |
| Guinea-Bissau | Gulf | Iberia |
| India | Indonesia | Iran |
| Iraq | Israel | Italy |
| Ivory Coast | Japan | Jordan |
| Kazakhstan | Kenya | Kyrgyzstan |
| Lebanon | Lesotho | Liberia |
| Libya | Madagascar | Malawi |
| Malaysia | Mali | Mauritania |
| Mexico | Mongolia | Morocco |
| Mozambique | Myanmar | Namibia |
| Nepal | Netherlands | New Zealand |
| Niger | Nigeria | North Korea |
| Northern South- | Pakistan | Papua-New |
| Peru | Philippines | Poland |
| Rest of the World | Russia | Rwanda |
| Scandinavia | Senegal | Sierra Leone |
| Singapore | Somalia | South Africa |
| South Korea | Southeast Asia | Sri Lanka |
| Sudan | Swaziland | Syria |
| Tajikistan | Tanzania | Thailand |
| Togo | Tunisia | Turkey |
| Turkmenistan | Uganda | Ukraine |
| United States | Uruguay | Uzbekistan |
| Vietnam | Zaire(DRC) | Zambia |
| Zimbabwe | | |

# APPENDIX B: IMPACT COMMODITIES

## *Livestock*

- ***Meat***

**1. Beef: beef and veal (Meat of bovine animals, fresh, chilled or frozen, with bone in) and buffalo meat (Fresh, chilled or frozen, with bone in or boneless).**

**2. Pork: pig meat (Meat, with the bone in, of domestic or wild pigs, whether fresh, chilled or frozen).**

**3. Poultry: chicken meat (Fresh, chilled or frozen. May include all types of poultry meat like duck, goose and turkey if national statistics do not report separate data).**

**4. Sheep and goat: (Meat of sheep and lamb, whether fresh, chilled or frozen, with bone in or boneless, and meat of goats and kids, whether fresh, chilled or frozen, with bone in or boneless).**

- ***Other Livestock Products***

**5. Eggs: (Weight in shell).**

**6. Milk: Cow, sheep, goat, buffalo and camel milk (Production data refer to raw milk containing all its constituents. Trade data normally cover milk from any animal, and refer to milk that is not concentrated, pasteurized, sterilized or otherwise preserved, homogenized or peptonized.).**

## *Fish*

**7. Low-value finfish: Carps, barbals and other cyprinids; Herrrings, sardines, anchovies, jacks, mullets, sauries, mackarel, snoeks, cutlassfish; tilapias and other cichlids; river eels, shads; miscellaneous freshwater fishes; miscellaneous diadromous fishes; miscellaneous marine fishes.**

**8. High-value finfish: Cods, hakes, haddocks, flounders, halibut, soles, redfishes, basses, confers, salmon, trout, smelts, shanks, rays, chimaeras, sturgeons, paddlefishes, tunas, bonitos, bullfishes.**

**9. Crustaceans: freshwater crustaceans, horseshoecrabs and other arachnoids; lobsters, spiny rock lobsters; miscellaneous marine crustaceans; sea-spiders, crabs, shrimp, prawns, squat-lobsters.**

**10. Mollusks: Abalones, winkles, conchs, clams, cockles, arkshells, freshwater mollusks, mussles, oysters, scallps, pectens, squids, cuttlefishes, octopuses, miscellaneous marine mollusks.**

**11. Fish meal and Fish Oil**

## *Crops*

- ***Grains***

**12. Maize: (Used largely for animal feed and commercial starch production).**

**13. Sorghum: (A cereal that has both food and feed uses).**

**14. Millet: (Used locally, both as a food and as a livestock feed).**

**15. Other coarse grains: barley (Varieties include with husk and without. Used as a livestock feed, for malt and for preparing foods.), oats (Used primarily in breakfast foods. Makes excellent fodder for horses.), rye (Mainly used in making bread, whisky and beer. When fed to livestock, it is generally mixed with other grains).**

**16. Rice: Rice milled equivalent (White rice milled from locally grown paddy. Includes semi-milled, whole-milled and parboiled rice).**

**17. Wheat: (Used mainly for human food).**

- ***Roots and Tubers***

**18. Cassava et al.: Cassava and other tubers, roots or rhizomes. (Cassava is the staple food in many tropical countries. It is not traded internationally in its fresh state because tubers deteriorate very rapidly).**

**19. Potatoes: (Mainly used for human food).**

**20. Sweet potatoes and yams: Sweet potatoes (Used mainly for human food. Trade data cover fresh and dried tubers, whether or not sliced or in the form or pellets) and yams (A starchy staple foodstuff, normally eaten as a vegetable, boiled, baked or fried).**

- ***Vegetables***

**21. Onions, Tomatoes, miscellaneous vegetables**

- . ***Fruits***

**22. Temperate Fruits: Apples, grapes and miscellaneous temperate fruits.**

**23. Tropical and Sub-tropical Fruits: Bananas, Canteloupes & other melons, citrus fruits, dates, grapefruit, lemons, limes, oranges, pineapples, plantains, watermelons, miscellaneous tropical fruits.**

- ***Dryland Pulses***

**24. Chickpeas.**

**25. Pigeonpeas.**

## *Other*

**27. Meals: copra cake, cottonseed cake, groundnut cake, other oilseed cakes, palm kernel cake, rape and mustard seed cake, sesame seed cake, soybean cake, sunflower seed cake, meat and blood meal (Residue from oil extraction, mainly used for feed).**

**28. Oils: vegetable oils and products, animal fats and products (Obtained by pressure or solvent extraction. Used mainly for food).**

**29. Soybeans: The most important oil crop (oil of soybeans under oils), but also widely consumed as a bean and in the form of various derived products because of its high protein content, *e.g.* soya milk, meat, *etc.*.**

**30. Groundnuts**

**31. Cotton**

## APPENDIX C: DEFINITIONS OF WATER BASINS

| | | |
|---|---|---|
| **Amazon** | **Amudarja** | **Amur** |
| **Arabian Peninsula** | **Arkansas** | **Baltic** |
| **Black Sea** | **Borneo** | **Brahmaputra** |
| **Brahmari** | **Britain** | **California** |
| **Canada-Arctic-Atlantic** | **Caribbean** | **Cauvery** |
| **Central African West Coast** | **Central America** | **Central Australia** |
| **Central Canada Slave Basin** | **Chang Jiang** | **Chotanagpul** |
| **Colorado** | **Columbia** | **Columbia Ecuador** |
| **Congo** | **Cuba** | **Danube** |
| **Dnieper** | **East African Coast** | **Eastern Ghats** |
| **Eastern Australia Tasmania** | **Eastern Mediterranean** | **Elbe** |
| **Ganges** | **Godavari** | **Great Basin** |
| **Great Lakes** | **Hai He** | **Horn of Africa** |
| **Hua He** | **Huang He** | **Iberia East Mediterranean** |
| **Iberia West Atlantic** | **India East Coast** | **Indonesia East** |
| **Indonesia West** | **Indus** | **Ireland** |
| **Italy** | **Japan** | **Kalahari** |
| **Krishna** | **Lake Balkhash** | **Lake Chad Basin** |
| **Langcang Jiang** | **Limpopo** | **Loire-Bourdeaux** |
| **Lower Mongolia** | **Luni** | **Madagascar** |
| **Mahi Tapti** | **Mekong** | **Middle Mexico** |
| **Mississippi** | **Missouri** | **Murray Australia** |
| **New Zealand** | **Niger** | **Nile** |
| **North African Coast** | **North Euro Russia** | **North Korea Peninsula** |
| **North South America** | **Northeast Brazil** | **Northwest Africa** |
| **Northwest South America** | **Ob** | **Oder** |
| **Ohio** | **Orange** | **Orinoco** |
| **Papua Oceania** | **Parana** | **Peru Coastal** |
| **Philippines** | **Red-Winnipeg** | **Rhine** |
| **Rhone** | **Rio Colorado** | **Rio Grande** |
| **Rest-of-World (ROW)** | **Sahara** | **Sahyada** |
| **Salada Tierra** | **San Francisco** | **Scandinavia** |
| **SE Asia Coast** | **Seine** | **Senegal** |
| **Songhua** | **South African Coast** | **South Korean Peninsula** |
| **Southeast African Coast** | **Southeast US** | **Sri Lanka** |
| **Syrdarja** | **Thai-Myan-Malay** | **Tierra** |
| **Tigris-Euphrates** | **Toc** | **Upper Mexico** |
| **Upper Mongolia** | **Ural** | **Uruguay** |
| **US Northeast** | **Volga** | **Volta** |
| **West African Coastal** | **Western Asia-Iran** | **Western Australia** |
| **Western Gulf Mexico** | **Yenisey** | **Yili He** |
| **Yucatan** | **Zambezi** | **Zhu Jian** |

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