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The Issue of Spatial Scale in Hydro-Economic Modeling of Global and National Food and Water Systems to Address Sustainable Agriculture and Natural Resources Management

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THE ISSUE OF SPATIAL SCALE IN HYDRO-ECONOMIC MODELING OF GLOBAL AND NATIONAL FOOD AND WATER SYSTEMS TO ADDRESS SUSTAINABLE AGRICULTURE AND NATURAL RESOURCES MANAGEMENT

There are numerous models available that aim to address food and water policy at different spatial scales. The question to be asked of these models is “What is the importance of spatial scale on hydro-economic modeling used to address environmental and hunger policy questions?”

The International Food Policy Research Institute’s (IFPRI) IMPACT-Water model was evaluated at 2 different spatial scales (69 basins vs 281 basins) and the results from each version were compared to evaluate the importance of spatial scale on environment and hunger policies. Most indicators and results such as those related to hunger require comparison at the local/regional scale. In order to provide a detailed analysis comparing the results between the two different spatial scales of IMPACT-Water, three case studies at the regional scale were chosen to represent different hydro-climates and economic heterogeneity: Central Asia, Europe, Southern Sub-Saharan Africa. Results from this analysis imply that spatial scale does have an impact on model results used to inform environment and hunger policy. Impacts are stronger in regions of economic and hydro-climate heterogeneity.

To evaluate yet another, more detailed spatial scale issue, the second part of the research focuses on evaluating the importance of spatial scale and management on river basin modeling for global food production. Four case studies were evaluated (Missouri River Basin, Senegal River Basin, Yellow River Basin, Volta River Basin) in addition to performing the analysis at 2 different global river basin representations; one with 69 basins and another with 126 basins. In general, one risks the possibility of overestimating available water in basin representations where rivers are in parallel. If this occurs in areas where irrigated agriculture is a significant contributor to the global irrigated production, one may be greatly overestimating the potential of global irrigated agriculture. There is little to no impact on basin representation where the main river is in series. While spatial representation may not be an issue, modeling the correct management may be. Global modelers must use caution in aggregating basin representations. One must determine the layout of each basin representation and the corresponding level of management to aid them in completing a useful and representative analysis.

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CHAPTER 1

INTRODUCTION

There are numerous models available that aim to address food and water policy at different spatial scales. The question to be asked of these models is "What is the importance of spatial scale on hydro-economic modeling used to address environmental and hunger policy questions?" The research set forth in this document aims to answer not only that question but also take it to another level and evaluate the importance of spatial scale and management on river basin modeling for global food production.

The first part of this research is provided in chapter 2 and evaluates the importance of spatial scale in hydro-economic modeling of global and national food and water systems to address environmental and hunger policy questions. Background to this research includes the driving force behind this research, a review of the existing models for policy, and a summary of available global water and food models.

The International Food Policy Research Institute's (IFPRI) IMPACT-Water model was evaluated at 2 different spatial scales (69 basins vs 281 basins) and the results from each version were compared to evaluate the importance of spatial scale on environment and hunger policies. Most indicators and results such as those related to hunger require comparison at the local/regional scale. In order to provide a detailed analysis comparing the results between the two different spatial scales of IMPACT-Water, three case studies at the regional scale were chosen to represent different hydro-climates and economic heterogeneity: Central Asia, Europe, Southern Sub-Saharan Africa.

The second part of this research is presented in chapter 4 and focuses on evaluating the importance of spatial scale and management on river basin modeling for global food production. Background to this research includes previous studies on scale, examples of global river basin modeling, and basin characteristics used to assess the importance of a basin representation's spatial scale. Case studies for this analysis include a theoretical analysis on the sequence of supply, storage and demands along a river, and four river basin case studies (Missouri River Basin, Senegal River Basin, Yellow River Basin, Volta River Basin).

Findings from these case studies were applied to 2 different global river basin representations; one with 69 basins and another with 126 basins and conclusions were made about the importance of spatial scale and management on river basin modeling for global food production.

Conclusions from both parts of this research are presented in chapter 5 and can be summarized by the following key findings:

- Spatial scale does have an impact on model results used to inform environment and hunger policy.
- Impacts are stronger in regions of economic and hydro-climate heterogeneity.
- One risks the possibility of overestimating available water in basin representations where rivers are in parallel which could lead to overestimating the potential of global irrigated agriculture.
- Properly representing the sequence of supply, storage, and demand is very important.
- Recognizing the level of a basin’s infrastructure is important.
- Modeling the correct management may be a significant issue if a basin is heavily managed.

CHAPTER 2

ISSUE OF SPATIAL SCALE IN HYDRO-ECONOMIC MODELING OF GLOBAL AND NATIONAL FOOD AND WATER SYSTEMS

Background

Driving Force Behind Research

> *"In a world where 75 percent of poor people depend on agriculture to survive, poverty cannot be reduced without investment in agriculture. Many of the countries with the strongest agricultural sectors have a record of sustained investment in agricultural science and technology. The evidence is clear, research for development generates agricultural growth and reduces poverty."*
>
> CGIAR 2005

This statement by the Consultative Group on International Agricultural Research (CGIAR) is a driving force behind the research presented hereafter. The CGIAR is a strategic alliance of countries, international and regional organizations, and private foundations supporting 15 international agricultural Centers that work with national agricultural research systems and civil society organizations including the private sector. Their mission is "To achieve sustainable food security and reduce poverty in developing countries through scientific research and research-related activities in the fields of agriculture, forestry, fisheries, policy, and environment."

The science that made possible the Green Revolution of the 1960's and 1970's was largely the work of CGIAR Centers and their national agricultural research partners. The scientists' work not only increased incomes for small farmers, it enabled the preservation of millions of hectares of forest and grasslands, conserving biodiversity and reducing carbon releases into the atmosphere. This alone installs great respect, accreditation and admiration upon the CGIAR.

In November of 2002, the CGIAR created the Challenge Program for Water and Food (CPWF).

> *"One of the greatest challenges of our time is to provide food and environmental security. A vital step towards reaching this goal is to increase the productivity of water used for agriculture, leaving more water for other users and the environment - getting more crop per drop. The CGIAR Challenge Program on Water and Food approaches this challenge from a research perspective."*
>
> CGIAR CPWF – 2005

The CGIAR states that this program will create research based knowledge and methods for growing more food with less water, and develop a transparent framework for setting targets and monitoring progress. The CPWF has created five interrelated research themes to support this goal and the research set forth in this document will draw heavily on theme 5:

1. Crop Water Productivity Improvement
2. Water and People in Catchments
3. Aquatic Ecosystems and Fisheries
4. Integrated Basin Water Management Systems
5. **Global & National Food And Water Systems**

Theme 5's goal is as follows:

> "To undertake research to improve basic and applied knowledge on how policies, institutions, and processes of change in the global and national food and water system affect food security, livelihoods, health, and the environment and to engage in action research, outreach and capacity building at the individual and institution level to facilitate better policy and implementation of necessary changes. " (CPWF 2005)

There are six research questions proposed under Theme 5:

1. How can globalization and trade liberalization be managed to best enhance environmental policy and the management of water quality and water-related ecosystems?
2. What proportion and types of investment should be made in water development versus agricultural research, education, health and nutrition?
3. How much money should be invested in dams, taking into account future water needs as well as the financial, social and environmental costs of dam building?
4. How can broader goals, including agricultural development, rural livelihoods, food security, water quality, and health and nutrition, best be integrated into international river basin agreements?
5. How will changes in global water cycles affect food production and change the ways in which the poor, women and disadvantaged groups access ecosystem services?
6. How can global and national policies and institutions prevent or mitigate the negative impacts of changes in global water cycles on water and food security and on the livelihoods of the poor, women and the socially excluded?

In order to give insight into these research questions, one can use models at the global and national scale. Previously, most of the agricultural models for policy one would look to were solely economically focused. Some scientists then realized that the hydro-climatic component could have great influence on the agricultural processes (e.g. drought years, competition from other non-ag water demands, etc.) they were modeling. Now, there are a few agricultural models for policy that have added water to their components.

Besides the difference of some models having a hydro-climate component, another main difference among these models is the spatial scale at which they are preformed. For example, some of the models represent the globe with 10 regions, other models use a country level representation, and others use a spatial scale somewhere in between. The question then becomes "What is the importance of spatial scale on hydro-economic modeling used to address environmental and hunger policy questions?" This is the question that the following research aims to answer.

Existing Models for Policy

There are a number of models that have been created to address agricultural among other policies. The following models look at food/agriculture alone:

- Basic Link System (BLS) – (Fischer et. al. 1988)
- World Food Model (WFM) – (FAO 2003)
- Global Trade and Environment Model (GTEM) – (Tulpule et. al. 2000)
- Food and Agricultural Policy Research Institute (FAPRI) Series of Models – (FAPRI 2005)
- Partial Equilibrium Agricultural Trade Model (PEATSim) – (Stout and Abler 2005)
- Grains, Livestock and Sugar (GLS) – (Tyers and Anderson 1988)
- International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) – (Rosegrant et. al. 2002)

The Basic Linked System (BLS) was produced by the International Institute for Applied Systems Analysis (IIASA). It consists of a set of linked national agricultural sector models. The BLS is comprised of 16 national (including European Union) models with a common structure, 4 models with country-specific structure and 14 regional group models. The 20 models in the first two groups cover approximately 80 percent of the world agricultural production; the remaining 20% is covered by the 14 regional models for countries with broadly similar attributes (for example African oil-exporting countries or Latin American high-income exporting countries.) The BLS is a general equilibrium model system, with representation of all economic sectors, empirically estimated parameters and no unaccounted supply sources or demand sinks. Countries are linked through trade, world market prices and financial flows.

The World Food Model (WFM) is produced by the Food and Agriculture Organization (FAO). The WFM system is a non-spatial, recursive-dynamic, synthetic, multi-regional, multi-product partial-equilibrium world trade model for basic food products. It provides a framework to forecast supply, demand and net trade for approximately 150 countries and 13 commodities. The WFM covers tariffs, export quotas and Producer and Consumer Subsidy Equivalents as policy instruments.

The Global Trade and Environment Model (GTEM) is produced by the Australian Bureau of Agricultural and Resource Economics (ABARE). GTEM is a computable general equilibrium model of the global economy and environment to address policy issues with long term global dimensions. It is derived from the Global Trade Analysis Project (GTAP) model. GTEM captures the impact of policy changes on large numbers economic variables in all sectors of the economy. A commonly used version of the database divides the world into 23 regions where 19 goods are produced. Each good is produced by a single industry. Other aggregations are possible and the model as such is not specific to any level of aggregation (although current dataset is limited to GTAP’s 66 regions and 62 sectors of the world economy.)

The Food and Agricultural Policy Research Institute (FAPRI) has produced the following set of food models:

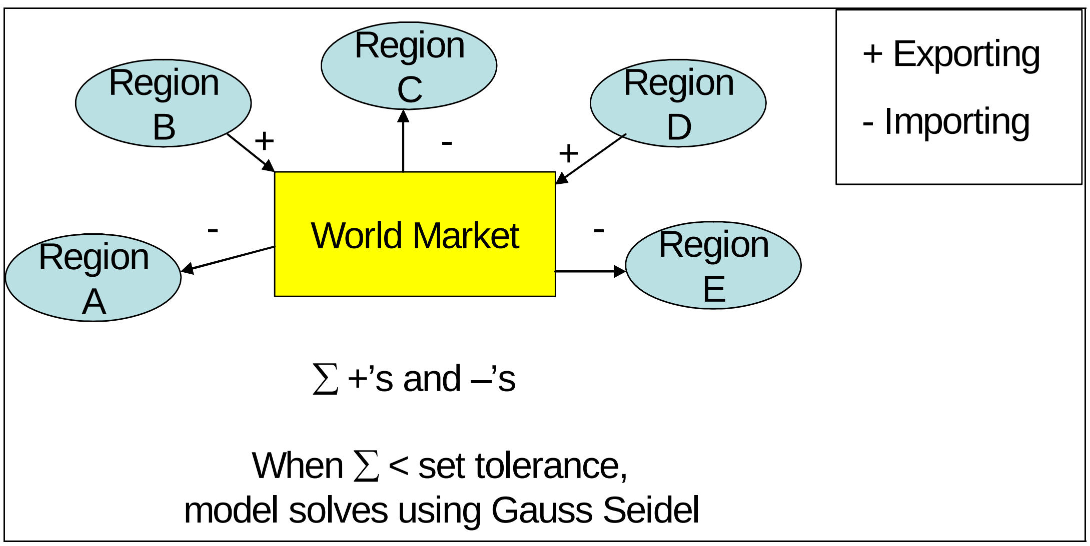
- Crop Insurance Model
- International Dairy Model
- International Grains Model
- International Livestock Model
- International Oilseeds Model
- International Sugar Model

The models project the area, production, usage, stocks, prices, and trade for associated commodities for several countries and regions of the world. Depending upon the model and commodity being evaluated, at most approximately 35 regions of the world are represented.

The Partial Equilibrium Agricultural Trade Model (PEATSim) is produced by the Penn State Department of Agricultural Economics and Rural Sociology. The PEATSim model is an applied partial equilibrium, multi-commodity (35), multiple-region (12) model of agricultural policy and trade. It is a non-spatial model, meaning that is does not distinguish a region's imports by their source or a region's exports by their destination. It is a gross trade model that accounts for exports and imports of each commodity in every region.

The Grains, Livestock and Sugar (GLS) model was developed by Tyers and Anderson in 1988. It includes seven commodity groups and 30 countries/regions. It uses a dynamic structure allowing it to forecast short and long-run effects of policy intervention.

Figure 1 IMPACT model solves when sum of net trade is less than set tolerance



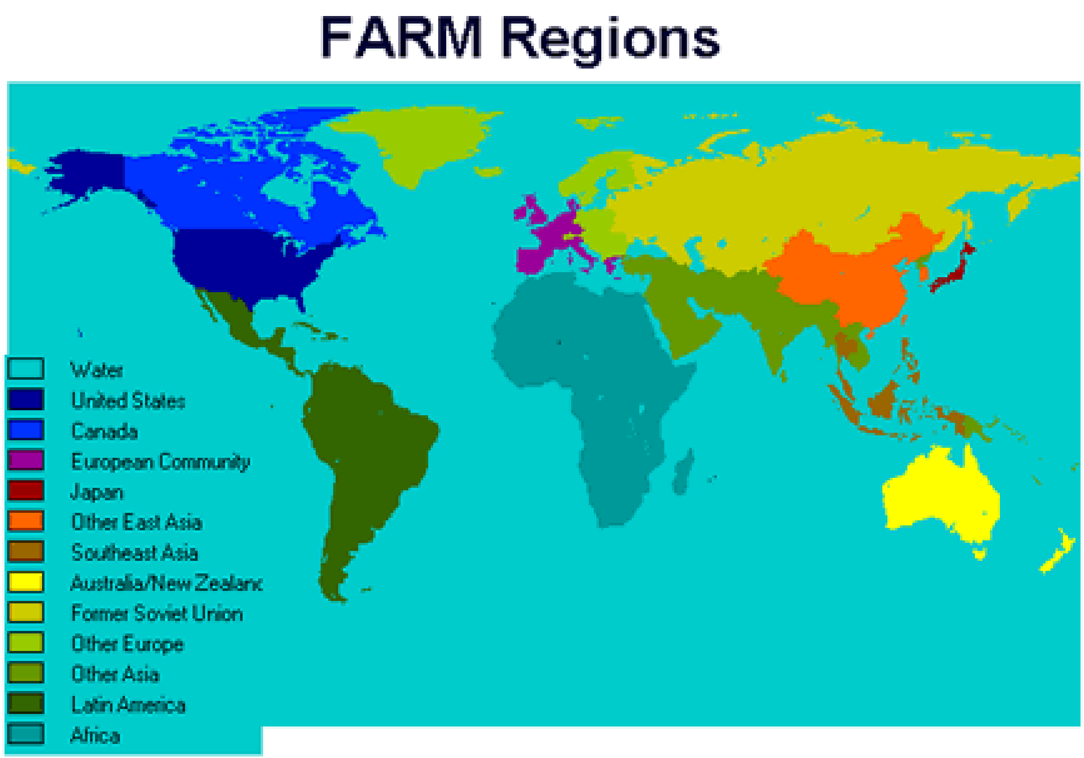
The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) is produced by the International Food Policy Research Institute (IFPRI). This model represents a competitive world agricultural market for crops and livestock. It uses a scale of 36 regions and 69 basins with 17 commodities. IMPACT is specified as a set of country or regional sub-models, within each of which supply, demand and prices for agricultural commodities are determined. These sub-models are linked through trade, a specification that highlights the interdependence of countries and commodities in the global agricultural markets. The model solves when the sum of net trade is less than a set tolerance (e.g. tolerance = 0.01) (Figure 1.) IMPACT uses a system of supply and demand elasticities incorporated into a series of linear and non-linear equations, to approximate the underlying production and demand functions. World agricultural commodity prices are determined annually at levels that clear international markets. Demand is a function of prices, income and population growth. Growth in crop production in each country is determined by crop prices and the rate of productivity growth.

The next set of models also includes water or hydro-climate components:

- Policy Dialogue Model (Podium) – (IWMI 2000)
- Future Agricultural Resources Model (FARM) – (Darwin et. al. 1995)
- Polestar – (Raskin et. al. 1998)
- IMPACT-Water (Rosegrant et. al. 2002b)

The Policy Dialogue Model (Podium) is produced by the International Water Management Institute (IWMI). This is a water and food security planning model. It has a very simple hydrologic component. Podium is applied at the country level scale and focuses on cereal crops. The model maps the complex relationships between the numerous factors that affect water and food security.

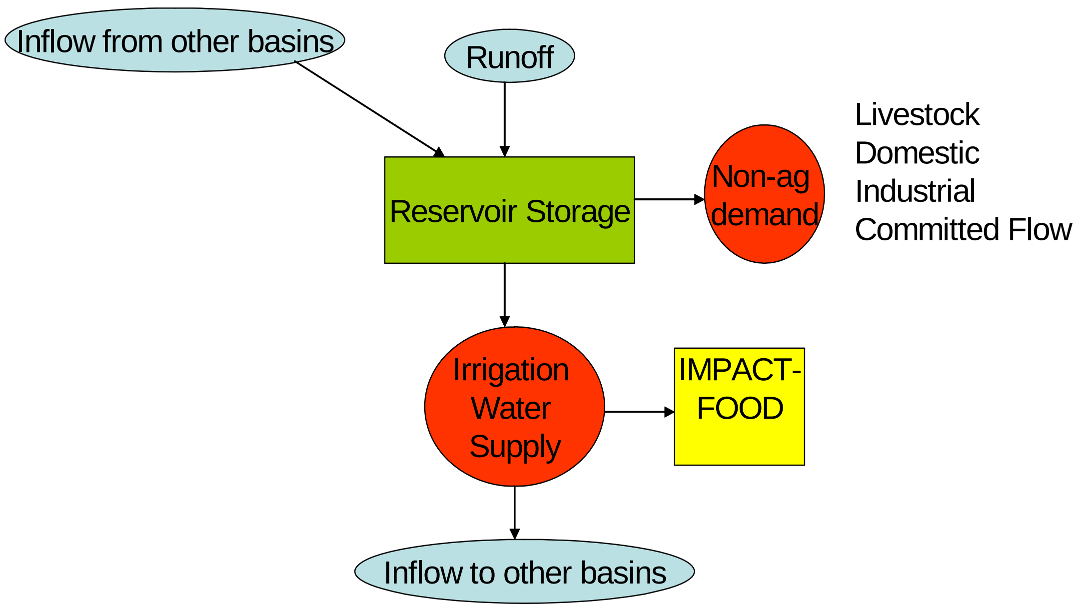
Figure 2 Farm Model Regions



The Future Agricultural Resources Model (FARM) was developed by the Economic Research Service. FARM estimates the agricultural effects of global changes in climate and other atmospheric conditions. As with the Podium model, the FARM model has simplistic water resources (runoff, water use, etc.). FARM uses 12 global regions (Figure 2) and 6 land classes. Analogous region models, which relay on the concept that similar climates mean similar production practices, implicitly capture changes in crop or livestock outputs, production inputs, or management practices that farmers are likely to adopt under new climatic conditions.

The PoleStar model is produced by the Stockholm Environment Institute. It is used for sustainability studies and covers social, economic, and environmental issues. The PoleStar system is applicable at national, regional, and global scales. One can customize data structures, time horizons, and spatial boundaries – all of which can be changed in the course of an analysis. To help one construct new applications, PoleStar comes with an initial framework, the Basic Structure, which for many applications will probably be sufficient to meet the needs of your study. The Basic Structure uses 10 global regions and 8 commodities.

Figure 3 Simplified River Basin Balance



The IMPACT-Water model, produced by IFPRI, adds a water component to the previously mentioned IMPACT model (Figure 3). The water component of the model determines the available water supply for irrigation (based on irrigation demand and available water supply) which it passes to the food component of the model. The food component then has a water extension where it determines if due to a lack of available water for irrigation crop yields and areas need to be reduced.

The food component of IMPACT-Water represents a competitive world agricultural market for crops and livestock (as previously described in the IMPACT model description.) The water component of IMPACT-Water performs a simplified river basin balance by taking into account, storage, groundwater, and inter-basin transfers (Figure 3). The river basin balance is performed monthly for a year at a time. The water demands evaluated include irrigation, livestock, domestic, industrial, and committed flow for environmental, ecological, and navigational uses. The water component derives water supply for each demand site. The water component first fills non-irrigation demands and then the irrigation demand so there is no competition among non-irrigation demand sectors.

Once the non-irrigation demands are met, the water component determines the available water supply for irrigation by calculating the irrigation demand (using evapotranspiration, ‘crop per drop' factor – kc, and effective precipitation) and also calculating the available water supply once other non-irrigation demands have been met. The available water supply for irrigation will never be more than the irrigation demand but may be less if there is a water shortage.

This available water supply for irrigation determined in the water component is then passed to the food component of IMPACT-Water. Crop demand and production is initially determined in the food component as mentioned in the IMPACT model description with the addition of a water extension. The water extension in the food component determines if due to a lack of available water for irrigation crop yields and areas need to be reduced thus impacting prices, production, etc.

One of the draw backs in IMPACT-Water is that the available water supply for irrigation is set by the water component for each crop and region regardless of prices and cannot be redistributed to other, possibly higher value crops, if needed in the food component. (This will be addressed in the next version of IMPACT-Water.)

IMPACT-Water has recently been updated to a 2000 base year from a previous 1995 base year. It projects water demand and supply for 25 years from 2000-2025. IMPACT-Water reports on crop areas, production, prices, demand, etc.

Summary of Global Water and Food Models

Global food, and water and food models have a major role in helping to inform international food policies. In addition to the different capabilities of the models previously listed, one of the main issues among the different models is their varying spatial scales (see Tables 1 and 2, pages 10 and 11). Not one of these model developers have evaluated the impact spatial scale has on their model's results. The question is whether spatial scale has an impact on the recommendations these models are providing to inform policy makers.

To answer this probing question, one can perform a spatial scale analysis on one of the models currently being used to inform policy. The IMPACT-Water model was chosen for this analysis because the authors of this paper believe that it has done a very good job at addressing both the economics and water resources affecting global food policy. To evaluate the affects of spatial scale on global water and food model policy recommendations, the IMPACT-Water model was evaluated at 2 different spatial scales and the results from each version were compared.

Table 1 Summary of Global Food Models

Model Name	Produced By	Spatial Detail	Summary
Basic Link System (BLS)	International Institute for Applied Systems Analysis (Fischer et. al. 1988)	34 Regions	The BLS is a general equilibrium model system, with representation of all economic sectors, empirically estimated parameters and no unaccounted supply sources or demand sinks. Countries are linked through trade, world market prices and financial flows.
World Food Model (WFM)	Food and Agriculture Organization (FAO 2003)	150 Countries, 13 Products	System is a non-spatial, recursive-dynamic, synthetic, multi-regional, multi-product partial-equilibrium world trade model for basic food products.
Global Trade and Environment Model (GTEM)	Australian Bureau of Agricultural and Resource Economics (Tulpule et. al. 2000)	66 Regions, 62 World Economy Sectors	GTEM captures the impact of policy changes on large numbers of economic variables in all sectors of the economy including gross domestic product, prices, consumption, production, trade, investment, efficiency, competitiveness and greenhouse gas emissions.
Food and Agricultural Policy Research Institute (FAPRI) Series of Models	FAPRI (FAPRI 2005)	35 Countries, 5 Commodities	Models project the area, production, usage, stocks, prices, and trade for associated commodities for several countries and regions of the world.
Partial Equilibrium Agricultural Trade Model (PEATSim)	Penn State Department of Agricultural Economics & Rural Sociology (Stout and Abler 2004)	12 Countries/ Regions, 35 Commodities	The PEATSim model is an applied partial equilibrium, multiple-commodity, multiple region model of agricultural policy and trade.
Grains, Livestock, Sugar Model (GLS)	Tyers and Anderson (Tyers and Anderson 1988)	30 Countries/ Regions, 7 commodities	Uses a dynamic structure allowing it to forecast short and long-run effects of policy intervention.
International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT)	International Food and Policy Research Institute (Rosegrant et. al. 2002)	69 Global Regions	Is a representation of a competitive world agricultural market for crops and livestock. The country and regional agricultural sub-models are linked through trade, a specification that highlights the inter-dependence of countries and commodities in the global agricultural markets.

Table 2 Summary of Global Food Models Continued

Model Name	Produced By	Spatial Detail	Summary
Podium	International Water Management Institute (IWMI 2000)	Country Level	The model maps the complex relationships between the numerous factors that affect water and food security
Future Agricultural Resources Model (FARM)	The Economic Research Service (Darwin et. al 1995)	12 Regions, 6 land classes	Estimates the agricultural effects of global changes in climate and other atmospheric conditions.
PoleStar	Stockholm Environment Institute (Raskin et. al. 1998)	10 Global Regions	An adaptable accounting system designed to assist the analyst engaged in sustainability studies
Impact-Water	International Food and Policy Research Institute (Rosegrant et. al. 2002b)	69 Global Regions	Incorporates water availability as a stochastic variable with observable probability distributions to examine the impact of water availability on food supply, demand, and prices.

IMPACT-Water Two Scales

The IMPACT-Water model's original spatial scale consists of 36 regions and 69 basins (Figure 4, next page). This spatial scale was disaggregated into 115 regions and 281 basins using the process described below (Figure 5, next page).

First, the physical boundaries of the regions and basins were disaggregated using GIS software and expert judgment. The original 69 basins were disaggregated into 281 Food Producing Units (FPU's) where the goal was to try and create basins containing similar economic status while holding true to hydrologic boundaries (e.g. do not combine non-adjacent countries as was done with the original spatial scale).

A collaborative effort between the University of Colorado, International Food Policy Research Institute, and International Water Management Institute provided the necessary data for the new disaggregated scale. The data was provided for a base year of 2000 either from new data sources or in cases where disaggregated data was not available; it was mapped from the original data in the 36 region model version.

The data in the disaggregated model version (FPU version) was then aggregated back to the 36 region model version using one of the techniques below depending on the parameter:

- Mapping
- Summing
- Averaging (direct or weighted averaging)

By starting with the data in the FPU model version and aggregating up to the 36 version, the integrity of consistent data between the two model versions was upheld.

Figure 4 IMPACT-Water 36 Regions, 69 Basins

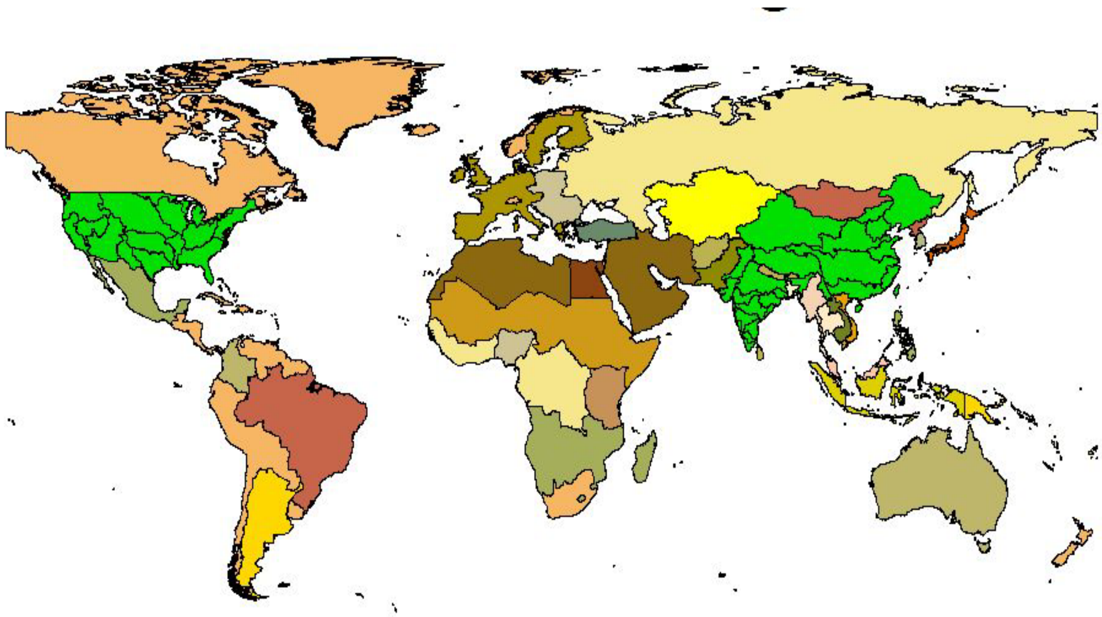
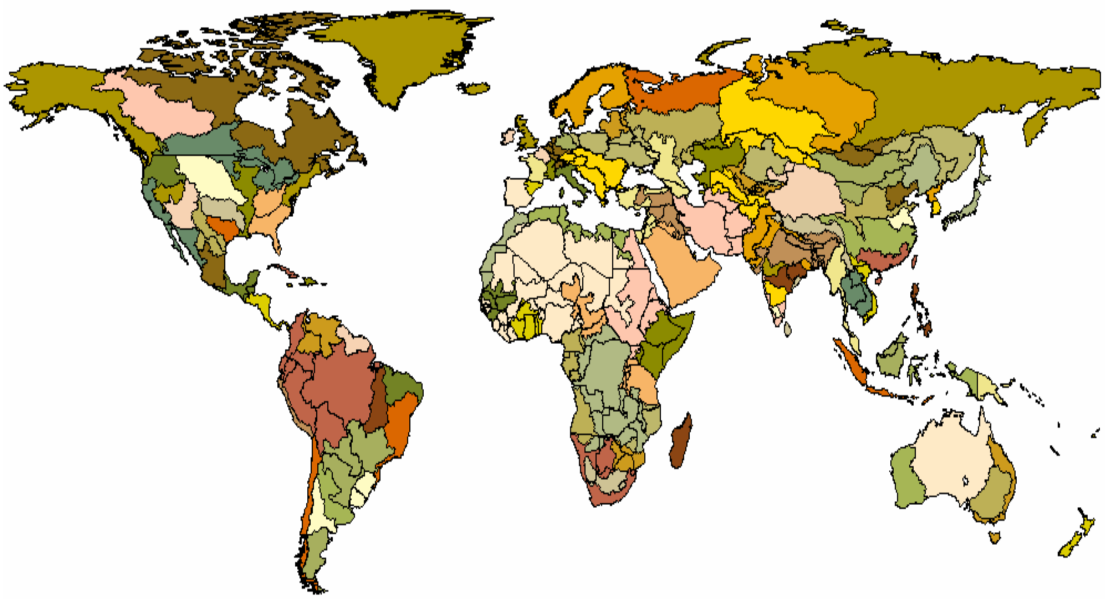


Figure 5 IMPACT-Water 115 Regions, 281 Basins



Comparing Results Between IMPACT-Water 36 Region Scale and FPU Scale

There are a number of results produced by the IMPACT-Water model. The results are useful for informing food policy, considered food policy indicators. Differences among food policy indicators can be explained by economics, hydro-climatology, or a combination of the two. These food policy indicators described below will be compared between the two different scale analyses of the IMPACT-Water model and the hydro-climatology results will help to explain the differences among these indicators.

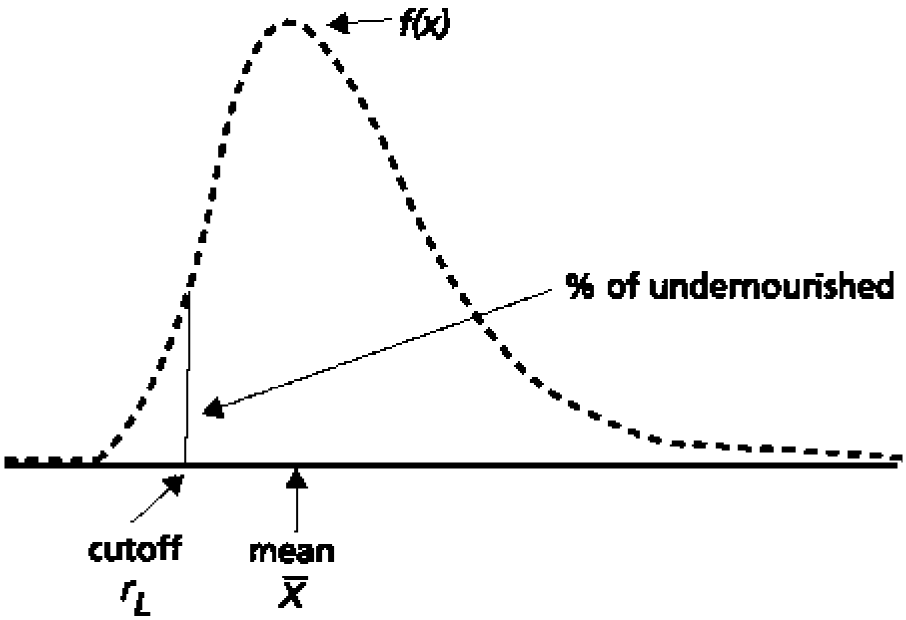
The food policy indicators evaluated in this research include the following:

- World Market Prices
- Total Crop Production
- Food Consumption
- Malnutrition
- Food Security or Food Self Sufficiency

The total crop production food policy indicator represents total production of wheat, maize, other grains, soybeans, potato, sweet potato and yams, cassava and other roots and tubers.

Total food consumption can be represented by the total modeled kilocalories per capita. The IMPACT-Water model only included a limited number of crops and livestock commodities; therefore the total food consumption is represented by the total *modeled* kcals/cap.

Figure 6 Framework for the calculation of the proportion of the population undernourished (Naiken 2002)



In addition to looking at the food consumption, an additional analysis on malnutrition was completed to determine the population at risk of hunger. The analysis is based on FAO's calculation of the proportion of the population undernourished (Figure 6) (Naiken 2002.) The percent of the population at risk of hunger is based on food consumption, the inequity of income

(Gini coefficient), and the coefficient of variation of dietary energy consumption. The cutoff ($r_L$in Figure 6) where below this value population is considered undernourished is 1885 kcals/cap.

The food policy indicator of food security or self sufficiency in crops (wheat, maize, other grains, soybeans, potato, sweet potatoes and yams, and cassava and other roots and tubers) can be represented by total supply divided by total demand. Values over one represent a region that is a net exporter while values less than one represent net importers. If a region is a net importer, they are dependent upon other countries for some or all commodities.

The hydro-climatology indicators evaluated in this research include the following:

- Rainfed ag (PEF/PET)
- Irrigation area vs rainfed area
- Irrigation supply (ETA/ETC)
- Non-irrigation water demands
- Time Series of Irrigation Water Supply

The hydro-climatology result of rainfed agriculture is represented by the effective precipitation divided by the potential evapotranspiration (PEF/PET). Values equal to one or higher relate to a region receiving all or more of the water necessary to meet the needs of rainfed agriculture. Values less than one relate to regions experiencing a shortage in rainfall available for rainfed agriculture and further imply a reduction in rainfed agriculture production.

Irrigation supply is represented by the actual evapotranspiration divided by the crop evapotranspiration (ETA/ETC) for months when crops are grown. This can also be described as the water available for a crop divided by that crop’s demand for water. This gives insight as to whether or not an irrigated crop received all the water it desired (a value of 1 or higher), or if not (a value less than one), its yield and area was reduced due to lack of available water.

The time series of irrigation water supply represents a combination of available water and demand. The water available for irrigation is calculated in the water model of IMPACT-WATER and is the water available after all non-irrigation water demands have been met. The irrigation demand is also calculated in the water model and is a function of evapotranspiration, effective precipitation, and a crop per drop factor (kc):

$$\text{Irrigation Demand} = PET * kc - PEF \qquad \text{Equation 1}$$

The irrigation water supply can never be more than irrigation demand, but can be less if the water is not available after the non-irrigation demands have been met. This hydro-climate result also gives one insight into the water available for nature. The less water supplied to irrigation reveals more water available for users downstream, nature and the environment.

Global Indicators

World Market Prices

Both the 36 Region version and the FPU version of IMPACT-Water report the same trend and approximately the same values for world market prices over the 25 year study period (2000-2025) (Figures 7 and 8, next page). In general the world market prices for the sixteen commodities evaluated decrease over time. The decreasing prices mean that production is going up and there is more food available. We see similar results between the two spatial representations of the model because they are driven by the same total population, economic growth, technical growth, etc. Global supply and demand have to meet for the model to solve (net trade equal to zero) therefore world market prices are likely to be very similar in the 36 region version and FPU version.

Figure 7 World Market Prices from the 36 Region IMPACT-Water Model

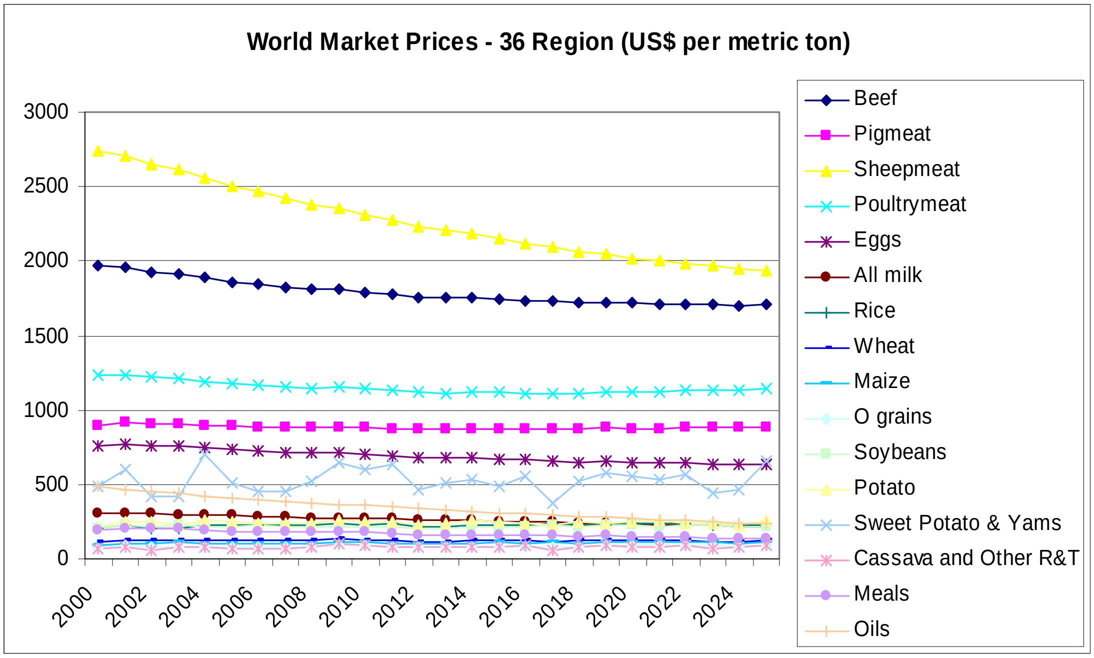
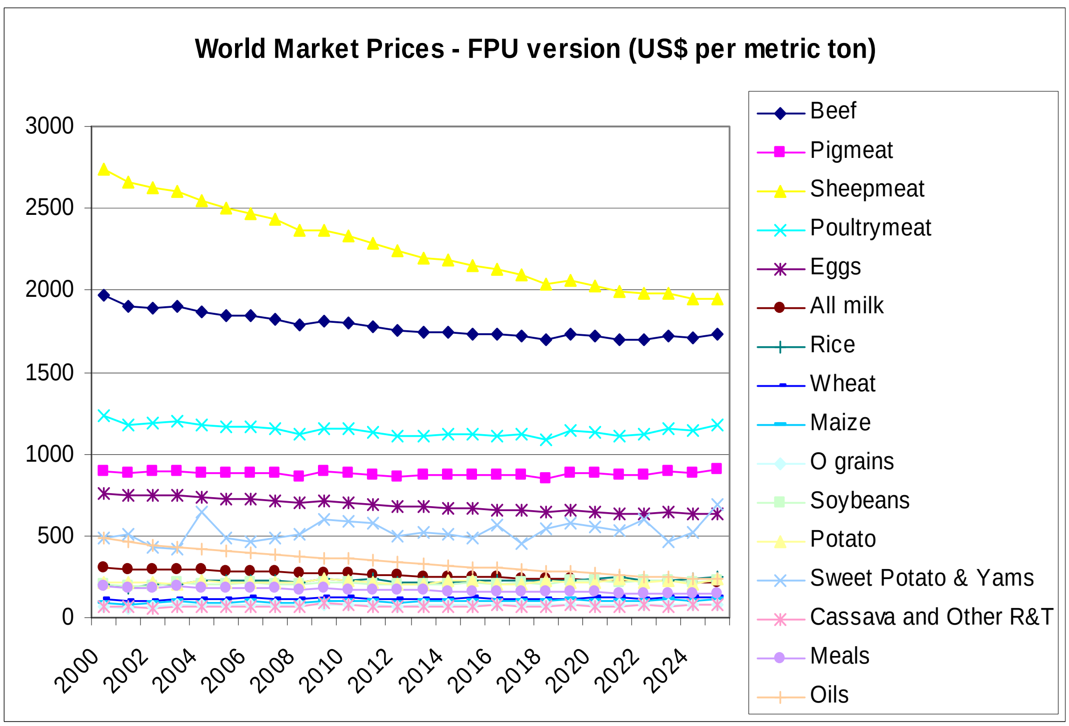


Figure 8 World Market Prices from the FPU IMPACT-Water version



When taking a closer look at the world market price for maize and wheat, one sees there is a slight difference between the two spatial representations of the model. In order to see how the prices are being affected by the hydrology in the model, the model was evaluated with and without the impacts of hydrology (Figures 9-12). One can see that the hydrology is the main cause of variations in the prices; without hydrology the prices remain mostly stable over time. An additional analysis is shown with wheat where the impacts of irrigation versus rainfed hydrology were evaluated (Figures 13-14). For wheat, the impacts of rainfed hydrology dominate the differences in world market prices between the two spatial scales.

Figure 9 World Market Price for Maize from FPU and 36 Reg.- With Hydrology

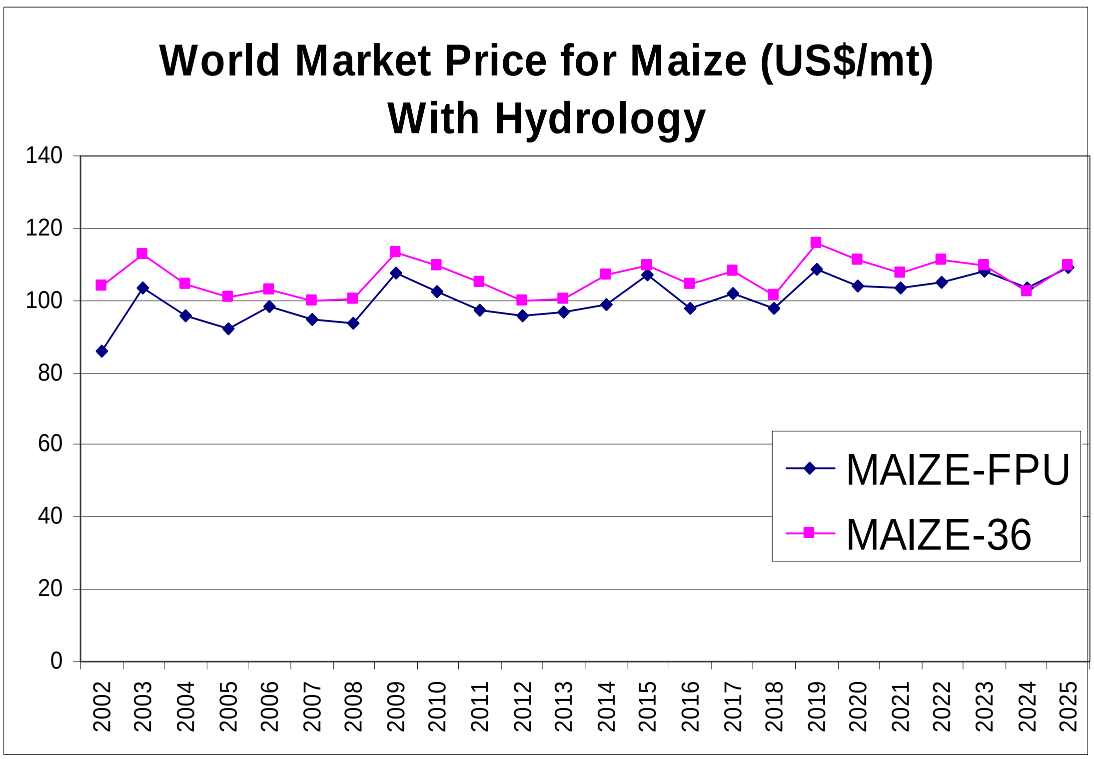


Figure 10 World Market Price for Maize from FPU and 36 Reg.- Without Hydrology

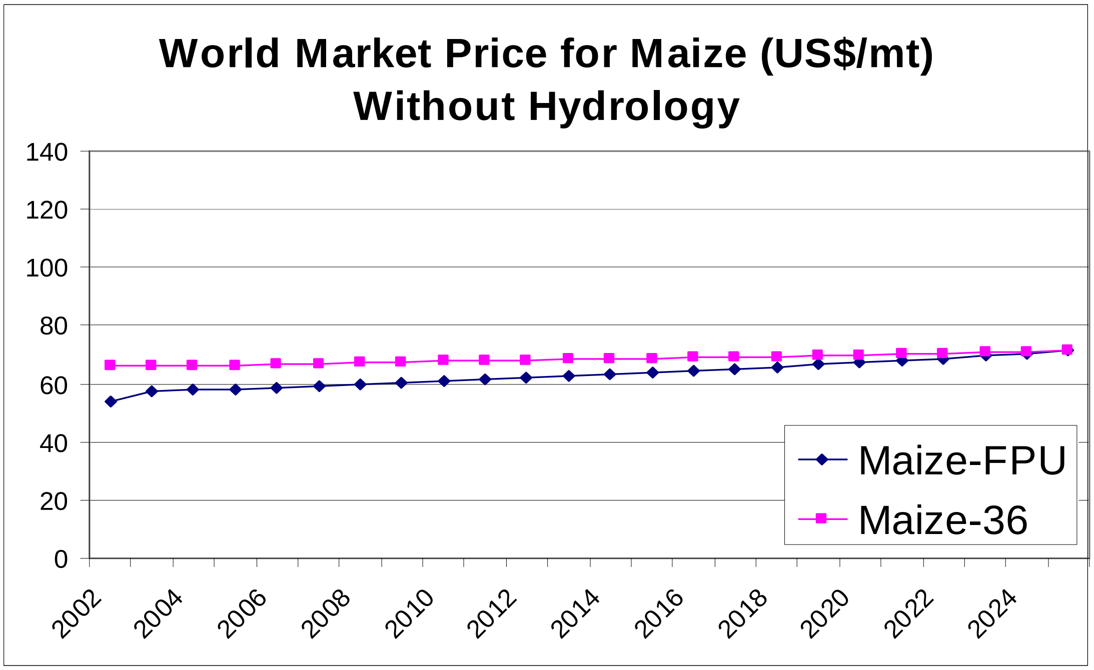


Figure 11 World Market Price for Wheat from FPU and 36 Reg.- With Hydrology

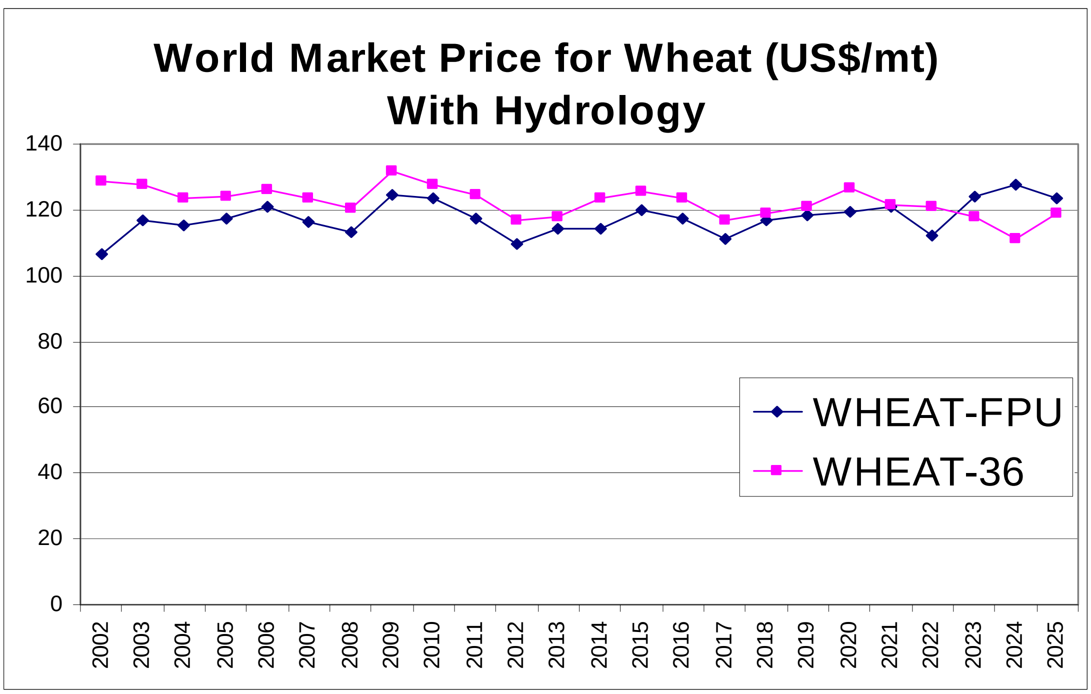


Figure 12 World Market Price for Wheat from FPU and 36 Reg.- Without Hydrology

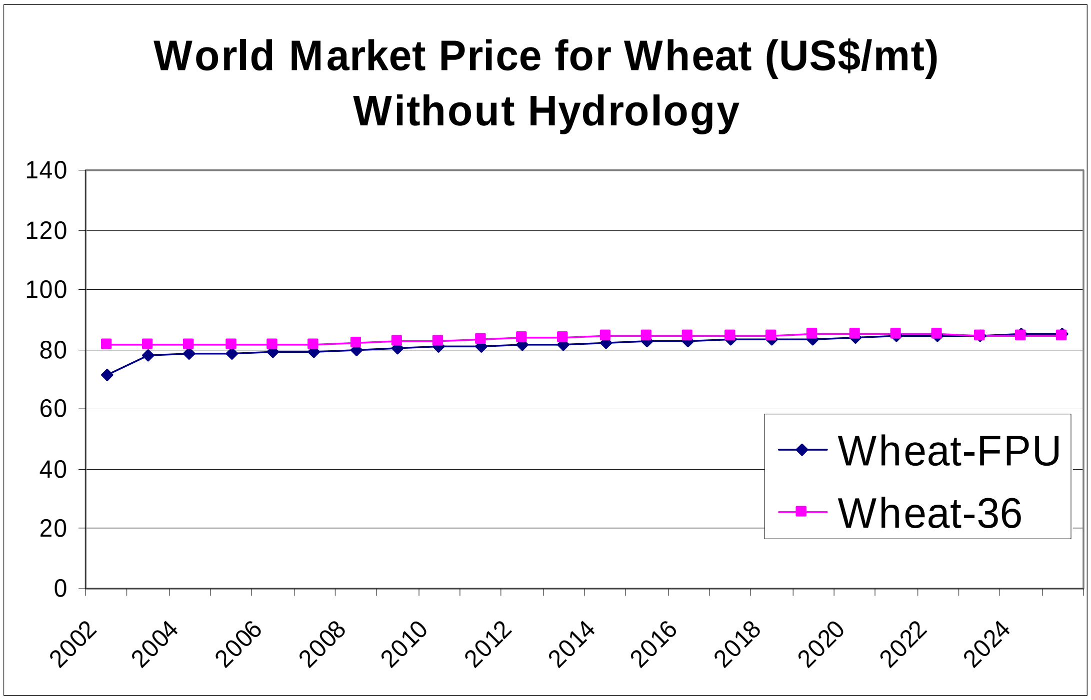


Figure 13 World Market Price for Wheat from FPU and 36 Reg.- Rainfed Hydrology

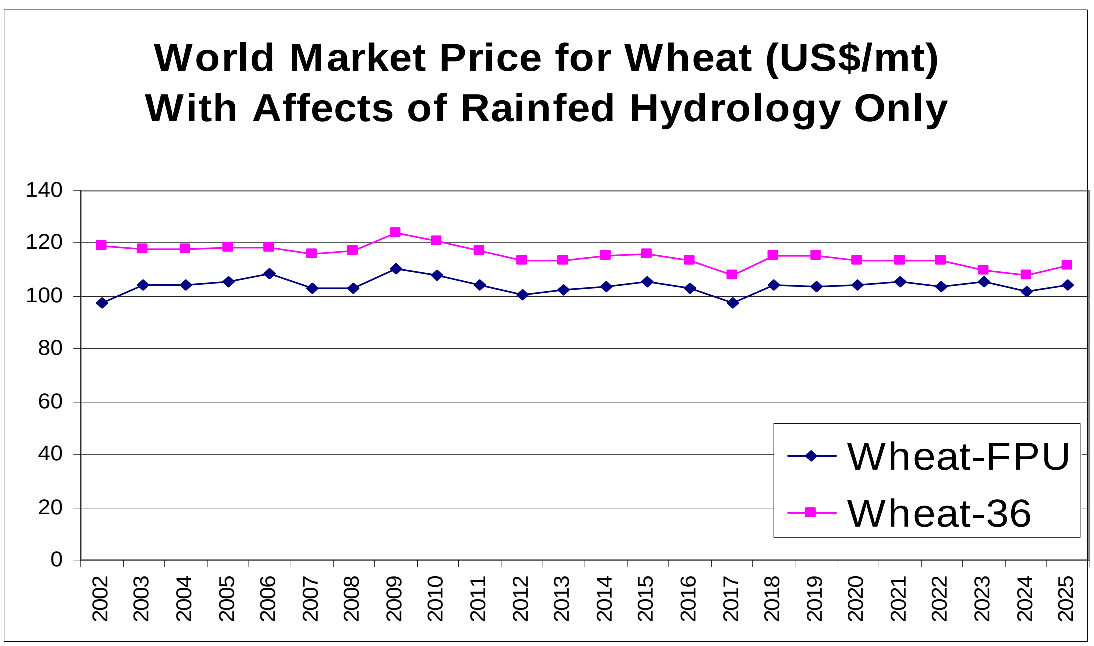
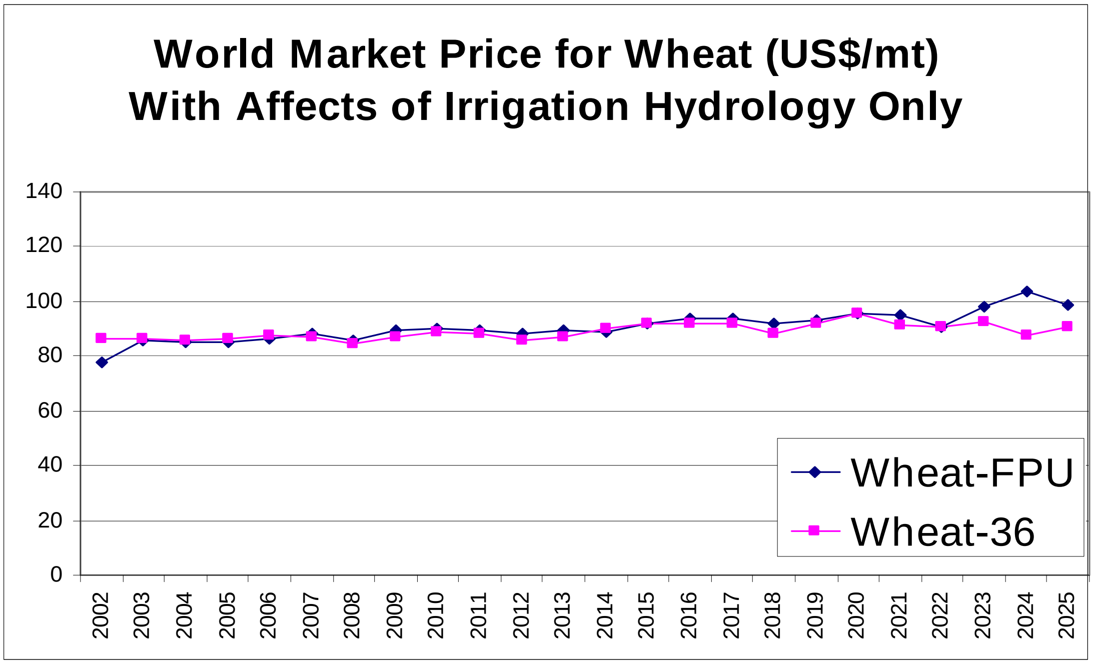


Figure 14 World Market Price for Wheat from FPU and 36 Reg.- Irrigation Hydrology



Regional Scale Indicators

While some of the policy indicators can be evaluated at the global scale, e.g. world market prices, other indicators and results such as those related to hunger require comparison at the local/regional scale. In order to provide a detailed analysis comparing the results between the two different spatial scales of IMPACT-Water, three case studies at the regional scale were chosen:

1. Central Asia
2. Europe
3. Southern Sub-Saharan Africa

The case studies were chosen to represent different hydro-climates and economic heterogeneity. Central Asia has a mix of irrigated and rainfed agriculture. It is a semi-arid region with multi-economic regions. Europe has mostly rainfed agriculture with regionally specific irrigation. Southern Sub-Saharan Africa is semi-arid with high climate variability and has mostly rainfed agriculture. To best understand the results, indicators and supporting outcomes from the models will be presented by case study.

Central Asia

Central Asia is represented as a single region and basin in the 36 region version of the IMPACT-Water model. In the FPU version, Central Asia is represented by 5 regions and 15 basins or Food Producing Units (Table 3 and Figure 15, next page). This region is semi-arid as seen by the humidity index in Figure 16. Most of the irrigation takes place along the southern area of the Central Asia region (Figure 17). The results for Central Asia from the two spatial scale versions of IMPACT-Water did not vary much over the 25 year study period, therefore this report will look at a snapshot of 2001 for most of the outcomes.

Table 3 Central Asia Basins and Regions in the FPU Version of the Model

Basin	Region	Country	FPU Code
Amudarja	Kazakhstan	Kazakhstan	AMD_KAZ
Lake_Balkhash	Kazakhstan	Kazakhstan	LBA_KAZ
Ob	Kazakhstan	Kazakhstan	OB_KAZ
Syrdarja	Kazakhstan	Kazakhstan	SYD_KAZ
Ural	Kazakhstan	Kazakhstan	URA_KAZ
Volga	Kazakhstan	Kazakhstan	VOG_KAZ
Yili_He	Kazakhstan	Kazakhstan	YHE_KAZ
Lake_Balkhash	Kyrgyzstan	Kyrgyzstan	LBA_KYR
Syrdarja	Kyrgyzstan	Kyrgyzstan	SYD_KYR
Amudarja	Tajikistan	Tajikistan	AMD_TAJ
Amudarja	Turkmenistan	Turkmenistan	AMD_TKM
Ural	Turkmenistan	Turkmenistan	URA_TKM
Western_Asia_Ira	Turkmenistan	Turkmenistan	WAI_TKM
Amudarja	Uzbekistan	Uzbekistan	AMD_UZB
Syrdarja	Uzbekistan	Uzbekistan	SYD_UZB

Figure 15 Map of Central Asia Region and FPUs

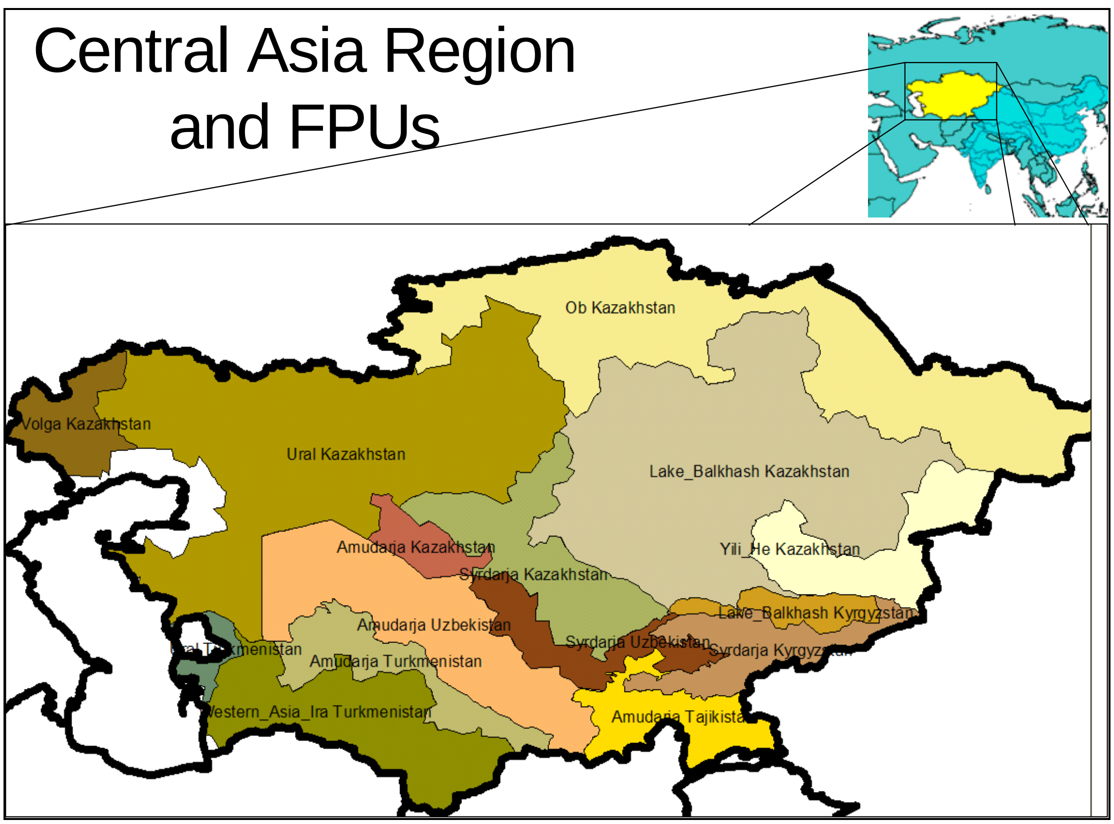


Figure 16 Humidity Index for Central Asia (0-wet, 9-dry) (UNEP 1991)

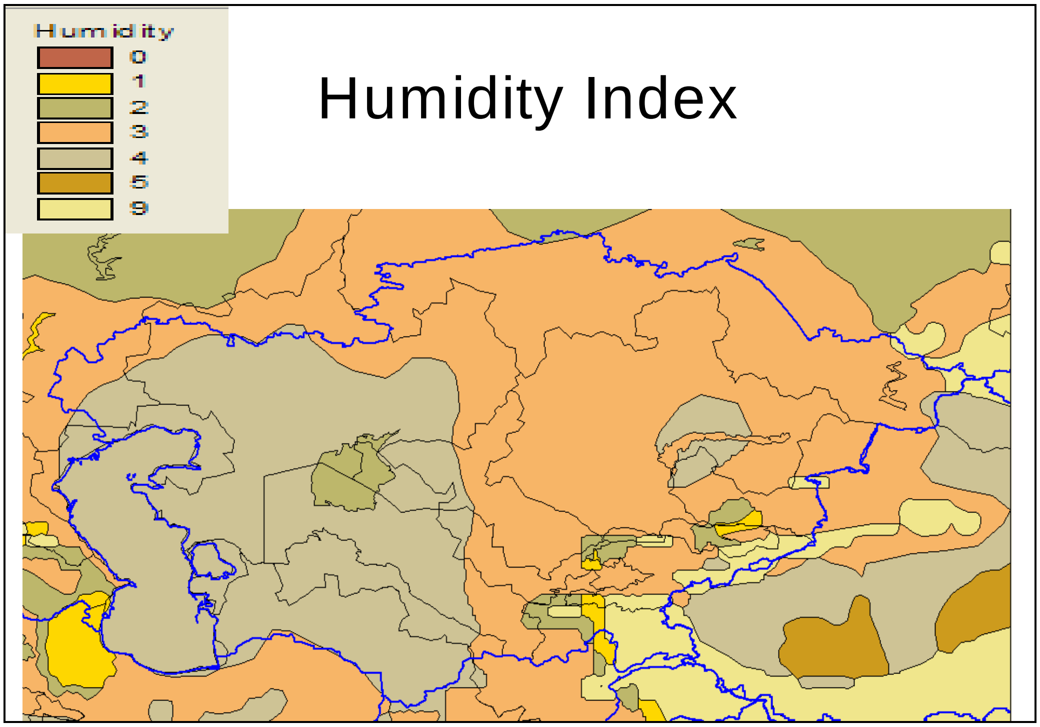


Figure 17 Irrigation Intensity in Central Asia (percentage of area irrigated) (FAO 2005)

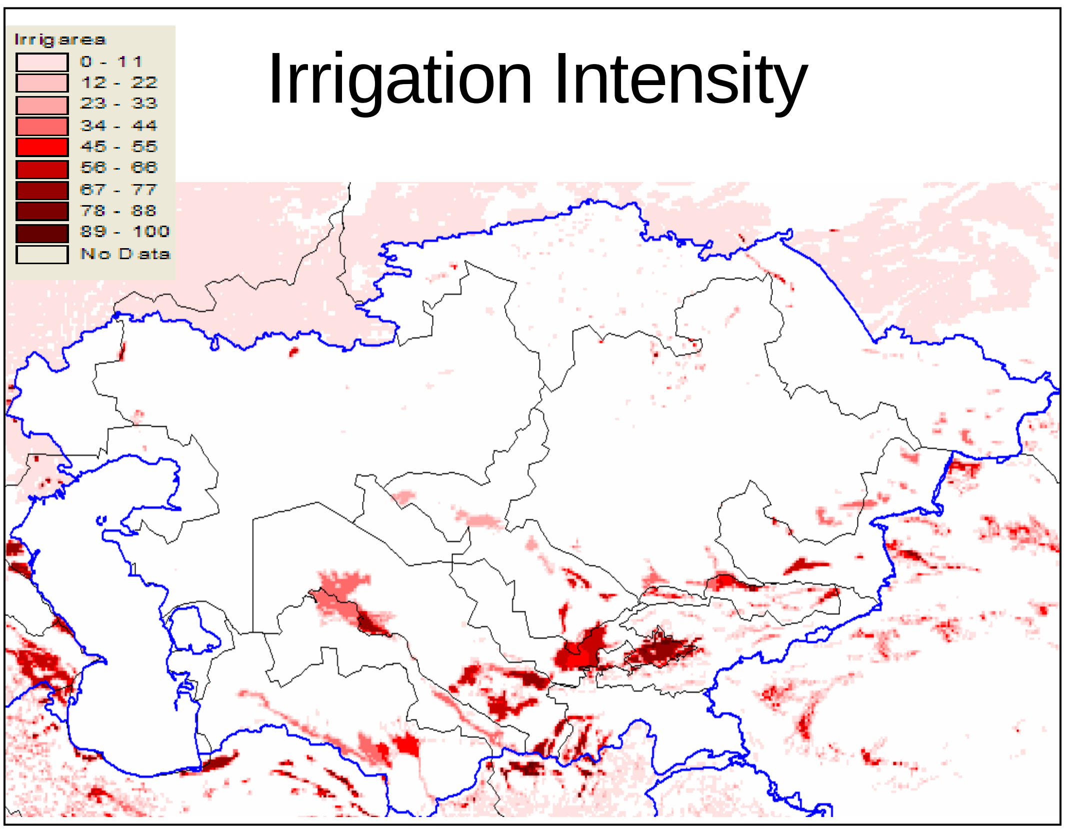
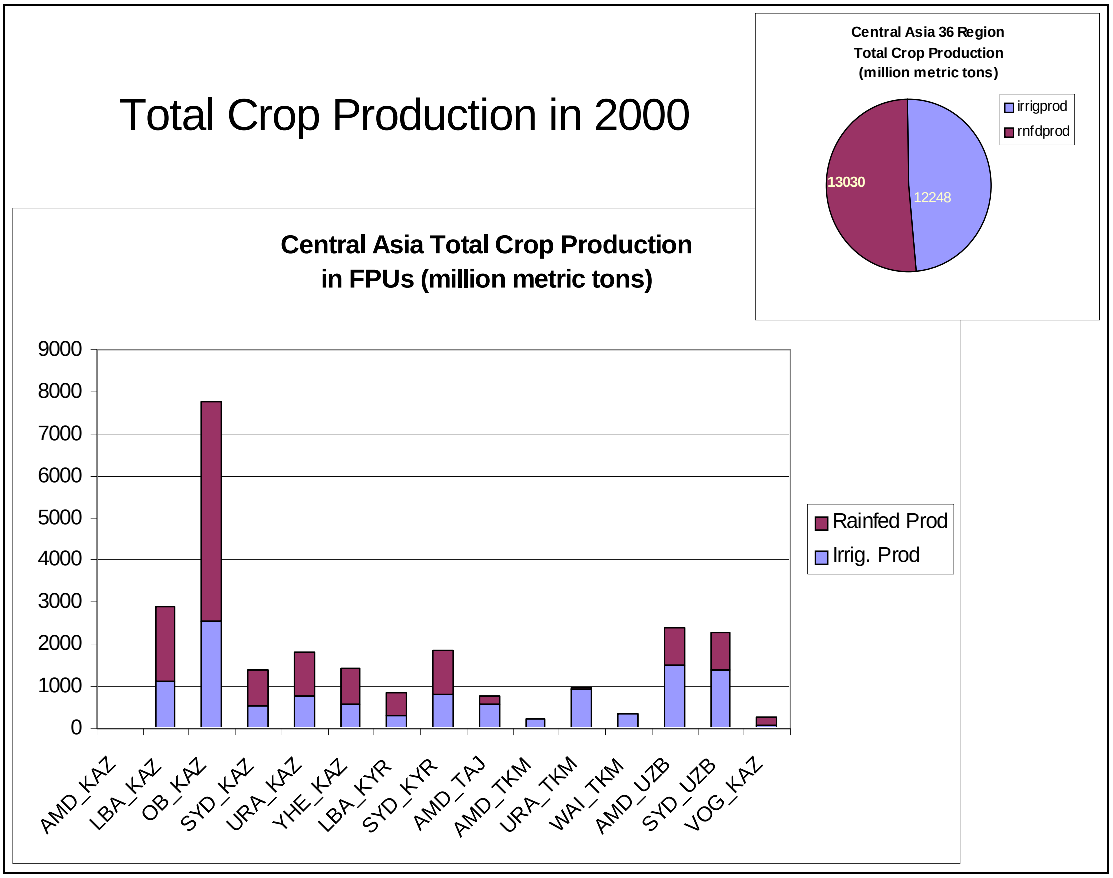
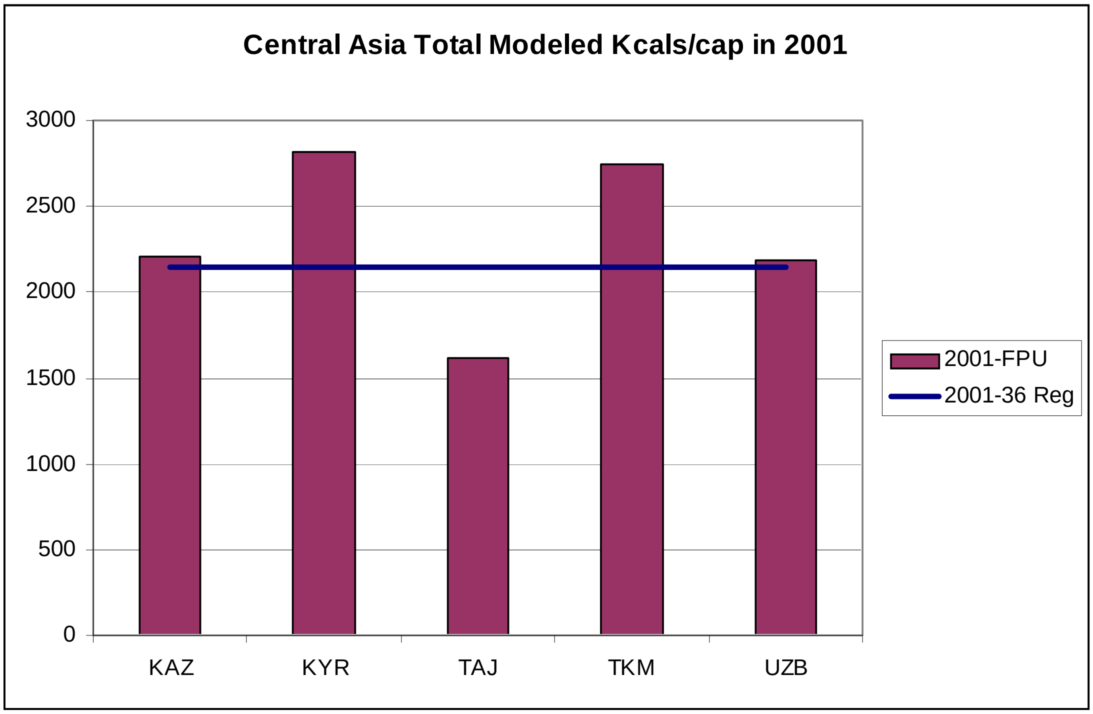


Figure 18 Total Crop Production in Central Asia in 2000



Central Asia's total crop production is divided almost equally among rainfed and irrigated production; leaning slightly towards rainfed production (Figure 18). By disaggregating to the FPU version one is informed as to where in the Central Asia region the crop production is occurring; predominantly in the "Ob Kazakhstan" FPU.

Figure 19 Total Food Consumption (modeled kcals/cap) in Central Asia



Food consumption in the Central Asia region is quite varied in the FPU version and this is masked in the 36 region version from the aggregation (Figure 19). If we evaluate the food consumption, or calories consumed per person, from a nutritional aspect, these results are very significant. In the year 2000, the 36 region version reports that Central Asia has 18% of its population at risk of hunger while in the FPU version we see that Tajikistan is actually experiencing 63% of its population at risk for hunger (Figure 20). The other remaining regions report 3-16% of their population at risk of hunger in the FPU region version; all below what was reported in the 36 region version. When we look at 2025, the population at risk of hunger in the 36 region version drops to only 5% (Figure 21). The FPU region version again reports Tajikistan at a much higher risk of 44% and also Uzbekistan is higher than the value reported in the 36 region version with 7%. The remaining regions are lower than reported in the 36 region version from 1-3%.

The food policy indicator of food security/self sufficiency is reported differently for Central Asia in the 36 region version versus the FPU version (Figure 22). The 36 region version shows Central Asia as a significant net exporter with a value of two. When looking at the FPU regions, there are 2 regions, Kazakhstan and Kyrgyzstan, that are net exporters and the remaining FPU regions are net importers. Kazakhstan is exporting predominantly more than all other regions and this is supported by the fact that total crop production is also predominantly in Kazakhstan.

Figure 20 Percent of Central Asia's Population at Risk of Hunger in 2000

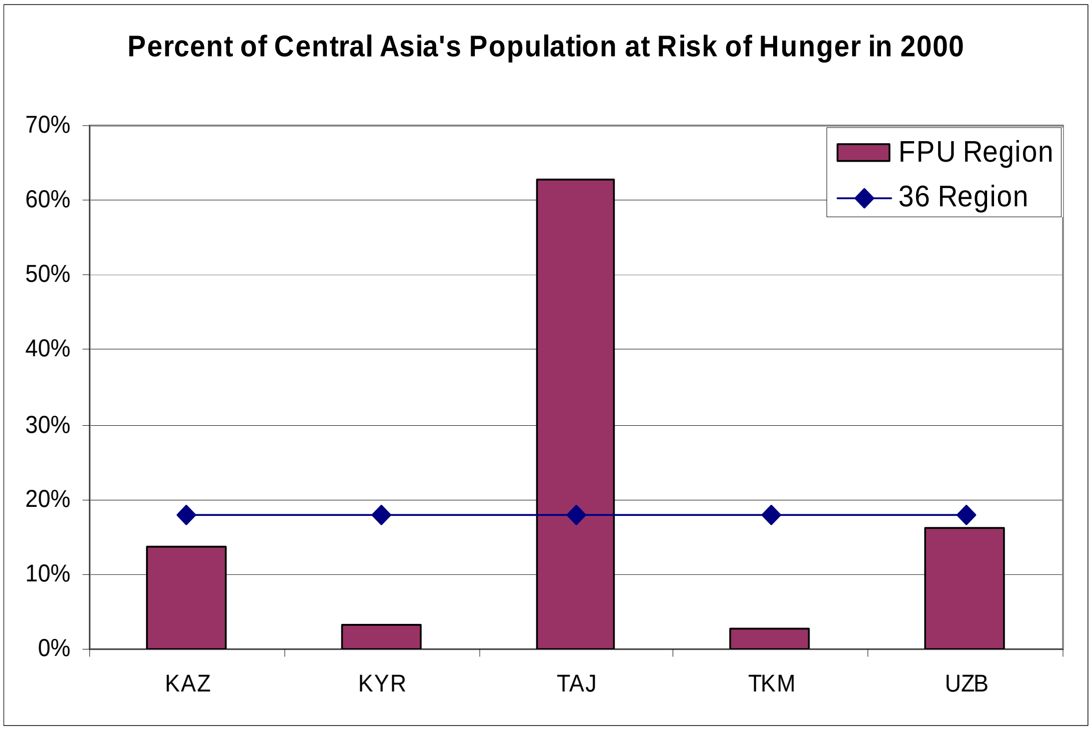


Figure 21 Percent of Central Asia's Population at Risk of Hunger in 2025

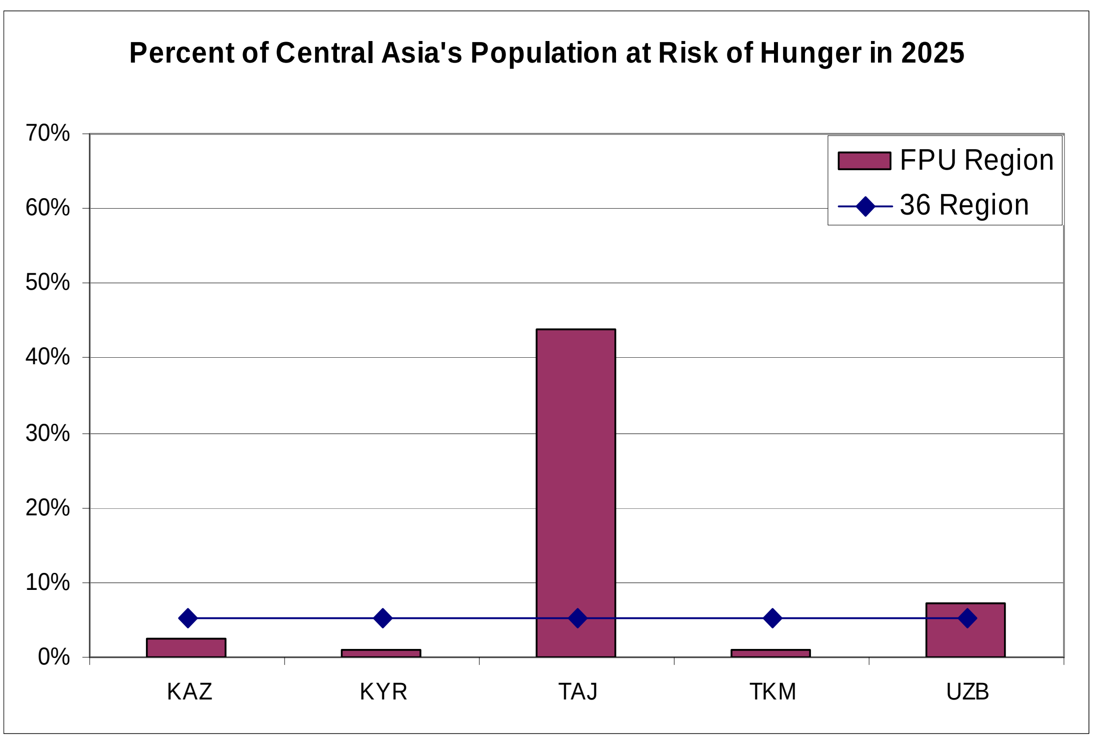
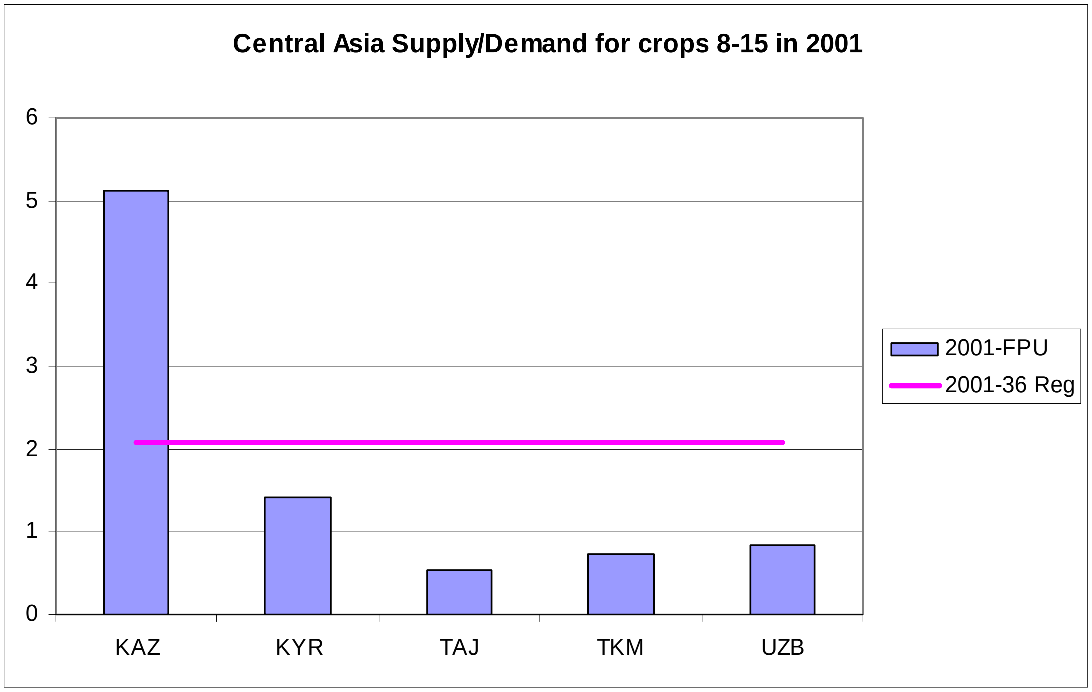


Figure 22 Food Security/Self Sufficiency in Central Asia



The hydro-climatology result of rainfed agriculture for Central Asia shows that in all regions, both 36 and FPU, there is a large shortage of rainfall available to meet the rainfed agriculture demand (all values much less than one) (Figure 33). The FPU regions show the variability among the disaggregated regions. This variability can be explained by comparing the humidity index with the location of the FPU regions (Figure 16). The more humid areas will have a slightly higher PEF/PET ratio. This variability is masked in the 36 region version.

In 2001, the hydro-climatology result of irrigated agriculture for Central Asia in the 36 region version reveals that there is almost enough water available to meet irrigated agriculture needs (ETA/ETC = 0.99). The results from the FPU version show that while most FPU regions have almost enough water available to meet irrigation needs (ETA/ETC = 0.99), others do not (LBA_KYR, AMD_TKM, URA_TKM, WAI_TKM, VOG_KAZ) (Figure X). The lack of water available to meet the irrigation needs in these regions results in a decrease in irrigated yields and areas, although this result is not very devastating considering these FPU regions are not the most significant crop producers (Figure 24).

There is a very slight if any difference between the non-irrigation water demands (domestic, industrial, livestock) in the 36 region version compared to the FPU version for the Central Asia region (Figure 25). This is because the drivers for these demands are the same between the two spatial scales and homogeneous across the region. Therefore only the results from the 36 region version are presented.

Figure 23 Rainfed Agriculture in Central Asia

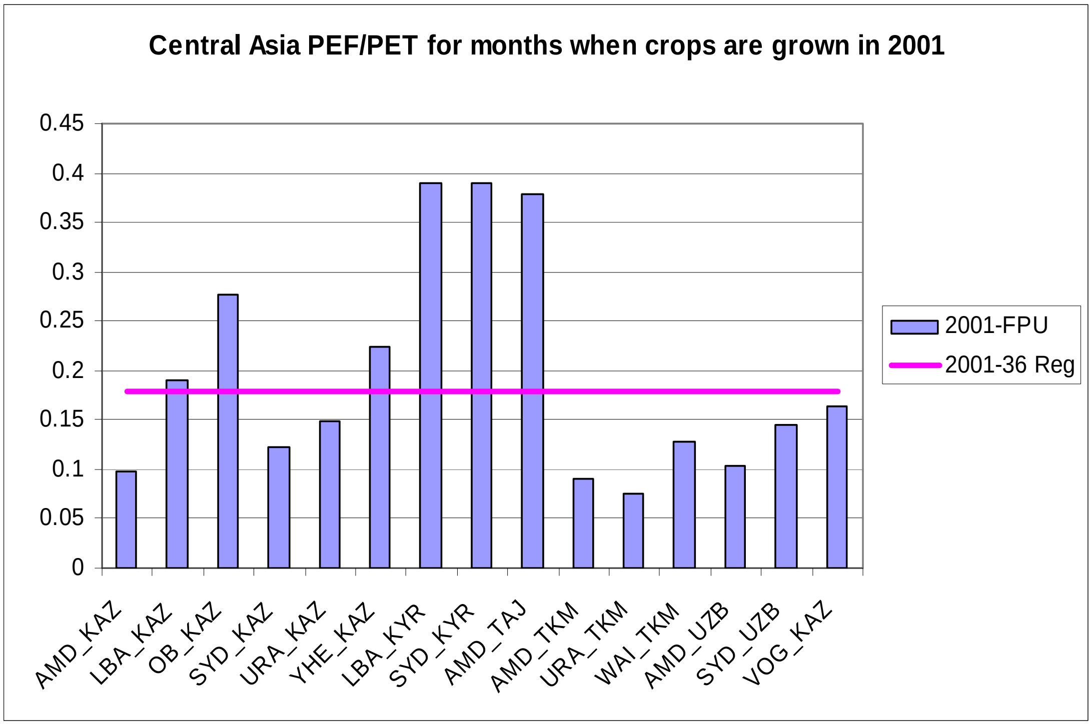


Figure 24 Irrigation Water Supplied for Irrigated Agriculture

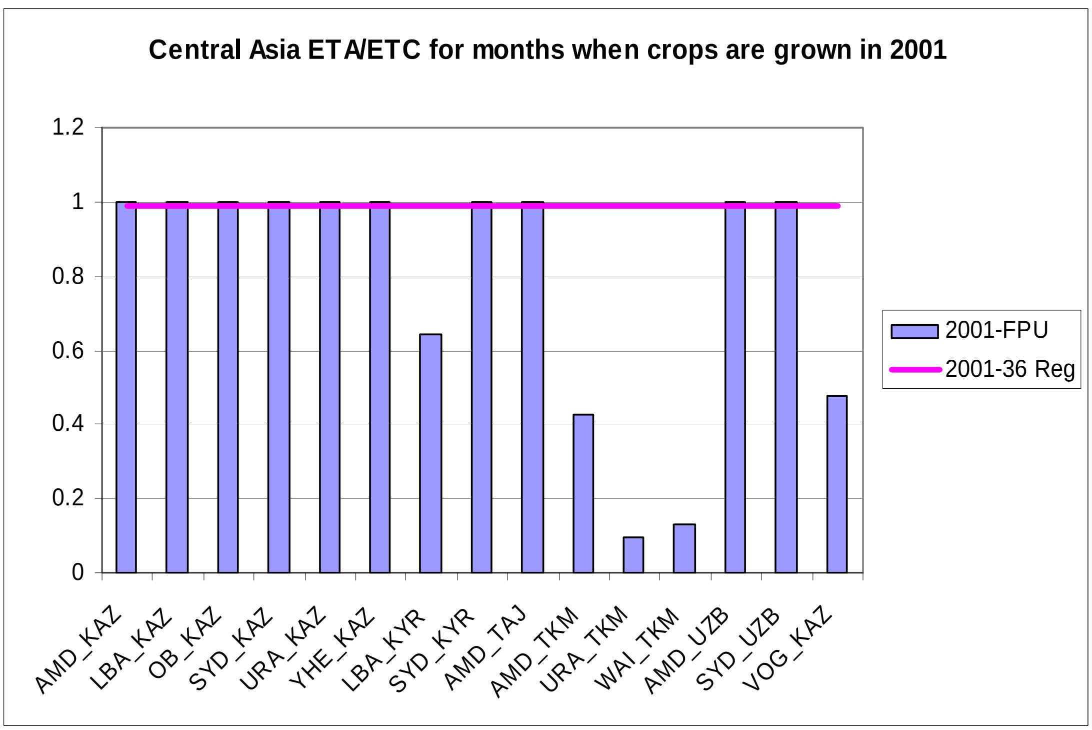


Figure 25 Non-Irrigation Water Demand in Central Asia

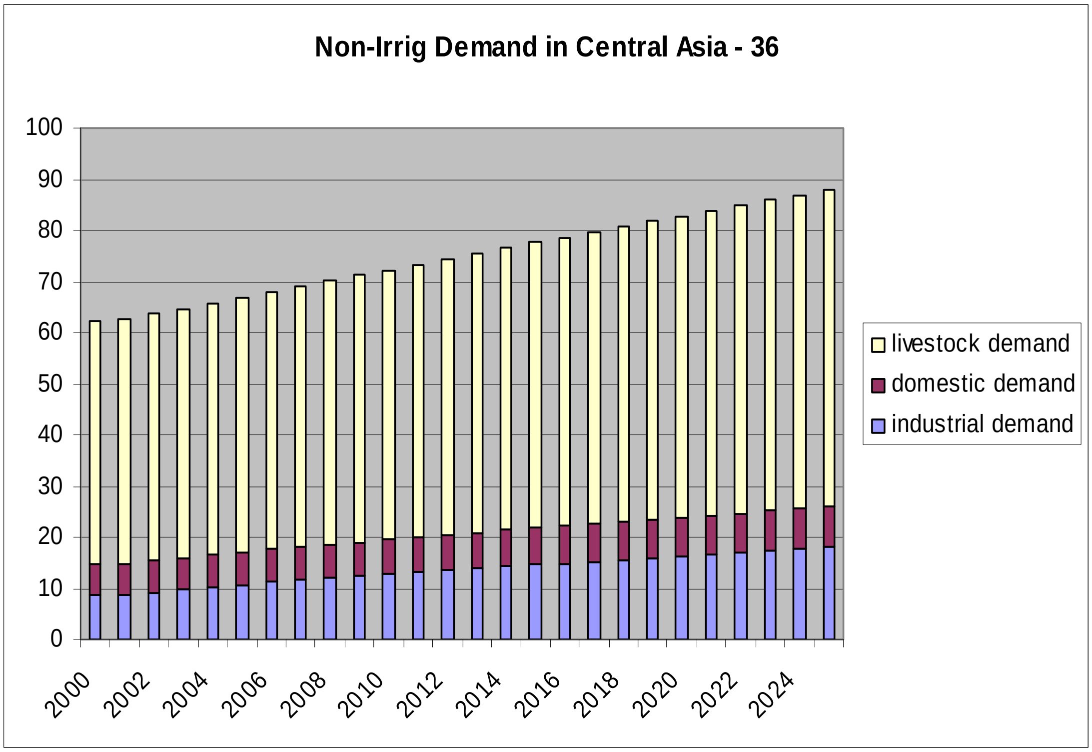


Figure 26 Irrigation Water Supply for Agriculture in Central Asia

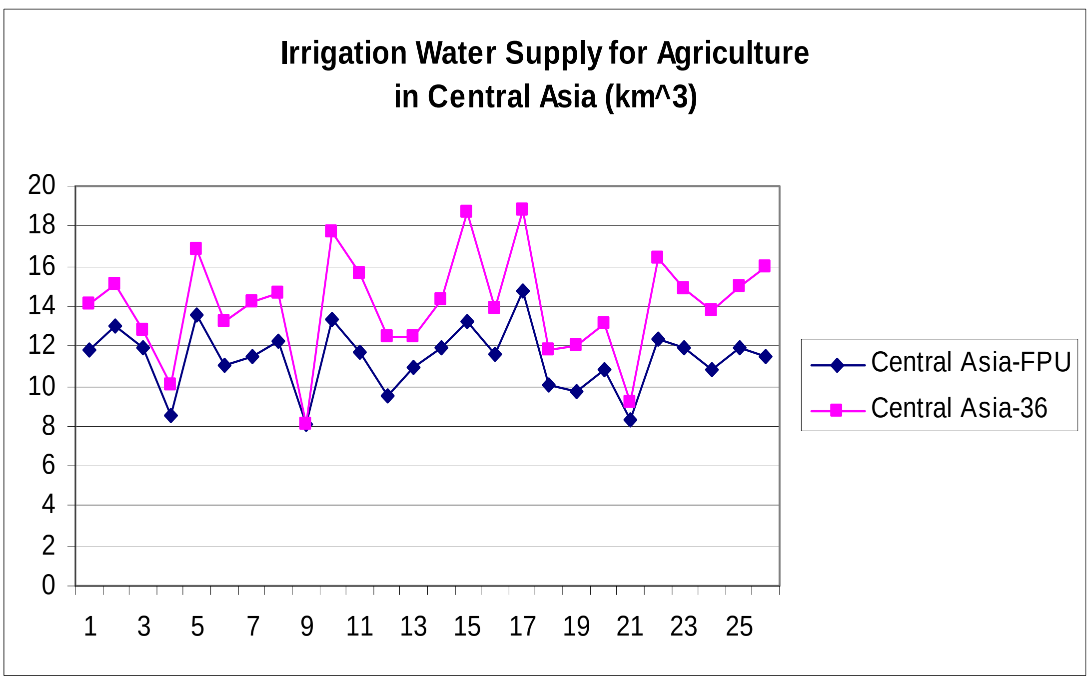
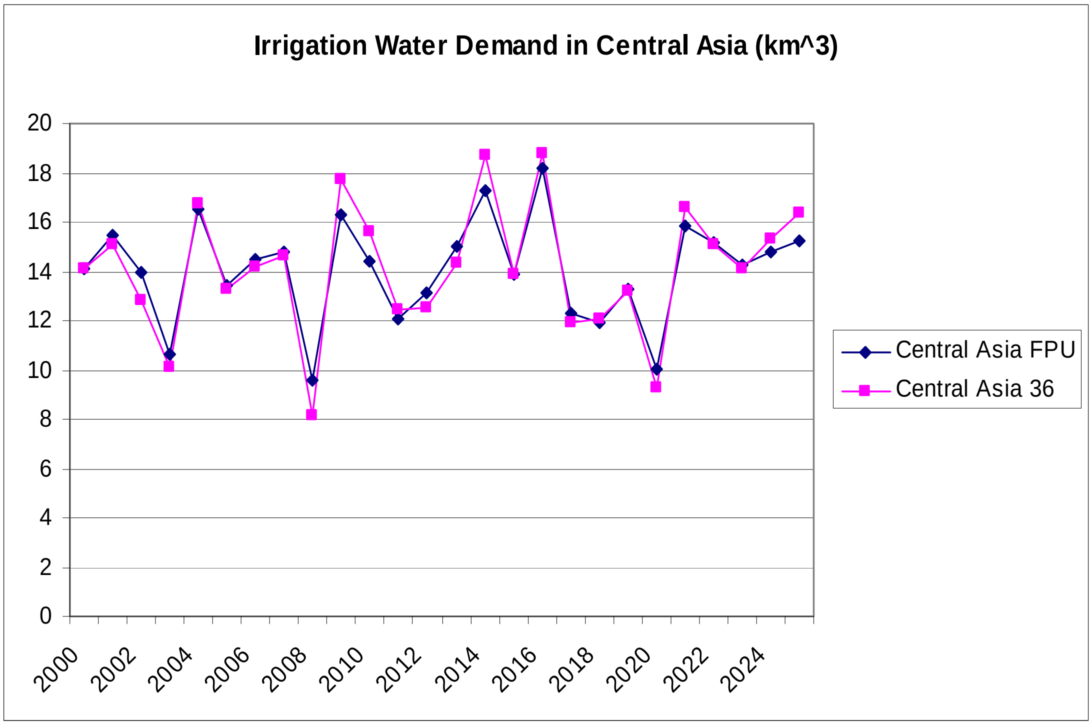


Figure 27 Irrigation Water Demand in Central Asia



The irrigation water supply for agriculture in Central Asia is slightly higher for the 36 region version compared to the FPU version (Figure 26). This difference is due to aggregation because there is more water available in the 36 region version as previously discussed. There is not enough water available in the FPU version to meet irrigation demands. The difference is not too significant because the region is mostly homogeneous and most of the irrigation is located in Kazakhstan and Uzbekistan. The climatic homogeneity and centralized irrigation results in the irrigation water demand calculated by both spatial representations of the model to be approximately the same (Figure 27).

In summary of evaluating the Central Asia region in both the 36 region version and the FPU version of IMPACT-Water, the results are different for most food policy indicators. The Central Asia region's economic disparity contributes to differences in food production, food consumption, malnutrition, and food security/self sufficiency in Central Asia's FPU regions. The climate of the region is fairly homogeneous being that Central Asia is mostly semi-arid. This climatic homogeneity leads to similar results for the hydro-climate outcomes where there is a lack of available water for most rainfed and some irrigated agriculture. There is slightly more water supplied for irrigation in the 36 region version because of the aggregation of available water even though the irrigation demands were fairly the same as the FPU version.

Europe

Europe is represented as a single region and basin in the 36 region version of the IMPACT-Water model. In the FPU version, Europe is represented by 9 regions and 18 basins or Food Producing Units (Table 4 and Figure 28). This region is fairly humid as seen by the humidity index in Figure 29. A small amount of irrigation takes place throughout the Europe region with a couple areas of higher intensity (Figure 30).

Table 4 Europe Basins and Regions in the FPU Version of IMPACT-Water

Basin	Region	Country	FPU Code
Danube	Alpine_Europe	Austria	DAN_AEU
Rhine	Belgium_Luxembourg	Belgium	RHI_BEL
Britain	British_Isles	United Kingdom	BRI_BRI
Ireland	British_Isles	Ireland	IRE_BRI
Ireland	British_Isles	United Kingdom	IRE_BRI
Loire_Bordeaux	France	France	LBO_FRA
Rhine	France	France	RHI_FRA
Rhone	France	France	RHO_FRA
Seine	France	France	SEI_FRA
Danube	Germany	Germany	DAN_GER
Elbe	Germany	Germany	ELB_GER
Oder	Germany	Germany	ODE_GER
Rhine	Germany	Germany	RHI_GER
Iberia_East_Med	Iberia	Spain	IEM_IBE
Iberia_West_Atla	Iberia	Portugal	IWA_IBE
Italy	Italy	Italy	ITA_ITA
Rhine	Netherlands	Netherlands	RHI_NET
Elbe	Scandinavia	Scandinavia	ELB_SCA
Scandinavia	Scandinavia	Norway	SCA_SCA
Scandinavia	Scandinavia	Sweden	SCA_SCA
Scandinavia	Scandinavia	Finland	SCA_SCA
Scandinavia	Scandinavia	Denmark	SCA_SCA

Figure 28 Map of Europe Region and FPUs

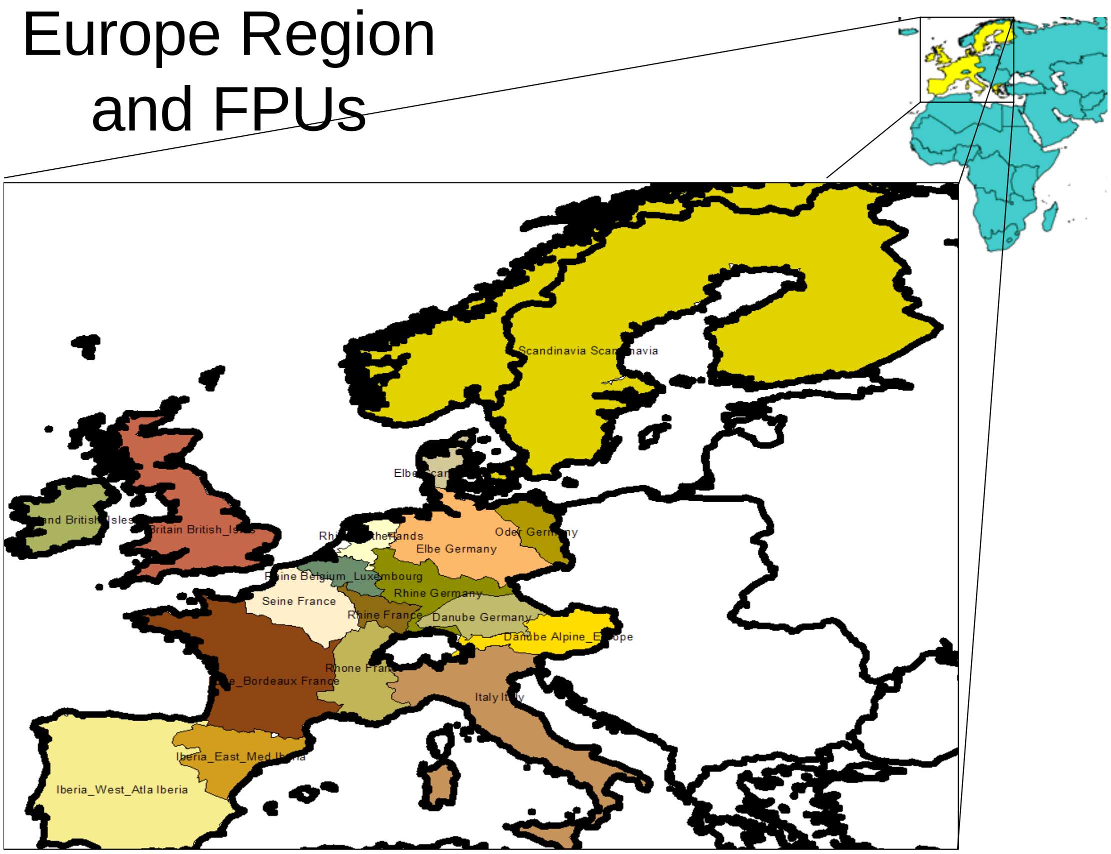


Figure 29 Humidity Index for Europe (0 = wet, 9 = dry) (UNEP 1991)

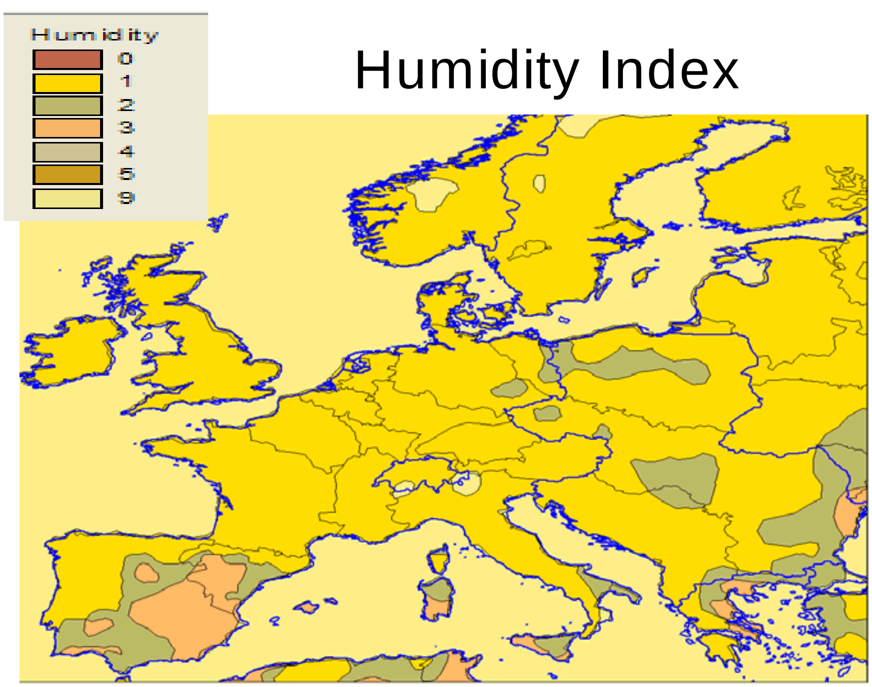


Figure 30 Irrigation Intensity in Europe (percentage of area irrigated) (FAO 2005)

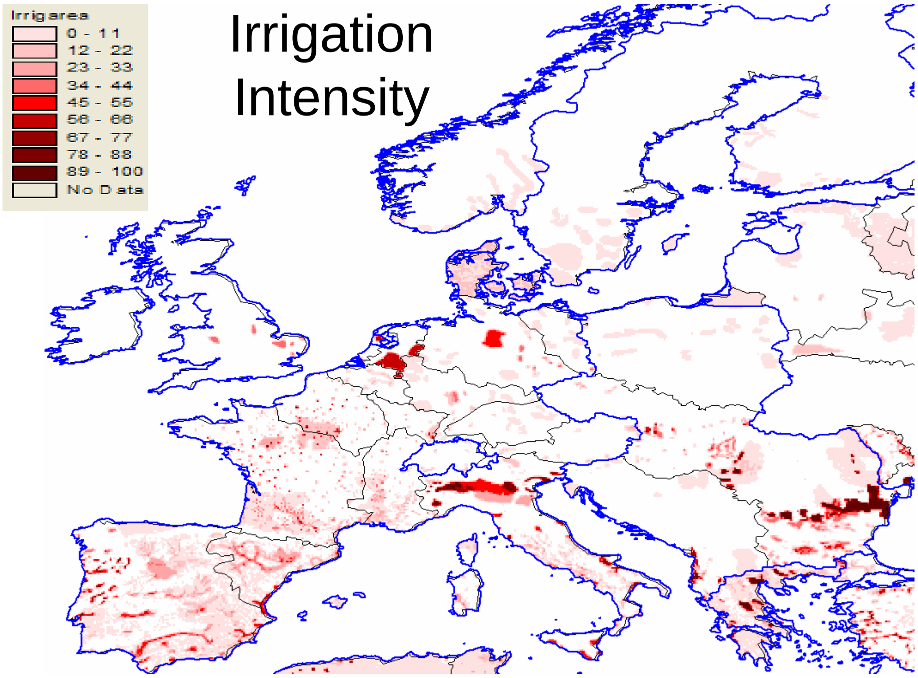
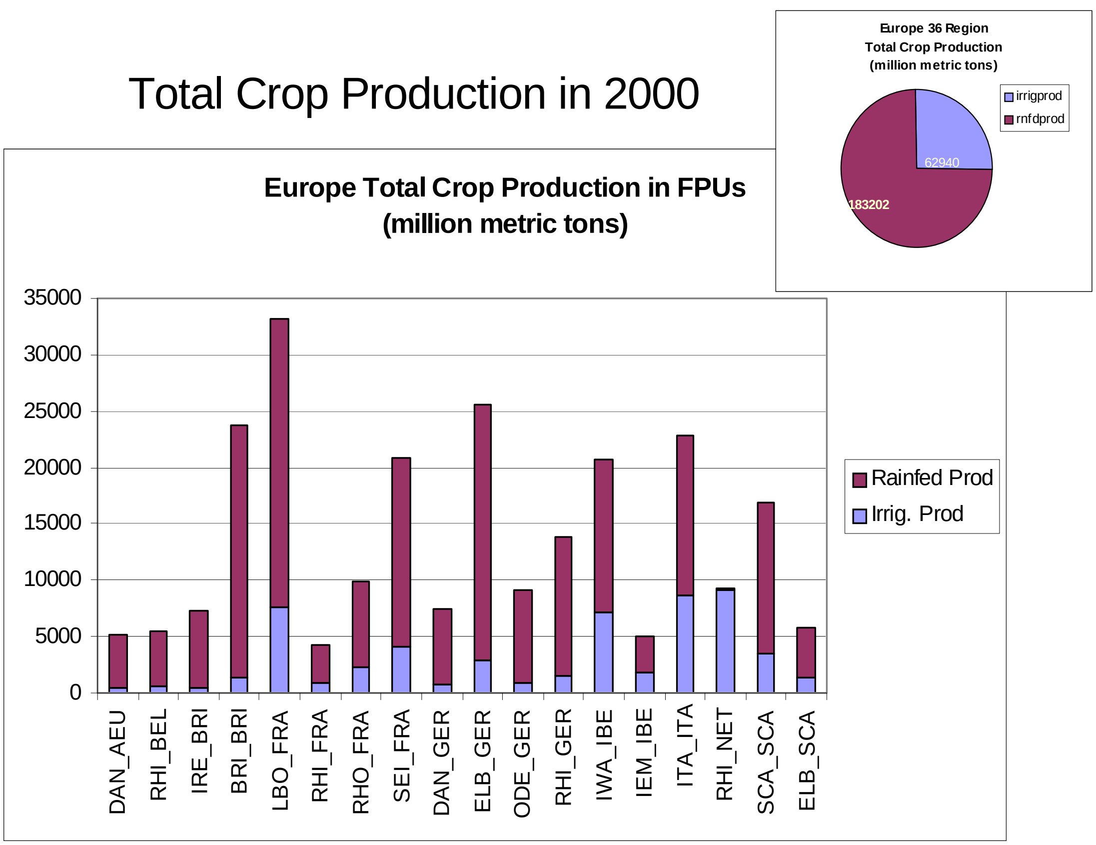


Figure 31 Total Crop Production in Europe in 2000



Europe's total crop production is dominated by rainfed production with approximately 75 percent of production being rainfed. (Figure 31). By disaggregating to the FPU version one is informed as to where in the Europe region the crop production is occurring.

Due to economic homogeneity in the Europe region, reported food consumption in both the 36 region version and the FPU version are approximately the same (Figure 32). While both spatial representative models claim that all regions associated with Europe are net exporters, the level at which they export varies greatly (Figure 33). The 36 region version claims Europe is exporting about 4.5 times their demand which is also what the FPU version reports for Germany, but France and Scandinavia are exporting much more than that and the remaining FPU regions are only exporting between 2 to 3 times their demands.

Figure 32 Total Food Consumption (modeled kcals/cap) in Europe

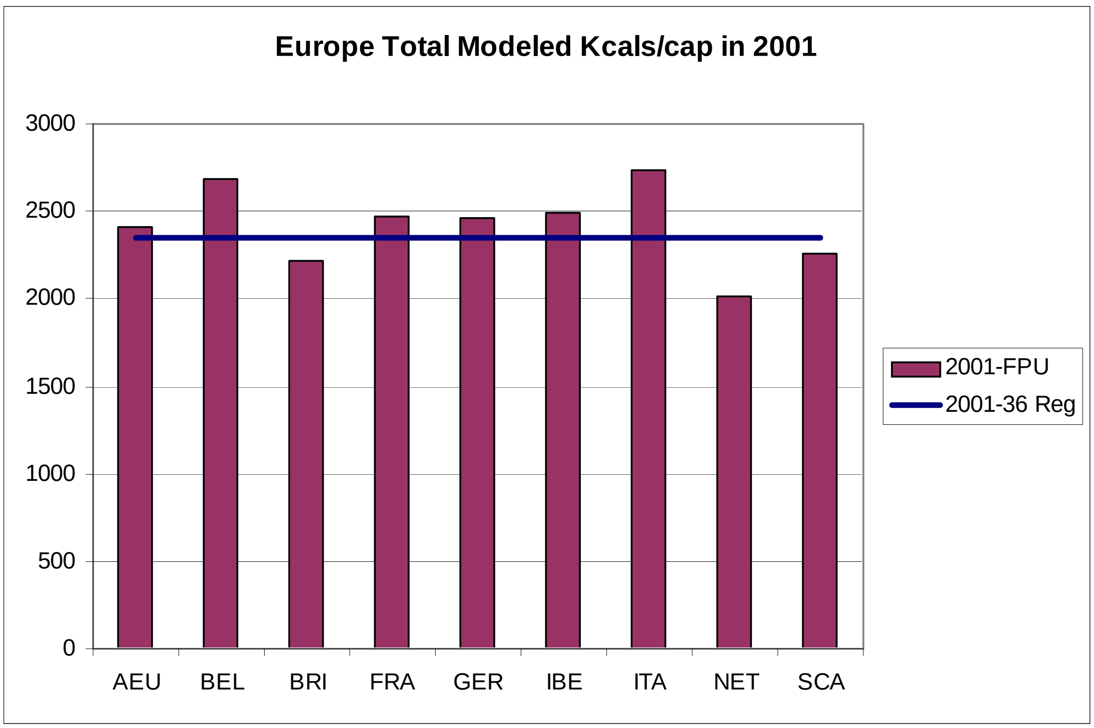


Figure 33 Food Security/Self Sufficiency in Europe

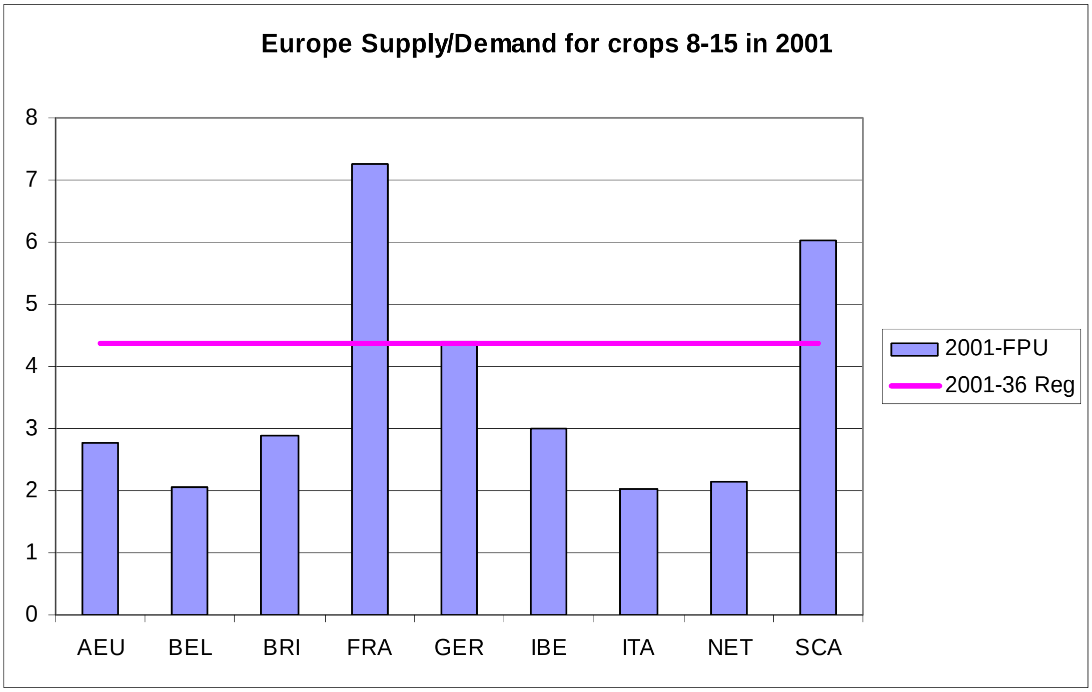
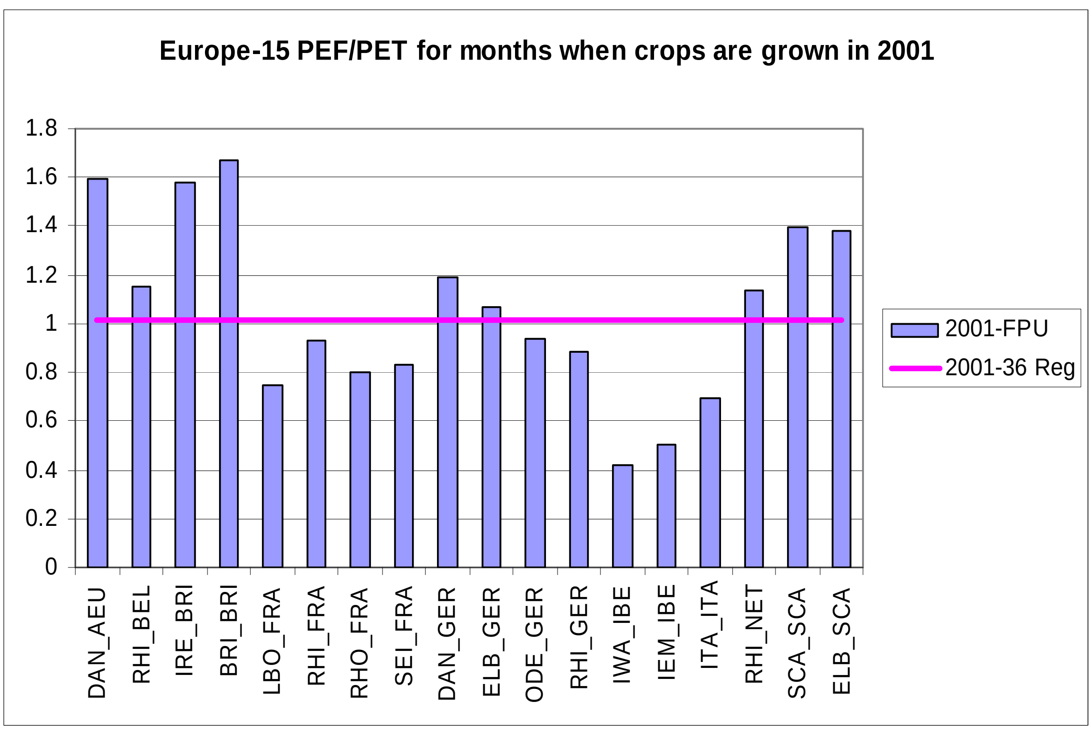
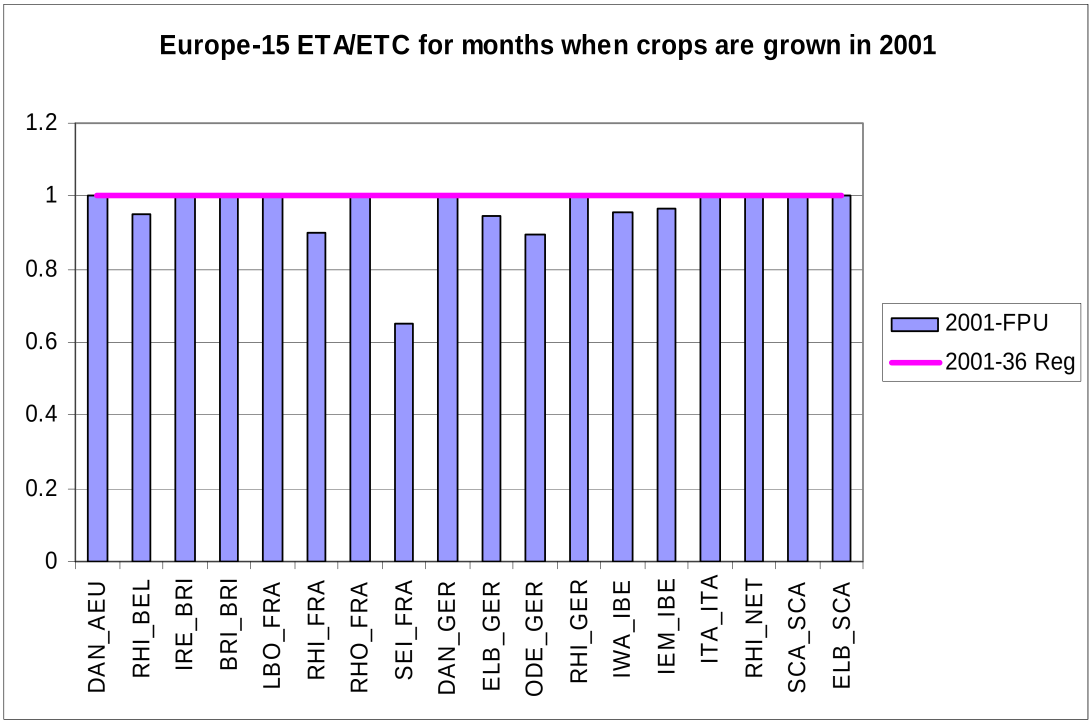


Figure 34 Rainfed Agriculture in Europe



The hydro-climatology result of rainfed agriculture for Europe in 2001 is varied (Figure 34). The 36 region version reports that there is enough rainfall to meet rainfed irrigation needs, while the FPU version claims the same is true for a few regions but not others. Some of this can be explained by variations in climate. As seen in the humidity index (Figure 29), areas of Iberia and Italy are drier which could lead to the unmet rainfed crop demand. These areas where rainfed agriculture is not being met is masked in the 36 region version.

Figure 35 Irrigation Water Supplied for Irrigated Agriculture in Europe



In 2001, the hydro-climatology result of irrigated agriculture for Europe in the 36 region version reveals that there is enough water available to meet irrigated agriculture needs. The results from the FPU version show that while most FPU regions have enough water available to meet irrigation needs, other FPU regions in Belgium, France, Germany and Iberia do not (Figure 35). The lack of water available to meet the irrigation needs in these regions results in a decrease in irrigated yields and areas.

As seen with the other previous region results, there is a very slight if any difference between the non-irrigation water demands (domestic, industrial, livestock) in the 36 region version compared to the FPU version for the Europe region (Figure 36). Therefore only the results from the 36 region version are presented.

Figure 36 Non-Irrigation Water Demand in Europe

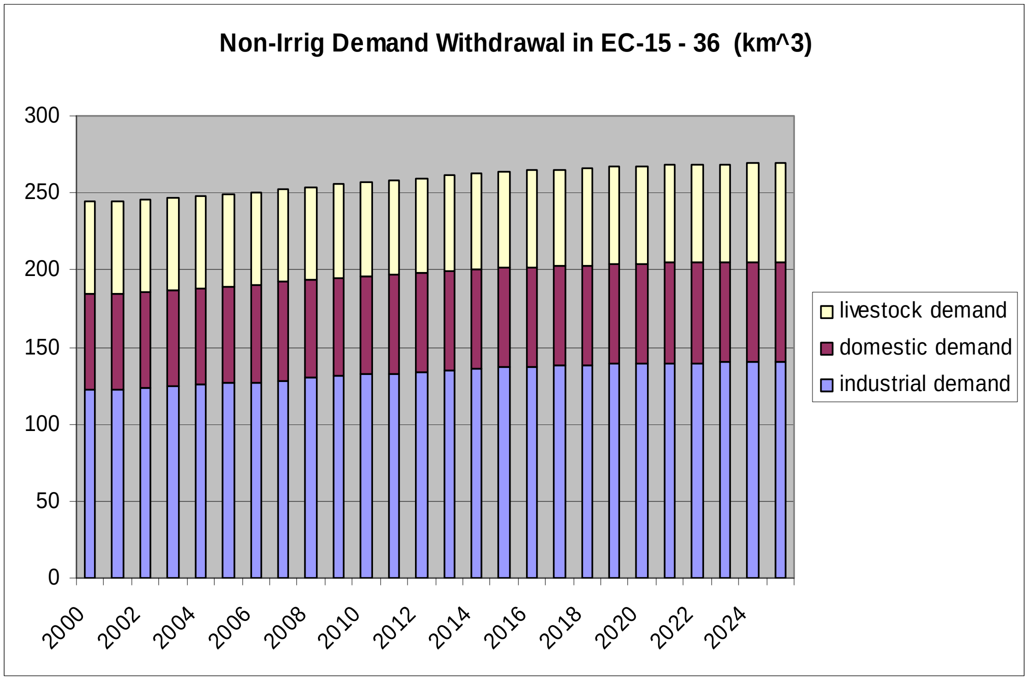
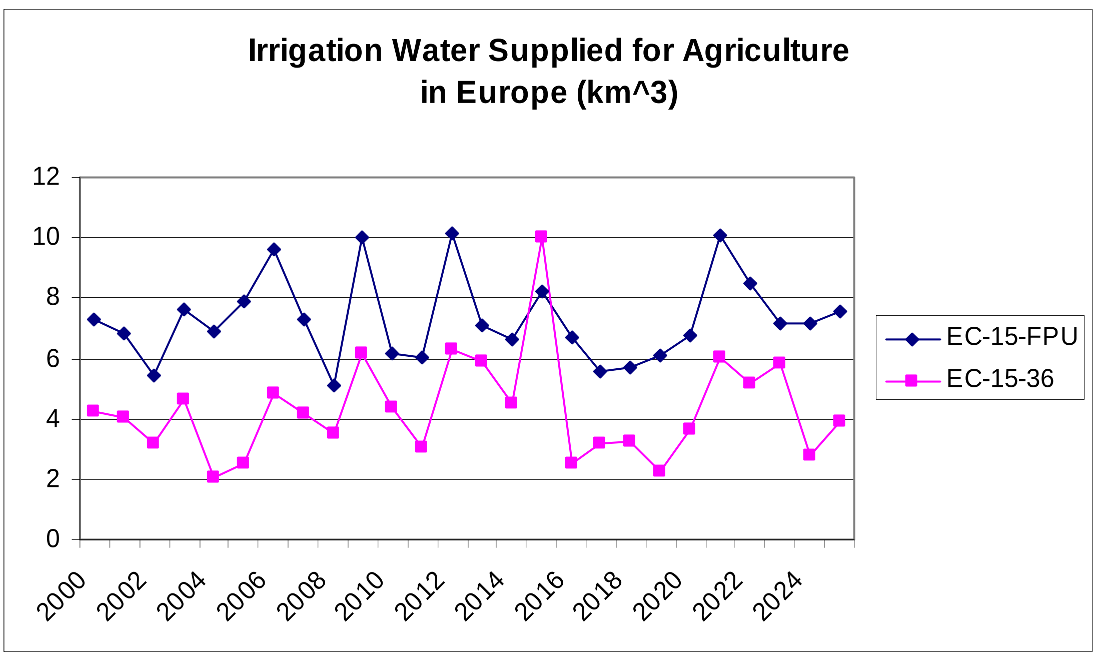


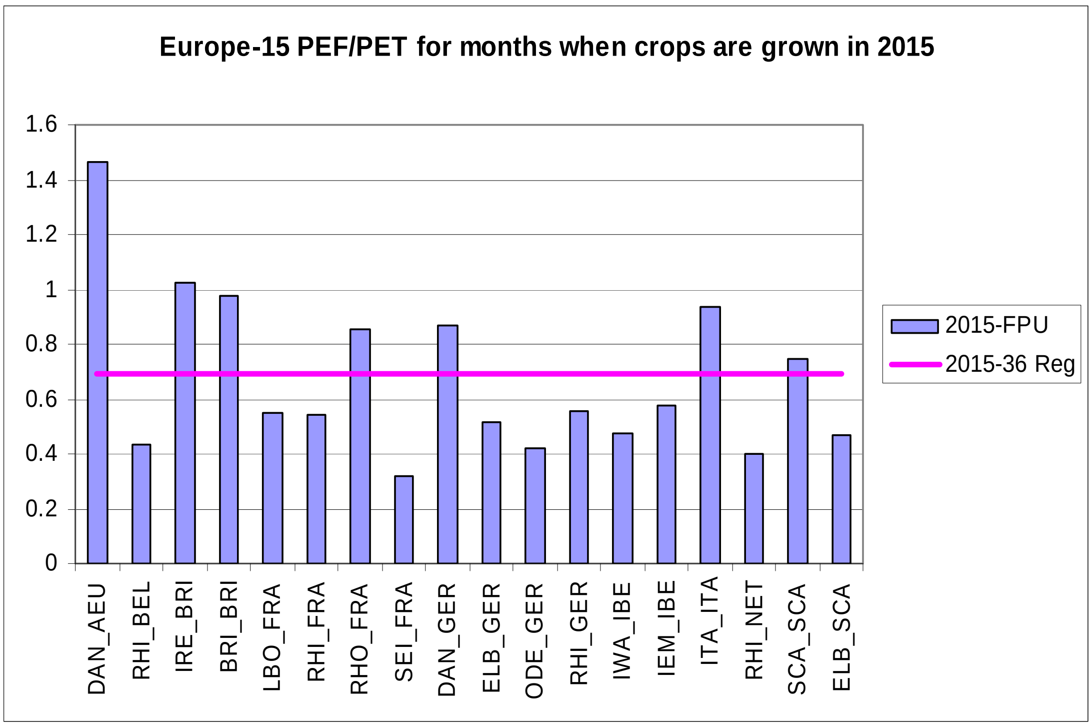
Figure 37 Irrigation Water Supply for Agriculture in Europe



One of the most interesting results from the Europe region analysis is seen with the irrigation water supply for agriculture (Figure 37). Unlike other regional results, the FPU version reports more irrigation water supply for agriculture than the 36 region version except for in the year 2015. There are two occurrences to explain here, one is why is the FPU version results for irrigation water supply for agriculture more than the 36 regions and two what is happening in 2015.

As described previously, irrigation water supply is a combination of actual water available after non-irrigation demands have been met and what the crops are actually demanding for irrigation water based on PET – PEF. When looking at what the crops are actually demanding for irrigation water, the FPU version reports a significantly higher demand than the 36 region version (Figure 38). In the 36 region version the aggregation shows this region's PET is slightly lower than the PEF resulting in lower irrigation demands. In the FPU version we see many locations where PEF/PET is less than one, therefore the irrigation demand is higher in this spatial representation.

Figure 38 Rainfed Agriculture in Europe in 2015



The impact of the FPU version revealing a higher amount of irrigation water supplied compared to the 36 region version tells one that the 36 region version is possibly overestimating the water available for the environment. As mentioned previously a lower amount of water supplied for irrigation results in more water available for nature.

In the year 2015, the 36 region version reports a jump in irrigation water supply which causes it to become higher than the value reported by the FPU version. First, the climate in 2015 shows a possible severe drought in this year with a significant drop in effective precipitation relative to potential evapotranspiration. While the 36 region version reports a drop in the ratio from 1 to 0.7, the FPU regions are also experiencing drops in the PEF/PET ratio (Figure 39). The combined effect of the drought on Europe in the FPU version is dampened by the distribution among the FPU regions.

In summary of evaluating the Europe region in both the 36 region version and the FPU version of IMPACT-Water, the results are similar for some food policy indicators and different for others. Due to the economic homogeneity of the region, food consumption was very similar between the two spatial scale representations. While both models reported Europe and its FPU regions to be net exporters, the amount being exported varied greatly across FPU regions which is masked in the 36 region version. The climate of the region is fairly homogeneous being that Europe is mostly humid with differences mainly in Iberia where the climate is a little drier. The 36 region underestimates irrigation demand because of the aggregation of PET and PEF. By underestimating irrigation demand, the 36 region version is also overestimating water available for the environment.

Southern Sub-Saharan Africa

Southern Sub-Saharan Africa (Southern SSA) is represented as a single region and basin in the 36 region version of the IMPACT-Water model. In the FPU version, Southern SSA is represented by 10 regions and 21 basins or Food Producing Units (Table 5 and Figure 40). This region is semi-arid with high climate variability as seen by the humidity index in Figure 41. Southern SSA has mostly rainfed agriculture with minimum irrigation intensity throughout the region (Figure 42).

Table 5 Southern SSA Basins and Regions in the FPU Version of the Model

Basin	Region	Country	FPU Code
Central_African_	Angola	Angola	CAF_ANG
Congo	Angola	Angola	CON_ANG
Zambezi	Angola	Angola	ZAM_ANG
Kalahari	Botswana	Botswana	KAL_BOT
Limpopo	Botswana	Botswana	LIM_BOT
Zambezi	Botswana	Botswana	ZAM_BOT
Orange	Lesotho	Lesotho	ORA_LES
Madagascar	Madagascar	Madagascar	MAD_MAD
Zambezi	Malawi	Malawi	ZAM_MLW
Limpopo	Mozambique	Mozambique	LIM_MOZ
Southeast_Africa	Mozambique	Mozambique	SAF_MOZ
Zambezi	Mozambique	Mozambique	ZAM_MOZ
Central_African_	Namibia	Namibia	CAF_NAM
Kalahari	Namibia	Namibia	KAL_NAM
Orange	Namibia	Namibia	ORA_NAM
Zambezi	Namibia	Namibia	ZAM_NAM
South_African_Co	Swaziland	Swaziland	SAC_SWA
Zambezi	Zambia	Zambia	ZAM_ZAM
Limpopo	Zimbabwe	Zimbabwe	LIM_ZIM
Southeast_Africa	Zimbabwe	Zimbabwe	SAF_ZIM
Zambezi	Zimbabwe	Zimbabwe	ZAM_ZIM

Figure 39 Map of Southern Sub-Saharan Africa Region and FPUs

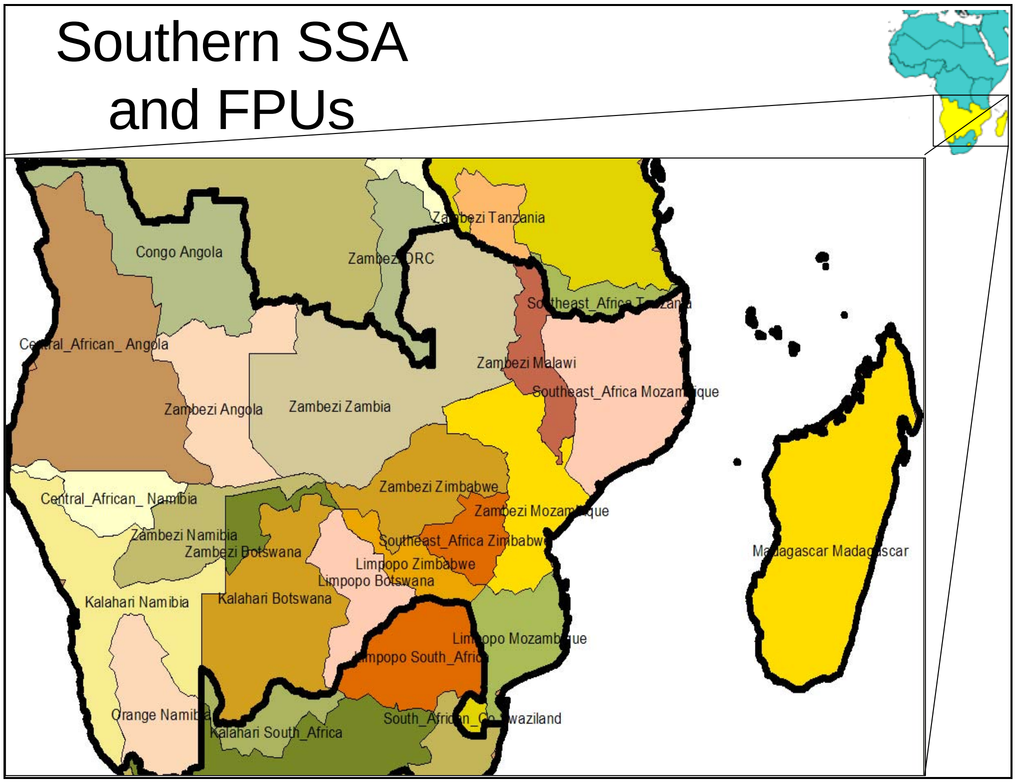


Figure 40 Humidity Index for Southern SSA (0-wet, 9-dry) (UNEP 1991)

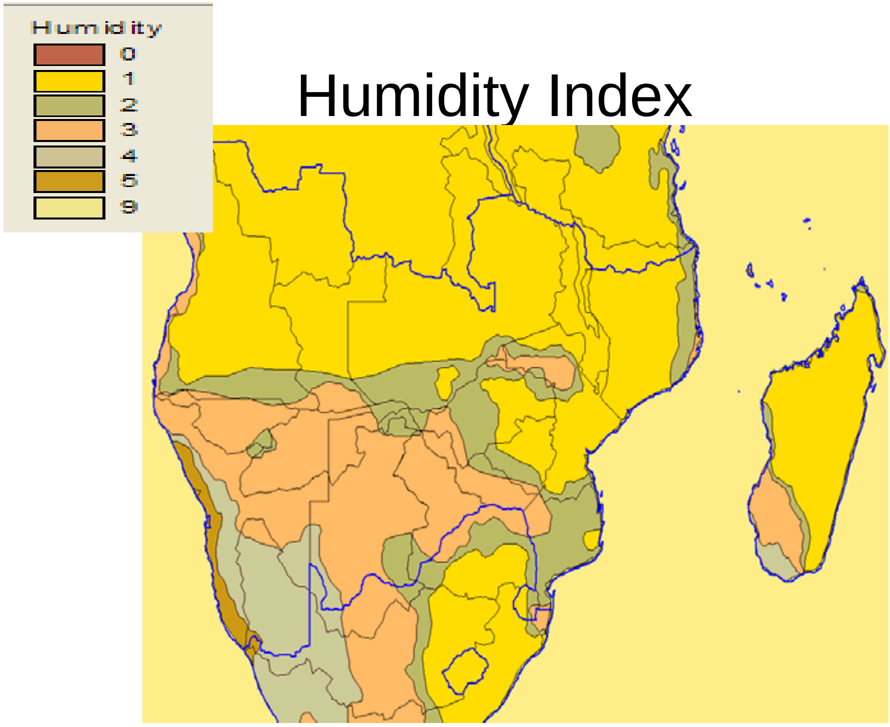


Figure 41 Irrigation Intensity in Southern SSA (percentage of area irrigated) (FAO 2005)

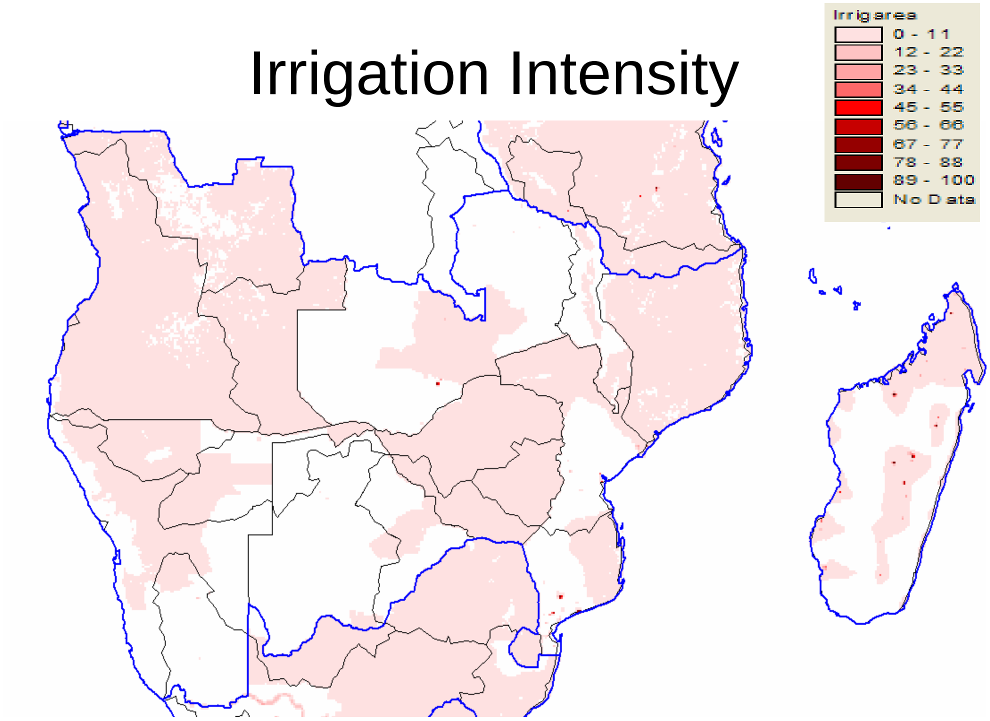
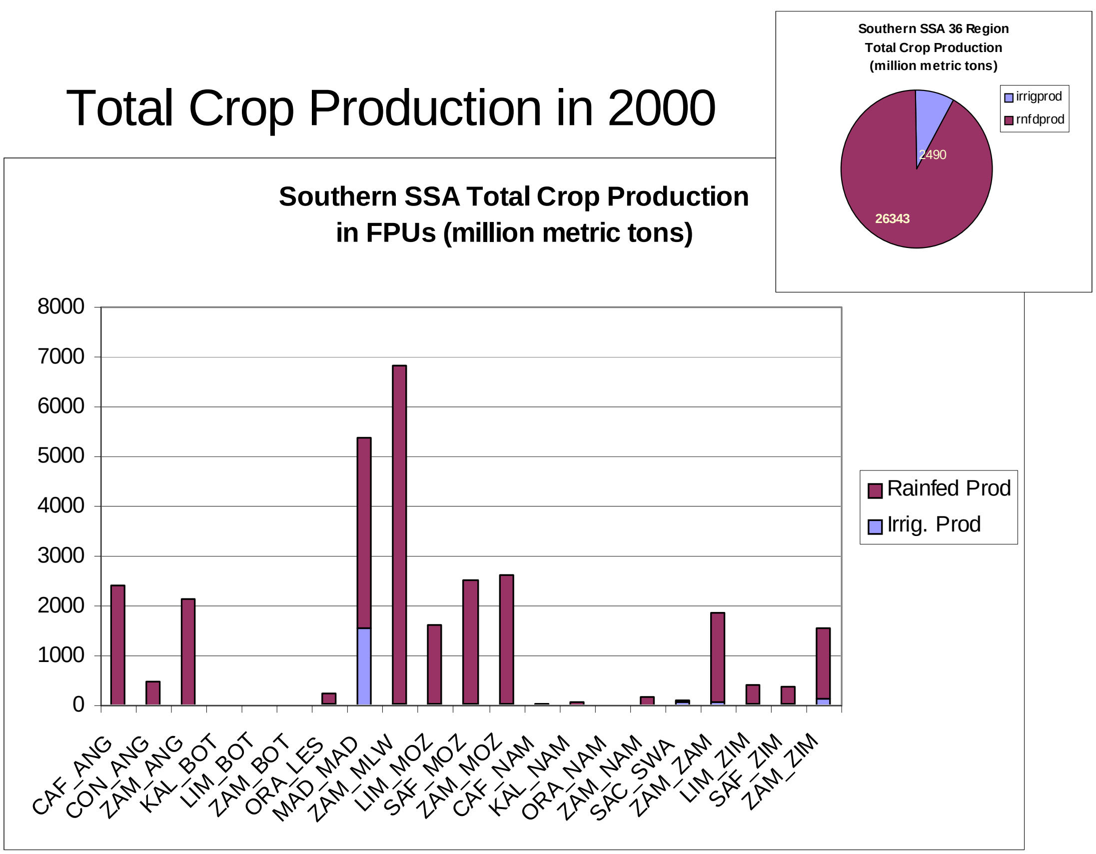
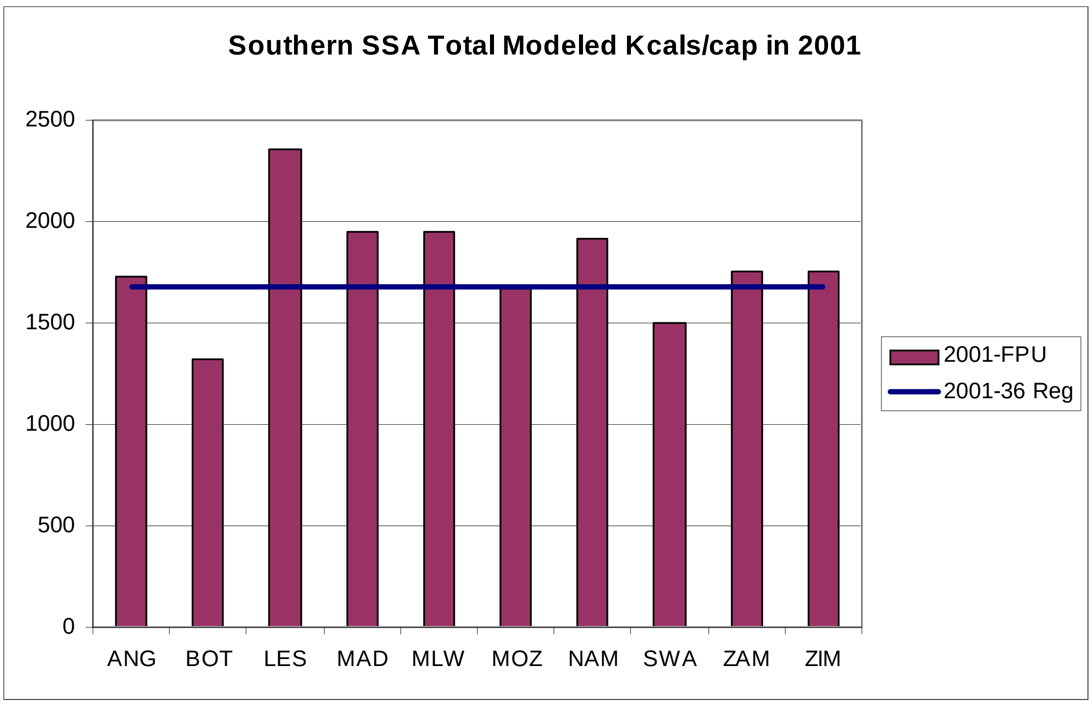


Figure 42 Total Crop Production Southern SSA in 2000



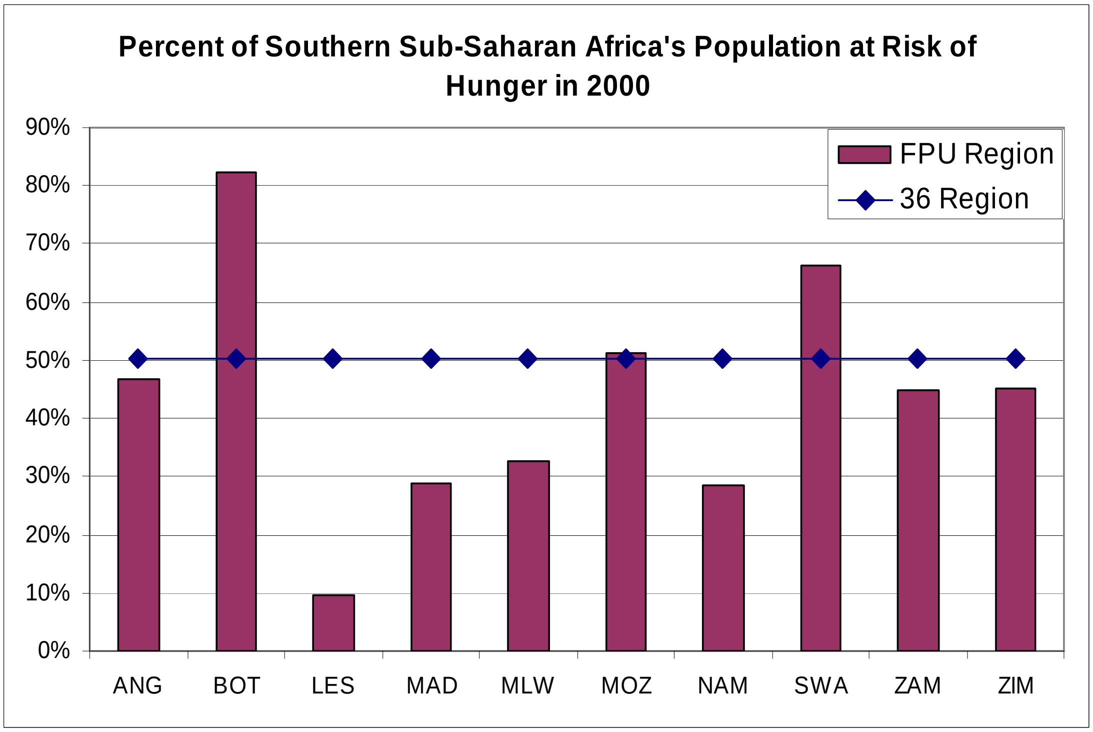
Southern SSA's total crop production is predominantly rainfed production (Figure 43). By disaggregating to the FPU version one is informed as to where in the Southern SSA region the crop production is occurring; predominantly in Angola, Madagascar, Malawi, Mozambique, Zambia, and Zimbabwe. The FPU version also shows that the small amount of irrigation is occurring mostly in Madagascar.

Figure 43 Total Food Consumption (modeled kcals/cap) in Southern SSA



Reported food consumption in both the 36 region version and the FPU version are fairly similar with slight variations among the FPU regions (Figure 44). While most regions experience the same average level of food consumption, the values vary above and below levels considered to be at risk of hunger.

Figure 44 Percent of Southern Sub-Saharan Africa's Population at Risk of Hunger in 2000



In the year 2000, the 36 region version reports that SSA has 50% of its population at risk of hunger while in the FPU version we see that Botswana and Swaziland are actually experiencing 82% and 66% respectively of their population at risk for hunger (Figure 45). The other remaining regions report 10-50% of their population at risk of hunger in the FPU region version; all at or below what was reported in the 36 region version. When we look at 2025, the population at risk of hunger in the 36 region version drops to 28% (Figure 46). Now, it's Angola, Madagascar, and Zambia in the FPU region version that report risks of 41%, 50%, and 30% respectively which is higher than the value reported in the 36 region version. The remaining regions are the same or lower than reported in the 36 region version from 1-28%.

Figure 45 Percent of Southern Sub-Saharan Africa's Population at Risk of Hunger in 2025

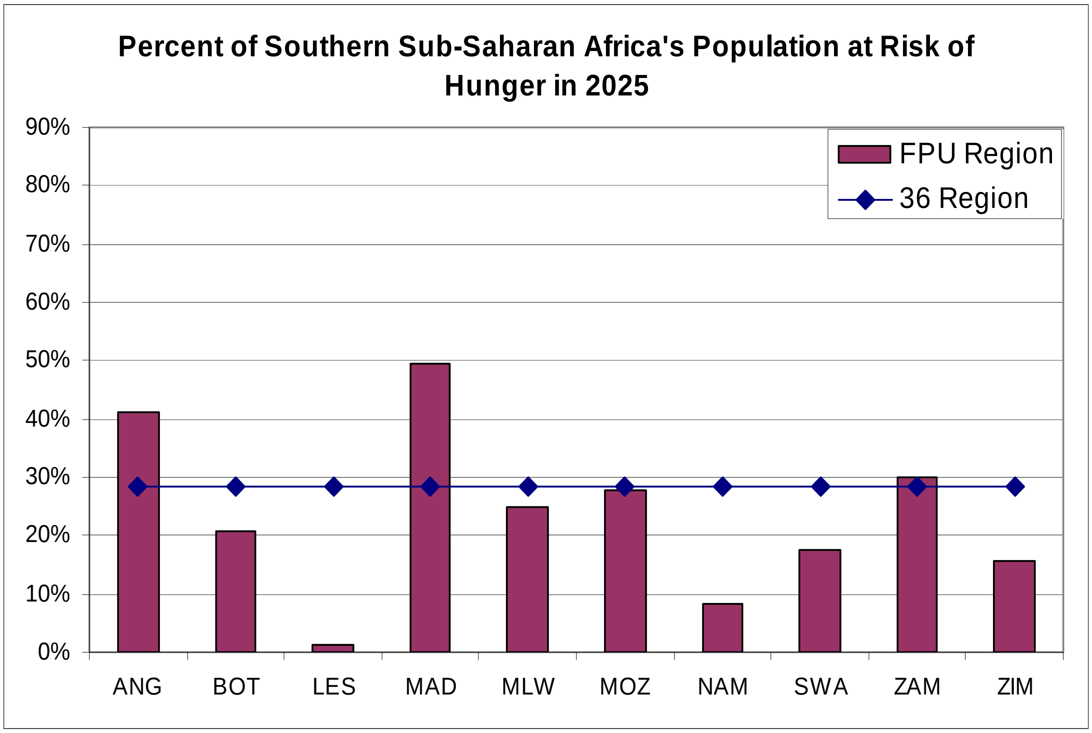
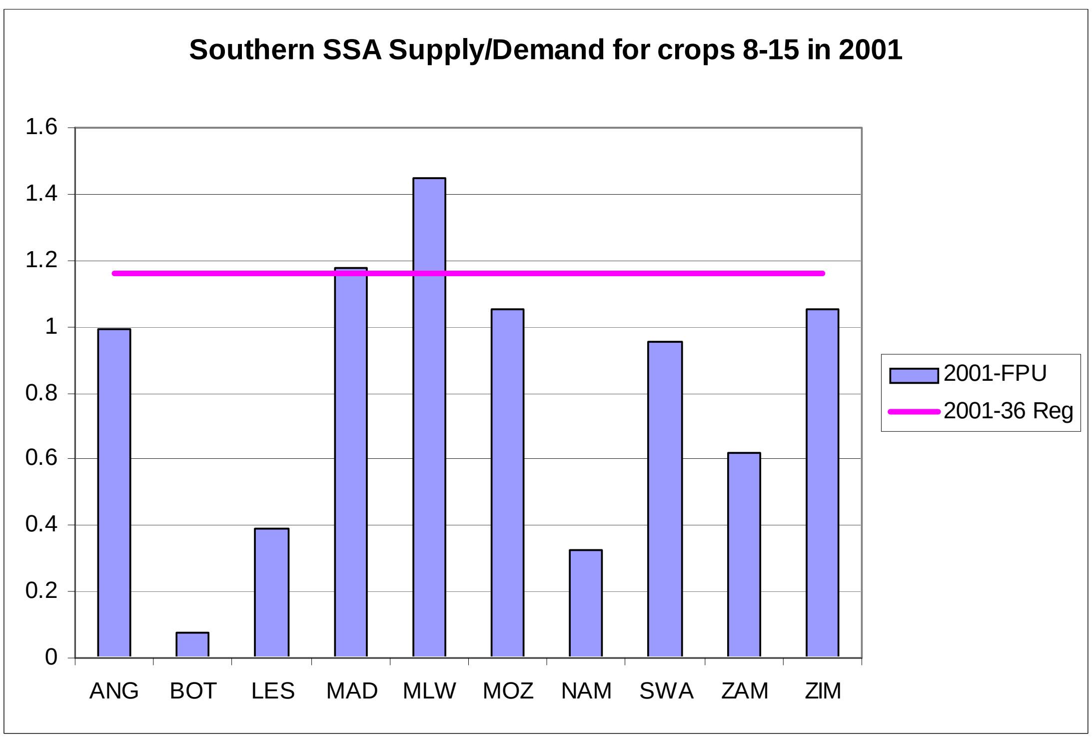
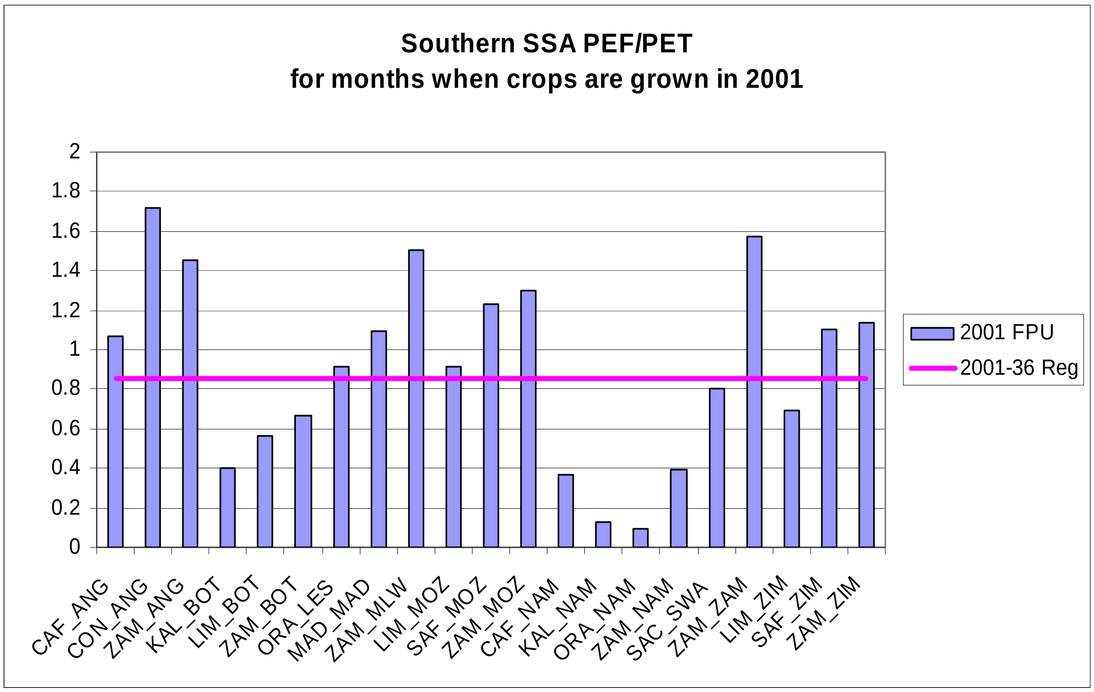


Figure 46 Food Security/Self Sufficiency in Southern SSA



The food policy indicator of food security/self sufficiency is reported quite differently for Southern SSA in the 36 region version versus the FPU version (Figure 47). The 36 region version shows Southern SSA as a net exporter with a value just over 1. When looking at the FPU regions, there are 4 regions (Madagascar, Malawi, Mozambique, Zimbabwe), that are net exporters and the remaining FPU regions are either net importers or approximately self sufficient as in Angola and Swaziland. These results are supported by comparing where crop production is taking place. The FPU regions where production is highest correlate to regions that are net exporters.

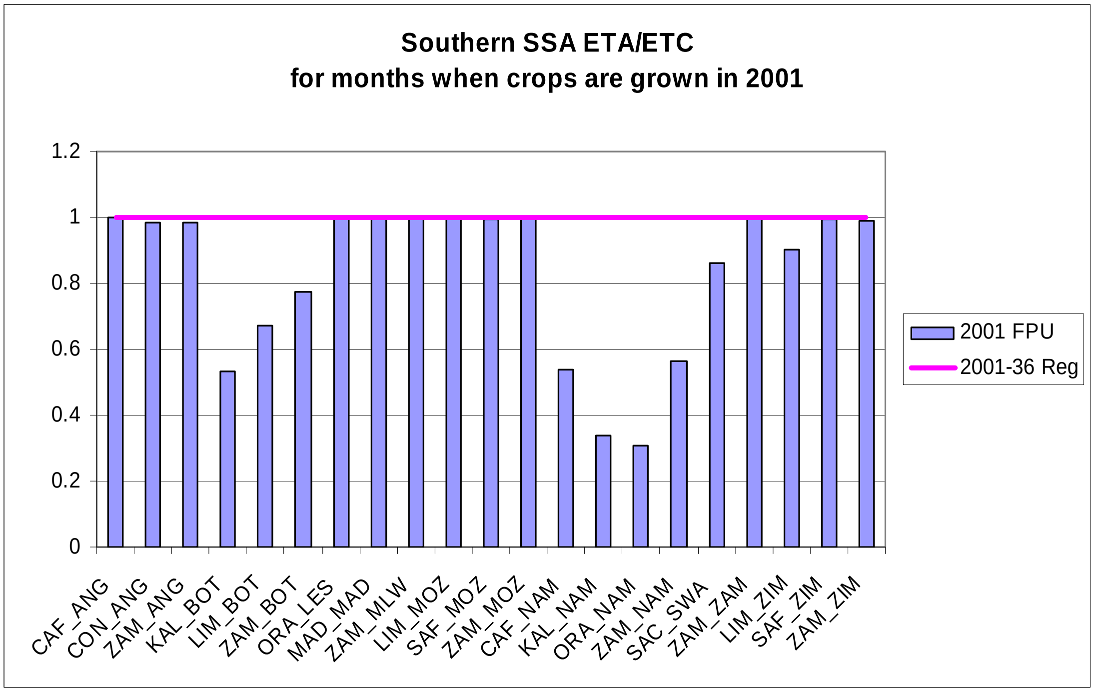
Figure 47 Rainfed Agriculture in Southern Sub-Saharan Africa



The hydro-climatology result of rainfed agriculture for Southern SSA in 2001 is varied (Figure 48). The 36 region version reports that there is not enough rainfall to meet rainfed irrigation needs, while the FPU version claims the same is true for some regions but not others. This can be explained by variations in climate as seen in the humidity index (Figure 41). For example, Namibia is a very dry area which correlates to very low PEF/PET ratios while Malawi is very humid and results in a PEF/PET ratio of over one. The 36 region version is not giving the whole picture for rainfed agriculture as seen with the FPU version results the region is quite varied.

In 2001, the hydro-climatology result of irrigated agriculture for Southern SSA in the 36 region version reveals that there is enough water available to meet irrigated agriculture needs. The results from the FPU version show that while most FPU regions have enough water available to meet irrigation needs, other FPU regions in Namibia, Botswana, Swaziland, and Zimbabwe do not (Figure 49). The lack of water available to meet the irrigation needs in these regions results in a decrease in irrigated yields and areas. These FPU regions are not significant contributors to the overall crop production (Figure 43).

Figure 48 Irrigation Water Supplied for Irrigated Agriculture in Southern SSA



As seen with the other previous region results, there is a very slight if any difference between the non-irrigation water demands (domestic, industrial, livestock) in the 36 region version compared to the FPU version for the Europe region (Figure 50). Therefore only the results from the 36 region version are presented.

The irrigation water supply for agriculture in Southern SSA is higher for the 36 region version compared to the FPU version (Figure 51). This difference is due to the irrigation water demanded in the 36 region version being significantly more than that demanded by the FPU version (Figure 52). These demands are different between the two spatial representations of the model because of the combination of the varying climate throughout Southern SSA correlated to where irrigated agriculture is taking place. The 36 region version overestimates irrigation demand by underestimating the PEF/PET ratio. By overestimating irrigation demand, the 36 region version is underestimating the amount of water available for the environment.

Figure 49 Non-Irrigation Water Demand in Southern SSA

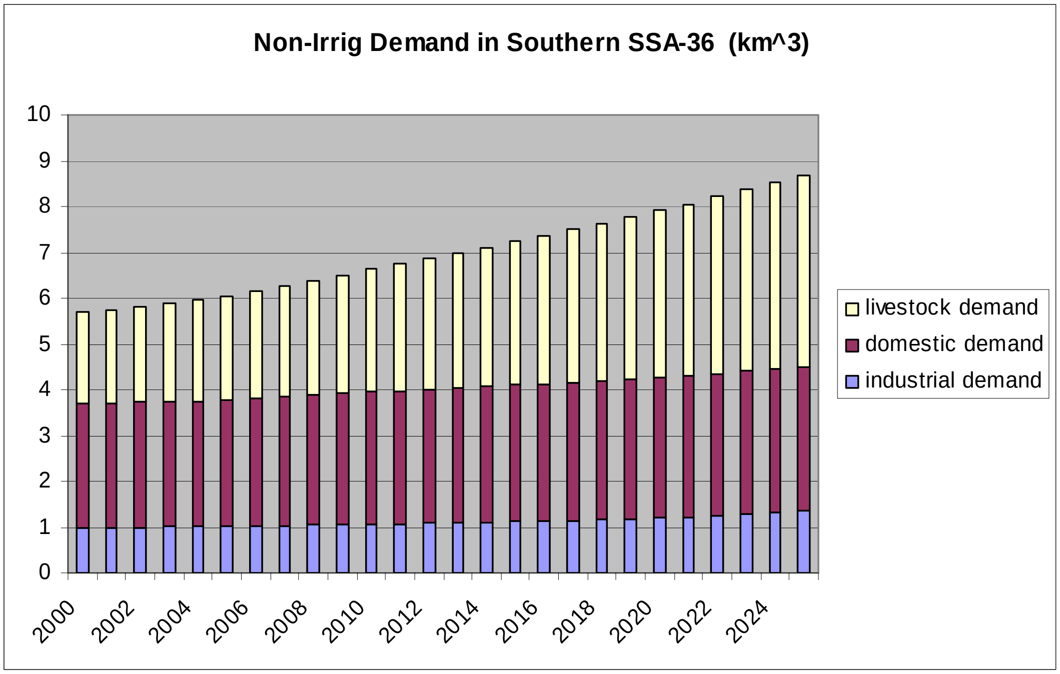


Figure 50 Irrigation Water Supply for Agriculture in Southern SSA

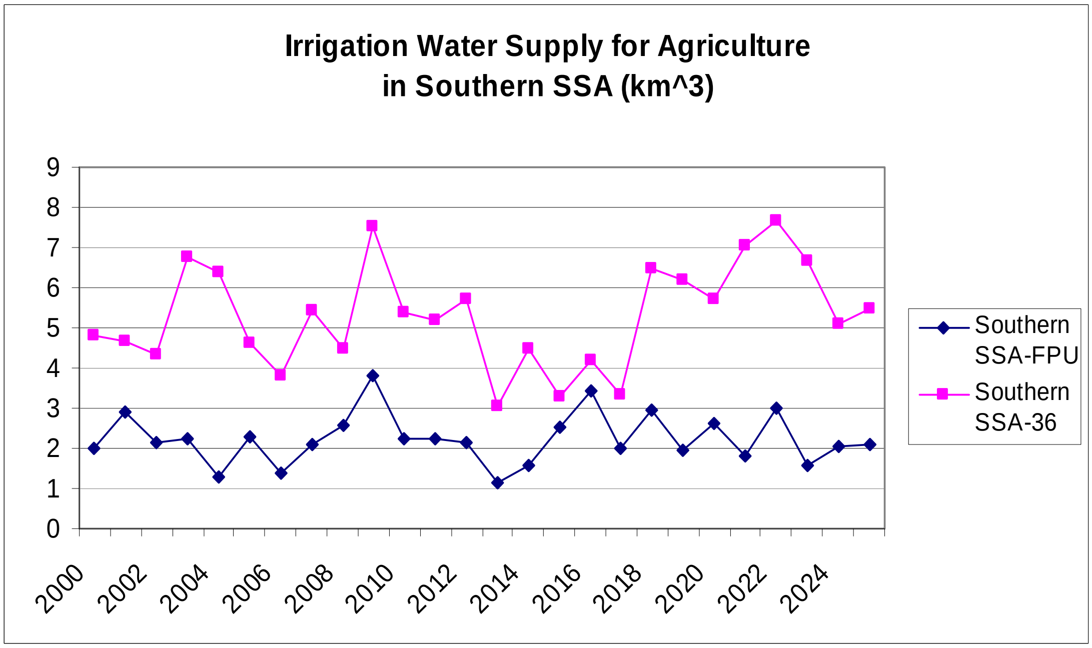
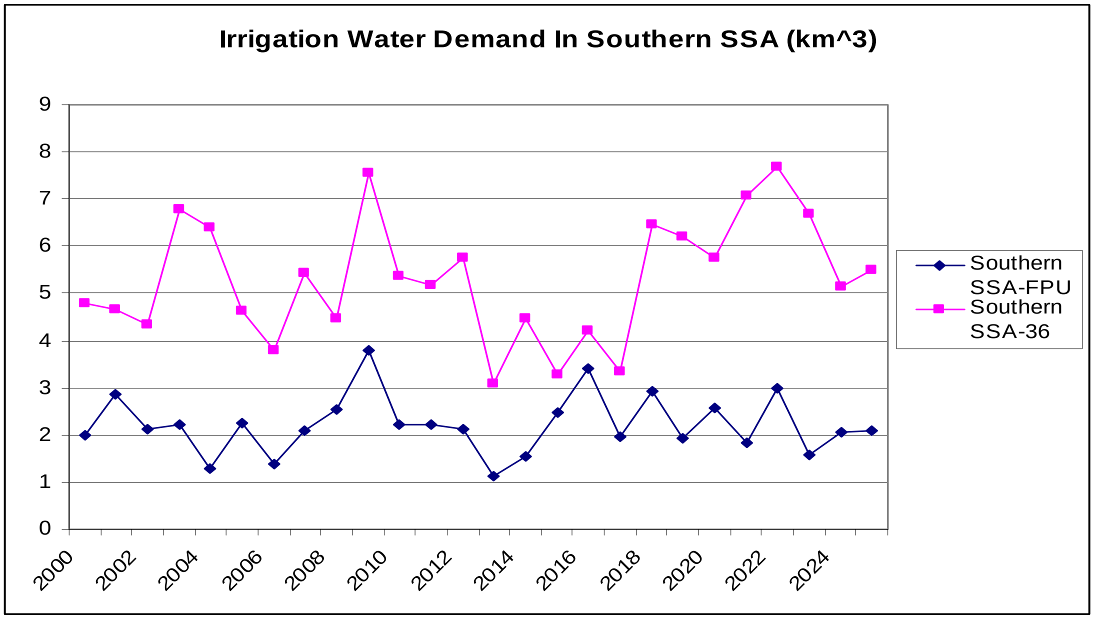


Figure 51 Irrigation Water Demand in Southern SSA



In summary of evaluating the Southern Sub-Saharan Africa region in both the 36 region version and the FPU version of IMPACT-Water, the results are different for most food policy indicators. The average population throughout this region is roughly of the same economic status resulting in fairly similar food consumption. Due to the amount of calories available boarding above and below undernourishment, there is a significant differences among the regions and their population at risk of hunger. The high climate variability in this region contributes to differences in food production, food security/self sufficiency, and hydro-climate outcomes in Southern SSA's FPU regions. The 36 region overestimates irrigation demand because of the aggregation of PET and PEF. By overestimating irrigation demand, the 36 region version is also underestimating water available for the environment.

Limitations of Global Study

While this study provided a number of sound conclusions regarding the importance of spatial scale on hydro-economic modeling, there are some limitations. The first limitation is that the results are based solely on an analysis performed on the IMPACT-WATER model. One could perform the analysis on other water and food models and compare findings. Building on this limitation is the fact that the data used in the IMPACT-WATER model has not been scrutinized. The data was provided by an outside source and used in the model without much analysis done on the data alone. Along the lines of data issues is also the fact that hydrologic data is available at 0.5°x0.5° so obtaining data at the disaggregated spatial scale is not a problem while economic data is mostly national so there is a limitation on how to disaggregate this data .

The analysis was only performed on two different spatial representations of the IMPACT-WATER model. It would be interesting to try other spatial disaggregations and aggregations of the model to compare findings. Another limitation is the analysis only compared one base scenario between the two spatial representations of the IMPACT-WATER model. It is desirable to look at various scenarios for example adding tariffs, subsidies, climate change, etc. and compare the affects of spatial scale on these scenarios. Lastly, it would be interesting to evaluate more case studies. Most conclusions from this study are based on results from three case studies. More case studies would help solidify the conclusions.

Summary of Global Study

IFPRI's IMPACT-Water model was evaluated at 2 different spatial scales (69 basins vs 281 basins-FPU version) and the results from each version were compared to answer the following research question: "What is the importance of spatial scale on hydro-economic modeling used to address environmental and hunger policy questions?" A number of environmental and hunger policy indicators were evaluated for three case studies of Central Asia, Europe, and Southern Sub-Saharan Africa.

An analysis on the percent of the population at risk of hunger was performed for Central Asia and Southern Sub-Saharan Africa. The results were quite varied between the two different spatial representations. While the 36 region version provides an 'average' value for the region, the FPU region version shows that depending on the sub-region the population could be at a much higher risk of hunger while others may be significantly less. This has great impact on informing policy makers about which populations are truly at a significant risk for hunger.

Total crop production at the more detailed scale gives insight as to where crops are being grown in the 2000 base year. As time goes by, variations in crop production between the two spatial scales can be explained by the climatic heterogeneity the region. The more heterogeneous a region's climate, the more variation one will see with total crop production between the two different spatial scale models.

Food security/self sufficiency can have quite different results depending on the spatial representation of the model. The two spatial scale models may both report a region to be a net importer or a net exporter, but the FPU version may reveal that there is predominantly one or two areas in the region that are contributing the exporting or importing as was the case with the Europe region. This variation was masked by the 36 region version. The differences are most directly related to crop production which is affected by the climatic heterogeneity of the region.

Non-irrigation water demand is very similar between the two spatial scale models because the drivers for these demands are the same between the two spatial scales and fairly homogeneous across the regions.

Irrigation water demand is a function of potential evapotranspiration and effective precipitation (Irrigation Demand = PET – PEF). When these hydro-climate variables are aggregated one may overestimate irrigation demand or underestimate irrigation demand depending on the climate relative to where the crops are grown. This was seen in Europe, a fairly humid region, where the 36 region version reported a lower irrigation demand than the FPU version. Similarly in Southern Sub-Saharan Africa, a fairly semi-arid region, where the 36 region version reported a much higher irrigation water demand.

Water available for irrigation is a combination of the irrigation water demanded by the crop as mentioned above and the water available in the region to give the crop. The available water in the region is the water available after all non-irrigation water demands have been met. If a region is climatically heterogeneous then one risks overestimating or underestimating available water when aggregating. There is also a risk for overestimating available water in regions that have a large body of water, river or wetlands.

The determination of the water available for irrigation directly affects the water available for the environment because any water remaining in the system after irrigation agriculture demands have been met will go to nature. By overestimating the water available for irrigation, one underestimates the water available for nature and visa versa.

In revisiting the CGIAR's Challenge Program Theme 5, one can ask how analysts answer the proposed research questions. The answer is through the use of global and national scale models as discussed in this research. The last question is how does the research presented here inform the modeling details of Theme 5? This research concludes first that global modelers must use caution in their spatial aggregation and second that food policy is not simply hydrology or economics, it is hydro-economics.

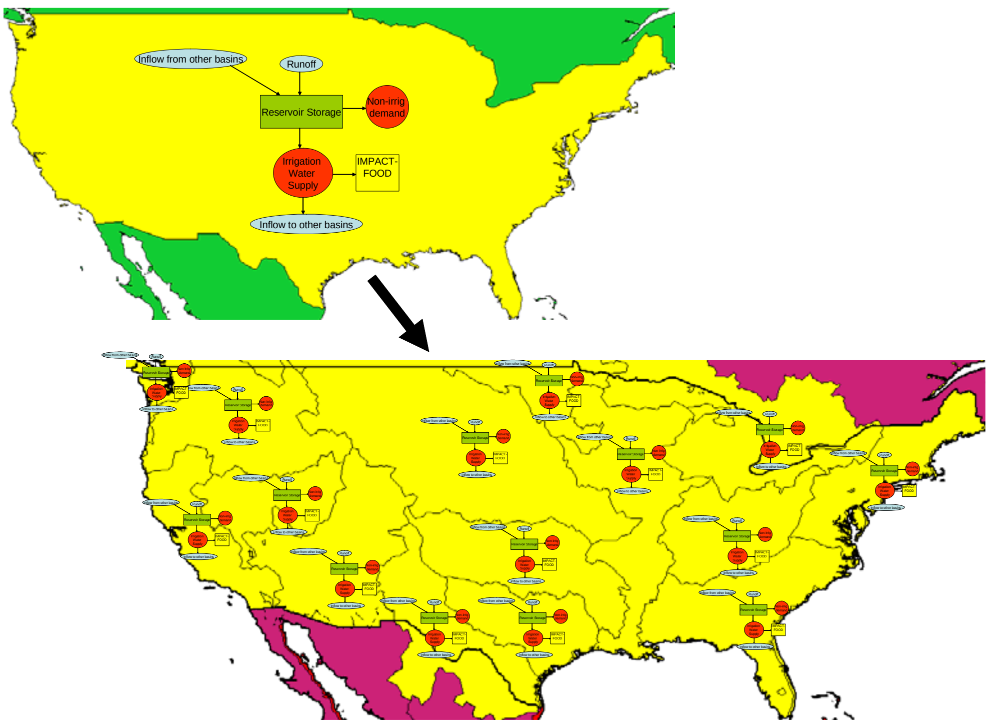
In summary, results from this analysis imply that spatial scale does have an impact on model results used to inform environment and hunger policy. Impacts are stronger in regions of economic and hydro-climate heterogeneity.

CHAPTER 3

FROM GLOBAL AND NATIONAL SCALES TO RIVER BASIN SCALE

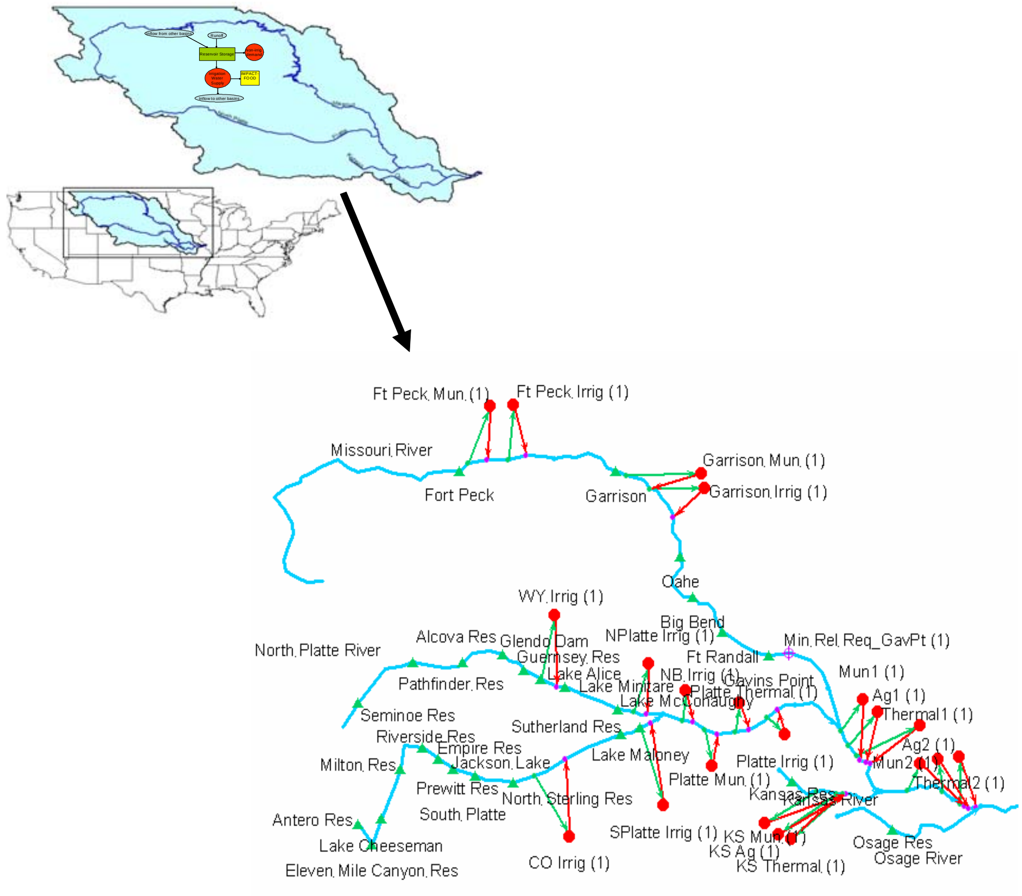
In the previous chapter, the IMPACT-Water model was evaluated at two different spatial scales; from 36 regions and 69 basins to 115 regions and 281 basins. Figure 53 shows an example of this disaggregation of the spatial scale. Conclusions from this evaluation indicate that spatial scale does have an impact on hydro-economic modeling of global and national food and water systems to address environmental and hunger policy questions. In addition, impacts are stronger in regions of economic and hydro-climate heterogeneity.

Figure 52 Example of Disaggregating Spatial Scale



Knowing that spatial scale does have an impact, is going from 36 regions and 69 basins to 115 regions and 281 basins enough disaggregation to get an accurate representation of what is happening with environmental and hunger related issues? To answer this question, the disaggregation was taken to yet another level for analysis. In the following chapter the importance of spatial scale and management on river basin modeling for global food production is evaluated. A number of case studies were disaggregated from the spatial scale representation presented in chapter 2 to various more detailed levels of disaggregation as seen with the example of the Missouri River Basin in Figure 54.

Figure 53 Example of Disaggregating at the River Basin Scale



CHAPTER 4

EVALUATING IMPORTANCE OF SPATIAL SCALE AND MANAGEMENT ON RIVER BASIN MODELING FOR GLOBAL FOOD PRODUCTION

Background

The issue of scale, whether spatial, temporal, or a combination of the two, continues to be a topic of debate throughout many disciplines. Water resources modeling is no exception. Attempts to globally model the world's water resources span over a variety of spatial scales. The purpose of this paper is to evaluate the importance of spatial scale and management at the river basin level for global food production.

Previous Studies on Scale

There have been attempts to address the issue of scale from various scientific approaches (Booij, 2003, Currit 2000, Antle et. al. 1999, Mamillapalli et. al. 1996, Irwin and Geoghegan 2001, Mitchel 1996.) "The scale of analysis can affect the value of information produced as well as the cost of that information." (Antle et.al. 1999) It is this balance between improved reliable results and cost of the study (in both time and money) that one wishes to achieve. Antle proposes a theoretical framework for characterizing the economically optimal spatial scale for conducting analysis of spatially variable economic and bio-physical processes.

Maximizing net benefits of information produced is Antle's definition of the economically optimal spatial scale. Antle applied his framework to carbon sequestration policy and found the economically optimal scale for analysis to be an increasing function of the scale at which the observed data exhibit maximum variability and the heterogeneity of the data. Also, the optimal number of data points is decreasing with the unit cost of data collection, and increasing as the per unit value of the outcome increases.

Currit explains that while Ordinary Least Squares (OLS) regression has been used to model relationships between variables operating at different scales, most hydrologic/agronomic models violate a key assumption of the OLS – the assumption of independence of observations. Currit proposes the use of the General Regression Neural Network (GRNN) that makes no assumptions about underlying data distributions, does not require independence of observations, and does not require a predetermination of the type of function operating between variables (i.e., linear, exponential, etc.) According to Currit, GRNN is a reliable predictor and capable of determining which input variables in a multivariate analysis are most influential in determining an output, but also has limitations in not being able to provide confidence intervals for its output, not providing standardized smoothing factors, and not being able to take into account uncertainty in the data.

From a hydrologic point of view, Booij studied the appropriate hydrological modeling of climate change impacts on river flooding. Booij identified the dominant processes and associated key variables and performed statistical analyses with respect to the key variables. This resulted in appropriate spatial and temporal scales for each key variable and relationships between the key variable scales and the output variable. These relationships were used to combine the appropriate scales to one model scale. Booij then selected mathematical process descriptions consistent with the model scales. “The appropriate spatial model scale turned out to be around 10km with a daily time step.” (Booij 2003)

Mamillapalli et. al. evaluated the spatial variability on basin scale modeling with a case study on a watershed in Texas, United States. The study found that in general, increasing level of discretization and increasing the number of soil and landuse combinations simulated within each subbasin increases the accuracy of the simulation. Mamillapalli et. al. also states that there is a level beyond which the accuracy can’t be improved, suggesting that more detailed simulation may not always lead to better results. Another interesting conclusion from Mamillapalli et. al.’s work is that from the different time periods considered, some of the coarser levels of discretization may perform well for one period, but not perform well for another period, whereas the finer simulations performed well throughout. This may suggest that climate may also influence the affect of scale.

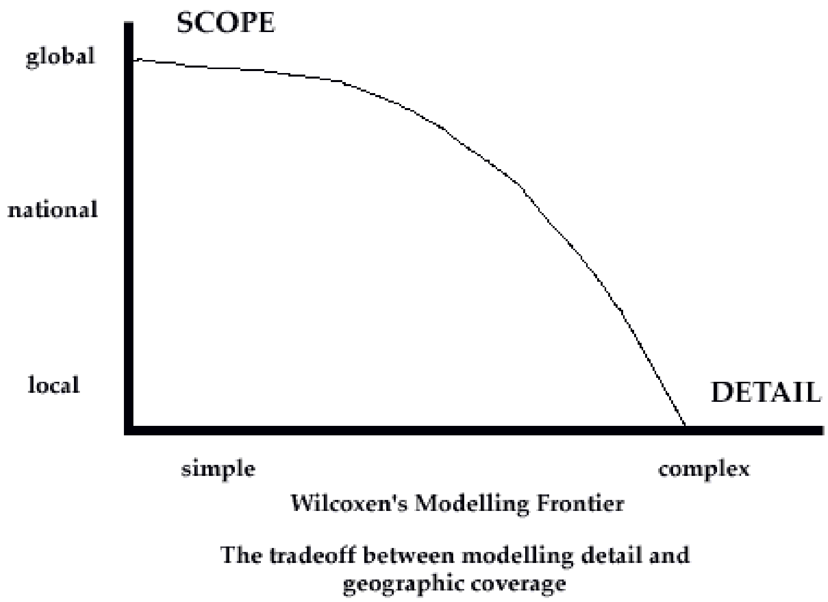
While these studies are all informative regarding the issue of scale, not one of them is applied at a global scale. One can use these studies for insight into impacts of spatial scale on global modeling, but the level of statistical analysis seen in these studies is unfeasible to perform at the global scale. This leads us to why the research set forth in this document is necessary.

Irwin and Geoghegan looked at the development of spatially explicit economic models of land use change. They concluded that “not taking into account spatial dependence or spatial heterogeneity when estimating a model can lead to biased or inconsistent estimates and false conclusions regarding the sign and significance of parameter estimates” (Irwin and Geoghegan 2001).

Mitchell looked at the effect of spatial resolution on estimating hydrologic responses and economic value of an urban forest. He found vastly different results between using data from site-survey and aggregated aerial photography. He concluded “spatial aggregation must be used with care. Maps are models. As in other modeling applications the scale of information processing must be adequate to support the information necessary to make proper management decisions.” (Mitchell 1996)

Evaluating spatial scale on a case by case basis is not always desired as seen in global models where the goal is to perform a consistent analysis encompassing the globe. Peter Wilcoxen from Texas A&M University proposes the modeling frontier (Figure 55.) This reflects modelers’ limited ability to handle the two dimensions, geographical scope and modeling detail simultaneously. His point is that only an omniscient deity could create a model capable of supporting locally and sectorally disaggregated coverage of the entire global change problem.(CIESIN 1995) While Wilcoxen’s Modeling Frontier is a hypothesis of how geographical scope and modeling detail interact, the research presented here will test this hypothesis and make further conclusions on the tradeoff.

Figure 54 Wilcoxen's Modeling Frontier

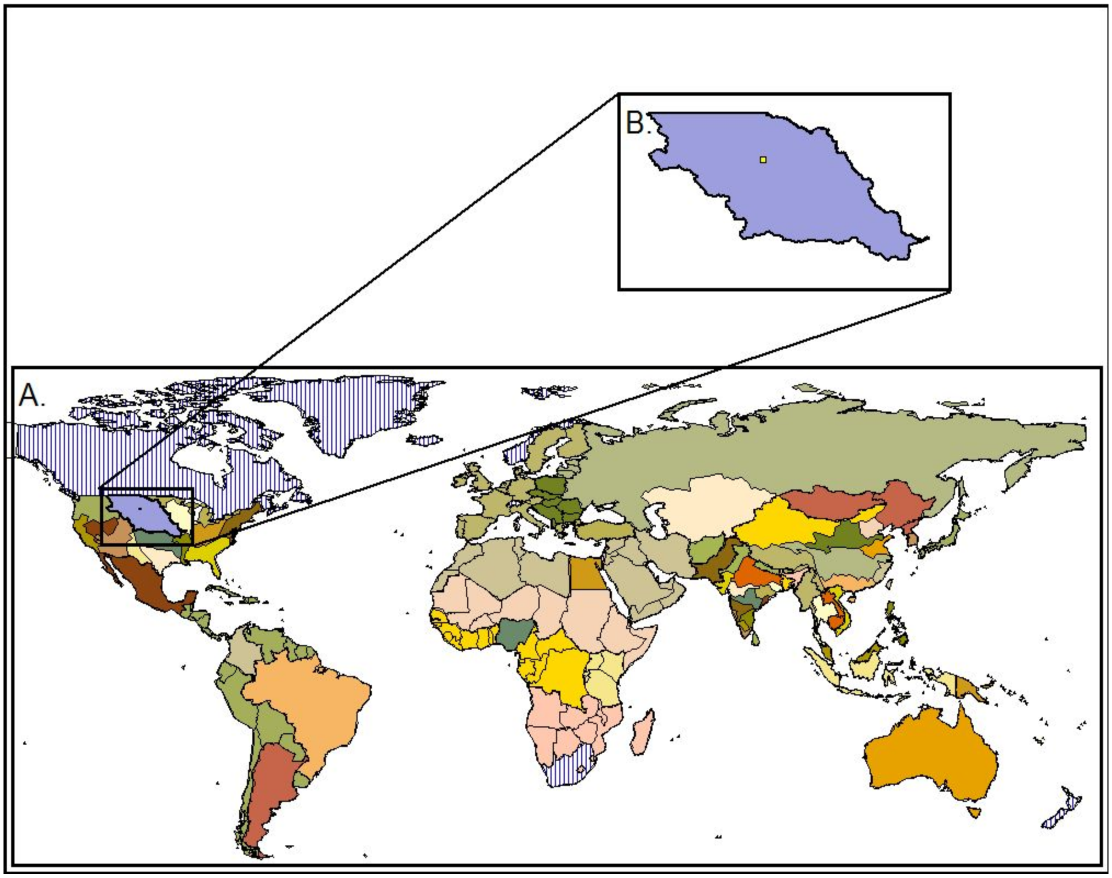


Examples of global river basin modeling

One attempt at global river basin modeling has been developed by the Center for Environmental Systems Research at the University of Kassel, Germany. Their global integrated water model WaterGAP 2.1 operates with a spatial resolution of 0.5º (Figure 1). This raster-based model is designed to simulate the characteristic macro-scale behavior of the terrestrial water cycle, including the human impact, and to take advantage of all the pertinent information that is globally available. While data is becoming more readily available, it is still very difficult to obtain data in many areas of the world at the country level, not to mention at a scale of 0.5º. Their approach takes country level domestic and industrial water demand data and disaggregates it by a 0.5º population dataset. Livestock and irrigation demands are based on gridded 0.5º datasets. Each 0.5º cell is associated with one of 13 world regions that area used to develop scenarios.

Another example of a global model is the Impact-Water Model produced by the International Food Policy Research Institute (IFPRI) in Washington D.C. (Figure 56). This model incorporates water availability as a stochastic variable with observable probability distributions to examine the impact of water availability on food supply, demand, and prices. This model is operated by dividing the globe into 69 basins (with some regions of more intensive water use broken down into several basins, including China, India, and the United States.) When dividing the globe into this number of basins, one must take care in aggregating regions. For example, as seen highlighted by blue stripes in Figure 1, one basin in the Impact-Water Model includes South Africa, New Zealand, Canada, Greenland, Iceland, Norway, and Switzerland. This collection may make sense for modeling some aspects of agriculture and development, but the climates are quite varied and it is difficult to aggregate the water characteristics of these countries into one basin.

Figure 55 Scale comparison of models.



Note: Box A. represents the 69 basins used in IFPRI's Impact-Water Model.
Box B. puts in perspective one 0.5º x 0.5º grid cell at which scale the WaterGap model is conducted.

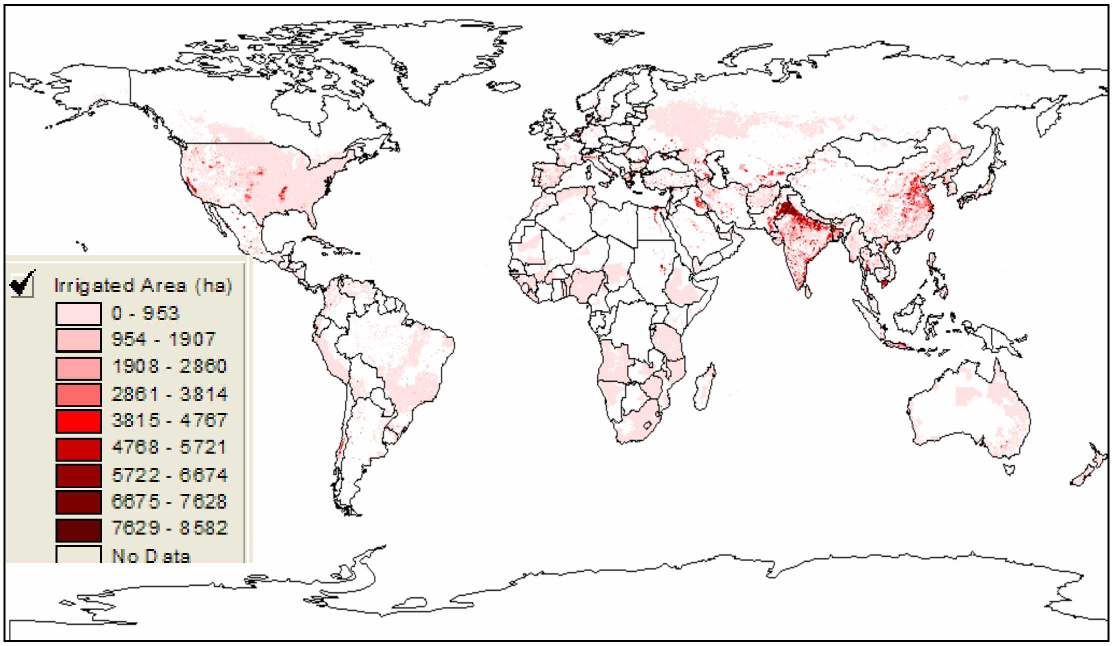
When deciding upon a proper scale at which to model, one must take into consideration what questions are being asked by the model. Is it socially and economically focused where political boundaries are important? Is it hydrologically focused where basin/runoff boundaries are important? Most likely it is both, which brings us to the debate of how to combine boundaries where both analyses are equally important and properly modeled.

Basin Characteristics

From a global modeling perspective, the importance of a basin representation's spatial scale is dependent on five main characteristics:

- Importance of the basin to global irrigated crop production
- Sequence of the supply, storage, and demands
- Layout of the river system (is the river system in series or parallel)
- Number of climate zones
- Level of management in basin
- Level of infrastructure in basin

Figure 56 Global Irrigated Area



An important basin characteristic when evaluating the issue of spatial scale is the basin's contribution to global irrigated crop production (Figure 57). In other words, should we be concerned about creating a more detailed and representative model if the basin does not contribute significantly to the global irrigated crop production? Irrigated agriculture is the largest demand for water across the globe. Of course one should also be concerned about correctly modeling water available for domestic and industry. In many global models these demands are given priority over agriculture, therefore they are implicitly taken care of. The main reason for having this as an important basin characteristic is to answer the question frequently asked, "Who cares?" If the majority of the globe's irrigated crop production is not being correctly modeled, then models that claim they have projections of future crop production, world agricultural markets, economic development, etc. need to take much caution in what their results are stating.

Each basin representation can be categorized by its sequence of water supply (i.e. location of majority of runoff), storage (i.e. reservoirs) and demands (i.e. domestic, industrial, agricultural). In most river basin analyses, representation the sequence of supply, storage, then demand is used where supply is aggregated and applied at the top of a basin then it is fed into a storage system and drawn on by demands below. In some cases, this is not the actual basin layout. For example, there may be little storage above the demands. The impact the sequence of supply, storage and demand has a basin's representation is evaluated by theoretical case studies in the next section.

Another important basin characteristic is the layout of the river system in the basin. Some basins contain one main long river that is fairly streamlined; these basins have rivers in series (Figure 58). Other basins have a number of significant river systems running throughout the basins; these basins have rivers in parallel (Figure 59). The impact a river system's layout has on the issue of modeling scale can be best analyzed by the case studies chosen in the next section.

Figure 57 Example of River System in Series– Yellow River Basin

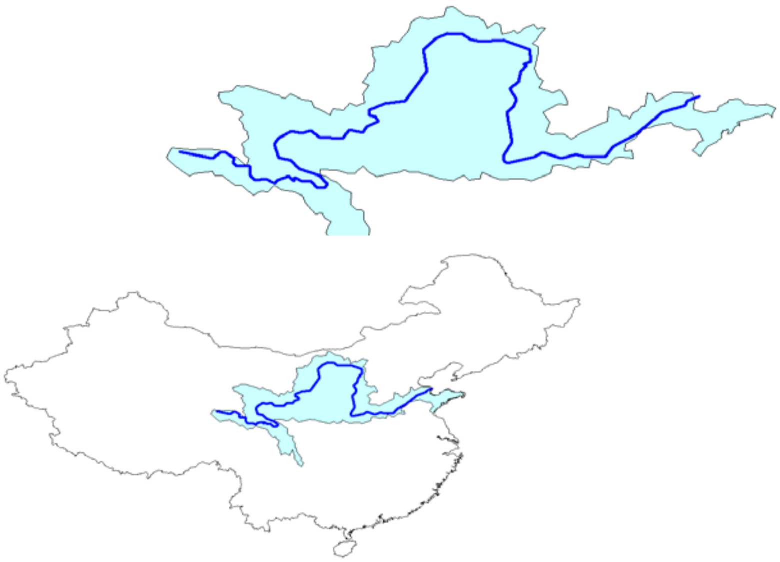
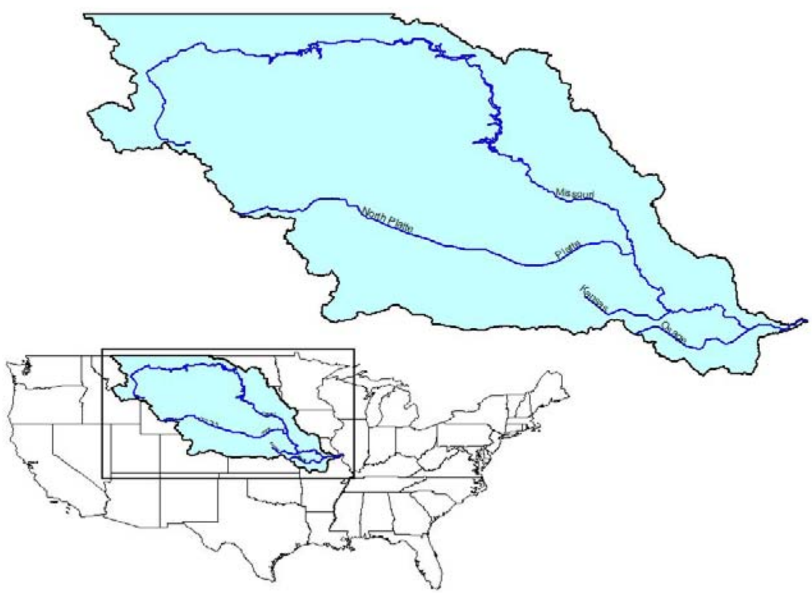


Figure 58 Example of River System in Parallel – Missouri River Basin



The number of climate zones in a basin is an important basin characteristic as it gives insight as to how the hydrology is distributed across the basin. This characteristic will draw attention to areas that may have a potential issue where water is located in one area of the basin; potentially not available where it is needed. The number of climate zones is based on the humidity index (UNEP 1991).

The importance of management will be evaluated by performing an analysis on one of the case studies. For the purpose of this study, management represents operational constraints in the basin. For example, how a reservoir is operated and/or flow requirements on the river.

In addition to the above basin characteristics, the level of infrastructure in the basin can give insight as to whether or not the basin can cope with difficulties in getting water from one location to another where it is needed. An estimate on the level of infrastructure in a basin is based the total storage in the basin relative to the total average annual runoff in a basin. Ratios less than 0.6 have low levels of infrastructure. Ratios between 0.6 and 1.2 have moderate levels of infrastructure and ratios over 1.2 have heavy levels of infrastructure.

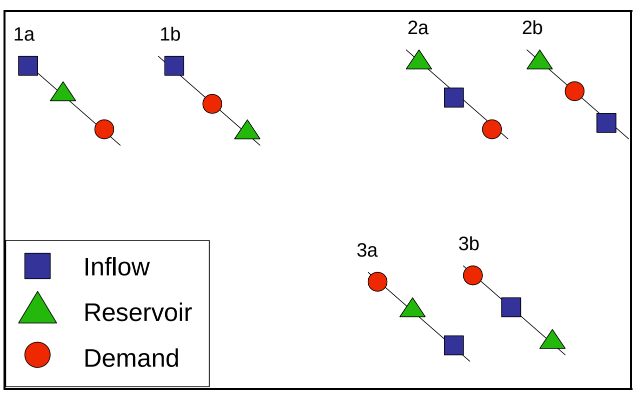
Case Studies

A number of case studies were compiled to address the importance of spatial scale and management on river basin modeling for global food production. The first case study involves a theoretical analysis on the sequence of supply, storage and demands. The next set of case studies involves specific basins where the spatial scale of the basin representations was varied in sequence to compare the importance of spatial scale on demand coverage, reservoir storage, hydropower, and relative crop production. An analysis that evaluated the importance of modeling management was also completed on one of the basins.

Theoretical Analysis on Sequence of Supply, Storage and Demands

In order to evaluate the importance of sequence of supply, storage, and demands along a river, six hypothetical situations were modeled in WEAP21 (Figure 60.) The WEAP21 (Water Evaluation and Planning) model is a river basin water balance model and is described in Appendix E.

Figure 59 Hypothetical Sequences of Supply, Storage, and Demand



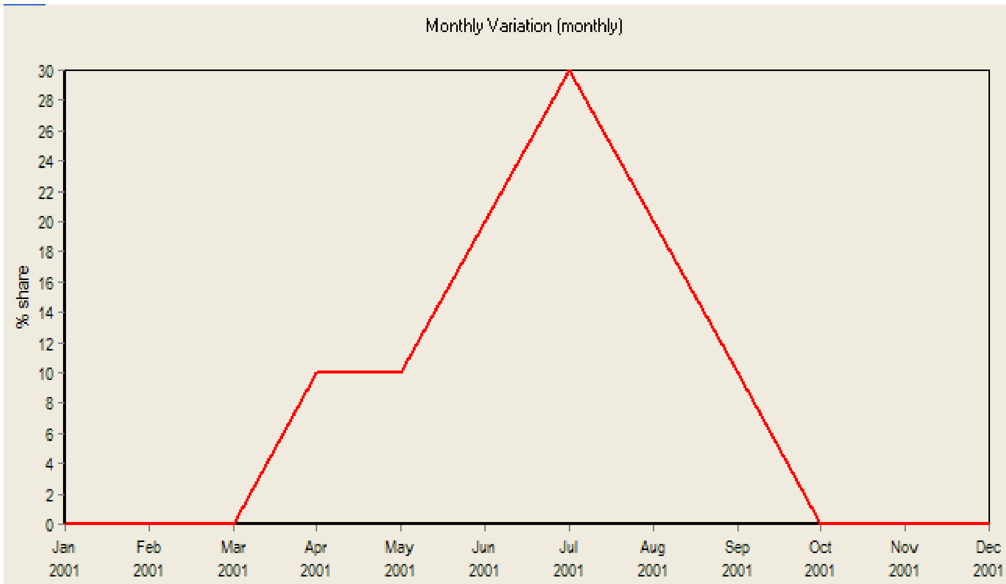
The six different representations of sequence represent the different possible sequences of having supply, storage, and demand on a river. The same values were used in each analysis:

Inflow = 100 cms

Reservoir = 5 billion m^3 capacity (initially full)

Demand = 1 billion ha; 2.5 thousand m^3/ha

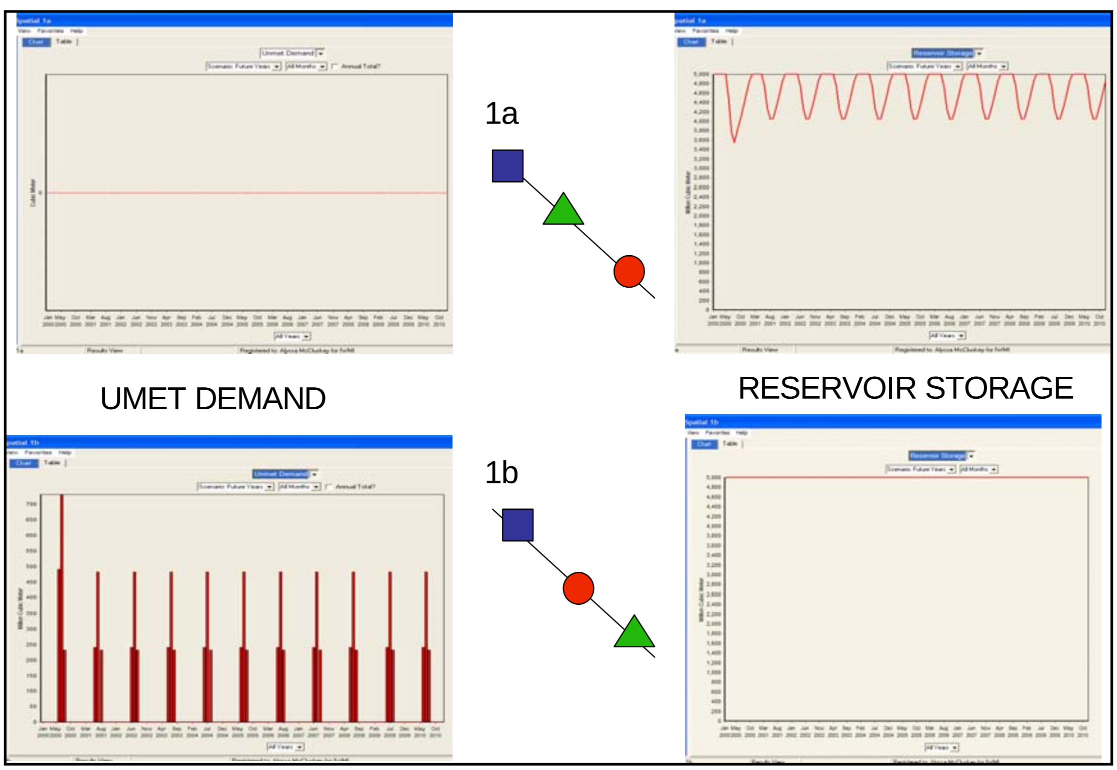
Figure 60 Monthly Distribution of Demand in Sequence Analysis



The monthly distribution of the demand is shown in Figure 61.

The results from this analysis show that the sequence of supply, storage, and demand greatly impacts the amount of demand met and reservoir storage. In most river basin analyses, representation 1a is used where supply is aggregated and applied at the top of a basin then it is fed into a storage system and drawn on by demands. In some cases, this is not the actual basin layout; there may be little storage above the demands as in representation 1b. It is unlikely to see basin layouts similar to 2a&b and 3a&b, but for this theoretical analysis, it is interesting to look at all possibilities.

Figure 61 Results from Sequence Analysis 1a and 1b



In the 1a representation of supply, storage, then demand, all demands are met and the reservoir storage shows slight fluctuations as the storage is drawn down during summer months for the agricultural demand (Figure 62). By switching the sequence of the reservoir and demand, we see that there is a significant amount of unmet demand and the reservoir is staying at capacity.

In the 2a representation of storage, supply, then demand, the reservoir slowly draws down its initial storage until depletion where the reservoir goes dry and demands are now only partially met by current available supply (Figure 63). By switching the demand and supply positions, the reservoir draws down much quicker and all of the demand is being unmet because there is no source of supply.

In the 3a representation of demand, storage, then supply, we see that the reservoir storage remains at capacity while none of the demands are being met (Figure 64.) There is no difference when the storage and supply switch locations because the initial storage is set at the capacity, although now all of the supply in 3b is being spilled from the reservoir.

Figure 62 Results from Sequence Analysis 2a and 2b

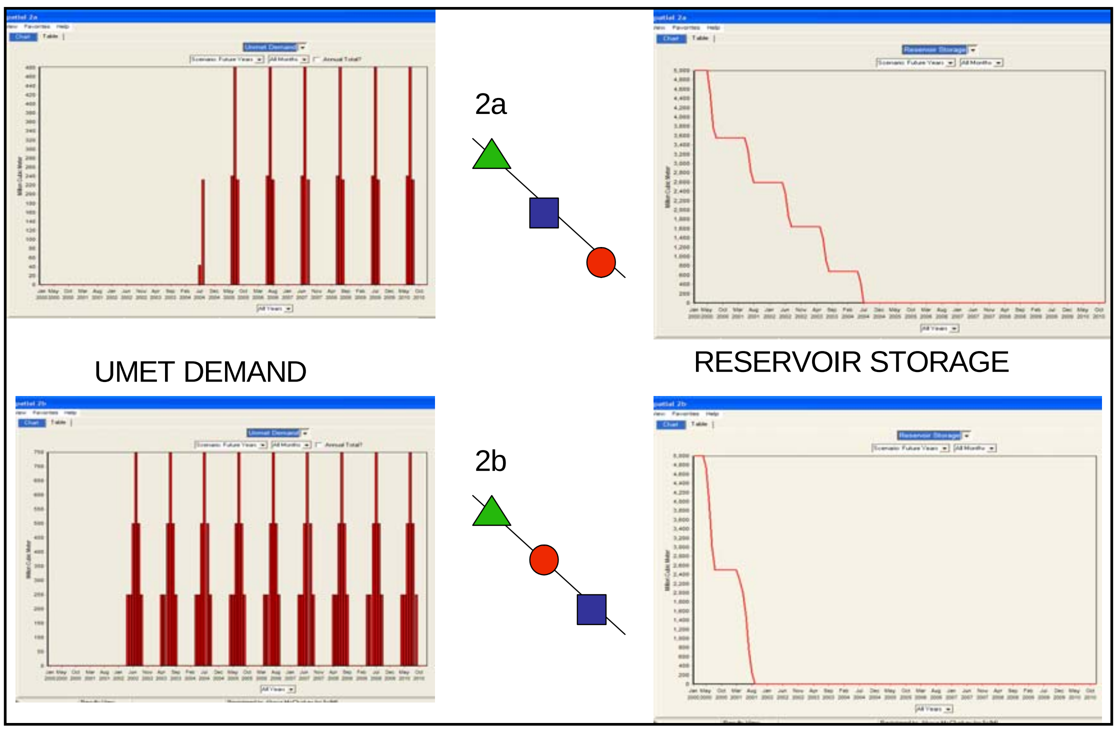
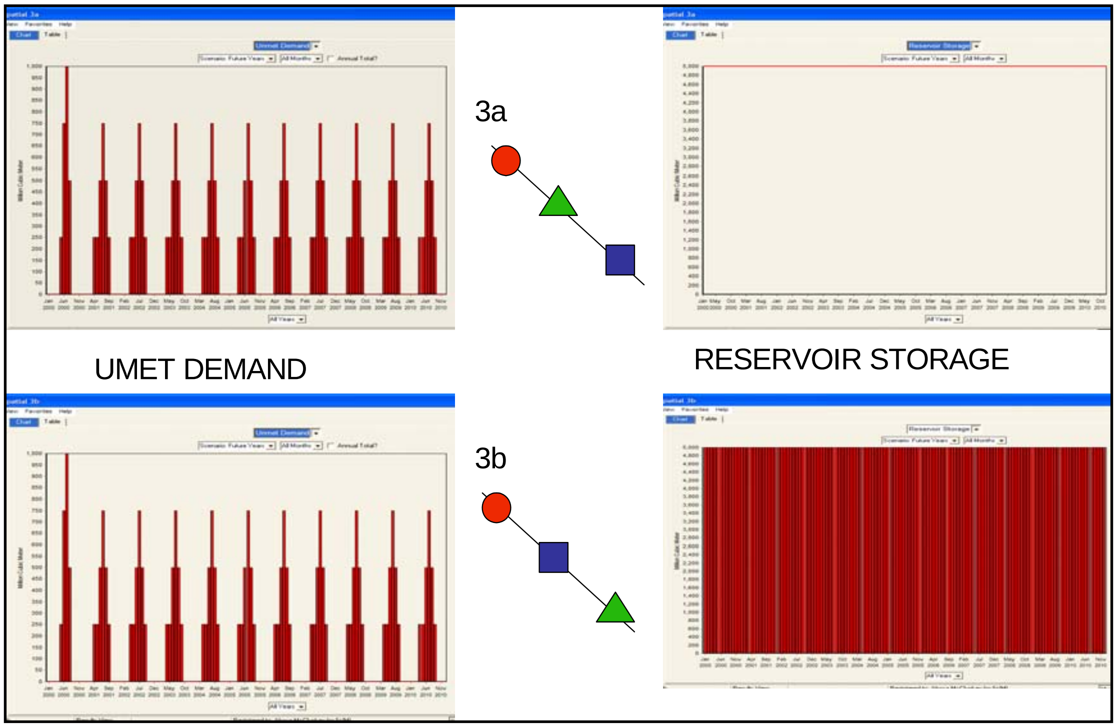


Figure 63 Results from Sequence Analysis 3a and 3b



In conclusion, it is important that the sequence of supply, storage and demands are properly represented as this does impact the results of the analysis.

River Basin Case Studies

To evaluate the importance of spatial scale and management on river basin modeling, the following four river basins were chosen as case studies:

1. Missouri River Basin, United States
2. Senegal River Basin, Western Africa
3. Yellow River Basin, China.
4. Volta River Basin, Western Africa

The basins were selected based on their different spatiality issues. The basins were represented in a stylized format using the Water Evaluation And Planning (WEAP) model (Appendix E). While the representations may not be exact in terms of matching precise supply and demand in each basin, they fully represent the spatial conditions in each area.

The basins were delineated using Arc View and a river basin network at a 0.5° x 0.5° scale. The runoff data for each basin (except the Volta Basin) was derived using a gridded global water balance model at the same 0.5° scale (Appendix A.) The demands and reservoir capacities were aggregated into larger basins by summing their values.

The hydropower is a difficult parameter to aggregate. For the purpose of this exercise, we assumed that there was no minimum turbine flow, a system efficiency of 75%, and power capacity was the aggregated power capacity. Using equation (1), gross head was varied until the maximum turbine flow equaled the combined maximum turbine flows of the aggregated hydropower systems.

Gross Head x Flow x System Efficiency (in decimal equivalent) x C = Power (kW)

Equation (1)

Gross Head = varied to obtain aggregated flow
Flow = aggregated maximum turbine flows
System Efficiency = 75% (0.75)
C = 9.81
Power = aggregated power generation capacity

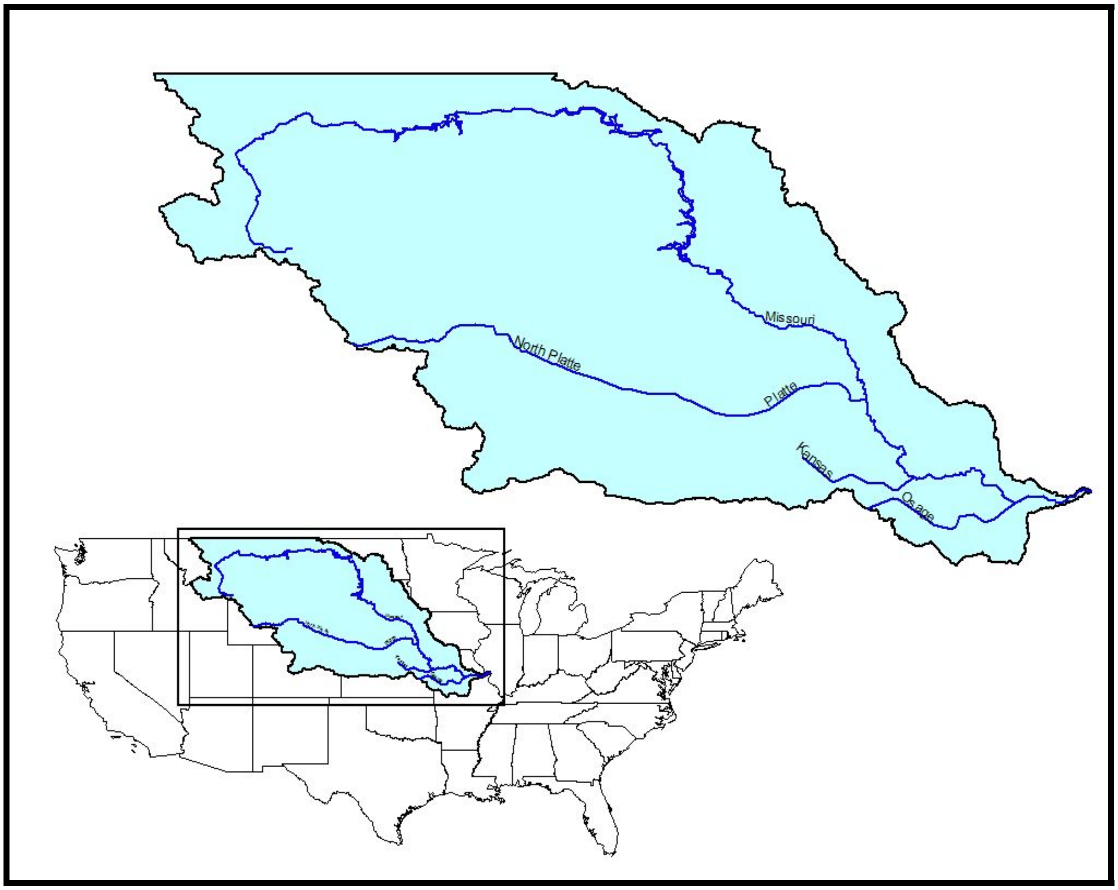
This is a very rough estimate in order to get comparisons among the different spatial scale representations.

The different spatial representation analyses were compared for the following results:

1. Average Monthly Demand Coverage (%)
2. Reservoir Storage Volume
3. Average Monthly Hydropower Generation
4. Relative crop production (actual production/ potential production)

An additional analysis was performed on the Yellow River Basin due to its complex management systems. We looked at the results from analyzing the basin with and without the correct management incorporated.

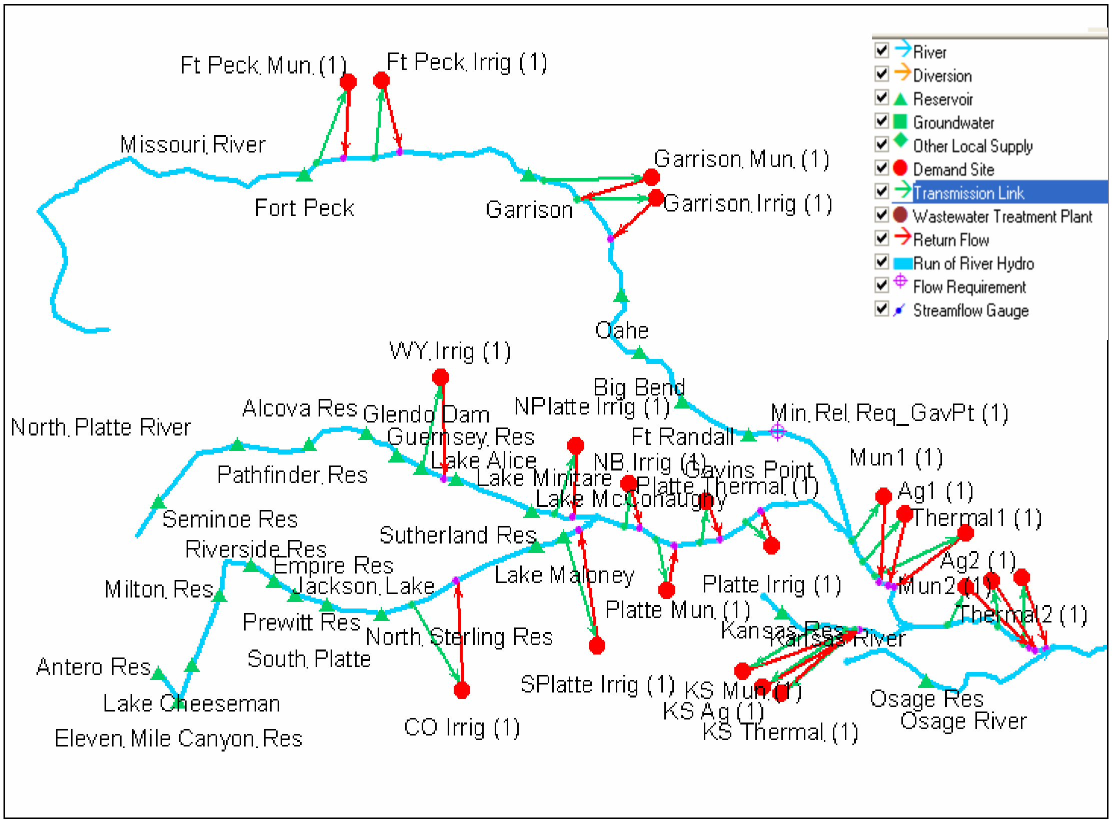
Figure 64 Missouri River Basin



Missouri River Basin

The Missouri River Basin (Figure 65) was taken as a case study because it represents a basin where spatiality is very important. The basin is wet in the north and dry in the south. It is considered to have three different climate zones according to the humidity index (UNEP 1991). The majority of irrigation occurs in the middle of the basin. Therefore, spatial details are important because water is not necessarily available where it is needed. The Missouri Basin can be categorized as a basin with rivers in parallel. The basin is considered to have a moderate level of management (storage/runoff ratio between 0.6 and 1.2). The Missouri Basin was modeled at 4 different scales; a full representation with all demands and reservoirs (Figure 66), a first level aggregation into 8 regions (Figure 67), a second level aggregation into upper, middle, and lower (Figure 68), and the highest aggregation into one region (Figure 69) .

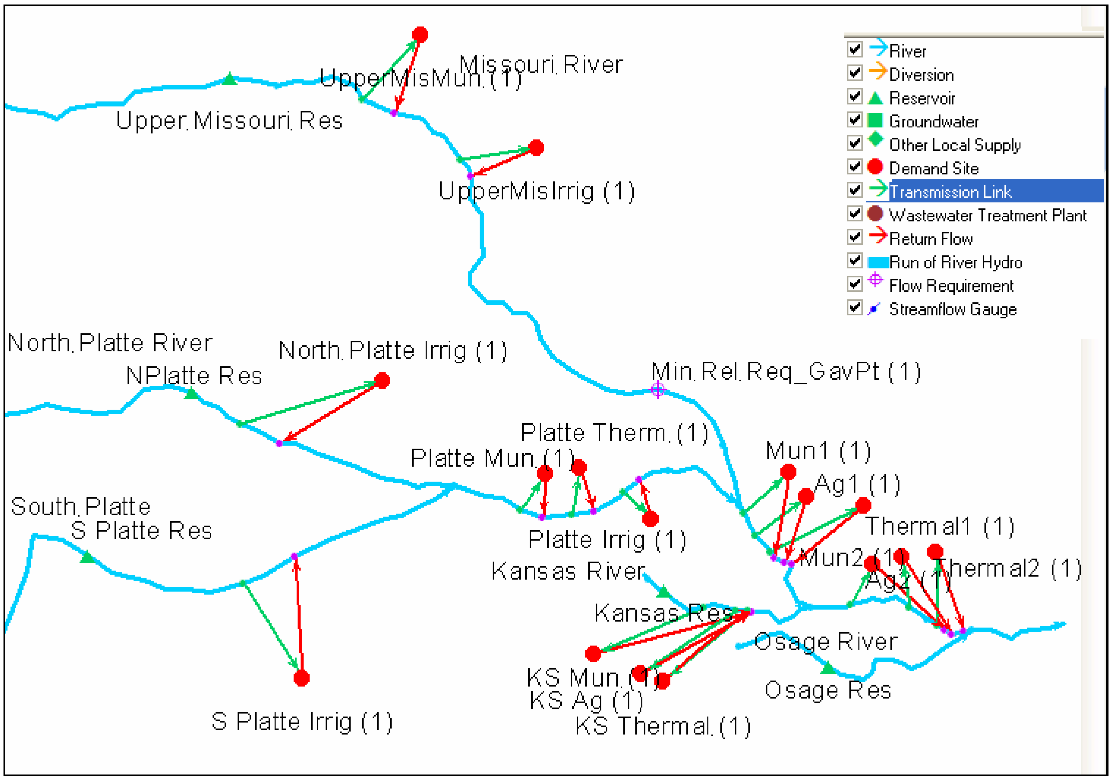
Figure 65 Missouri River Full Representation in WEAP



The WEAP model represents the Missouri River Basin by including the main stem of the Missouri River, the Kansas River, the North Platte River, the South Platte River, the Platte River, and the Osage River (Figure 65). There are 6 reservoirs and 10 main demands on the Missouri, 8 reservoirs and 2 demands on the North Platte, 10 reservoirs and 2 demands on the South Platte, 4 demands on the Platte, 1 reservoir and 3 demands on the Kansas, and 1 reservoir on the Osage (Figure 66).

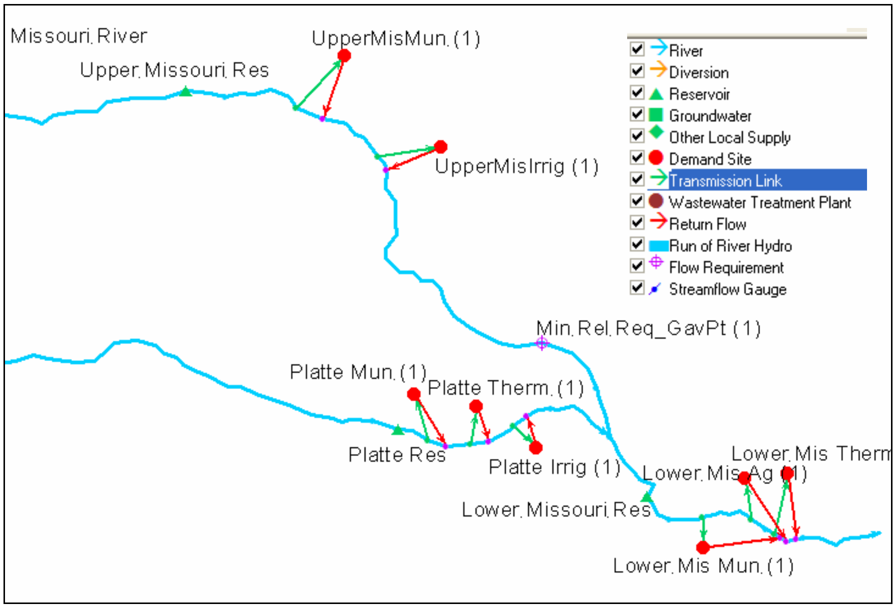
There is one minimum flow requirement on the Missouri River that is required for navigational purposes. Hydropower occurs at the following seven reservoirs: Fort Peck, Garrison, Oahe, Big Bend, Fort Randall, Gavins Point, and Lake McConaughy. Water withdrawals or demands are categorized into three categories; agriculture, municipal, and thermal. The demand and infrastructure data for this analysis was mainly provided by the US Army Corps of Engineers and the USGS.

Figure 66 Missouri River 8-Region Basin in WEAP



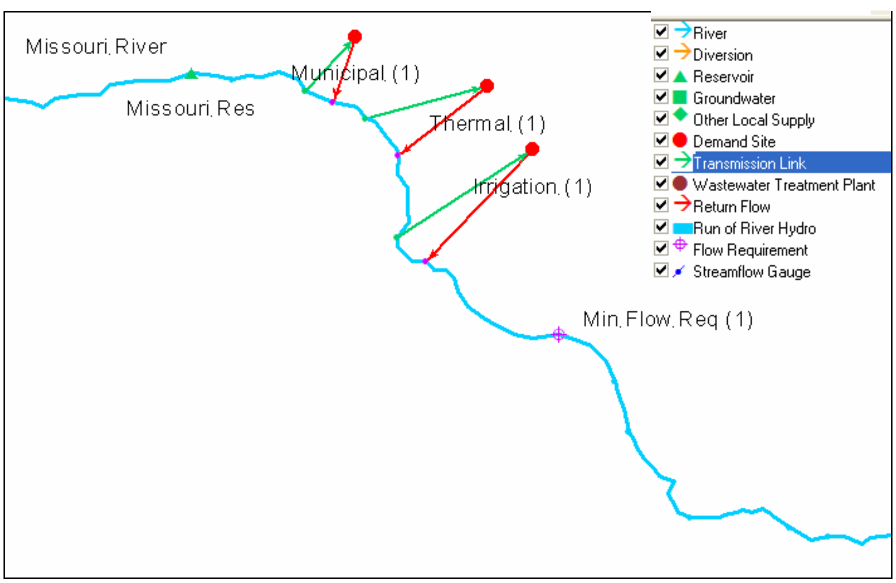
The Missouri River Basin representation was first aggregated into 8 regions by adding all storage, hydropower parameters, municipal demands, thermal demands, and irrigation demands in each of the following regions: the Upper Missouri, North Platte, South Platte, Platte, Middle Missouri, Kansas, Osage, and Lower Missouri (Figure 67).

Figure 67 Missouri River 3-Region Basin in WEAP



The Missouri River Basin representation was also aggregated into 3 regions by adding all storage, municipal demands, thermal demands, and irrigation demands in each of the following regions: the Upper Missouri, Platte, and Lower Missouri (Figure 68).

Figure 68 Missouri River 1-Region Basin in WEAP



The Missouri River Basin representation was finally aggregated into 1 region by adding all storage, municipal demands, thermal demands, and irrigation demands in the entire basin (Figure 69).

For the average monthly demand coverage by sub-basin see Appendix B. In the full representation of the Missouri River basin, there are multiple sites where the demands are not met. The locations of the deficits are located in the mid-western region of the basin. The lack of coverage occurs mostly during the summer months, but also year-round in quite a few of the demand sites. The deficits are extreme, sometimes resulting in no demand coverage at all.

In the 8-region Missouri River basin representation, there is a deficit of available water. The deficit occurs at the demand sites located along the Platte River system (North Platte Irrigation, Platte Irrigation, Platte Municipal, Platte Thermal, and South Platte Irrigation) during the summer months. There is slight improvement in demand coverage compared to the full representation.

The results for the 3-Region Missouri River representation follow the same expectations that there is an improvement in the demand coverage compared to the 8-region representation. There is still a very significant deficit in water supply. The deficit occurs in the demand sites located along the aggregated Platte (Platte Irrigation, Platte Municipal, and Platte Thermal) during the summer months.

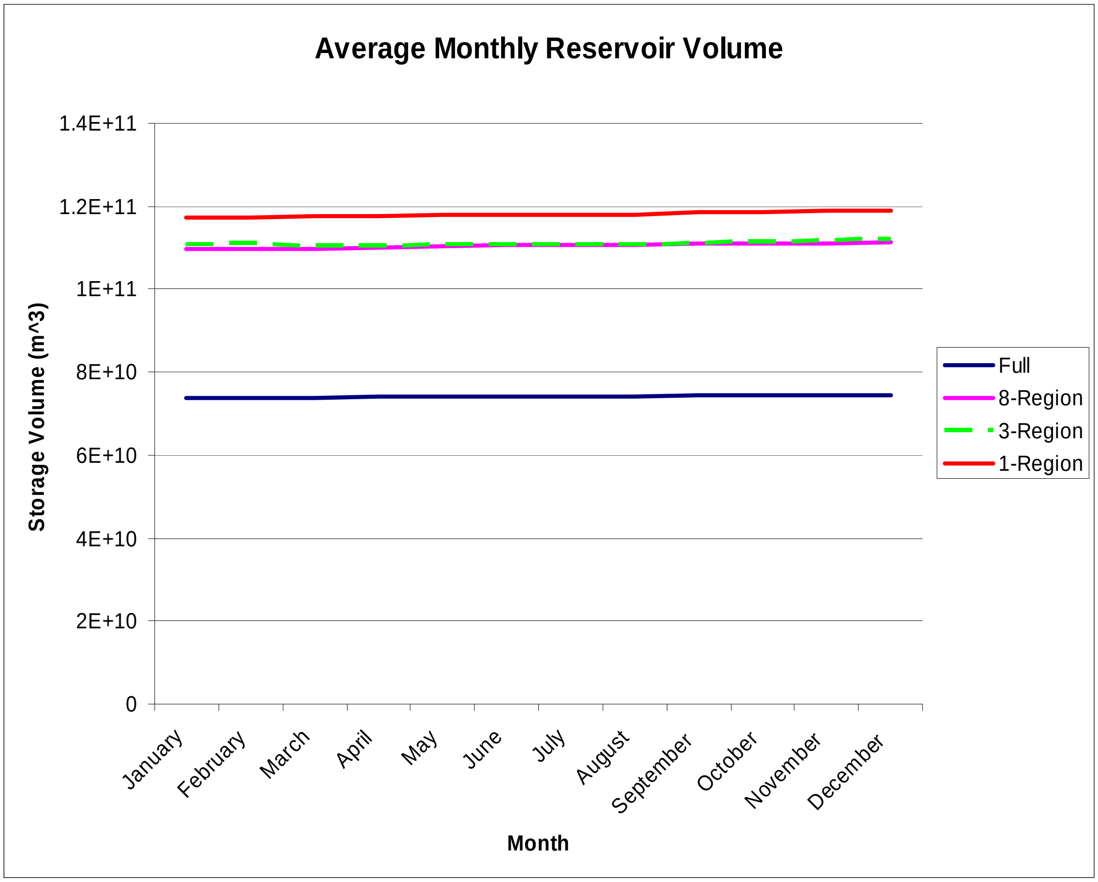
The results for the 1-Region Missouri River representation show there is **no** deficit in water supply.

Table 6 Average Annual Demand Coverage in the Missouri River Basin

Missouri Representation	Average Annual Demand Coverage
Full	47%
8-Region	53%
3-Region	65%
1-Region	100%

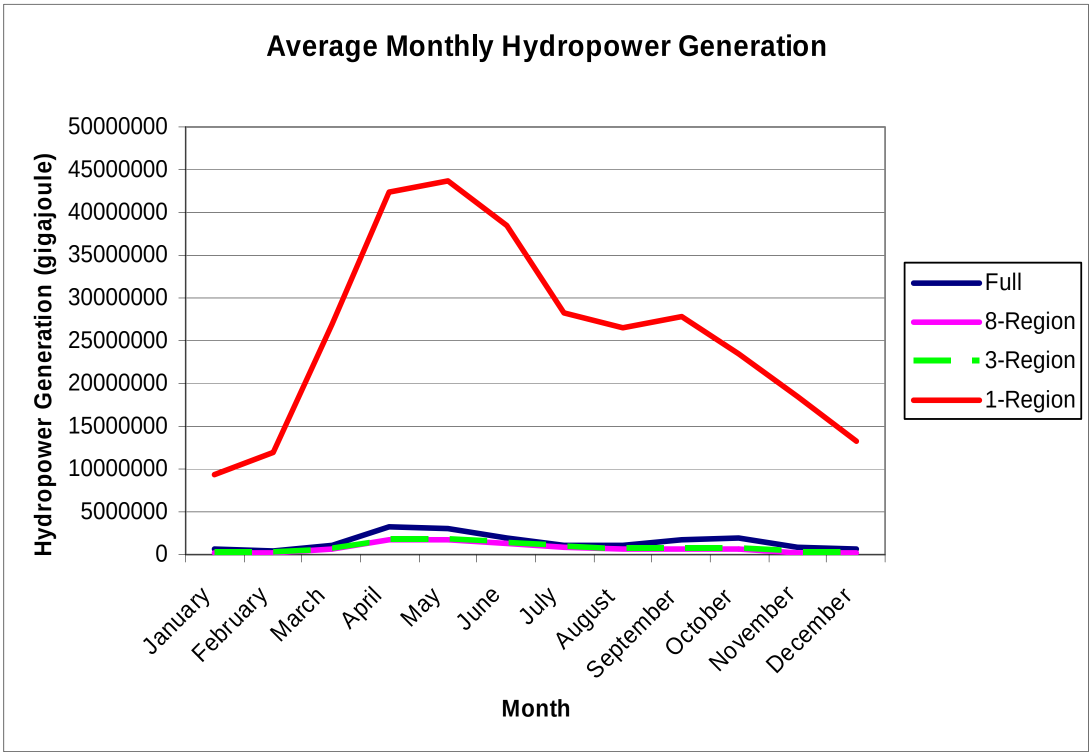
As a summary, the average annual demand coverage is presented in Table 6; showing similar results that are mentioned above for the average monthly demand coverage. The 1-Region representation has 100 percent coverage because all of the runoff in the basin is available for the demands. The full representation shows the lowest amount of coverage because of the spatial disaggregation. The largest demand occurs in the western region (Platte area). By continuing to aggregate the supply and demand of the region, the average annual demand coverage is also increased until being fully met when the region is aggregated to one region.

Figure 69 Average Monthly Reservoir Volume in all Spatial Representations of the Missouri River Basin



For the reservoir storage by sub-basin for the 30 year time series see Appendix C. In the full region Missouri River basin representation, all reservoirs except Big Bend, Fort Peck, Ft Randall, Garrison, Gavins Point, Kansas Res, Oahe, and Osage reservoirs located in the north go dry after the first year. This results in the full representation having the lowest average monthly reservoir volume (Figure 70.) In the 8-region representation, the North Platte and South Platte Reservoirs go dry within the first few months of the analysis. Similarly, in the 3-region Missouri River basin representation, the Platte Reservoir goes dry only during the summer months when demands are higher than available supply. The 8-region and 3-region representations have similar average monthly reservoir volume as seen in Figure 70. The results for the 1-Region Missouri River representation show the reservoir does not go dry. The reservoir slowly fills to capacity in the first few months of the analysis and stays near capacity for most of the analysis; thus resulting in the highest level of reservoir volume among the different representations.

Figure 70 Average Monthly Hydropower Generation in each of the Missouri River Spatial Representations



For the average monthly hydropower by sub-basin see Appendix D. Hydropower occurs at the following seven reservoirs: Fort Peck, Garrison, Oahe, Big Bend, Fort Randall, Gavins Point, and Lake McConaughy; or North Platte Reservoir and Upper Missouri Reservoir in the aggregated representations.

In the full representation of the Missouri River, hydropower generation is spread out across the region (mostly in the north where there are no deficits), but is similar in magnitude to the 8 and 3-region representations.

Hydropower generation is basically negligible for most months in the North Platte Reservoir in the 8-Region Missouri River representation, but produced year round in the Upper Missouri Reservoir.

The results are similar for hydropower generation in the 3-Region and 8-Region Missouri River representations. The average monthly production is the same in the Upper Missouri Reservoir in both the 3-Region representation and 8-Region representation (Figure 71.) Due to aggregating the Platte, there are slightly different hydropower results between the North Platte Reservoir (8-Region) and the Platte Reservoir (3-Region). Hydropower generation is basically negligible for most months in the North Platte Reservoir, while the Platte Reservoir produces minimal hydropower in the first four months of the year. This can be explained by looking at the reservoir storage volumes in Appendix C. The Platte Reservoir volume cycles, going very low to dry in the summer months, while the North Platte Reservoir volume goes very low to dry within the first few months of the simulation.

In the single representation of the Missouri River Basin, hydropower can be generated year round in the representative reservoir and produces the most power among all the spatial representations. By aggregating the Missouri River Basin into one region, hydropower generation is greatly over estimated.

The relative crop production is the actual production divided by the potential production. This was determined based on the relative amount of water supplied to the agriculture demands. The production was decreased by the relative amount of water deficit.

Table 7 Comparison of Relative Crop Production in the Missouri River Basin

Missouri Representation	Relative Crop Production
Full	41%
8-Region	48%
3-Region	62%
1-Region	100%

The disaggregation of the Missouri River Basin representation has great impact on the relative crop production (Table 7.) The majority of agriculture demand in the Missouri Basin is located in the Platte Region. This is also a region of water stress. Therefore, aggregating the supply will allow for more crop production in an area where in reality the water is not available. The full representation reveals that only 41% of crop production can occur because of the deficit of the available water. Similarly, the 8-region and 3-region representations allow for 48% and 62% relative crop production respectively. In the 1-region representation, the relative crop production is 100%; all crop production can occur at this model scale.

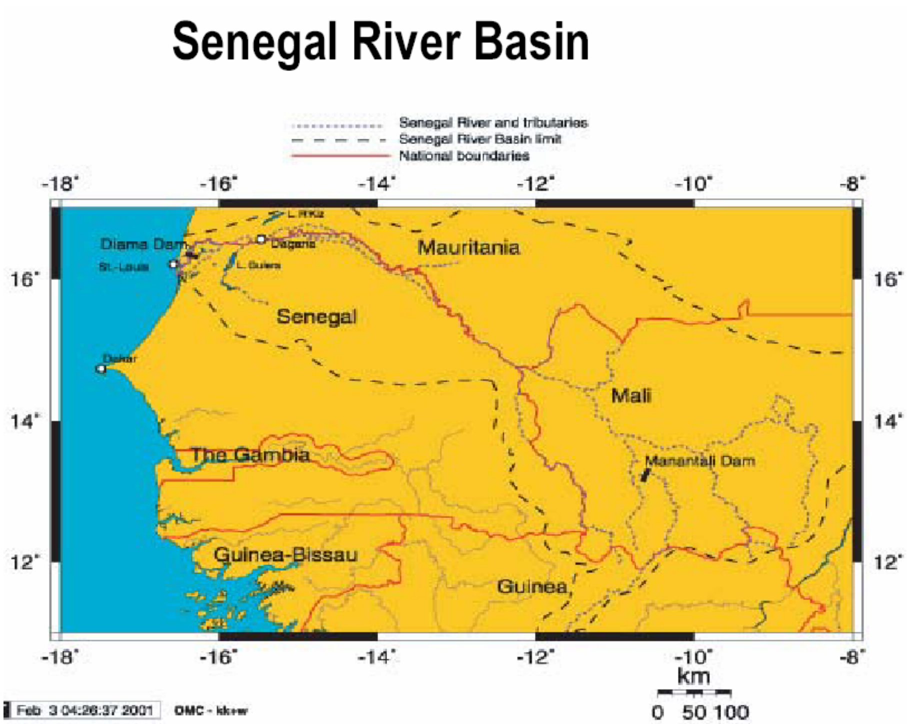
There is significant difference among the results of the different spatial representations of the Missouri River Basin (Table 8.) The basin is wet in the north and dry in the south. The majority of irrigation occurs in the middle of the basin. There are significant water shortages in the mid-western area of the Platte that become masked when the region is aggregated. In the detailed representation, some reservoirs go dry after the first year resulting in limited hydropower generation and limitations in demand coverage throughout mid-western area. The detailed representation also reveals that due to constraints in available water, crop production is greatly reduced. Aggregating to 8 and 3 regions reveals similar results as the full representation in that there are significant water shortages in the Platte area. When the region is aggregated to a one region representation, all shortages are masked and results reveal that there is plenty of water available to meet all the water demands, including year round hydropower generation in the Missouri River Basin (at a much higher level than in the other representations) and full crop production.

Table 8 Missouri River Basin Spatial Analysis Results Summary

Spatial Representation	Demand Coverage	Reservoir Storage	Hydropower Generation	Relative Crop Production
Detailed	Limited in mid-western region (47% coverage)	Most reservoirs go dry after 1st year	Year round generation	Very limited crop production (41% production)
8-Region	Limited in Platte region (53% coverage)	Platte reservoirs go dry within 1st few months (49% more annual storage than detailed)	Year round generation, with North Platte producing negligible amounts (49% less annual generation than detailed)	Very limited crop production (48% production)
3-Region	Limited in Platte region (65% coverage)	Platte reservoir goes dry during summer months (50% more annual storage than detailed)	Year round generation, with Platte producing very little (48% less annual generation than detailed)	Limited crop production (62% production)
1-Region	Complete (100% coverage)	Reservoir fills to capacity and remains there (59% more annual storage than detailed)	Year round generation at much higher levels than all other representations (1668% more annual generation than detailed)	Complete crop production (100% production)

Note: Percentage values listed for reservoir storage and hydropower generation are based on annual sum

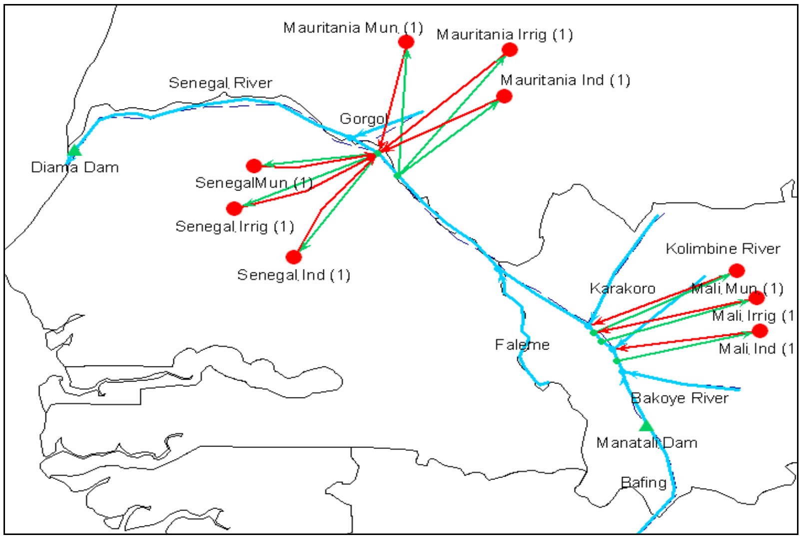
Figure 71 Senegal River Basin (Gaye et. al. 2002)



Senegal River Basin

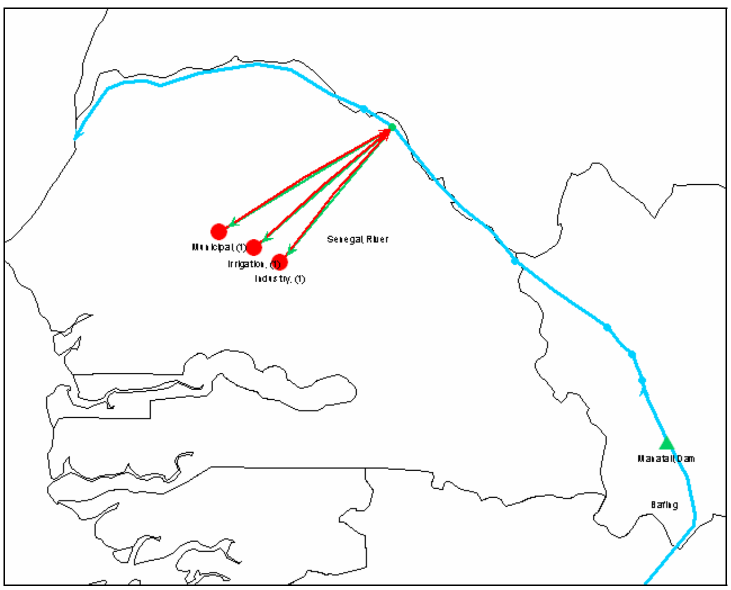
The Senegal River Basin is formed by the confluence of the Bafing and Bakoye Rivers in Guinea. This approximately 300,000 km^2 basin is bordered by Guinea, Mali, Mauritania, and Senegal (Figure 72). While the Senegal is an important river basin, it is fairly homogeneous and simplistic in nature with main concerns regarding impacts from dams. According to the humidity index, the Senegal River Basin has 3 different climate zones (UNEP 1991). It is drier in the north and slightly more humid in the south. The basin is considered to have a low level of infrastructure (storage/runoff <0.6). The Senegal River Basin is considered to have rivers in series because it is represented by one main river with few tributaries. The flow from the tributaries is insignificant relative to the flow in the main river. The Senegal Basin was modeled at 2 different scales; a full representation where demands are disaggregated by spatial location, and an aggregated representation of 1 region. The data and infrastructure were derived from UNESCO's World Water Development Report on the Senegal River Basin.

Figure 72 Senegal River Full Representation



The WEAP model represents the Senegal River Basin by including the demands along the river from adjacent countries (Figure 73).

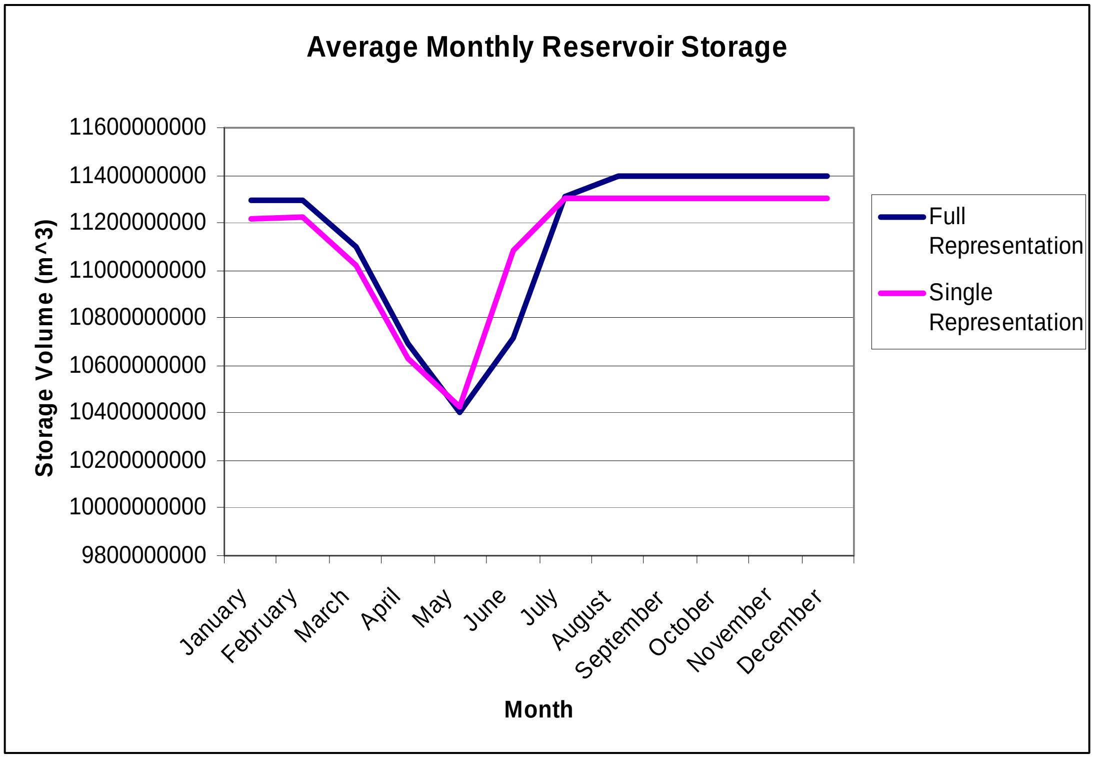
Figure 73 Senegal River 1 Region Representation



Next, the country level demands and supply were aggregated into one region representation (Figure 74).

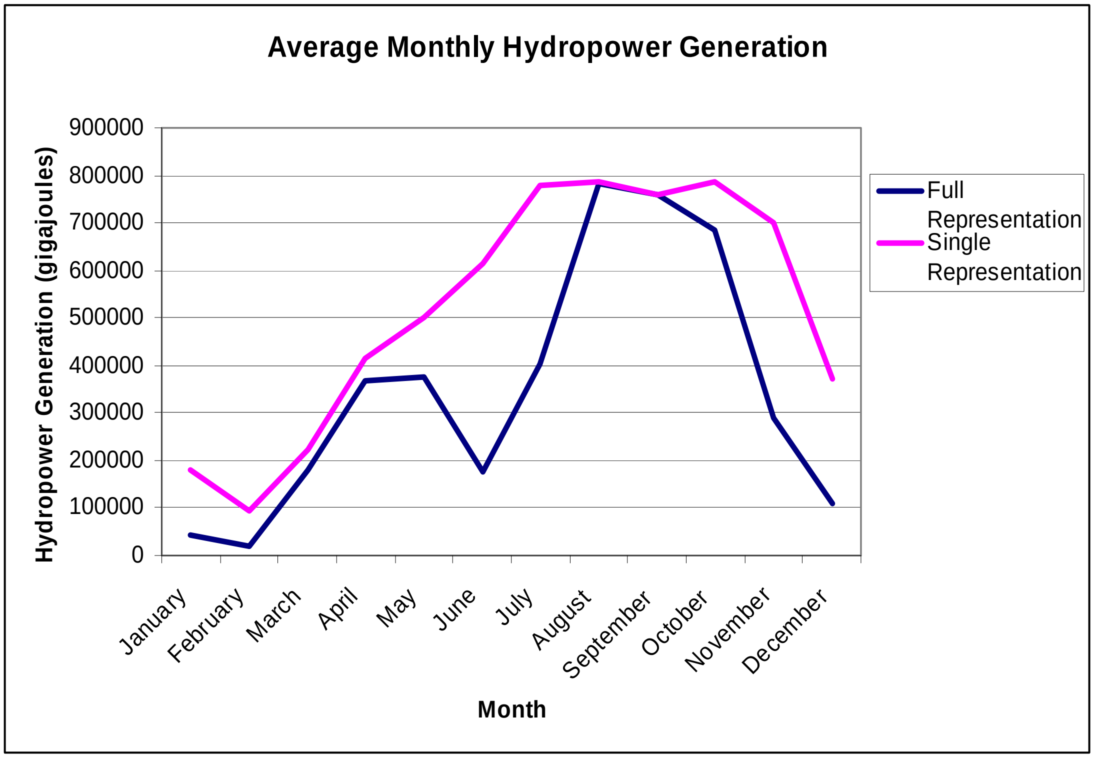
Due to the homogeneity, location of storage, and high water supply to demand ratio, there is no difference on meeting water demands between the two representations of the Senegal River Basin. Demands are fully met in both representations.

Figure 74 Average Monthly Reservoir Storage in the Senegal River Basin



For the reservoir storage by sub-basin for the 30 year time series see Appendix C. In the multi-region representation there are two reservoirs represented (Manatalli and Diama.) Their storage capacity was aggregated into one reservoir in the single region representation. The Diama reservoir accounts for about 1% of the aggregated reservoir volume in the single region representation. In the Senegal River Basin representations there does not seem to be much difference in reservoir storage between the multi and single region representations (Figure 75).

Figure 75 Average Monthly Hydropower Generation in the Senegal River Basin



For the average monthly hydropower by sub-basin see Appendix D. Following the same pattern as with the reservoir storage volume, the average monthly hydropower generation is very similar between the full and single representations of the Senegal River Basin (Figure 76). There is a dip in the power generation occurring in the full representation during the summer. This is not seen in the single representation because of the affects of aggregation (supply, demand, and storage.) By aggregating the storage volume and runoff in the basin we do mask a drop in hydropower generation.

Table 9 Comparison of Relative Crop Production in the Senegal River Basin

Senegal Representation	Relative Crop Production
Full	100%
1-Region	100%

With plenty of water available throughout the basin to meet demands, crop production is at 100% in all spatial representations (Table 9).

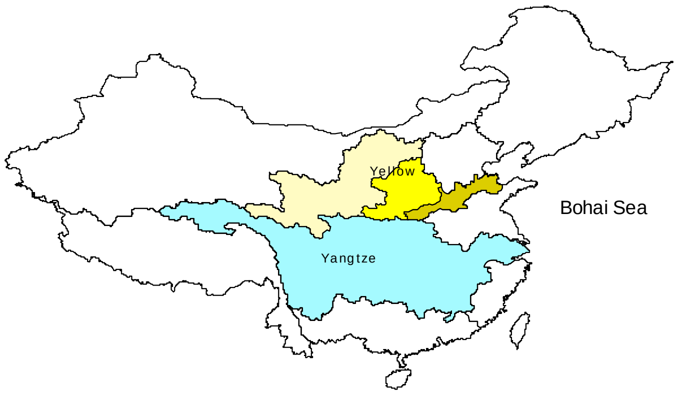
Table 10 Summary of the Spatial Analysis of the Senegal River Basin

Spatial Representation	Demand Coverage	Reservoir Storage	Hydropower Generation	Relative Crop Production
Detailed	Complete (100%)	Near capacity	Year round generation with dip in summer	Complete Crop Production (100%)
Single	Complete (100%)	Near capacity (0.3% less annual storage than detailed)	Year round generation no dip in summer (48% more generation than detailed)	Complete Crop Production (100%)

Note: Percentage values listed for reservoir storage and hydropower generation are based on annual sum

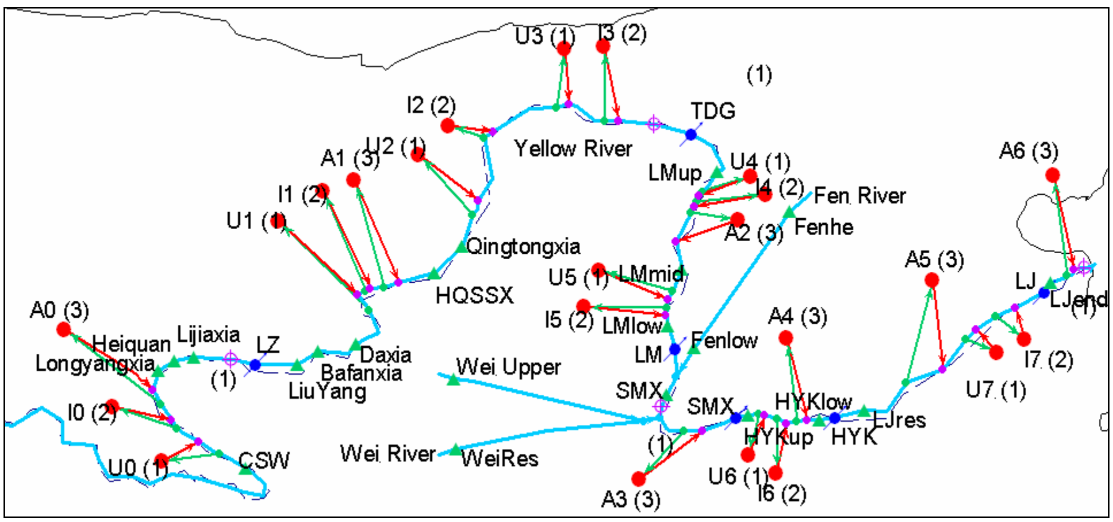
The Senegal River Basin is fairly simplistic in nature with relatively few major demand sites. Demands are fully met in both spatial representations. Storage capacity is increased by about 1 percent when the two reservoirs are aggregated into one. With the slight storage capacity increase and the aggregated supply and inflow into the reservoir, the hydropower generation is slightly increased in the single region representation (Table 10).

Figure 76 Yellow River Location in China



Cai, X. Rosegrant, M. *Optional Water Development Strategies for the Yellow River Basin*

Figure 77 Yellow River Basin Full Representation



Yellow River Basin

The Yellow River Basin represents a basin where the river is in series (Figure 77). It is also interesting that the majority of the runoff in the basin occurs at the head flow of the Yellow River. In addition, it is a heavily managed basin with storage and flow requirements throughout. The Yellow River Basin is considered to have a low level of infrastructure because of its large amount of total runoff in the basin relative to its total storage capacity. This basin is considered to have 4 different climate zones according to the humidity index (UNEP 1991). The representations of the Yellow River Basin were derived from data collected from the Yellow River Conservancy Commission and reports based on data from the Yellow River Conservancy Commission. The full representation is made up of 11 sub-basins (Figure 78). The basin representation was then aggregated to 4 regions (Figure 79). When aggregating to 3 regions it was interesting to look at two representations; one that combines the upper and TDG sub-basins

Figure 78 Yellow River Basin 4-Region Representation

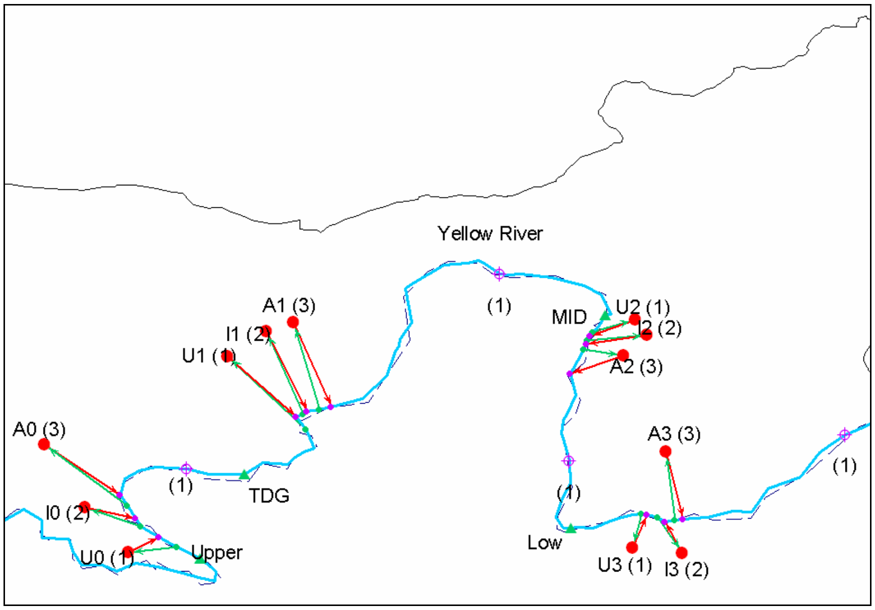
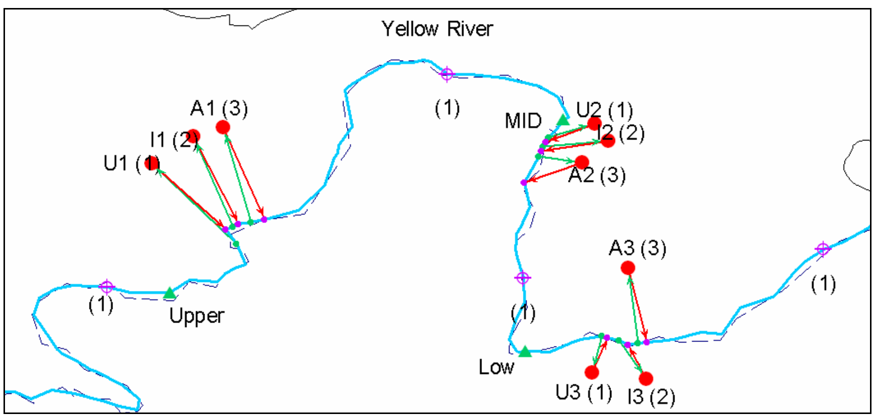


Figure 79 Yellow River Basin 3A-Region Representation



(Figure 80) and another that combines the TDG and mid sub-basins (Figure 81). Lastly, the basin representation was aggregated into a single region (Figure 82).

The reservoir data was provided by the International Commission On Large Dams database and aggregated into the sub-basins. It was found that while there is a large amount of storage capacity along the Yellow River, the active storage is significantly less (about half total capacity) due to operation for flood control and sedimentation. The reservoirs are operated to be drawn down before the flood season, which starts in August. There are also flow requirements placed along the river representing a 20 billion cubic meter requirement to flush sediments through the river. The spatial scale analysis was carried out first with management included and secondly without knowledge of management. The results are quite interesting.

Figure 80 Yellow River Basin 3B-Region Representation

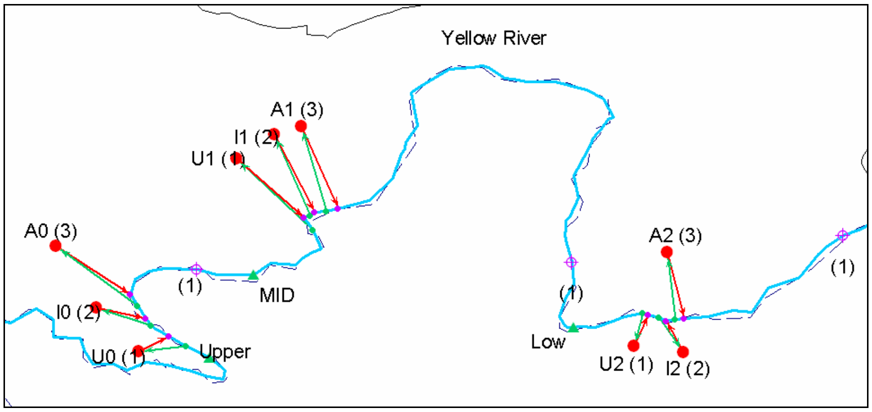
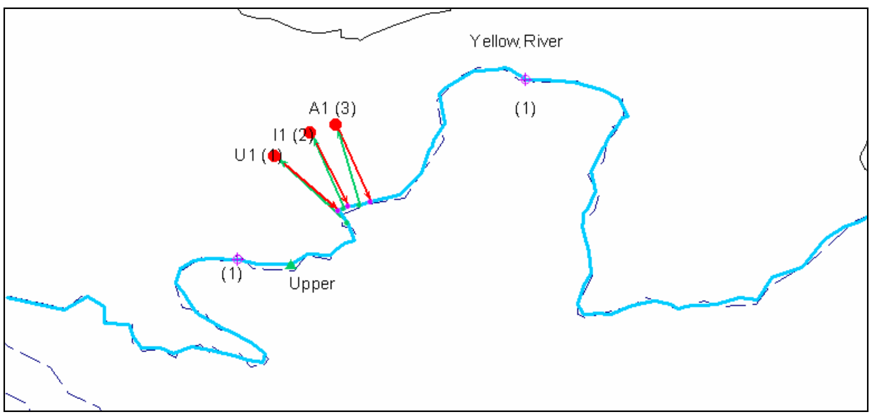


Figure 81 Yellow River Basin 1-Region Representation



In general, the results from the different spatial resolutions with management (reduced reservoir storage capacity and flow requirements) do not vary by a significant amount. Because the river system is in series and the majority of the runoff occurs at the headflow of the Yellow River, the issue of scale does not seem to have as much impact in this basin.

For the average monthly demand coverage by sub-basin see Appendix B. The irrigated agriculture is the major demand in the Yellow River Basin, taking place during March through August. Another significant demand is the flow requirement of 20 billion m^3 for flushing sediment. This requirement is spread out over June July and August. In each spatial representation we see deficits in demand coverage occurring March through August. The average annual demand coverage is similar among the different spatial representations of the Yellow River Basin with management (Table 11).

Table 11 Average Annual Demand Coverage in the Yellow River Basin with Management

Yellow River Representation	Average Annual Demand Coverage
Full	72%
4-Region	68%
3A-Region	68%
3B-Region	66%
1-Region	61%

For the reservoir storage by sub-basin for the 30 year time series see Appendix C. The trend of declining reservoir volume in July is seen in each spatial representation. The single representation and detailed representation are the most similar in their results, showing the main reservoir going dry during the summer. The return flow from the irrigated agriculture cannot be used by other demands in the single representation, causing a little more stress on the system. The 4-region and 3-region representations show slight improvement in that the reservoir storage is not drawn down as far, but still significantly impacted. The average monthly reservoir storage volume is shown in the Figure 83 below; showing fairly similar results among the different spatial representations.

Figure 82 Average Monthly Reservoir Storage Volume in the Yellow River Basin with Management

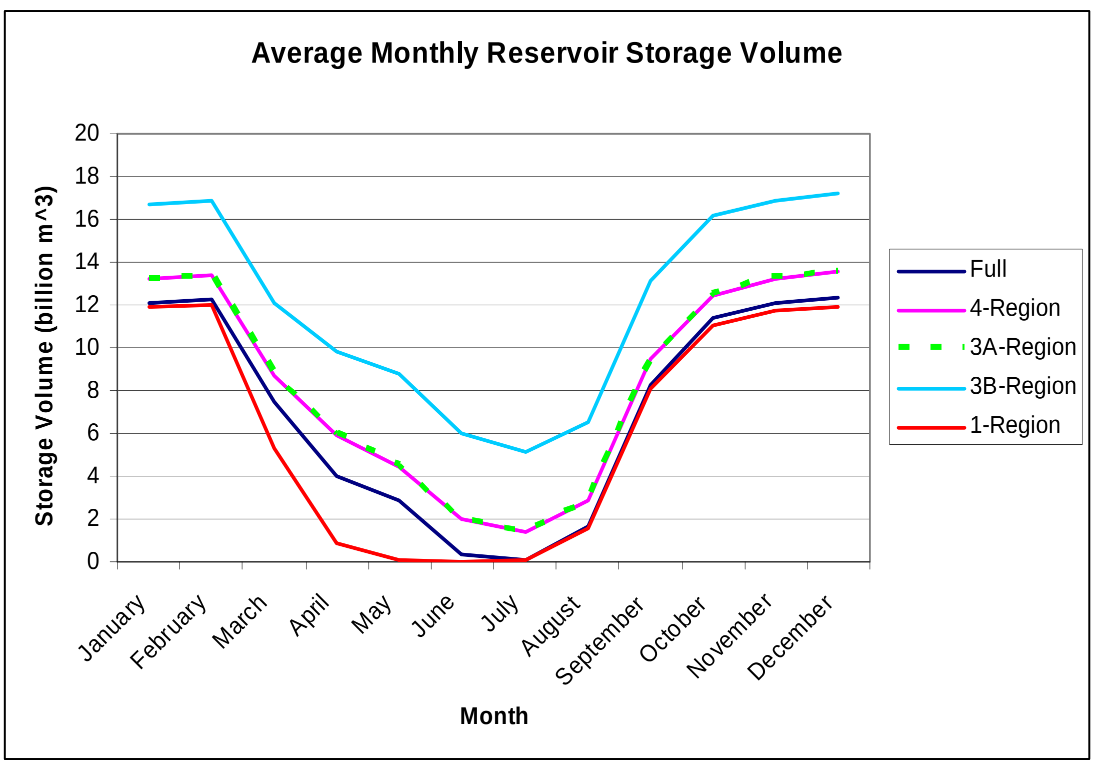
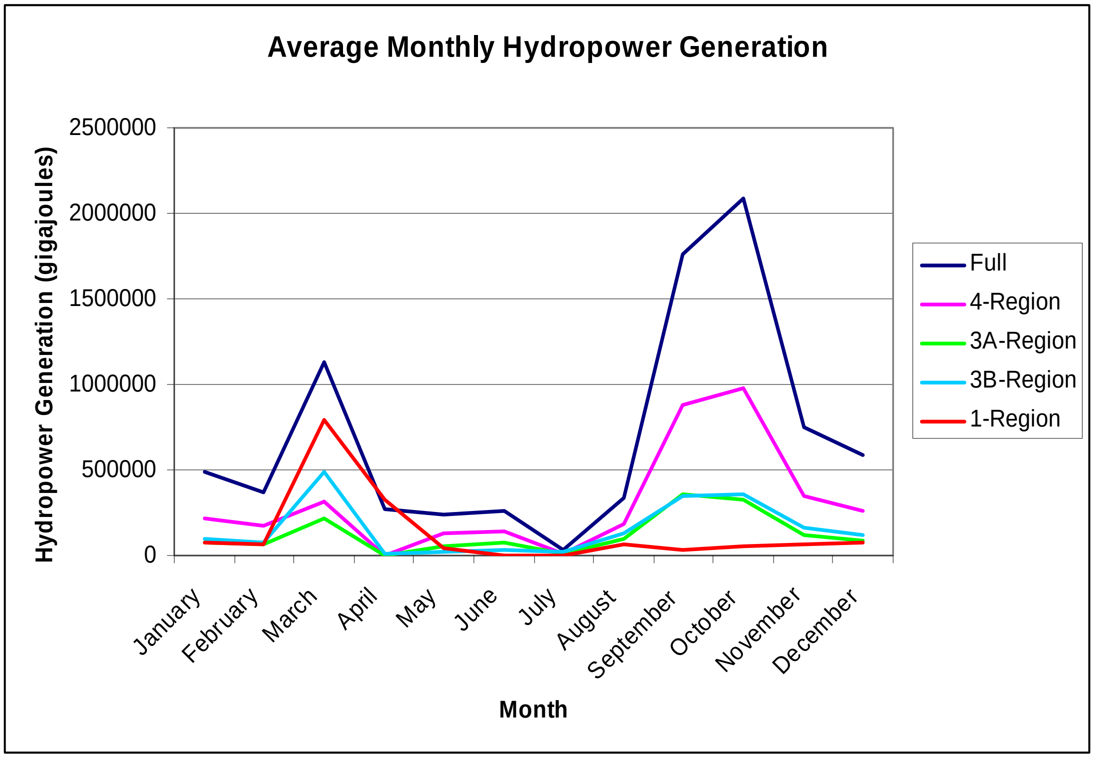


Figure 83 Average Monthly Hydropower Generation in the Yellow River Basin with Management



For the average monthly hydropower by sub-basin see Appendix D. From the results we see that by aggregating the basin representation, we are not getting the full hydropower potential. In the detailed representation max hydropower generation is about 2 million gigjoules. We see a similar monthly distribution in the 4-region representation and 3A-region representation, but with a max generation of only 970 thousand gigajoules and 360 thousand gigajoules respectively. In the 3B-region representation and the single region representation we see a similar monthly distribution, peaking in March, but different maximum hydropower generations of about 500 thousand gigajoules and 800 thousand gigajoules respectively. In general we see similar results among the different representations, with the detailed representation showing a significantly larger amount of hydropower being generated than the other representations (Figure 84).

As seen with the results from the average monthly demand coverage and reservoir storage, there is also very little difference in the relative crop production among the different spatial representations of the Yellow River basin with management (Table 12). In fact, we see a slight decrease in crop production when the basin is aggregated to one region. This may be due to the fact that the agriculture return flows cannot be used by other demands, thus limiting another source of water supply.

Table 12 Comparison of Relative Crop Production in the Yellow River Basin with Management

Yellow River Representation	Relative Crop Production
Full	66%
4-Region	63%
3A-Region	63%
3B-Region	62%
1-Region	56%

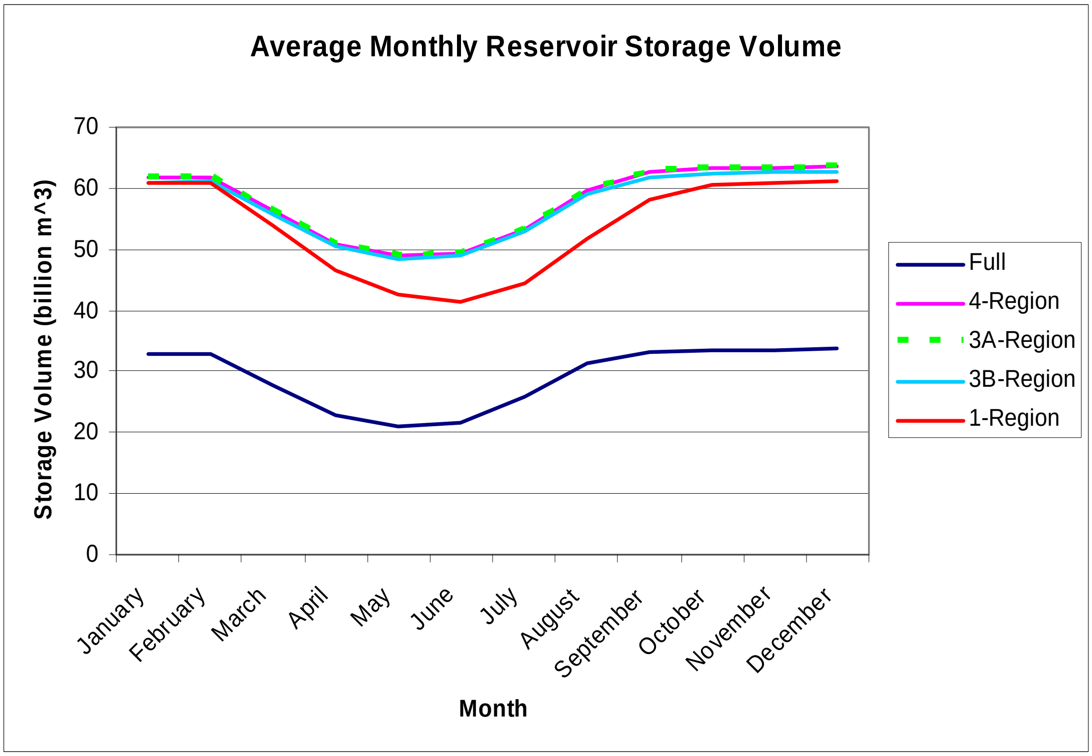
The following section of results deals with running the same spatial representations of the Yellow River, but the management aspects have been removed. Many times in global analyses management issues are not addressed because a global approach is taken and all basins are usually treated the same. The following results show the impacts of simply allowing full storage capacity to be available and removing the flow requirements along the river. We see similar results as in the previous section where the impact of spatiality on this river in series is not very significant, but we now see very different results between including management and not addressing management.

For the average monthly demand coverage by sub-basin see Appendix B. By removing the management issues, i.e. increasing storage capacity and removing flow requirements, demands are mostly met in all spatial representations with 100 percent coverage in the single representation. The average annual demand coverage is reported in Table 13, showing nearly 100 percent coverage for all demands in each spatial representation.

Table 13 Average Annual Demand Coverage in the Yellow River Basin without Management

Yellow River Representation	Average Annual Demand Coverage
Full	99%
4-Region	100%
3A-Region	99%
3B-Region	98%
1-Region	100%

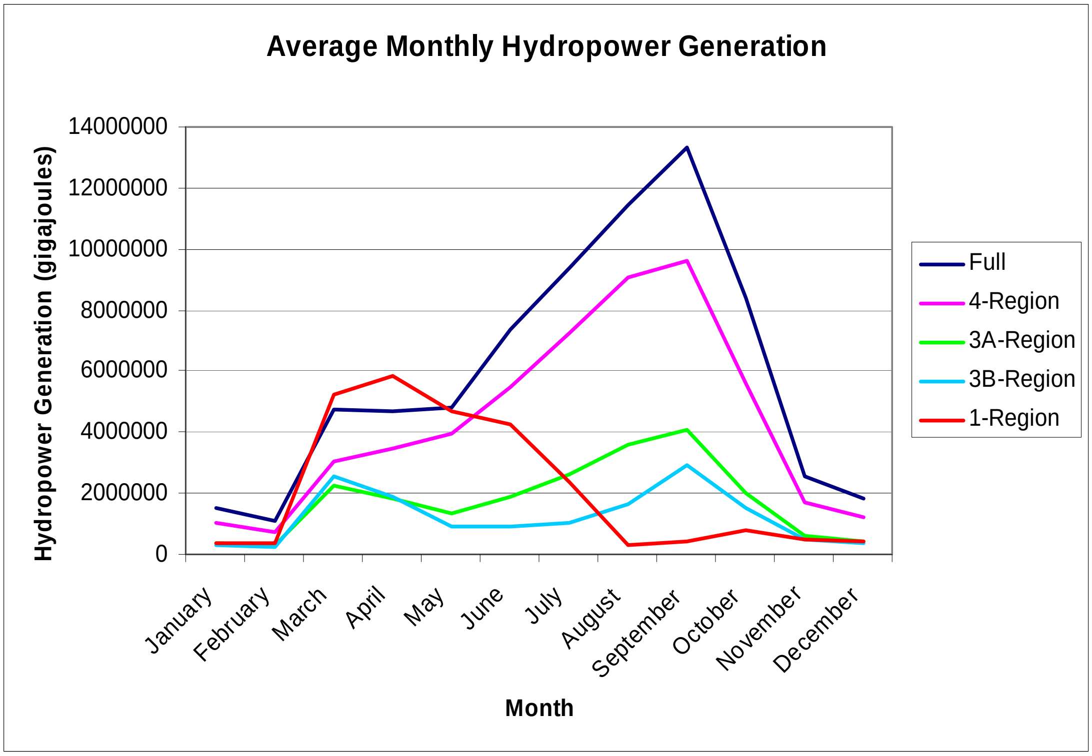
Figure 84 Average Monthly Reservoir Storage Volume in the Yellow River Basin without Management



For the reservoir storage by sub-basin for the 30 year time series see Appendix C. By allowing the full storage capacity to become the active storage, we do not see the reservoir going dry as was seen when the management was included (Figures 85). There is also a significant increase in the amount of storage. Comparing the single region representations; in the analysis with management the storage was around 12 billion m^3 and without management storage is around 60 billion m^3.

For the average monthly hydropower by sub-basin see Appendix D. As in the analysis with management, we see slightly varied hydropower generation among the different scale representations (Figures 86). By not including management, results show a very significant increase in the amount of hydropower production compared to the results where management was included, reaching maximum production of 12 million gigajoules versus 2 million gigajoules respectively.

Figure 85 Average Monthly Hydropower Generation in the Yellow River Basin without Management



By allowing all storage capacity to be active and removing flow requirements along the river, practically all crop production can take place regardless of which spatial representation you use (Table 14). In the analysis with management we saw almost a 40 percent decrease in crop production (Table 12). By not including management issues, one will greatly overestimate the crop production in the Yellow River Basin.

Table 14 Comparison of Relative Crop Production in the Yellow River Basin without Management

Yellow River Representation	Relative Crop Production
Full	99%
4-Region	99%
3A-Region	99%
3B-Region	97%
1-Region	100%

The Yellow River Basin represents a river that is heavily managed and is in series in orientation. The majority of the runoff occurs at the head of the Yellow River. Due to the fact that most of the supply is upstream and the river runs in series, there is not much difference in the results from the different spatial representations (Table 15). The main concern in a basin like the Yellow, is the management issues. The active storage capacity is actually only about half the total storage capacity of the basin and there is 20 billion m^3 flow requirement along the river to address the issue of sediment flushing.

Table 15 Summary of the Spatial Analysis of the Yellow River Basin with Management

Spatial Representation	Demand Coverage	Reservoir Storage	Hydropower Generation	Relative Crop Production
Detailed	Very limited for all demands in the summer months (72% coverage)	All reservoirs drawn down if not completely going dry in summer	High amount generated (avg. 8 million gigajoules annually)	Limited crop production (66% production)
4-Region	Very limited for all demands in the summer months (68% coverage)	Reservoirs drawn down, one does not go dry (19% more storage than detailed)	56% less generation than detailed	Limited crop production (63% production)
3A-Region	Very limited for all demands in the summer months (68% coverage)	Reservoirs drawn down, one does not go dry (19% more storage than detailed)	82% less generation than detailed	Limited crop production (63% production)
3B-Region	Very limited for all demands in the summer months - a couple demands not met at all in certain months (66% coverage)	Reservoirs drawn down, one does not go dry (81% more storage than detailed)	77% less generation than detailed	Limited crop production (62% production)
1-Region	Very limited for all demands in the summer months (61% coverage)	Reservoir goes dry in summer (12% less storage than detailed)	81% less generation than detailed	Lowest crop production of all representations (56% production)

Note: Percentage values listed for reservoir storage and hydropower generation are based on annual sum

Table 16 Summary of the Spatial Analysis of the Yellow River Basin without Management

Spatial Representation	Demand Coverage	Reservoir Storage	Hydropower Generation	Relative Crop Production
Detailed	Very close to complete (99% coverage)	Stay near capacity with a dip in summer	High amount generated (avg. 71 million gigajoules annually)	Very close to complete (99% production)
4-Region	Complete (100% coverage)	Stay near capacity with a dip in summer (99 % more storage than detailed)	27% less generation than detailed	Very close to complete (99% production)
3A-Region	Very close to complete (99% coverage)	Stay near capacity with a dip in summer (99 % more storage than detailed)	70% less generation than detailed	Very close to complete (99% production)
3B-Region	Very close to complete (98% coverage)	Stay near capacity with a dip in summer (97 % more storage than detailed)	79% less generation than detailed	Very close to complete (99% production)
1-Region	Complete (100% coverage)	Stay near capacity with a dip in summer (84 % more storage than detailed)	64% less generation than detailed	Complete crop production (100% production

Note: Percentage values listed for reservoir storage and hydropower generation are based on annual sum

Typically in global modeling management issues are not addressed because all basins are treated the same with supply, demand, and storage and extra effort is not spent on researching the individual basin specific issues. This is definitely a concern as shown in the results from the analysis where management was removed from the system (Table 16). While spatial representation may not have much affect on modeling the Yellow River Basin, management definitely does. For example, by not including management, one would over estimate crop production by about 40 percent (Table 17).

Table 17 Summary of Modeling the Yellow River Basin with and without Management

Management	Demand Coverage	Reservoir Storage	Hydropower Generation	Relative Crop Production
Modeled with Management	On average among spatial representations, coverage was 67%	Reservoirs were drawn down significantly. On average, spatial representations had only 27% more storage volume than the detailed representation	An average of 8 million gigajoules generated annually in detailed representation. On average, spatial representations generated 74% less than detailed representation.	Limited crop production (62% production on average)
Modeled without Management	On average among spatial representations, coverage was 99%	Reservoirs were near capacity and on average spatial representations had 95% more annual storage volume than the detailed representation.	Much higher amount generated in detailed representation (avg. 71 million gigajoules annually). On average, spatial representations generated 60% less than detailed representation	Very close to complete (99% production on average)

Volta River Basin

The Volta basin is located in Western Africa (Figure 87). The Volta basin is considered to have 3 different climate zones according to the humidity index (UNEP 1991) and also contains heavy infrastructure (storage/runoff >1.2). It covers about 140 thousand square kilometers. The basin is located in six countries:

- Burkina Faso (42% of basin)
- Ghana (40% of basin)
- Togo (6% of basin)
- Mali (5% of basin)
- Benin (4% of basin)
- Ivory Coast (of basin 3%).

Figure 86 Volta River Basin

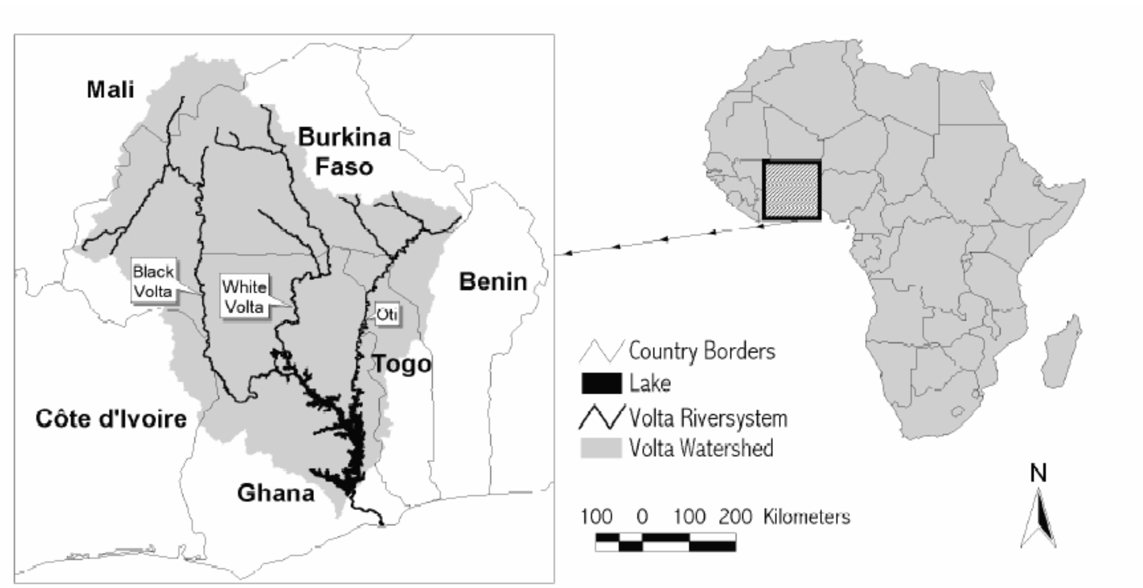


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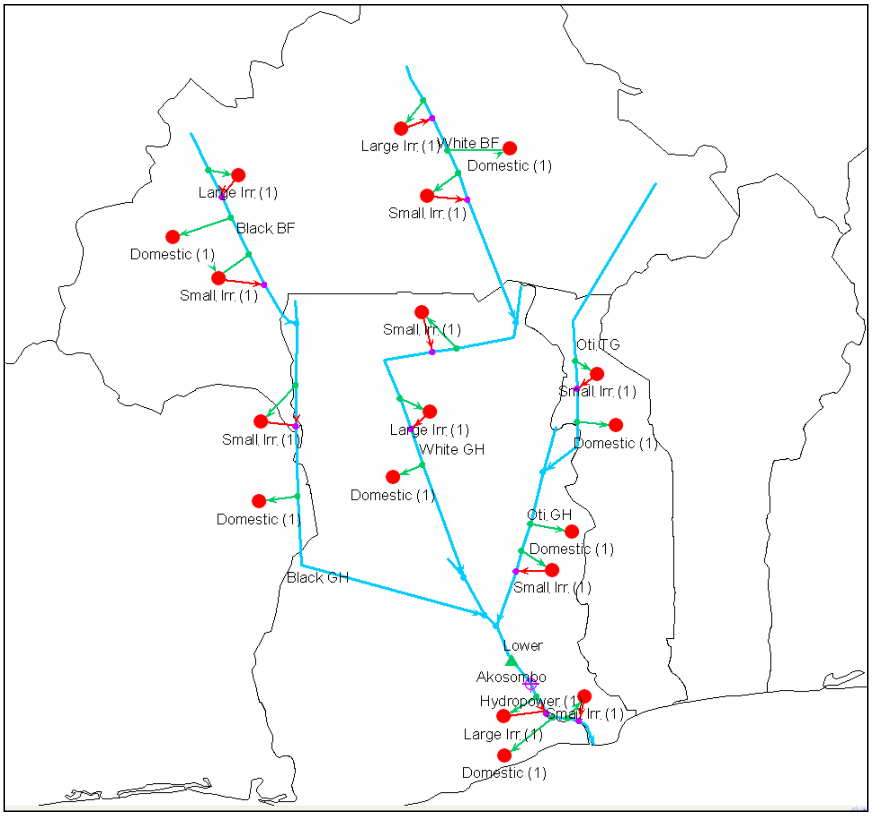
Figure 87 Full Representation of the Volta River Basin



The WEAP model represents the Volta River Basin by including the Black and White Volta and the Oti river with demands along the associated rivers (Figure 88).

The first aggregation of the Volta basin consists of aggregating the demands and supply by country; Burkina Faso, Ghana, and Togo. There are two country level representations; one (Country Level-1 Aggregation) is with Ghana divided into an upper and lower (Figure 89), and a second representation (Country Level-2 Aggregation) where Ghana has been aggregated into one region (Figure 90).

Figure 88 Country Level -1 Aggregation (Ghana Upper and Lower) of Volta Basin

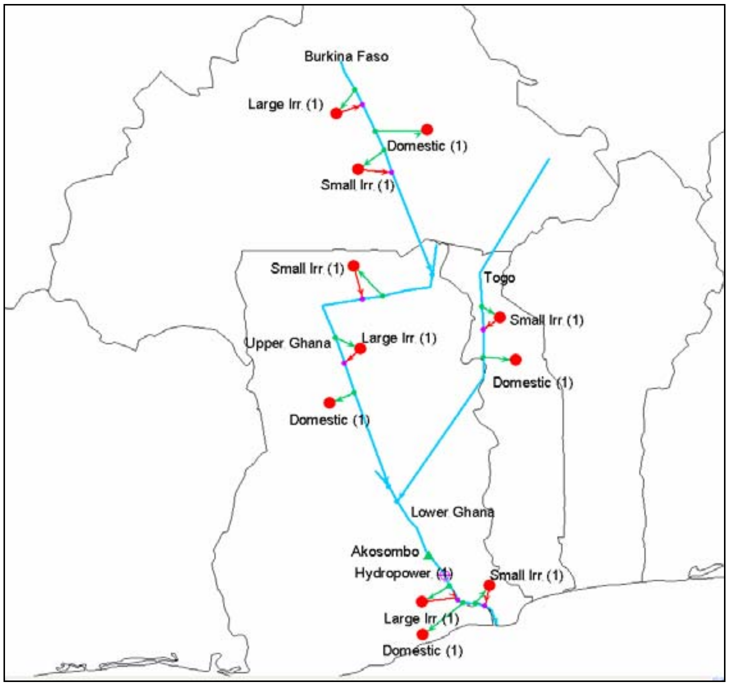


Figure 89 Country Level-2 Aggregation (Ghana as one region) of Volta Basin

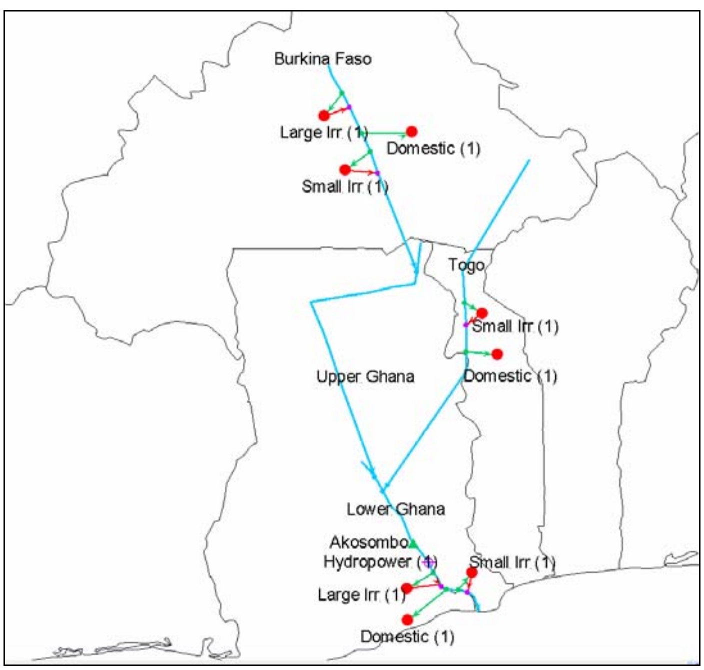
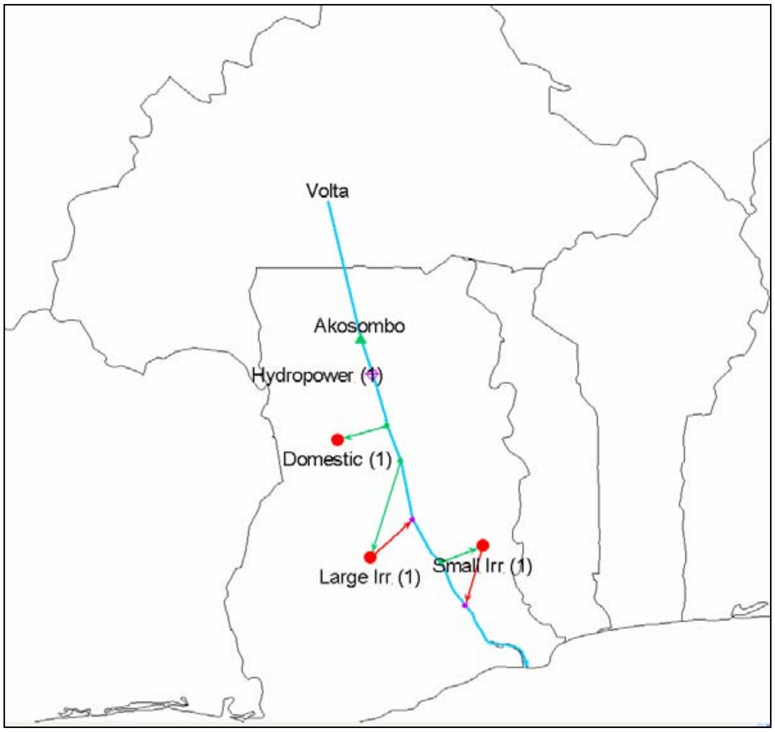


Figure 90 Volta River Single Region Representation



The Volta basin representation was aggregated into one single region representation (Figure 91).

For the average monthly demand coverage by sub-basin see Appendix B. In the full representation of the Volta River basin, most areas experience some shortage in water supply. The demands located on the lower Volta under the reservoir are fully met in each spatial representation. The differences in the two versions of the country level aggregation is that in the first aggregation Ghana's demands are split into upper and lower. In the second country level aggregation Ghana's demands are aggregated below the reservoir on the lower Volta.

In the first country level aggregation, the upper Ghana demands are not met. In the second country level aggregation all of Ghana's demands are met because they are now aggregated into a single demand set below the reservoir. When all demands are aggregated into a single representation, all demands are fully met. This shows the importance of the reservoir location in relation to the demands. When looking at the average annual demand coverage in the Volta River Basin, there is only a slight difference between the different spatial aggregations (Table 18).

From an annual perspective, aggregation does not have much affect, but looking at monthly demand coverage shows that some areas are facing deficits much larger than others (Appendix B.) One must look to see what months have deficits (may be very important to crop growth) and which demands are experiencing deficits (if domestic, there may be devastating affects on local population.)

Table 18 Average Annual Demand Coverage in the Volta River Basin

Volta River Representation	Average Annual Demand Coverage
Full	93%
Country-1	94%
Country-2	95%
1-Region	100%

For the reservoir storage by sub-basin for the 30 year time series see Appendix C. The average monthly reservoir storage in the Volta Basin was fairly consistent across the different spatial representations (Figure 92). The country level 1 representation revealed a very slight decrease in reservoir storage compared to the detailed representation while the other representations show a very slight increase in reservoir storage. The results are a combination of aggregating supply above the reservoir (allowing more available water for storage), and aggregating demand above and below the reservoir (affecting water available for storage.)

Figure 91 Average Monthly Reservoir Storage Volume in the Volta River Basin

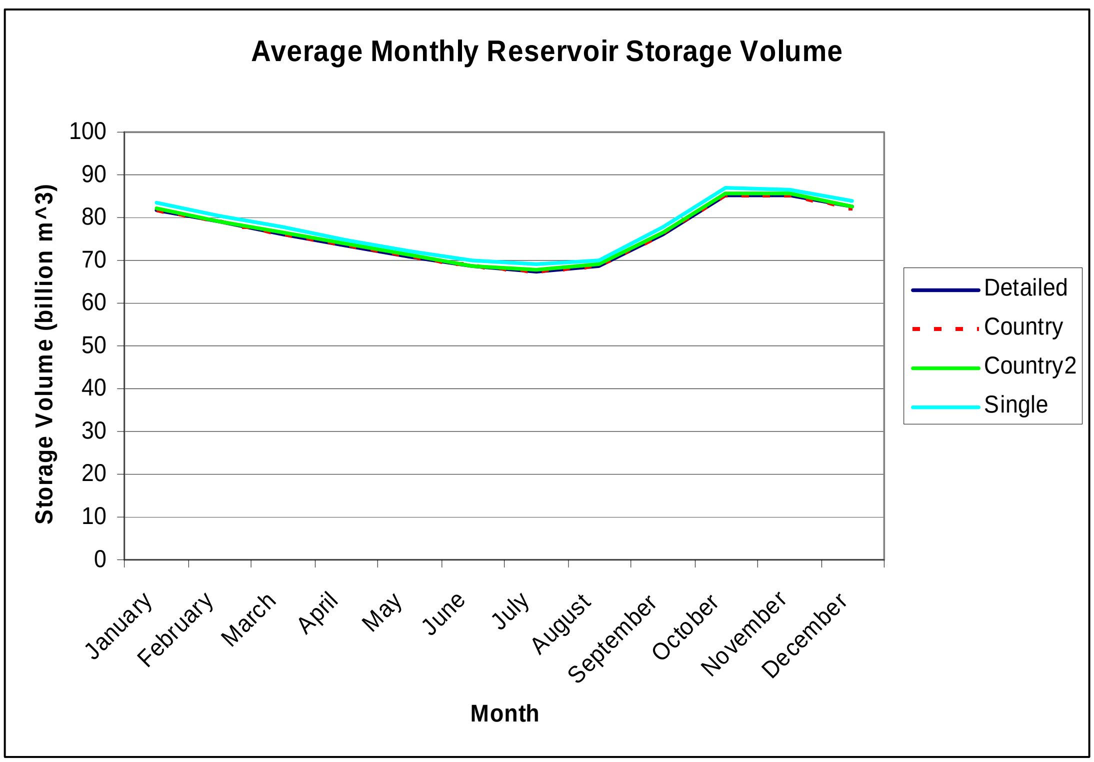
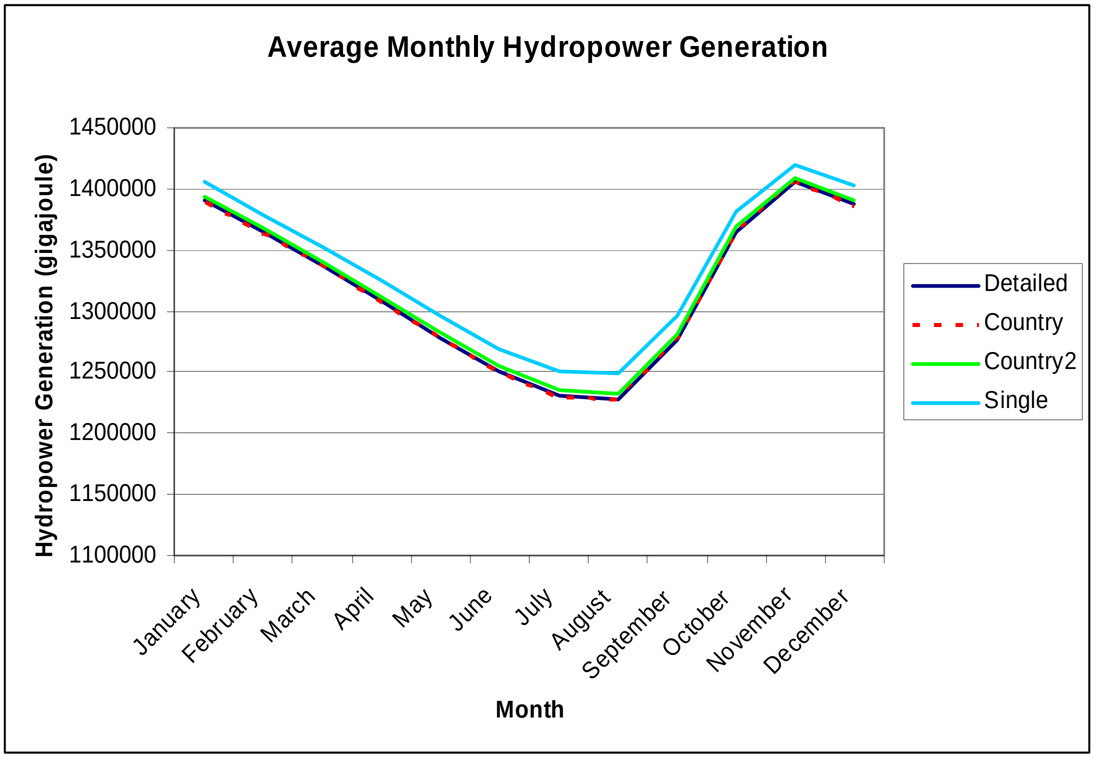


Figure 92 Average Monthly Hydropower Generation in the Volta River Basin



For the average monthly hydropower by sub-basin see Appendix D. Similarly to the average monthly reservoir storage, the average monthly hydropower generation did not vary much among the different spatial representations (Figure 93). These two results are directly related as the volume in the reservoir determines the amount of hydropower that can be generated.

Table 19 Comparison of Relative Crop Production in the Volta River Basin

Senegal Representation	Relative Crop Production
Full	91%
Country-1	94%
Country-2	95%
Single	100%

There is not a tremendous difference in crop production among the different spatial representations of the Volta River basin (Table 19). By aggregating the basin into a single representation, crop production is over estimated by about ten percent.

Table 20 Summary of the Spatial Analysis of the Volta River Basin

Spatial Representation	Demand Coverage*	Reservoir Storage	Hydropower Generation	Relative Crop Production
Detailed	93%	-	-	91%
Country Level-1	94%	0.1% less storage than detailed representation	Same generation as detailed representation	94%
Country Level-2	95%	0.5% more storage than detailed representation	0.3% more generation as detailed representation	95%
Single	100%	2.1% more storage than detailed representation	1.3% more generation as detailed representation	100%

Note: Percentage values listed for reservoir storage and hydropower generation are based on annual sum
**Demand coverage reported is the annual demand coverage. Monthly demand coverage in the Volta River Basin showed areas of significant water shortages that were masked by looking at the annual demand coverage.*

There was not much difference among the spatial representations of the Volta River Basin (Table 20). The only differences were associated with demand coverage and relative crop production. It is important to look at monthly demand coverage and the breakdown of location of the demand coverage (Appendix B). The monthly demand coverage showed areas of significant water shortages that were masked by looking at the annual demand coverage. One must decide while these demands are small relative to the whole basin, how do they rank in importance in insuring the demands are covered. Due to the fact that there was only one reservoir modeled in all of the representations, there was not much affect on reservoir storage and hydropower generation. Had there been more management on the Volta, we may have seen different results.

Summary of River Basin Case Studies

Four case studies were chosen for a more detailed analysis to represent different spatial scale issues. The Missouri River Basin represents an area where supply and demand are in different locations and there is a large amount of storage located throughout the basin. The Senegal River Basin represents an area where there is little management and the infrastructure is in series along the main river. The Yellow River Basin is one of the most managed basins in the world and the infrastructure is in series along the main river. Lastly, the Volta River Basin represents an area where the rivers are in parallel and cross international borders. Between 2 to 5 different spatial representations of each river basin were modeled.

Table 21 Summary of the Spatial Analysis of all River Basin Case Studies

River Basin	Layout of Basin	Sequence*	Basin Contribution to Global Irrigated Agriculture Production	Demand Coverage among Representations	Reservoir Storage among Representations	Hydropower Generation among Representations	Relative Crop Production among Representations
Missouri	Rivers in Parallel	1a	4.2% of global irrigated agriculture production	Varied between 47-100%	Varied 49-59% increase over detailed representation	Varied from 49% less generation to 1668% more generation than detailed representation	Varied from 41-100%
Senegal	Rivers in Series	1a	0.05% of global irrigated agriculture production	Same at 100%	Only varied by 0.3% less than detailed representation	Varied by 48% more than detailed representation	Same at 100%
Yellow (without management)	River in Series	1a	3.8% of global irrigated agriculture production	On average among spatial representations, coverage was 99%	Reservoirs were near capacity and on average spatial representations had 95% more annual storage volume than the detailed representation.	Much higher amount generated in detailed representation (avg. 71 million gigajoules annually). On average, spatial representations generated 60% less than detailed representation	Very close to complete (99% production on average)
Volta	Rivers in Parallel	1b	0.02% of global irrigated agriculture production	Varied between 93-100%**	Varied from 0.1% less to 2.1% more storage than detailed representation	Varied from 0.3-1.3% more generation than detailed representation	Varied between 91-100%

**Sequence 1a = Supply, Storage, followed by Demand; Sequence 1b = Supply, Demand, followed by Storage*
*** Monthly demand coverage in the Volta River Basin showed areas of significant water shortages that were masked by looking at the annual demand coverage (reported here).*

By taking a close look at a the case study basins, we can make some observations on the importance of the layout of the river system (in series or parallel) and the sequence of the supply, storage, and demand (Table 21). In general, results from modeling river systems in series seem to be less affected by the issue of scale while results from modeling river systems in parallel have the potential of being dramatically affected by the issue of scale. Most basin models follow the sequence of supply, then storage, followed by demand. If this sequence is not necessarily true for a basin, results have the potential of being significantly different as seen in the theoretical analysis on sequence.

Applying Case Study Results Globally

As an exercise in global analysis, the globe was divided first into 69 basins and second into 126 basins. Each basin was categorized by the river system, the sequence of supply, storage, and demand, its contribution to global irrigated agriculture production, its number of climate zones, and its level of infrastructure (Tables 22-24).

Table 22 69 Basins categorized by river layout, sequence and contribution to global irrigated ag. production

Basin Name	River Layout	Sequence	Basin Contribution to Global Irrigated Agriculture Production	Number of Climate Zones (humidity index)	Level of Infrastructure (storage/ runoff)
Southeast	P	1a	2.0%	1	low
Mississippi-d	s	1a	0.0%	1	N/A
Ohio	S	1a	1.4%	1	low
NEng-mid-atla	P	1a	1.5%	1	low
Southwest	P	1a	0.6%	2	low
Great-lakes	P	1b	0.4%	2	low
Chotanagpur	S	1a	0.8%	1	low
Great-basin	P	1a	0.7%	2	low
Rio-Grande	P	1a	0.2%	2	heavy
Texas-gulf	P	1a	1.0%	3	moderate
South-atlantic	P	1a	0.7%	1	low
Cauvery	S	1a	0.2%	2	moderate
Colorado	S	1a	0.4%	2	heavy
Sahyadri	S	1a	0.7%	2	low
Ghats-coastal	P	1a	0.3%	3	low
Ark-white-red	P	1a	3.2%	3	low
Carlifornia	P	1a	0.3%	2	low
Nigeria	P	N/A	0.0%	3	low
Eastern SSA	P	N/A	0.0%	2	low
Central W SSA	P	N/A	0.1%	1	low
Colombia	P	N/A	0.1%	2	low
Malaysia	P	N/A	0.1%	1	low
Other SE Asia	P	N/A	0.2%	1	low
Rest of the World	P	N/A	0.0%	2	low
Southern SSA	P	N/A	0.3%	3	low
Argentina	P	N/A	0.3%	3	low
Other E Asia	P	N/A	0.4%	3	low
Myanmar (Burma)	P	N/A	0.5%	1	low
Brazil	P	N/A	0.4%	1	low
Northern SSA	P	N/A	0.2%	3	low
South Korea	P	N/A	0.3%	2	low
Turkey	P	N/A	0.7%	3	low
Philippines	P	N/A	0.5%	2	low
Japan	P	N/A	0.7%	1	low
Egypt	P	N/A	0.9%	1	heavy
Mississippi-u	S	1a	4.2%	1	low
Luni	S	1a	0.2%	2	moderate
Mahi-Tapti-Purna	S	1a	0.8%	1	low
Columbia	P	1a	1.2%	3	low
Brahmaputra	S	1a	0.4%	1	low
Indian-coastal	P	1a	0.4%	3	low
Huaihe	S	1a	7.3%	2	low
Hailuan	S	1a	3.4%	3	heavy
Brahmari	S	1a	1.5%	2	low
ZhuJiang	S	1a	2.0%	1	low
Godavari	S	1a	1.1%	3	low
Siongliao	P	1a	4.9%	3	low
Other L America	P	N/A	1.1%	3	low
Other S Asia	P	N/A	1.3%	3	low
Mexico	P	N/A	1.4%	3	low
Krishna	S	1a	0.7%	3	moderate
Inland	P	1b	1.1%	4	heavy
Other Developed	P	N/A	0.6%	3	low
Vietnam	P	N/A	1.7%	1	low
Australia	P	N/A	0.6%	3	low
Thailand	P	N/A	2.0%	1	low
Indonesia	P	N/A	1.9%	1	low
Bangladesh	P	N/A	2.2%	2	low
Other WANA	P	N/A	3.8%	3	low
Eastern Europe	P	N/A	1.7%	2	low
Missouri	P	1a	4.2%	3	moderate
Central Asia	P	N/A	2.1%	2	moderate
Indus	P	1a	3.0%	4	low
Huanghe	S	1a	3.8%	3	low
Pakistan	P	N/A	4.2%	3	moderate
Rest of Former USSR	P	N/A	1.8%	3	low
Ganges	S	1a	7.3%	3	low
EC15	P	N/A	2.3%	2	low
Yangze	S	1a	3.5%	2	low

Table 23 126 Basins Categorization

Basin Name	River Layout	Sequence	Basin Contribution to Global Irrigated Agriculture Production	Number of Climate Zones (humidity index)	Level of Infrastructure (storage/ runoff)
Amazon	P	1a	0.3%	2	low
Amur	S	1b	0.9%	3	low
Arabian_Peninsul	P	1b	0.2%	2	N/A
Baltic	P	1a	0.0%	1	low
Borneo	P	1b	0.1%	1	low
Canada_Arctic_At	P	1a	0.0%	2	N/A
Carribean	P	1a	0.0%	2	low
Cauvery	S	1a	0.2%	2	moderate
Central_African_	P	1a	0.0%	2	N/A
Central_America	P	1a	0.1%	1	low
Central_Australi	P	1a	0.1%	2	N/A
Central_Canada_S	P	1a	0.0%	3	N/A
Chotanagpui	S	1a	0.8%	1	low
Colorado	S	1a	0.4%	2	heavy
Congo	S	1a	0.0%	1	low
Cuba	P	1a	0.0%	2	low
East_African_Coa	P	1a	0.0%	2	N/A
Eastern_Australi	P	1a	0.1%	3	N/A
Great_Basin	P	1a	0.7%	2	low
Great_Lakes	P	1b	0.4%	1	low
Horn_of_Africa	P	1a	0.1%	3	low
Iberia_East_Med	S	1a	0.2%	3	low
Indonesia_East	P	1a	0.1%	2	low
Ireland	P	1a	0.0%	1	low
Kalahari	P	1a	0.0%	2	low
Lake_Balkhash	P	1a	0.3%	1	low
Lake_Chad_Basin	P	1b	0.0%	4	low
Langcang_Jiang	S	1a	1.3%	2	low
Limpopo	P	1a	0.1%	3	moderate
Lower_Mongolia	P	1a	0.2%	2	low
Madagascar	P	1a	0.3%	2	low
New_Zealand	P	1a	0.0%	1	low
Niger	S	1a	0.1%	4	low
North_African_Co	P	1a	0.2%	3	N/A
North_Euro_Russi	P	1a	0.0%	1	N/A
North_Korea_Peni	P	1a	0.4%	1	N/A
Northeast_Brazil	P	1a	0.0%	2	low
Northwest_Africa	P	1a	0.3%	3	N/A
Ohio	S	1a	1.4%	1	low
Orange	S	1a	0.1%	3	heavy
Orinoco	S	1a	0.2%	3	low
Peru_coastal	P	1a	0.1%	3	low
ROW	P	N/A	0.0%	1	N/A
Rhine	S	1a	0.2%	1	low
Rhone	S	1a	0.1%	1	low
Rio_Colorado	S	1a	0.0%	3	heavy
Rio_Grande	P	1a	0.4%	1	heavy
Sahara	P	N/A	0.0%	2	low
Salada_Tierra	P	1a	0.1%	4	low
San_Francisco	P	1a	0.1%	3	low
Scandinavia	P	1a	0.1%	2	low
Seine	S	1a	0.1%	1	low
Senegal	S	1a	0.0%	3	low
South_African_Co	P	1a	0.2%	3	N/A
Southeast_Africa	P	1a	0.0%	2	N/A
Southeast_US	P	1a	0.7%	1	low
Sri_Lanka	P	1a	0.2%	2	low
Tierra	P	1a	0.0%	3	low
Toc	S	1a	0.0%	1	low
US_Northeast	P	1a	1.6%	1	low
Upper_Mexico	P	1a	0.2%	2	heavy
Upper_Mongolia	P	1a	0.0%	2	low
Uruguay	S	1a	0.1%	1	low
Volta	P	1b	0.0%	3	heavy
West_African_Coa	P	1a	0.0%	1	N/A
Western_Australi	P	1a	0.1%	2	N/A
Western_Gulf_Mex	S	1a	1.0%	3	moderate
Yenisey	S	1a	0.1%	2	low
Yucatan	P	1a	0.4%	2	low
Zambezi	P	1a	0.0%	3	moderate

Table 24 126 Basins Categorization Continued

Basin Name	River Layout	Sequence	Basin Contribution to Global Irrigated Agriculture Production	Number of Climate Zones (humidity index)	Level of Infrastructure (storage/ runoff)
Arkansas	P	1a	3.3%	3	low
Britain	P	1a	0.0%	1	low
California	P	1a	0.3%	3	low
Easten_Ghats	P	1a	0.3%	3	low
Eastern_Med	P	1a	0.5%	4	low
Elbe	S	1a	0.1%	1	low
Japan	P	1a	0.7%	1	low
Luni	S	1a	0.2%	2	moderate
Mississippi	S	1a	4.3%	1	low
Parana	P	1a	0.2%	3	moderate
Philippines	P	1a	0.6%	2	low
Sahyada	S	1a	0.7%	3	low
South_Korea_Peni	P	1a	0.4%	2	N/A
Syrdarja	S	1a	0.4%	2	moderate
Thai_Myan_Malay	P	1a	1.0%	1	low
Thai_Myan_Malay	P	1a	1.0%	1	low
Ural	S	1a	0.4%	2	low
Amudarja	S	1a	0.7%	3	low
Columbia	P	1a	1.2%	3	low
Columbia_Ecuador	P	1a	0.0%	2	N/A
Hail_He	S	1a	3.5%	2	heavy
Hual_He	S	1a	7.4%	2	low
India_East_Coast	P	1a	0.4%	2	low
Italy	P	1a	0.5%	3	low
Loire_Bordeaux	P	1a	0.3%	1	low
Mahi_Tapti	S	1a	0.8%	3	low
Middle_Mexico	P	1a	0.6%	4	low
Red_Winnipeg	P	1a	0.2%	3	low
Brahmari	S	1a	1.5%	2	low
Godavari	S	1a	1.1%	3	low
Murray_Australia	P	1a	0.4%	3	moderate
Ob	P	1a	0.8%	4	low
Oder	P	1a	0.0%	2	low
Songhua	S	1a	4.1%	3	low
Tigris_Euphrates	P	1a	1.5%	3	moderate
Zhu_Jiang	S	1a	1.7%	1	low
Black_Sea	S	1b	0.6%	3	low
Dnieper	P	1a	0.6%	2	low
Iberia_West_Atla	P	1a	0.6%	3	N/A
Krishna	S	1a	0.7%	3	moderate
Nile	P	1b	0.8%	4	heavy
SE_Asia_Coast	P	1a	2.0%	1	low
Brahmaputra	S	1a	1.8%	2	low
Indonesia_West	P	1a	1.7%	1	low
Mekong	S	1a	1.9%	1	low
Volga	P	1a	0.4%	3	low
Western_Asia_Ira	P	1a	2.3%	2	N/A
Yili_He	S	1a	1.0%	4	heavy
Danube	S	1a	1.8%	2	low
Missouri	P	1a	4.3%	3	moderate
Huang_He	S	1a	3.9%	4	low
Indus	P	1a	6.4%	3	low
Ganges	S	1a	8.7%	3	low
Chang_Jiang	S	1a	3.5%	2	low

Figure 93 River Layout in 69 Basin Representation of the World

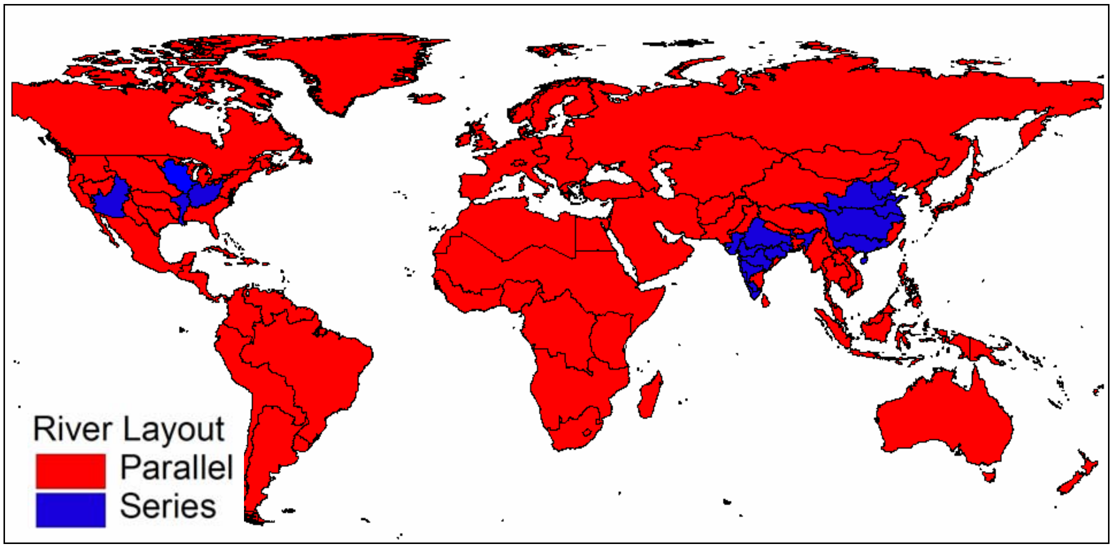
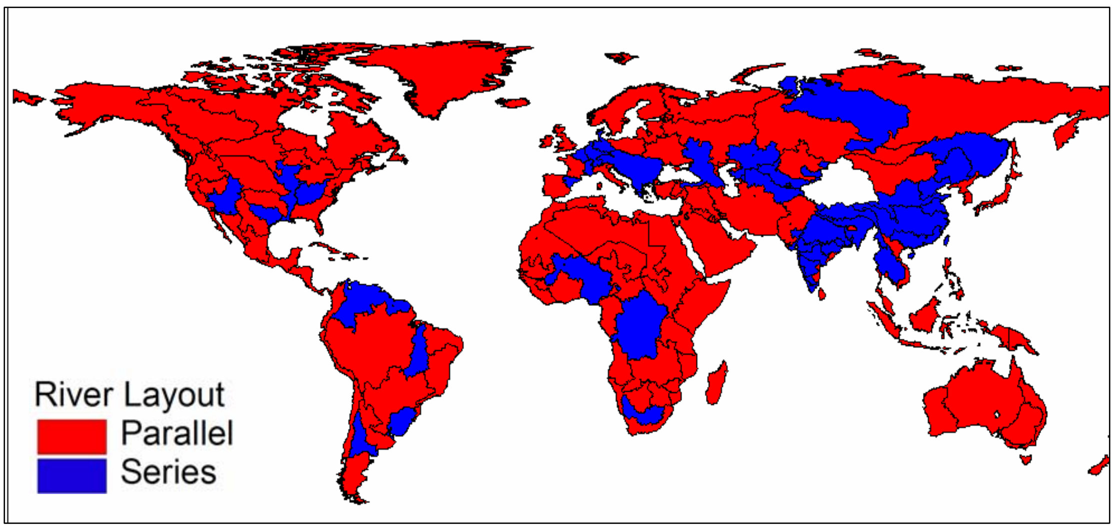


Figure 95 River Layout in 126 Basin Representation of the World



In the 69 basin representation, 72% of the basins were categorized as being in parallel and 28% in series (Figure 94). In the 126 basin representation 55% of the basins were categorized as being in parallel and 45% in series (Figure 95). This shows the potential of overestimating the available water to be 64% and 55% in the 69 and 126 basin representations respectively. The basins with the potential of overestimating the available water in the 69 basin representation and 126 basin representation also represent approximately 60% and 42% of the world's irrigated agricultural area respectively.

Figure 94 Basin Sequence of the 69 Basin Representation of the World

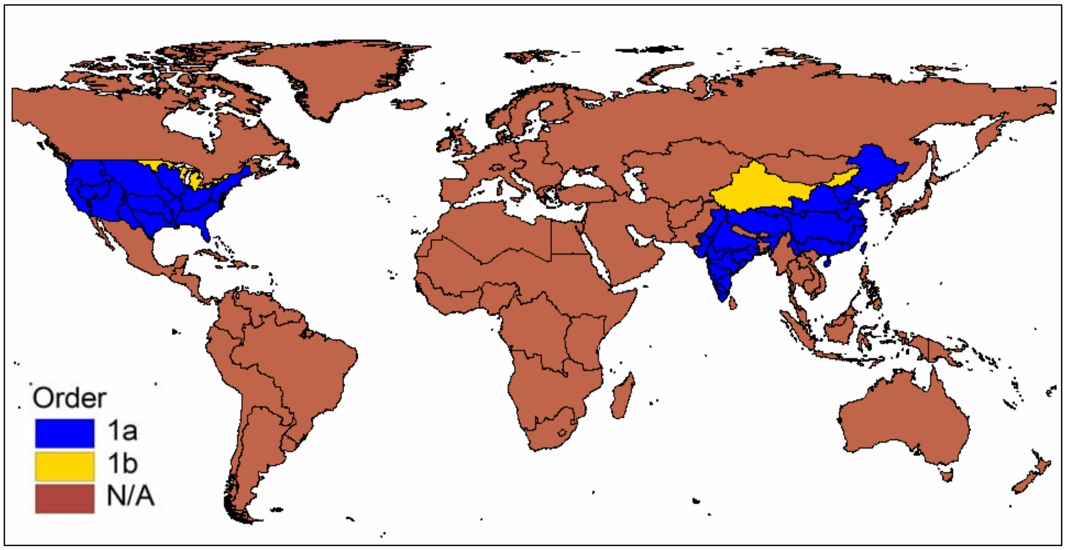
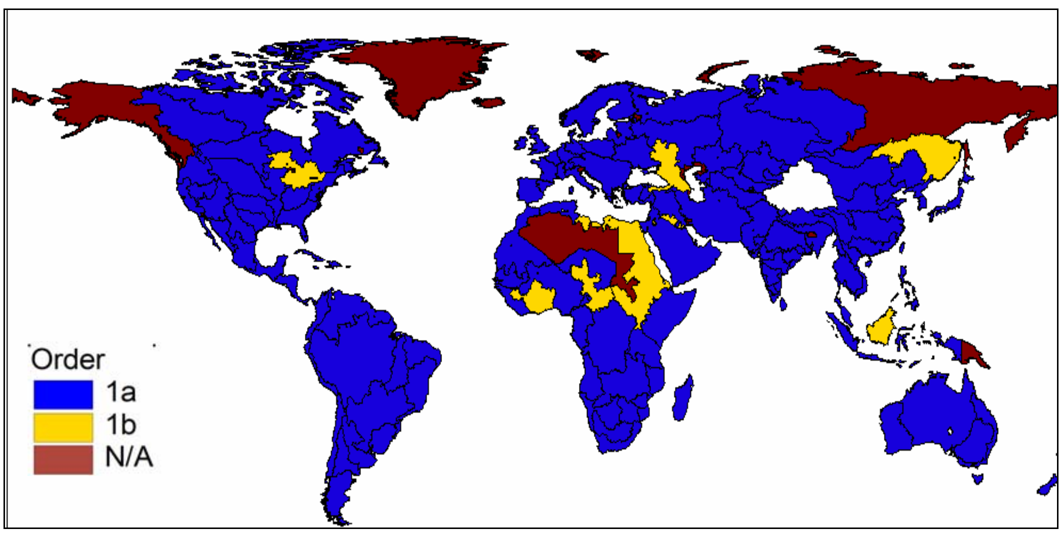


Figure 97 Basin Sequence of the 126 Basin Representation of the World



In the 69 basin representation a majority of the basins could not be categorized into a sequence system due to the gross size of the basins. Sequence 1a represents supply first, storage second, and demands third. The 1b sequence represents supply first, demand second and storage third. Out of the basins that could be categorized in the 69 basin representation, the majority follow the 1a sequence (Figure 96). The majority of the basins in the 126 representation also follow the 1a sequence (Figure 97). Most global models use the 1a representation; therefore the majority of the basins in the 126 basin representation are being modeled correctly when it comes to sequence.

Figure 95 Number of Climate Zones of the 69 Basin Representation of the World

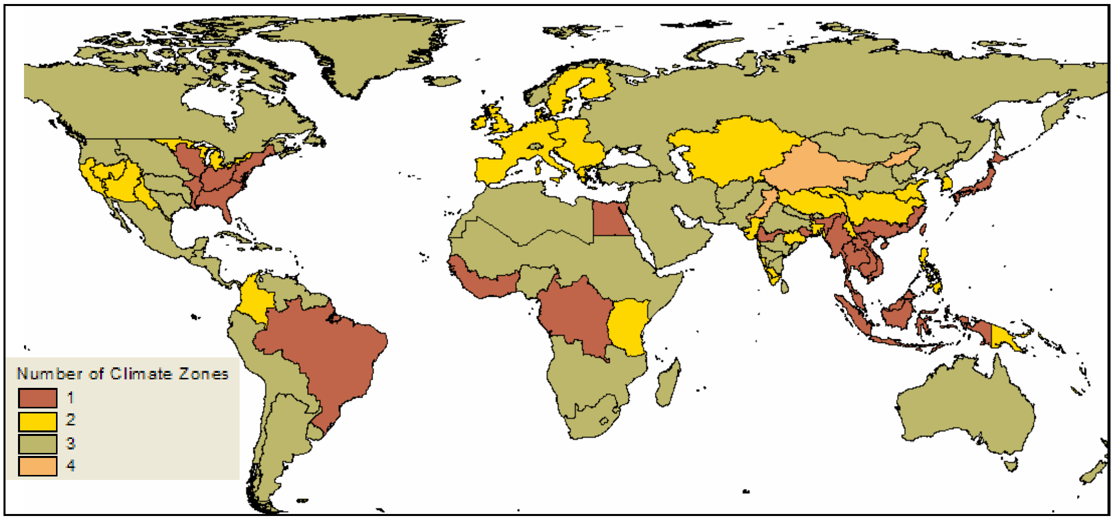
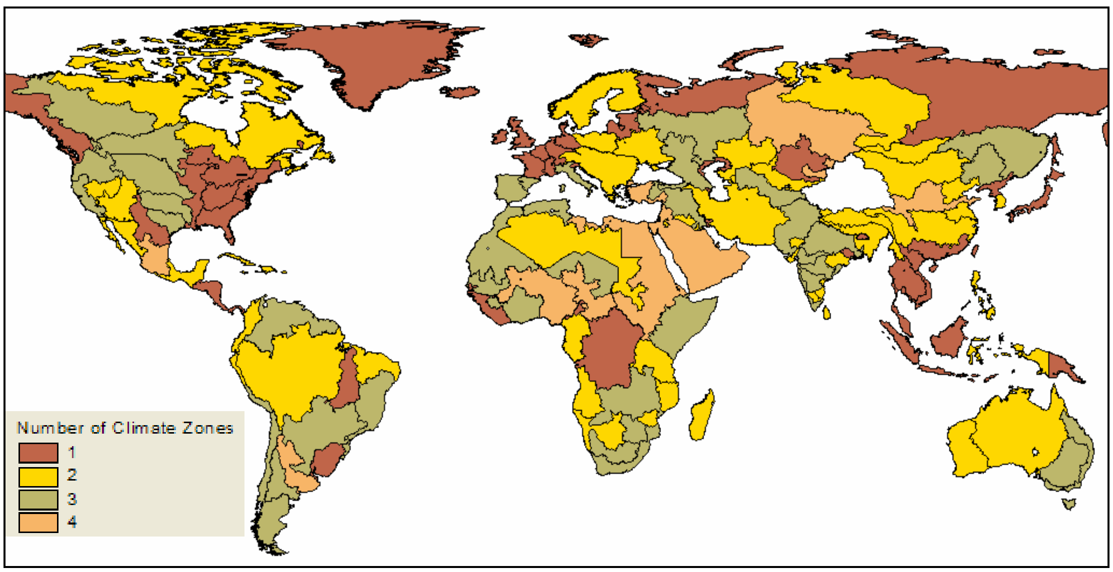


Figure 96 Number of Climate Zones of the 126 Basin Representation of the World



In the 69 basin representation, 41% of the basins were categorized as having more than 2 climate zones and 59% having 2 or less climate zones (Figure 98). In the 126 basin representation 30% of the basins were categorized as having more than 2 climate zones and 70% having 2 or less climate zones (Figure 99). The climate zones are determined by the humidity index (UNEP 1991). While this can give further insight as to how the hydrology is distributed across a basin, it does not have as much weight as the other basin characteristics when determining basins in danger of having their irrigated agriculture production overestimated.

Figure 97 Level of Infrastructure of the 69 Basin Representation of the World

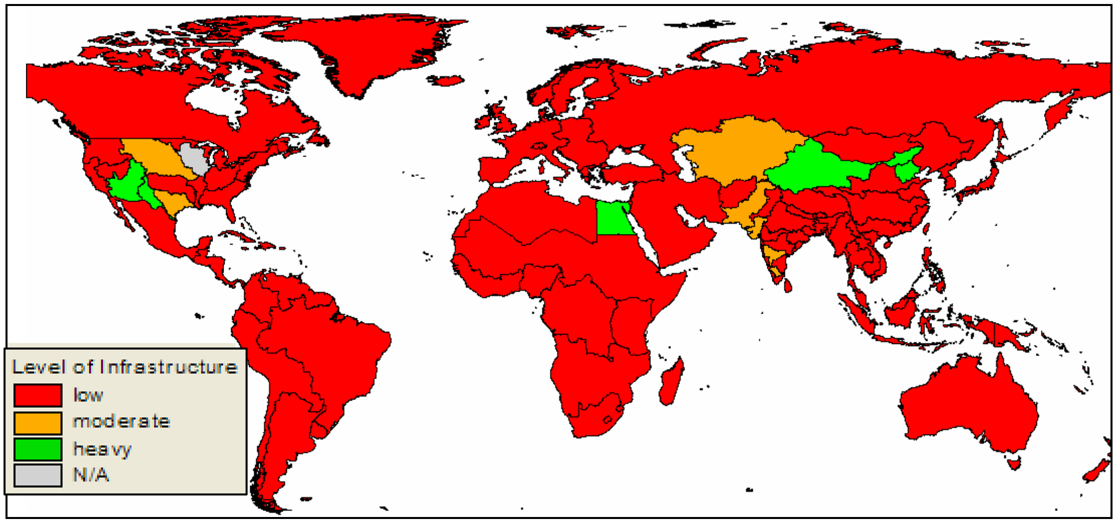
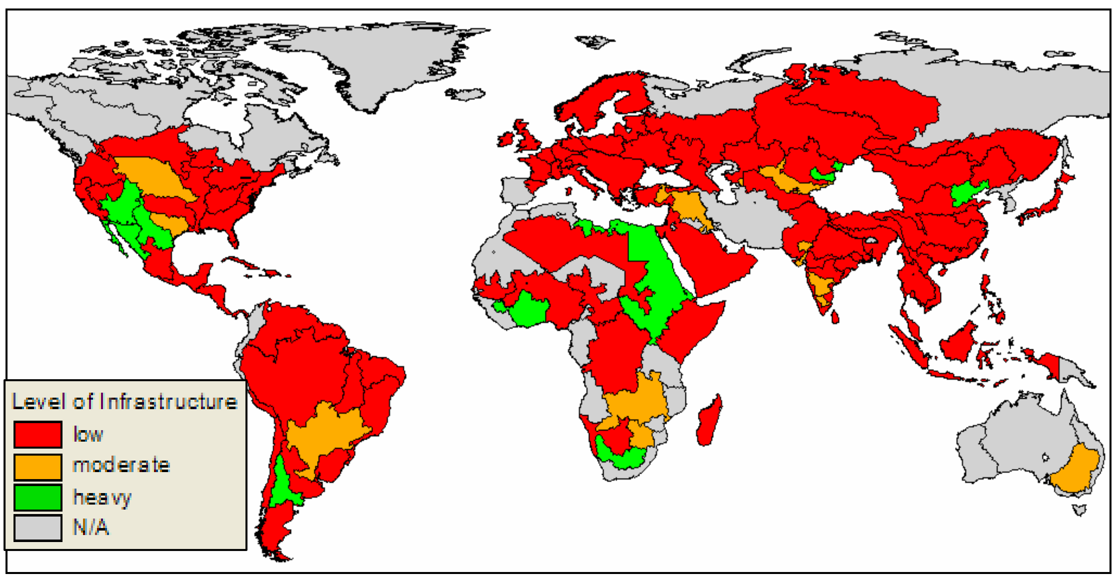


Figure 98 Level of Infrastructure of the 126 Basin Representation of the World



In the 69 basin representation, only 5 of the basins were categorized as having heavy infrastructure, meaning that these basins can most likely move and store water around the basin to reach demands (Figure 100). In the 126 basin representation 10 of the basins were categorized as having heavy infrastructure (Figure 101). The 69 basin representation does not capture basin infrastructure at the level of the 126 basin representation.

Figure 99 Contribution to Global Irrigated Agriculture of the 69 Basin Representation of the World

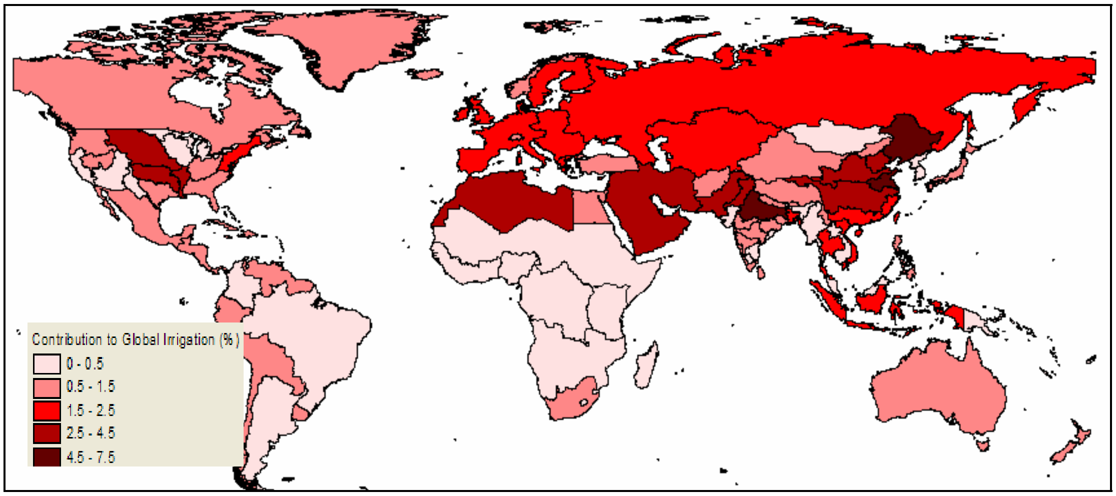
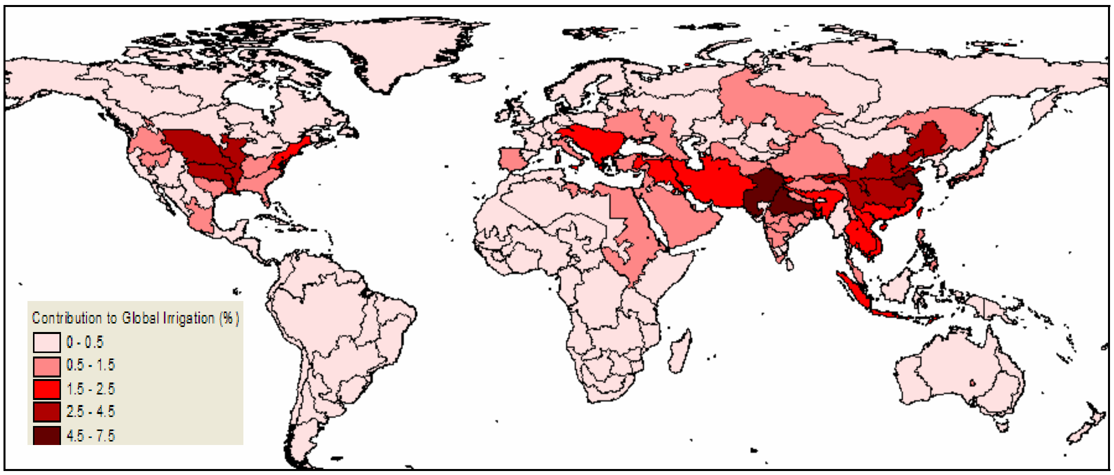


Figure 100 Contribution to Global Irrigated Agriculture of the 126 Basin Representation of the World



The basins were categorized by their contribution to global irrigated agriculture. In the 69 basin representation, most of the basins show significant contribution to global irrigated agriculture (Figure 102). This is due to the large aggregation of basins, with the exception of USA, India, and China. Fifty-seven percent, or 39 of the 69 basins contribute to 90% of the world's irrigated agriculture. In the 126 basin representation, most of the basins fit into 0-0.5 percent contribution to global irrigated agriculture (Figure 103). Once the basin representations have been disaggregated as with the 126 basin representation we have a better representation of which basins are actually contributing the most to global irrigated agriculture. Forty percent or 50 of the 126 basin representations contribute to 90% of the world's irrigated agriculture. The 69 basin representation greatly overestimates the production of irrigated agriculture.

Figure 101 Risk of Overestimating Irrigated Agriculture Production in the 69 Basin Representation of the World

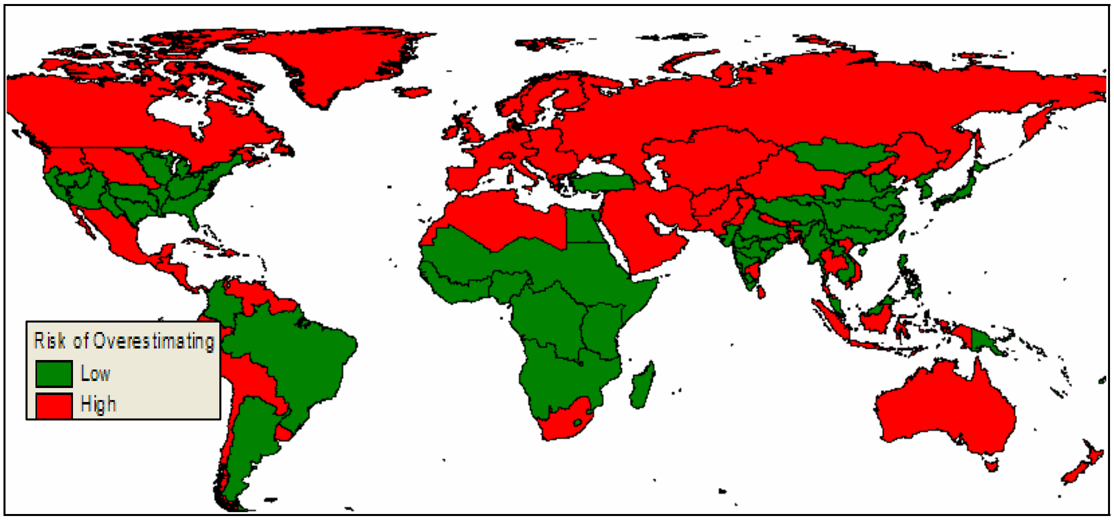
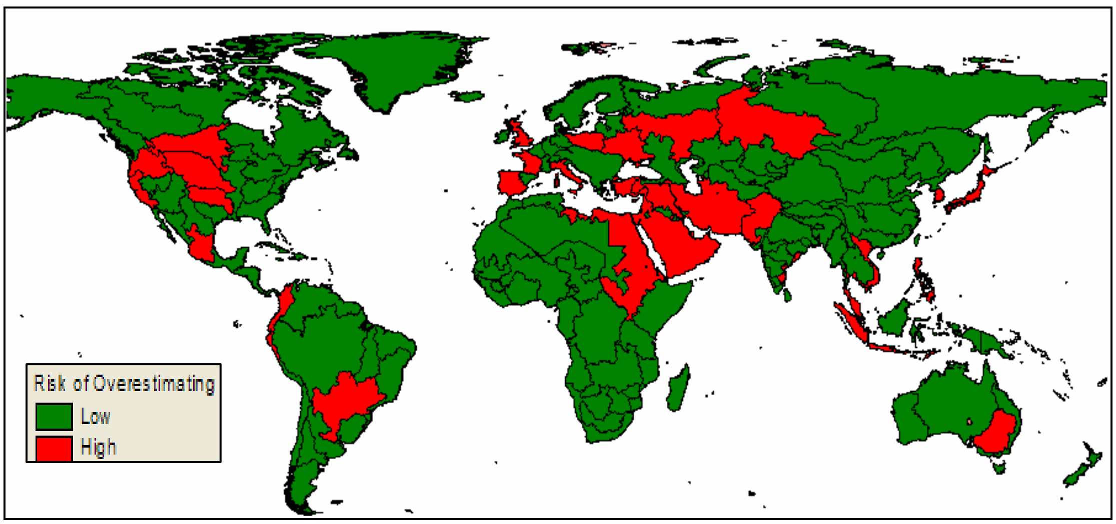


Figure 102 Risk of Overestimating Irrigated Agriculture Production in the 126 Basin Representation of the World



In the 69 representation, 29 (42%) of the 69 basins are at risk of overestimating irrigated agriculture production as their river layout is in parallel, they significantly contribute to global irrigated agriculture, and only have low to moderate levels of management (Figure 104). In the 126 representation, 21 (17%) of the 126 basin representation are at risk of overestimating irrigated agriculture production (Figure 105). The basins at risk of overestimating irrigated agriculture production in the 69 basin representation and 126 basin representation also represent approximately 54% and 33% of the world's irrigated agricultural area respectively.

Limitations of River Basin Study

While this study provided a number of sound conclusions regarding the importance of spatial scale and management on river basin modeling for global food production, there are some limitations. One limitation is the methodology for aggregating hydropower. More research needs to be done in this area.

Another limitation is the categorization of the basins by series and parallel using expert judgment. It appears that there may be a more robust/scientific approach to this categorization process using the Strahler number (Gregory and Walling, 1973.) The Strahler number is derived from a stream ordering method which helps identify streams with many tributaries. A number of algorithms could be developed to come up with an objective parameter based on the percentage of tributary flow to total flow and its connections and layout. This process of combining the Strahler number and flow could be automated using GIS.

Lastly, it would be interesting to evaluate more realistic case studies in addition to the stylized representative case studies presented in this research. More realistic case studies would help solidify the conclusions.

Summary of River Basin Study

Attempts to globally model the world's water resources span over a variety of spatial scales. The purpose of the modeling efforts described in this paper was to evaluate the importance of spatial scale and management at the river basin level for global food production. To evaluate the impact scale has on river basin analyses, there were six main basin characteristics evaluated: river layout in a basin representation (rivers in parallel versus rivers in series), sequence of supply, storage and demand, the importance of the basin to global irrigated agriculture, the number of climate zones in the basin, the level of infrastructure in the basin, and the level of management in the basin.

The results of four case studies (Missouri River Basin, Senegal River Basin, Yellow River Basin, Volta River Basin) show that the layout of the basin representation impacts its response to different spatial representations. If the basin's main river is in series as with the Yellow River and Senegal River, there is not much difference among the different spatial representations. If the basin representation contains river systems in parallel as with the Missouri and Volta, the impacts from different spatial representations are quite varied. River systems in parallel have the risk of having their available water greatly overestimated. In basins where the model spatial representation significantly affects the results of the analysis, one must be careful as results could be overestimating crop production, reservoir storage, demand coverage, etc. This result supports Antle's conclusions that "optimal scale for analysis to be an increasing function of the scale at which the observed data exhibit maximum variability and the heterogeneity of the data." (Antle 1999) There should be a note of caution regarding aggregating hydropower generation as this subject needs more research. The current approach is a very basic estimate and should not be heavily weighted.

In addition to the spatial analysis of the case studies, an analysis on the affect of modeling management was applied to the Yellow River Basin. The active reservoir storage capacity in the Yellow River Basin is about half the actual storage capacity and there is a large flow requirement on the river to address sediment flushing in the river. One would need to do research to discover these management issues and unfortunately in many global analyses there is neither the time nor money to research every basin for management issues. Ignoring management issues in one's model can have significant implications as seen in the Yellow River Basin. By removing the management issues from the Yellow River Basin, one would over estimate crop production by approximately 40 percent, over estimate demand coverage by as much as 90 percent in one month for the single representation comparison, and greatly over estimate reservoir storage and hydropower production.

An analysis was done on 2 different global river basin representations; one with 69 basins and another with 126 basins. The five main river basin characteristics were compared between the two global river basin representations. The potential of overestimating the available water based on river layout in a basin was over 50% in both representations. The basins with the potential of overestimating the available water also represent approximately 60% (in the 69 basin representation) and 42% (in the 126 basin representation) of the world's irrigated agricultural area. This potential of overestimating the available water in a basin can be mitigated by the amount of infrastructure in a basin. Basin representations with heavy infrastructure are removed from being a threat of overestimating water availability because they have the ability to move and store water.

When combining the threat of overestimating available water with the level of infrastructure and the areas where irrigated agriculture is significant to global production, one finds that 42% of the basins in the 69 representation and 17% of the basins in the 126 representation are at risk of overestimating the amount of irrigated agriculture. The basins at risk of overestimating irrigated agriculture production in the 69 basin representation and 126 basin representation also represent approximately 54% and 33% of the world's irrigated agricultural area respectively. It was found that most global river basin models sequence their water resource components as supply, storage, followed by demand therefore this basin characteristic was not included in determining the risk of overestimating the amount of irrigated agriculture production. Also, the number of basin representations with more than 2 climate zones was well under 50% in both scale representations; therefore this characteristic was not used in determining the potential of overestimating irrigated agriculture production.

Depending on the magnitude of the overestimation (very significant in the case of the Missouri River Basin) this could have dramatic effects on the results of the analysis. This supports Irwin and Geoghegan's conclusions that "not taking into account spatial dependence or spatial heterogeneity when estimating a model can lead to biased or inconsistent estimates and false conclusions regarding the sign and significance of parameter estimates" (Irwin and Geoghegan 2001).

Figure 103 Modeling Frontier with Spatial Complexity

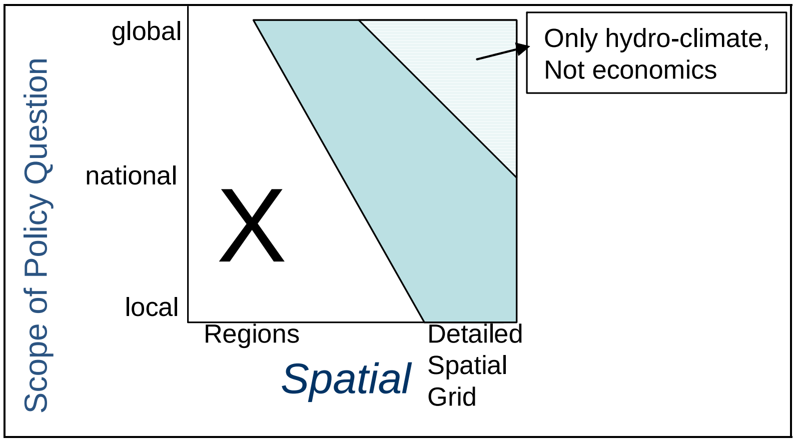
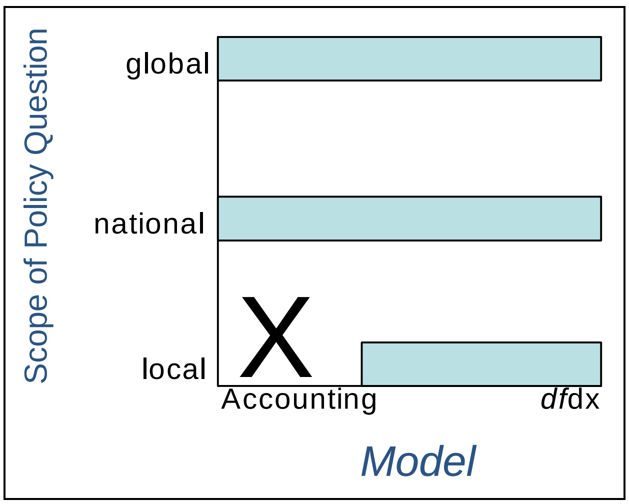


Figure 104 Modeling Frontier with Model Complexity



The research presented in this report does not necessarily support Wilcoxen's Modeling Frontier which hypothesizes how geographical scope and modeling detail interact (Figure 55). The research presented here suggests that the tradeoff is not as simple as solely varying geographical scope as presented by Wilcoxen. The model detail should cover both spatial and model complexity. The modeling frontier should reflect that a simple model with detailed spatial representation is better than a detailed model with a simple spatial representation. When looking at spatial complexity, one cannot perform regional analyses to answer local and national policy questions (Figure 106). At the same time, there is a limitation to the usefulness of a detailed spatial grid analysis due to data constraints. One could perform analyses for hydro-climate related policy questions at the detailed spatial grid scale, but this could not be done for economic related policy questions (Figure 106). When looking at model complexity, it is acceptable to use various levels of model complexity to answer policy questions at the global and national levels, but one must use caution when trying to inform policy at the local scale. Due to specifics in local scale policy questions, these analyses require more complex models (Figure 107).

In summary, spatial representation in a model can have significant impacts on the results in basin representations where rivers are in parallel. In general, one risks the possibility of overestimating available water in basin representations where rivers are in parallel. If this occurs in areas where irrigated agriculture is a significant contributor to the global irrigated production, one may be greatly overestimating the potential of global irrigated agriculture. There is little to no impact on basin representation where the main river is in series. While spatial representation may not be an issue, modeling the correct management may be. Global modelers must use caution in aggregating basin representations. One must determine the layout of each basin representation and the corresponding level of management to aid them in completing a useful and representative analysis.

CHAPTER 5

CONCLUSIONS

The main research question asked in this study was “What is the importance of spatial scale on hydro-economic modeling of global and national food and water systems to address environmental and hunger policy questions?” To answer this question, The International Food Policy Research Institute’s (IFPRI) IMPACT-Water model was evaluated at 2 different spatial scales (69 basins vs 281 basins) and the results from each version were compared. Most indicators and results such as those related to hunger require comparison at the local/regional scale. In order to provide a detailed analysis comparing the results between the two different spatial scales of IMPACT-Water, three case studies at the regional scale were chosen to represent different hydro-climates and economic heterogeneity: Central Asia, Europe, Southern Sub-Saharan Africa. Results from this analysis imply that spatial scale does have an impact on model results used to inform environment and hunger policy. The study also concluded that impacts are stronger in regions of economic and hydro-climate heterogeneity.

To further evaluate the issue of spatial scale, a second research question was proposed, “What is the importance of spatial scale and management on river basin modeling for global food production?” Four case studies were evaluated (Missouri River Basin, Senegal River Basin, Yellow River Basin, Volta River Basin) in addition to performing the analysis at 2 different global river basin representations; one with 69 basins and another with 126 basins. The key findings from this analysis are as follows:

- One risks the possibility of overestimating available water in basin representations where rivers are in parallel which could lead to overestimating the potential of global irrigated agriculture.
- Properly representing the sequence of supply, storage, and demand is very important.
- Recognizing the level of a basin’s infrastructure is important.
- Modeling the correct management may be a significant issue if a basin is heavily managed.

In conclusion, global modelers need to be aware that the spatial scale of their models is important. Modelers must also use caution when aggregating basin representations. One must determine the layout of each basin representation and the corresponding level of management to aid them in completing a useful and representative analysis.

Future Research

While this research provided a number of sound conclusions regarding the importance of spatial scale on hydro-economic modeling and river basin modeling, there are some areas that can be researched further. Suggestions for future research are listed below:

- Perform the same analysis that was conducted on the IMPACT-WATER model on other water and food models and compare the findings.
- Research alternative ways to disaggregate economic data that is mostly at the national scale.
- Perform the analysis that was conducted on the IMPACT-WATER model at various other spatial disaggregations and aggregations of the model to compare findings (i.e. +100 regions, +700 regions, 12 regions, 1 region, etc.)
- Evaluate various other scenarios with the IMPACT-WATER model between the two spatial representations for example adding tariffs, subsidies, climate change, etc. and compare the affects of spatial scale on these scenarios.
- Evaluate more case studies with the IMPACT-WATER model. These additional case studies would help solidify the conclusions.
- Research alternative methodologies for aggregating hydropower.
- Research more robust/scientific approaches to the process of categorizing basins by series and parallel. One possibility may be to use a combination of the Strahler number (Gregory and Walling, 1973) and flow using GIS techniques.
- Evaluate more realistic river basin case studies in addition to the stylized representative case studies presented in the current research. More realistic case studies would help solidify the conclusions.

CHAPTER 6

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APPENDIX A

GIS REPRESENTATIONS OF THE MISSOURI, YELLOW, AND SENEGAL SUB-BASINS

The following set of figures shows the sub-basin boundaries for the different spatial representations of the Missouri, Yellow, and Senegal sub-basins. These spatial representations were used to determine the runoff. A global 0.5° x 0.5° gridded rainfall runoff model was used to calculate runoff for these 3 basins. The Volta Basin is not included in this set because the analysis of the Volta Basin was based on a previous study that included the runoff already. The heavy blue line in the figures represents the river (not available for all basins). The thinner lines represent the runoff network. The red lines in the Senegal figures represent country boundaries.

Missouri River Basin

Figure 105 Missouri River Full and 8-Region Representation

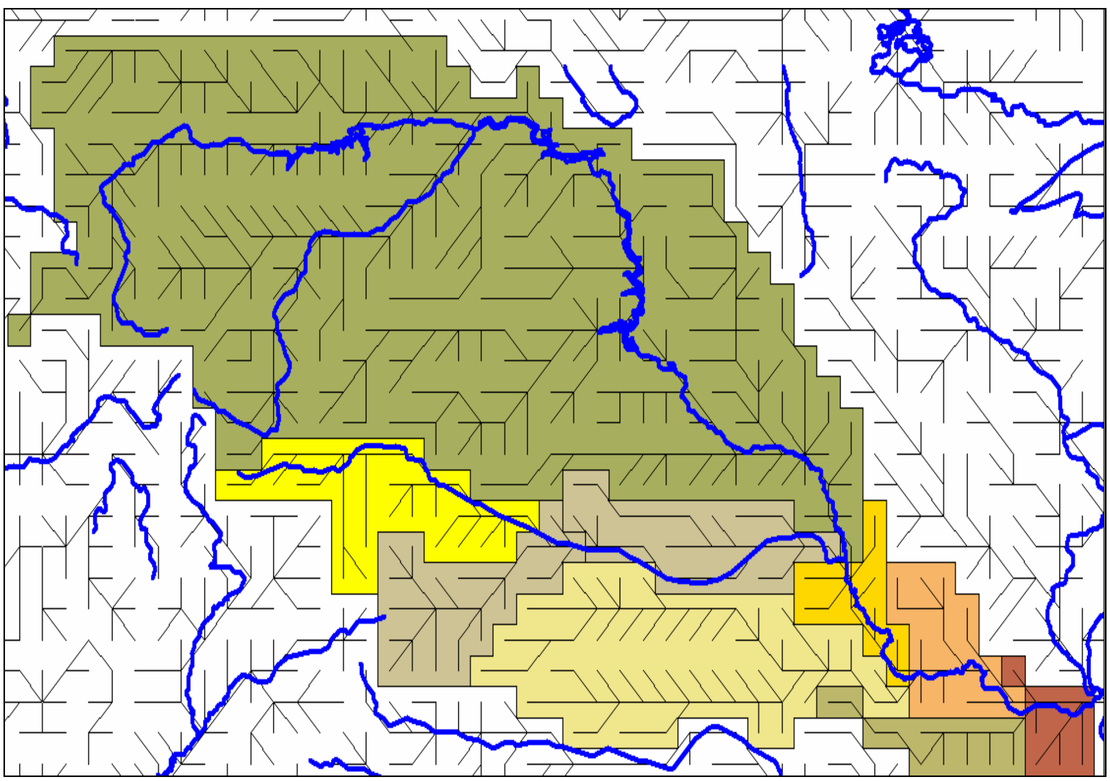


Figure 106 Missouri River 3-Region Basin

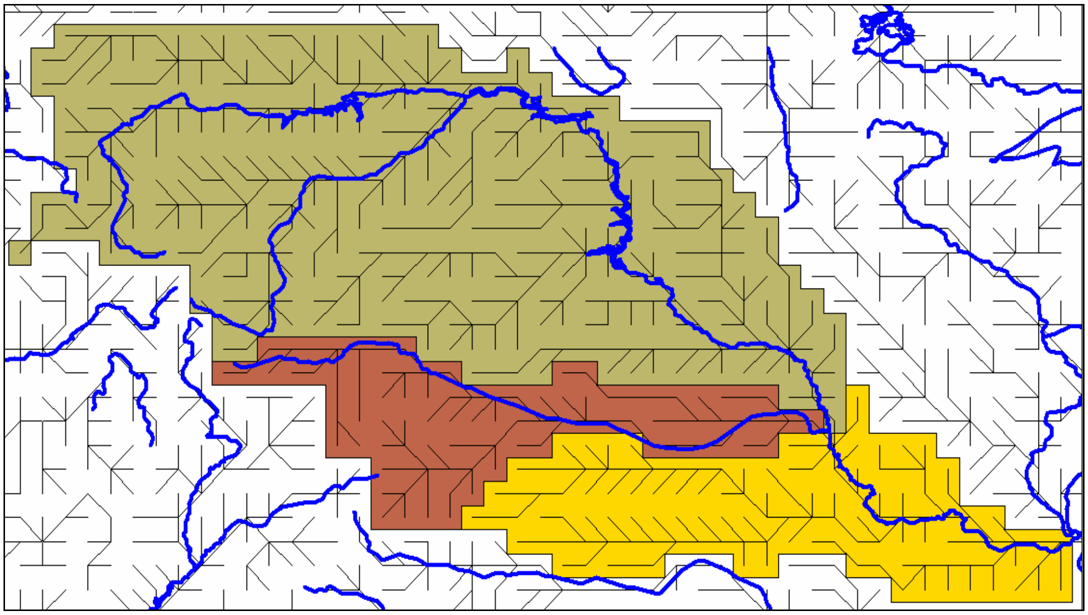
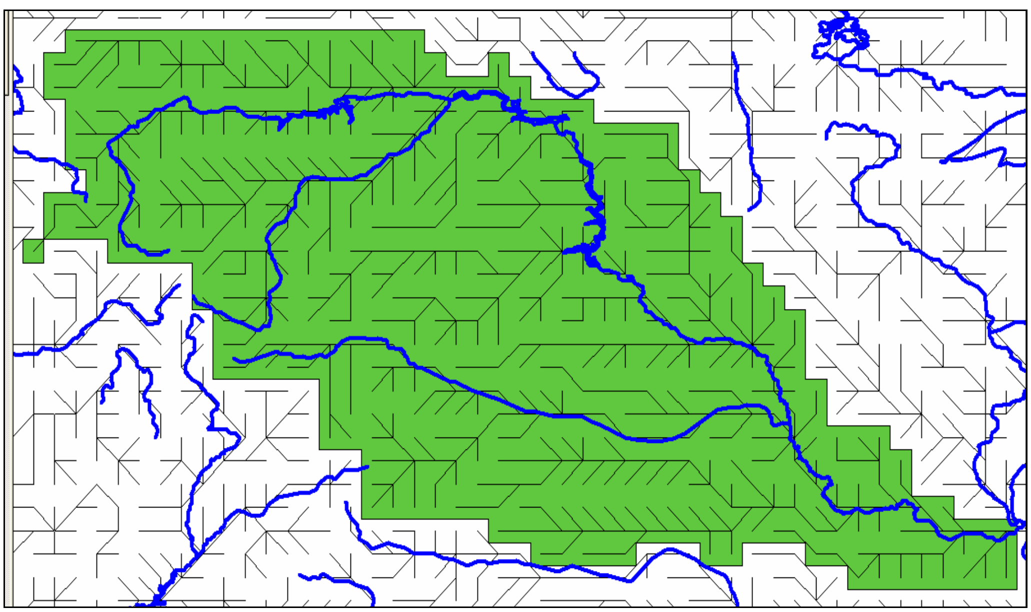


Figure 107 Missouri River 1-Region Basin



Senegal River Basin

Figure 108 Senegal River Full Representation

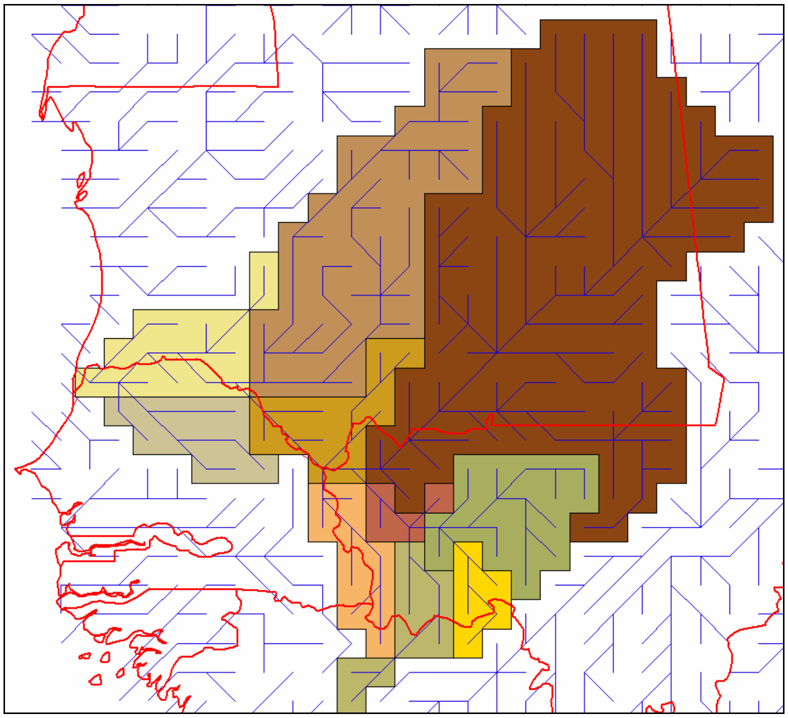
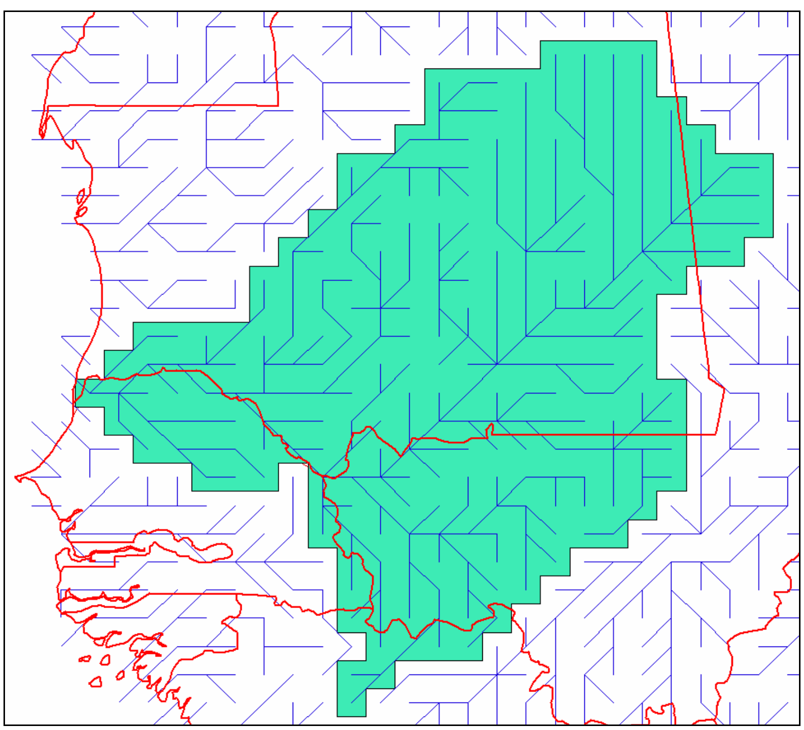


Figure 109 Senegal River 1-Region Representation



Yellow River Basin

Figure 110 Yellow River Basin Full Representation

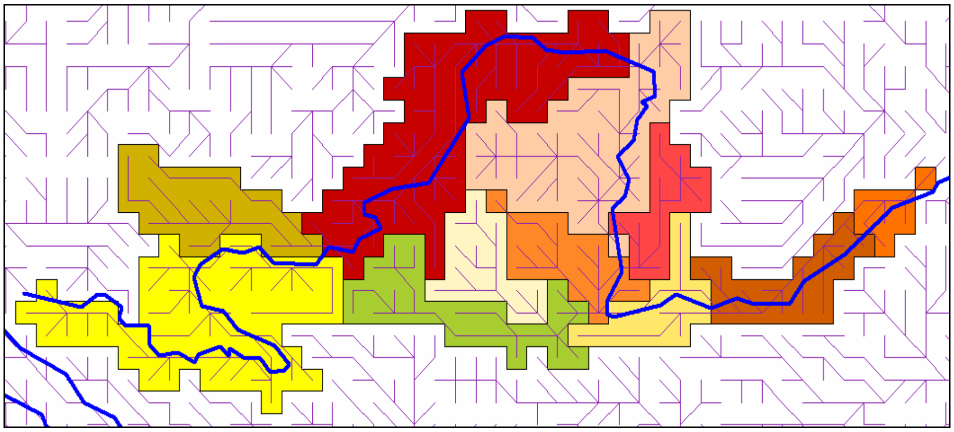


Figure 111 Yellow River Basin 4-Region Representation

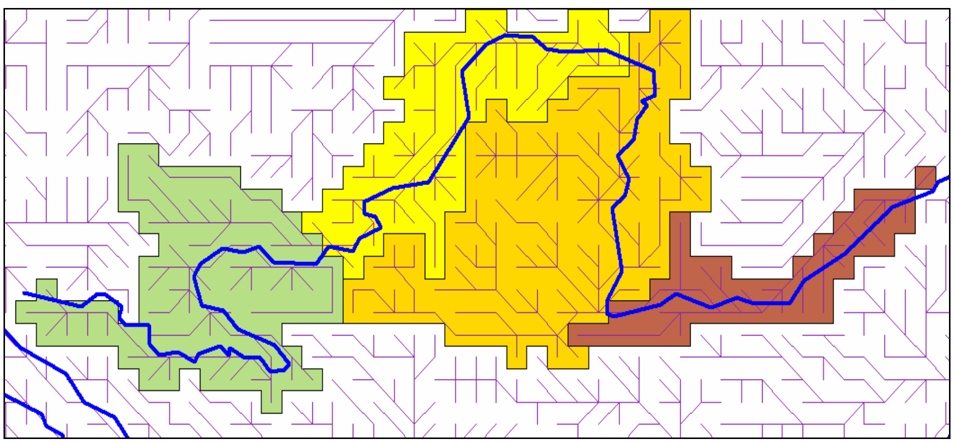


Figure 112 Yellow River Basin 3A-Region Representation

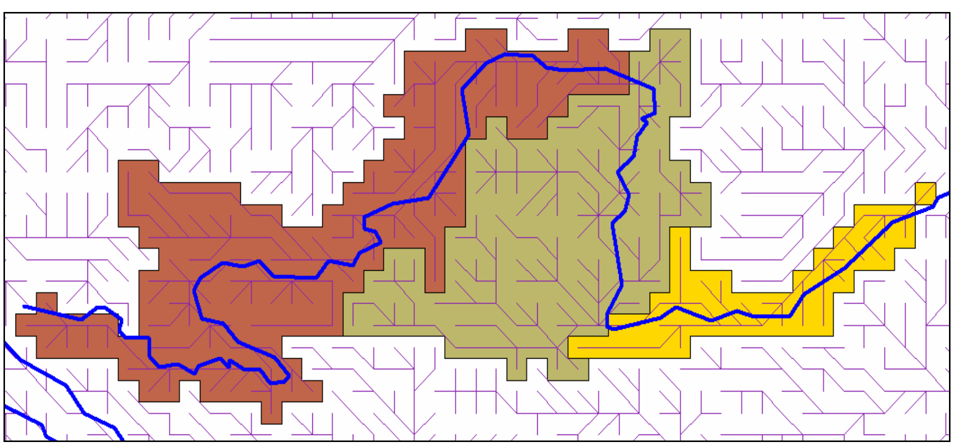


Figure 113 Yellow River Basin 3B-Region Representation

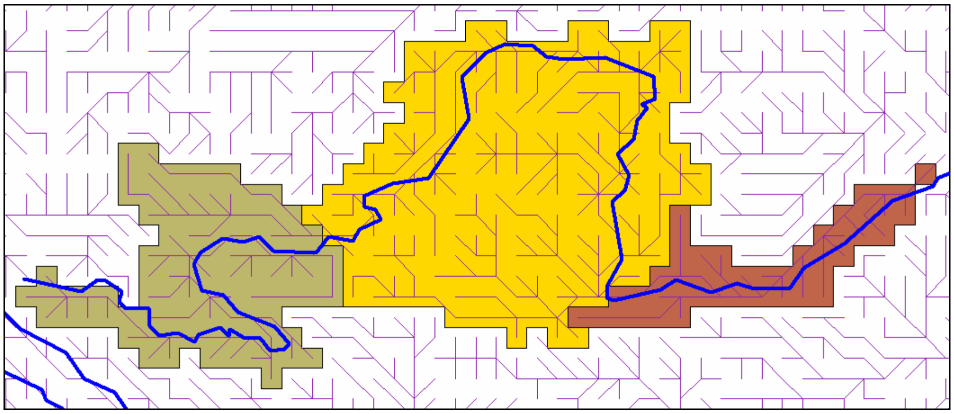
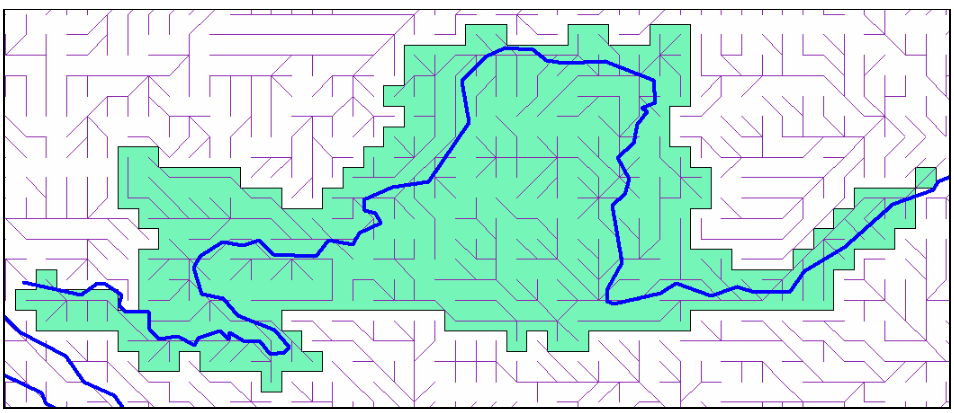


Figure 114 Yellow River Basin 1-Region Representation



APPENDIX B

AVERAGE MONTHLY DEMAND COVERAGE FOR EACH BASIN'S SPATIAL REPRESENTATION

Missouri River Basin

Table 25 Average Monthly Demand Coverage in Full Representation of Missouri Basin

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ag1	100	100	100	100	100	100	100	100	100	100	100	100
Ag2	100	100	100	100	100	100	100	100	100	100	100	100
CO Irrig	100	100	3	1	1	1	1	1	2	100	100	100
Ft Peck Irrig	100	100	100	100	100	100	100	100	100	100	100	100
Ft Peck Mun	100	100	100	100	100	100	100	100	100	100	100	100
Garrison Irrig	100	100	100	100	100	100	100	100	100	100	100	100
Garrison Mun	100	100	100	100	100	100	100	100	100	100	100	100
KS Ag	100	100	100	100	100	100	100	100	100	100	100	100
KS Mun	100	100	100	100	100	100	100	100	100	100	100	100
KS Thermal	100	100	100	100	100	100	100	100	100	100	100	100
Mun1	100	100	100	100	100	100	100	100	100	100	100	100
Mun2	100	100	100	100	100	100	100	100	100	100	100	100
NB Irrig	100	100	4	5	5	2	1	1	2	100	100	100
NPlatte Irrig	100	100	3	3	3	1	0	0	0	100	100	100
Platte Irrig	100	100	4	5	5	2	1	1	2	100	100	100
Platte Mun	41	41	4	5	5	2	1	1	2	75	62	49
Platte Thermal	41	41	4	5	5	2	1	1	2	75	62	49
SPlatte Irrig	100	100	3	1	1	1	1	1	2	100	100	100
Thermal1	100	100	100	100	100	100	100	100	100	100	100	100
Thermal2	100	100	100	100	100	100	100	100	100	100	100	100
WY Irrig	100	100	3	3	3	1	0	0	0	100	100	100

Table 26 Avg. Monthly Demand Coverage in 8-Region Representation of Missouri Basin

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ag1	100	100	100	100	100	100	100	100	100	100	100	100
Ag2	100	100	100	100	100	100	100	100	100	100	100	100
KS Ag	100	100	100	100	100	100	100	100	100	100	100	100
KS Mun	100	100	100	100	100	100	100	100	100	100	100	100
KS Thermal	100	100	100	100	100	100	100	100	100	100	100	100
Mun1	100	100	100	100	100	100	100	100	100	100	100	100
Mun2	100	100	100	100	100	100	100	100	100	100	100	100
North Platte Irrig	100	100	3	3	3	3	2	0	0	100	100	100
Platte Irrig	100	100	97	90	87	88	92	95	100	100	100	100
Platte Mun	100	100	97	90	87	88	93	95	100	100	100	100
Platte Therm	100	100	97	90	87	88	93	95	100	100	100	100
S Platte Irrig	100	100	8	2	2	1	2	1	2	100	100	100
Thermal1	100	100	100	100	100	100	100	100	100	100	100	100
Thermal2	100	100	100	100	100	100	100	100	100	100	100	100
UpperMisIrrig	100	100	100	100	100	100	100	100	100	100	100	100
UpperMisMun	100	100	100	100	100	100	100	100	100	100	100	100

Table 27 Avg. Monthly Demand Coverage in 3-Region Representation of Missouri Basin

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lower Mis Ag	100	100	100	100	100	100	100	100	100	100	100	100
Lower Mis Mun	100	100	100	100	100	100	100	100	100	100	100	100
Lower Mis Therm	100	100	100	100	100	100	100	100	100	100	100	100
Platte Irrig	100	100	93	49	31	20	23	22	42	100	100	100
Platte Mun	100	100	93	49	31	20	23	22	42	100	100	100
Platte Therm	100	100	93	49	31	20	23	22	42	100	100	100
UpperMisIrrig	100	100	100	100	100	100	100	100	100	100	100	100
UpperMisMun	100	100	100	100	100	100	100	100	100	100	100	100

Table 28 Avg. Monthly Demand Coverage in 1-Region Representation of Missouri Basin

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Irrigation	100	100	100	100	100	100	100	100	100	100	100	100
Municipal	100	100	100	100	100	100	100	100	100	100	100	100
Thermal	100	100	100	100	100	100	100	100	100	100	100	100

Yellow River Basin with Management

Table 29 Average Monthly Demand Coverage in the Yellow River Basin Detailed Representation with Management

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
A0	100	100	59	60	89	16	14	100	100	100	100	100
A1	100	100	91	60	89	17	14	100	100	100	100	100
A2	100	100	97	79	89	24	17	100	100	100	100	100
A3	100	100	97	79	89	57	47	100	100	100	100	100
A4	100	100	100	96	93	57	47	100	100	100	100	100
A5	100	100	100	96	93	57	47	100	100	100	100	100
A6	100	100	100	99	96	57	47	100	100	100	100	100
I0	100	100	100	100	100	29	29	50	100	100	100	100
I1	100	100	100	100	100	36	31	50	100	100	100	100
I2	100	100	100	100	100	36	31	50	100	100	100	100
I3	100	100	100	100	100	36	31	50	100	100	100	100
I4	100	100	100	100	100	36	31	50	100	100	100	100
I5	100	100	100	100	100	36	31	50	100	100	100	100
I6	100	100	100	100	100	74	77	84	100	100	100	100
I7	100	100	100	100	100	74	77	84	100	100	100	100
U0	100	100	100	100	100	81	87	92	100	100	100	100
U1	100	100	100	100	100	82	87	92	100	100	100	100
U2	100	100	100	100	100	82	87	92	100	100	100	100
U3	100	100	100	100	100	82	87	92	100	100	100	100
U4	100	100	100	100	100	83	88	93	100	100	100	100
U5	100	100	100	100	100	83	88	93	100	100	100	100
U6	100	100	100	100	100	91	97	99	100	100	100	100
U7	100	100	100	100	100	91	97	99	100	100	100	100

Table 30 Average Monthly Demand Coverage in the Yellow River Basin 4-Region Representation with Management

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
A0	100	100	70	44	88	16	15	100	100	100	100	100
A1	100	100	70	44	88	16	15	100	100	100	100	100
A2	100	100	89	49	88	19	23	100	100	100	100	100
A3	100	100	100	99	97	81	77	100	100	100	100	100
I0	100	100	100	100	100	37	29	50	100	100	100	100
I1	100	100	100	100	100	40	32	50	100	100	100	100
I2	100	100	100	100	100	45	35	61	100	100	100	100
I3	100	100	100	100	100	90	87	97	100	100	100	100
U0	100	100	100	100	100	87	87	92	100	100	100	100
U1	100	100	100	100	100	88	87	92	100	100	100	100
U2	100	100	100	100	100	90	91	95	100	100	100	100
U3	100	100	100	100	100	99	98	99	100	100	100	100

Table 31 Average Monthly Demand Coverage in the Yellow River Basin 3A-Region Representation with Management

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
A1	100	100	68	43	88	16	15	100	100	100	100	100
A2	100	100	91	52	88	20	22	100	100	100	100	100
A3	100	100	100	99	97	81	78	100	100	100	100	100
I1	100	100	100	100	100	40	31	50	100	100	100	100
I2	100	100	100	100	100	45	35	61	100	100	100	100
I3	100	100	100	100	100	90	87	97	100	100	100	100
U1	100	100	100	100	100	88	87	92	100	100	100	100
U2	100	100	100	100	100	90	91	95	100	100	100	100
U3	100	100	100	100	100	99	98	99	100	100	100	100

Table 32 Average Monthly Demand Coverage in the Yellow River Basin 3B-Region Representation with Management

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
A0	100	100	79	25	34	0	0	100	100	100	100	100
A1	100	100	79	35	81	17	20	100	100	100	100	100
A2	100	100	100	100	100	95	93	100	100	100	100	100
I0	100	100	100	100	100	0	0	0	100	100	100	100
I1	100	100	100	100	100	41	35	60	100	100	100	100
I2	100	100	100	100	100	100	100	100	100	100	100	100
U0	100	100	100	100	100	4	7	8	100	100	100	100
U1	100	100	100	100	100	89	91	95	100	100	100	100
U2	100	100	100	100	100	100	100	100	100	100	100	100

Table 33 Average Monthly Demand Coverage in the Yellow River Basin 1-Region Representation with Management

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
A1	100	100	96	70	64	11	22	100	100	100	100	100
I1	100	100	100	100	100	46	62	73	100	100	100	100
U1	100	100	100	100	100	91	96	98	100	100	100	100

Yellow River Basin without Management

Table 34Average Monthly Demand Coverage in the Yellow River Basin Detailed Representation without Management

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
A0	100	100	63	99	98	100	100	100	100	100	100	100
A1	100	100	100	99	98	100	100	100	100	100	100	100
A2	10	100	100	99	98	100	100	100	100	100	100	100
A3	100	100	100	99	98	100	100	100	100	100	100	100
A4	100	100	100	100	98	100	100	100	100	100	100	100
A5	100	100	100	100	98	100	100	100	100	100	100	100
A6	100	100	100	100	99	100	100	100	100	100	100	100
I0	100	100	100	100	100	100	100	100	100	100	100	100
I1	100	100	100	100	100	100	100	100	100	100	100	100
I2	100	100	100	100	100	100	100	100	100	100	100	100
I3	100	100	100	100	100	100	100	100	100	100	100	100
I4	100	100	100	100	100	100	100	100	100	100	100	100
I5	100	100	100	100	100	100	100	100	100	100	100	100
I6	100	100	100	100	100	100	100	100	100	100	100	100
I7	100	100	100	100	100	100	100	100	100	100	100	100
U0	100	100	100	100	100	100	100	100	100	100	100	100
U1	100	100	100	100	100	100	100	100	100	100	100	100
U2	100	100	100	100	100	100	100	100	100	100	100	100
U3	100	100	100	100	100	100	100	100	100	100	100	100
U4	100	100	100	100	100	100	100	100	100	100	100	100
U5	100	100	100	100	100	100	100	100	100	100	100	100
U6	100	100	100	100	100	100	100	100	100	100	100	100
U7	100	100	100	100	100	100	100	100	100	100	100	100

Table 35 Average Monthly Demand Coverage in the Yellow River Basin 4-Region Representation without Management

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
A0	100	100	99	98	99	100	100	100	100	100	100	100
A1	100	100	99	98	99	100	100	100	100	100	100	100
A2	100	100	100	99	99	100	100	100	100	100	100	100
A3	100	100	100	100	100	100	100	100	100	100	100	100
I0	100	100	100	100	100	100	100	100	100	100	100	100
I1	100	100	100	100	100	100	100	100	100	100	100	100
I2	100	100	100	100	100	100	100	100	100	100	100	100
I3	100	100	100	100	100	100	100	100	100	100	100	100
U0	100	100	100	100	100	100	100	100	100	100	100	100
U1	100	100	100	100	100	100	100	100	100	100	100	100
U2	100	100	100	100	100	100	100	100	100	100	100	100
U3	100	100	100	100	100	100	100	100	100	100	100	100

Table 36 Average Monthly Demand Coverage in the Yellow River Basin 3A-Region Representation without Management

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
A1	100	100	99	98	98	100	100	100	100	100	100	100
A2	100	100	100	99	99	100	100	100	100	100	100	100
A3	100	100	100	100	100	100	100	100	100	100	100	100
I1	100	100	100	100	100	100	100	100	100	100	100	100
I2	100	100	100	100	100	100	100	100	100	100	100	100
I3	100	100	100	100	100	100	100	100	100	100	100	100
U1	100	100	100	100	100	100	100	100	100	100	100	100
U2	100	100	100	100	100	100	100	100	100	100	100	100
U3	100	100	100	100	100	100	100	100	100	100	100	100

Table 37 Average Monthly Demand Coverage in the Yellow River Basin 3B-Region Representation without Management

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
A0	100	100	99	93	79	63	95	100	100	100	100	100
A1	100	100	99	97	97	99	100	100	100	100	100	100
A2	100	100	100	100	100	100	100	100	100	100	100	100
I0	100	100	100	100	100	100	100	100	100	100	100	100
I1	100	100	100	100	100	100	100	100	100	100	100	100
I2	100	100	100	100	100	100	100	100	100	100	100	100
U0	100	100	100	100	100	100	100	100	100	100	100	100
U1	100	100	100	100	100	100	100	100	100	100	100	100
U2	100	100	100	100	100	100	100	100	100	100	100	100

Table 38 Average Monthly Demand Coverage in the Yellow River Basin 1-Region Representation without Management

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
A1	100	100	100	100	100	100	100	100	100	100	100	100
I1	100	100	100	100	100	100	100	100	100	100	100	100
U1	100	100	100	100	100	100	100	100	100	100	100	100

Volta River Basin

Table 39 Average Monthly Demand Coverage in Full Representation of Volta Basin

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Domestic Black BF	94	86	89	89	93	95	97	99	100	100	100	100
Domestic Black GH	95	88	91	91	94	95	97	99	100	100	100	100
Domestic Lower	100	100	100	100	100	100	100	100	100	100	100	100
Domestic Oti GH	98	93	93	93	94	95	97	99	100	100	100	100
Domestic Oti TG	98	93	93	93	94	95	97	99	100	100	100	100
Domestic White Bfr	69	45	86	87	91	93	97	99	100	100	100	96
Domestic White GH	91	75	90	90	94	95	97	99	100	100	100	99
Large Irr Black BF	100	100	100	100	100	100	100	100	100	100	100	100
Large Irr Lower	100	100	100	100	100	100	100	100	100	100	100	100
Large Irr White BF	100	100	100	100	100	100	100	100	100	100	100	100
Large Irr White GH	91	75	100	100	100	95	97	99	100	100	100	99
Small Irr Black BF	94	86	100	100	100	95	97	99	100	100	100	100
Small Irr Black GH	95	88	100	100	100	95	97	99	100	100	100	100
Small Irr Lower	100	100	100	100	100	100	100	100	100	100	100	100
Small Irr Oti GH	98	93	100	100	100	95	97	99	100	100	100	100
Small Irr Oti TG	98	93	100	100	100	95	97	99	100	100	100	100
Small Irr White BF	69	45	100	100	100	93	97	99	100	100	100	96
Small Irr White GH	91	75	100	100	100	95	97	99	100	100	100	99

Table 40 Average Monthly Demand Coverage in Country Level -1 Representation of Volta Basin

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Domestic BF	87	65	88	88	92	95	97	99	100	100	100	98
Domestic Lo GH	100	100	100	100	100	100	100	100	100	100	100	100
Domestic TG	98	93	93	93	94	95	97	99	100	100	100	100
Domestic Up GH	94	86	91	91	94	95	97	99	100	100	100	100
Large Irr BF	100	100	100	100	100	100	100	100	100	100	100	100
Large Irr Lo GH	100	100	100	100	100	100	100	100	100	100	100	100
Large Irr UP GH	94	86	100	100	100	95	97	99	100	100	100	100
Small Irr BF	87	65	100	100	100	95	97	99	100	100	100	98
Small Irr Lo GH	100	100	100	100	100	100	100	100	100	100	100	100
Small Irr TG	98	93	100	100	100	95	97	99	100	100	100	100
Small Irr Up Gh	94	86	100	100	100	95	97	99	100	100	100	100

Table 41 Average Monthly Demand Coverage in Country Level -2 Representation of Volta Basin

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Domestic BF	87	66	88	88	92	95	97	99	100	100	100	98
Domestic Lo GH	100	100	100	100	100	100	100	100	100	100	100	100
Domestic TG	98	94	93	93	94	95	97	99	100	100	100	100
Large Irr BF	100	100	100	100	100	100	100	100	100	100	100	100
Large Irr Lo GH	100	100	100	100	100	100	100	100	100	100	100	100
Small Irr BF	87	66	100	100	100	95	97	99	100	100	100	98
Small Irr Lo GH	100	100	100	100	100	100	100	100	100	100	100	100
Small Irr TG	98	94	100	100	100	95	97	99	100	100	100	100

Table 42 Average Monthly Demand Coverage in Single Basin Representation of Volta

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Domestic	100	100	100	100	100	100	100	100	100	100	100	100
Large Irr	100	100	100	100	100	100	100	100	100	100	100	100
Small Irr	100	100	100	100	100	100	100	100	100	100	100	100

APPENDIX C

RESERVOIR STORAGE FOR EACH BASIN'S SPATIAL REPRESENTATION

Missouri River Basin

Figure 115 Reservoir Storage in the Full Representation of the Missouri Basin

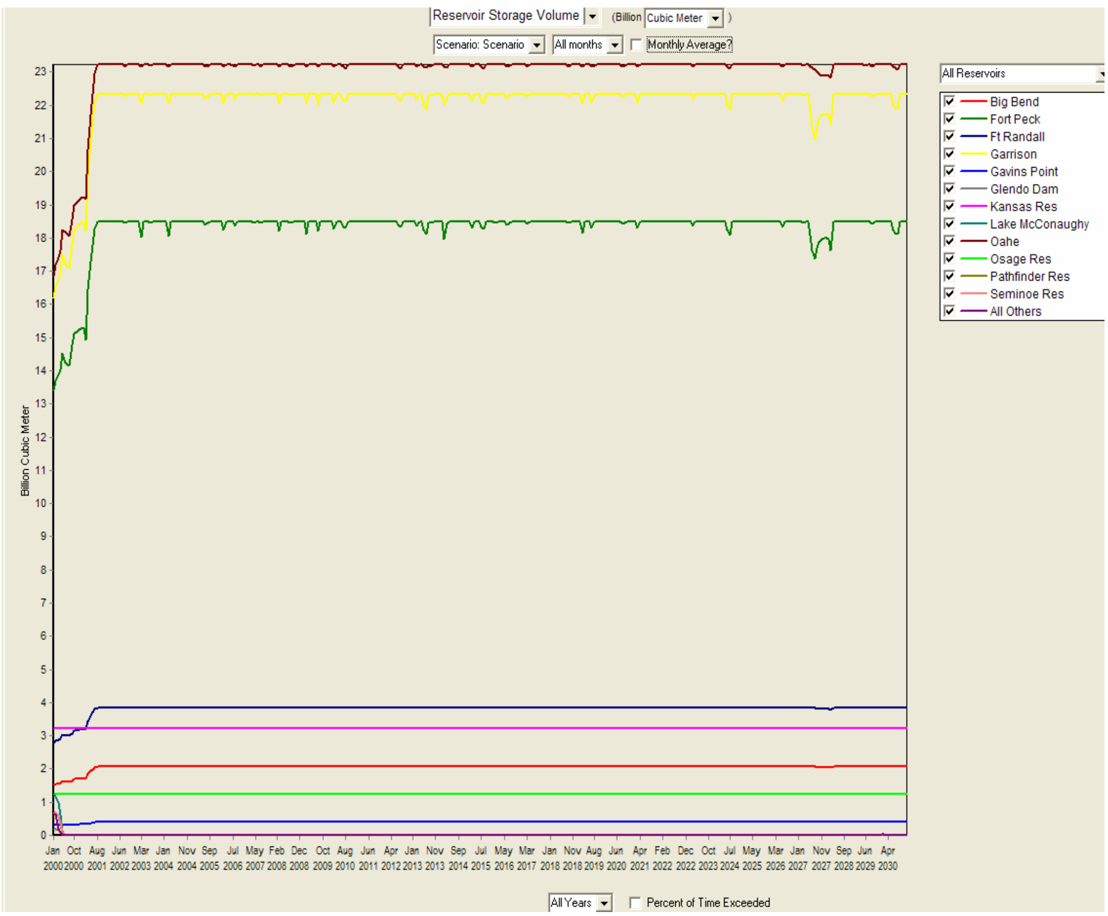


Figure 116 Reservoir Storage in the 8-Region Representation of the Missouri Basin

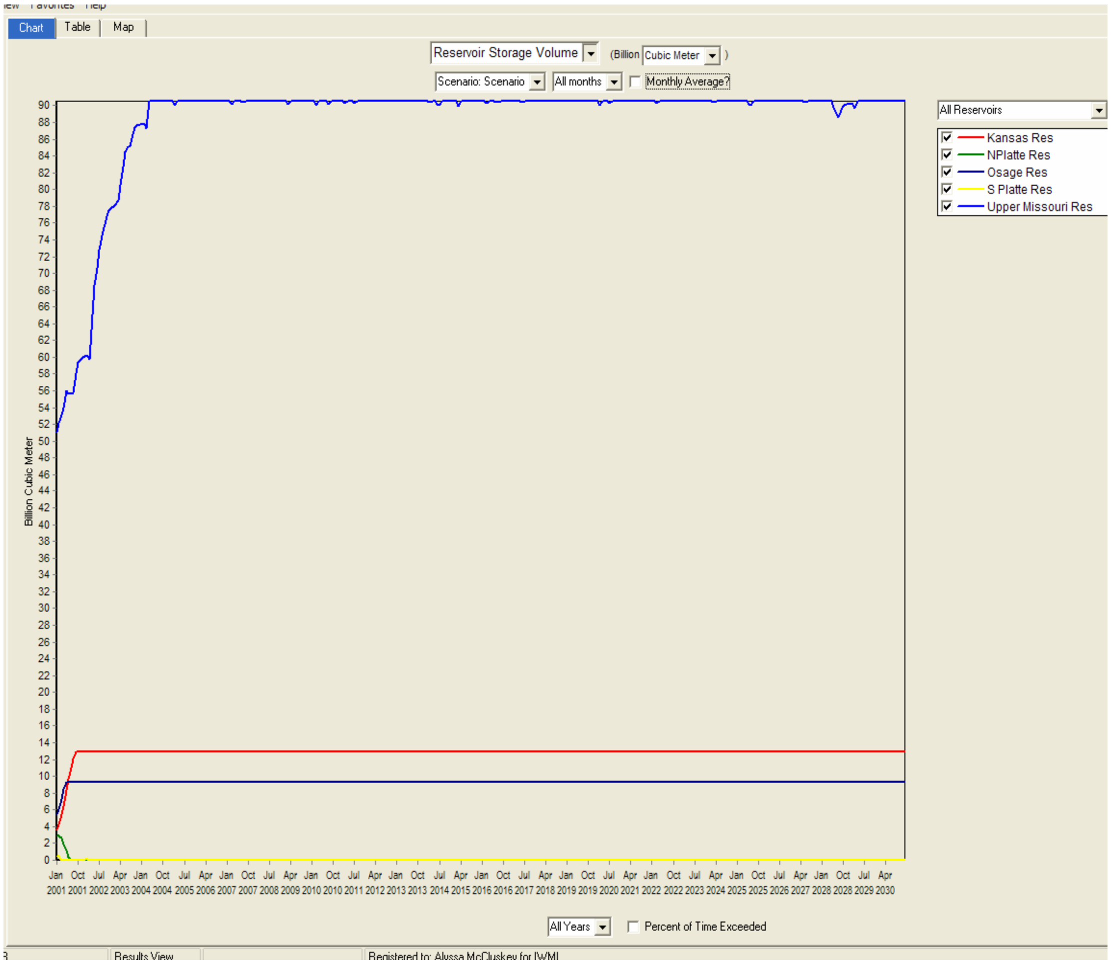


Figure 117 Reservoir Storage in the 3-Region Representation of the Missouri Basin

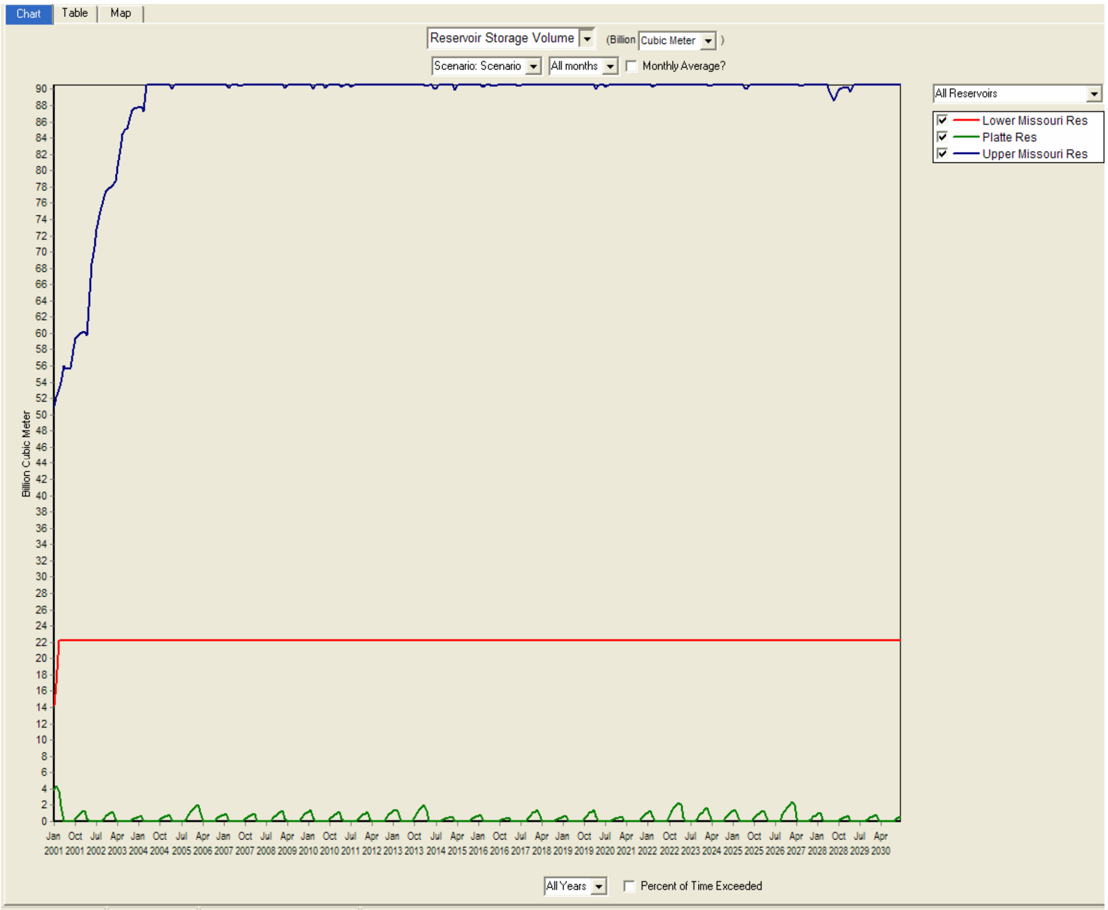
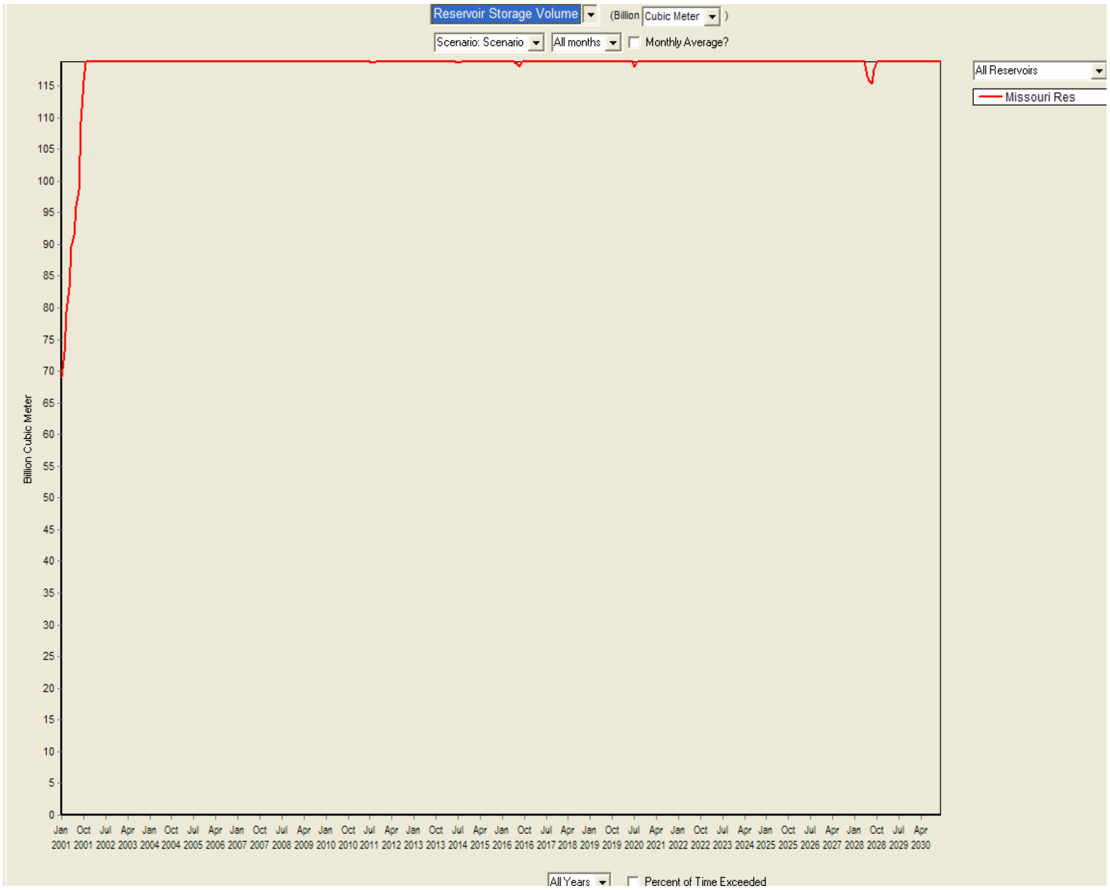


Figure 118 Reservoir Storage in the 1-Region Representation of the Missouri Basin



Senegal River Basin

Figure 119 Reservoir Storage in the Full Representation of the Senegal

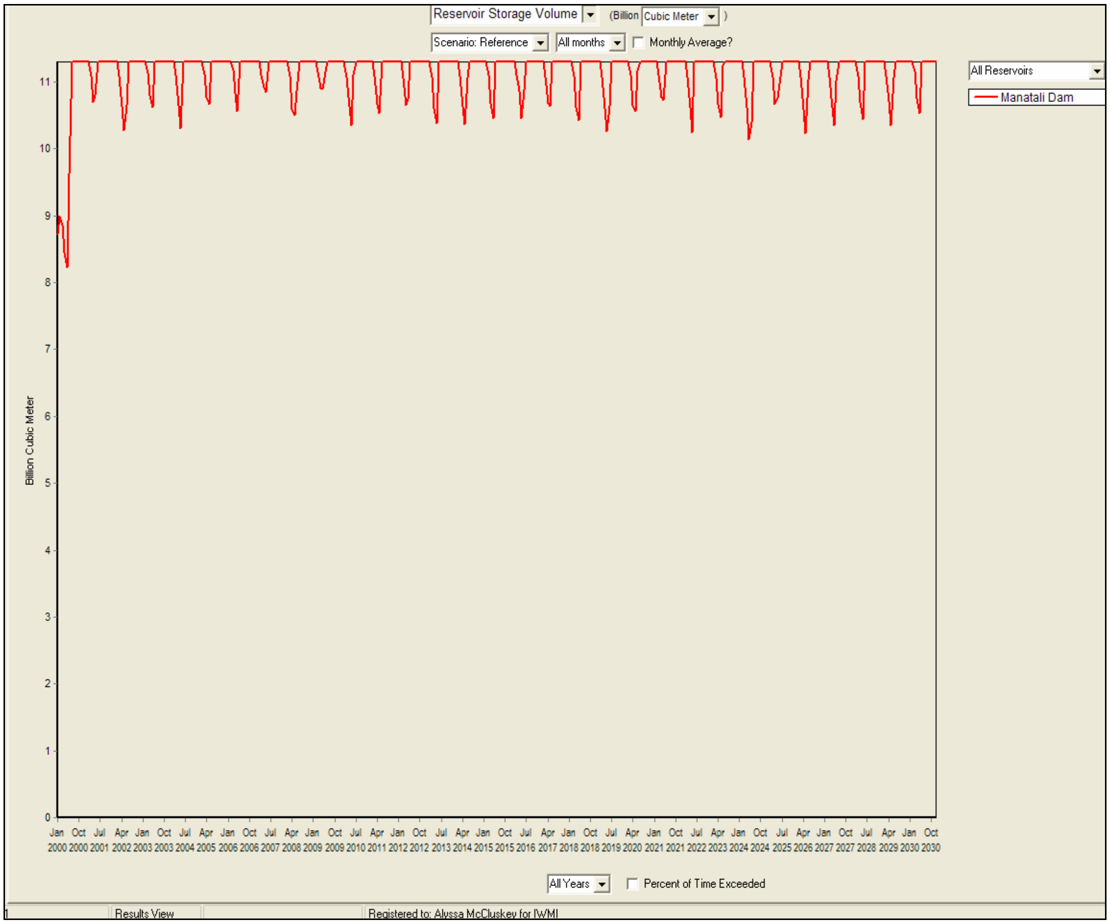
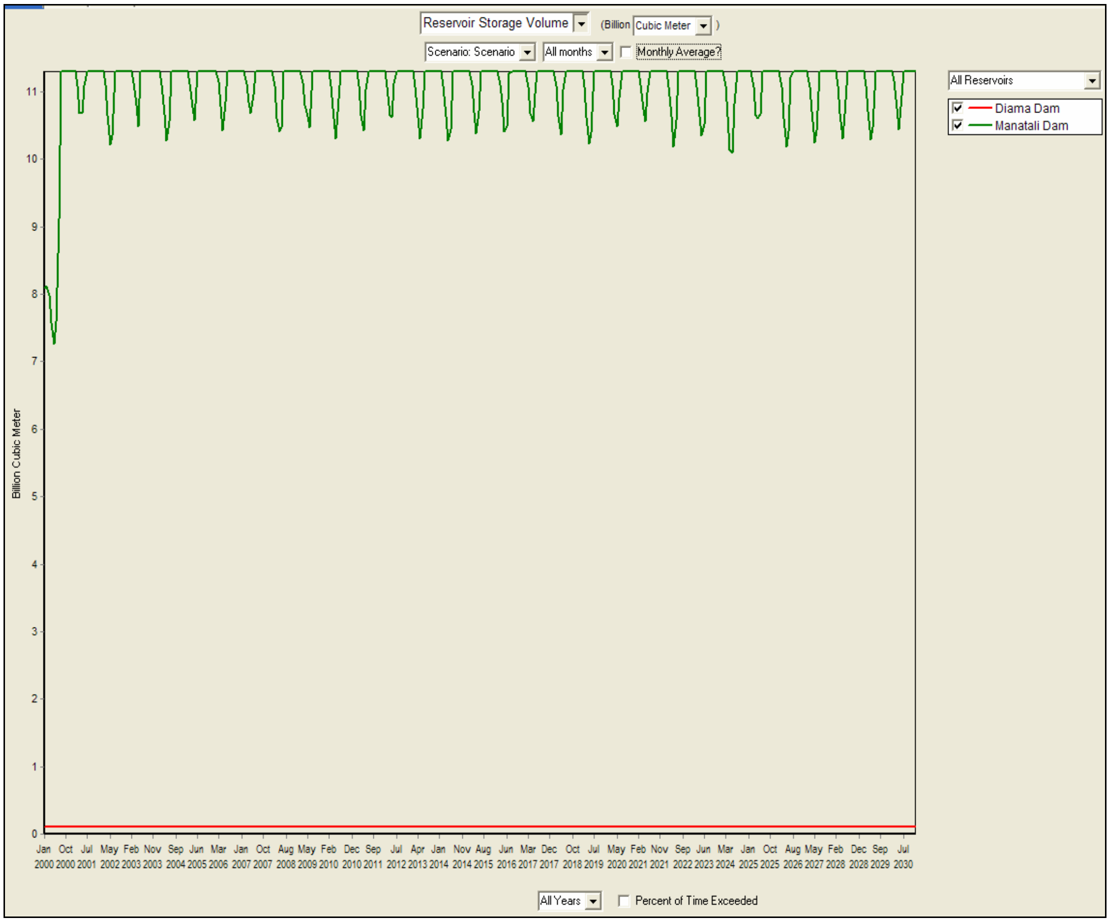


Figure 120 Reservoir Storage in the 1-Region Representation of the Senegal



Yellow River Basin with Management

Figure 121 Average Monthly Reservoir Storage Volume in Yellow River Detailed Representation with Management

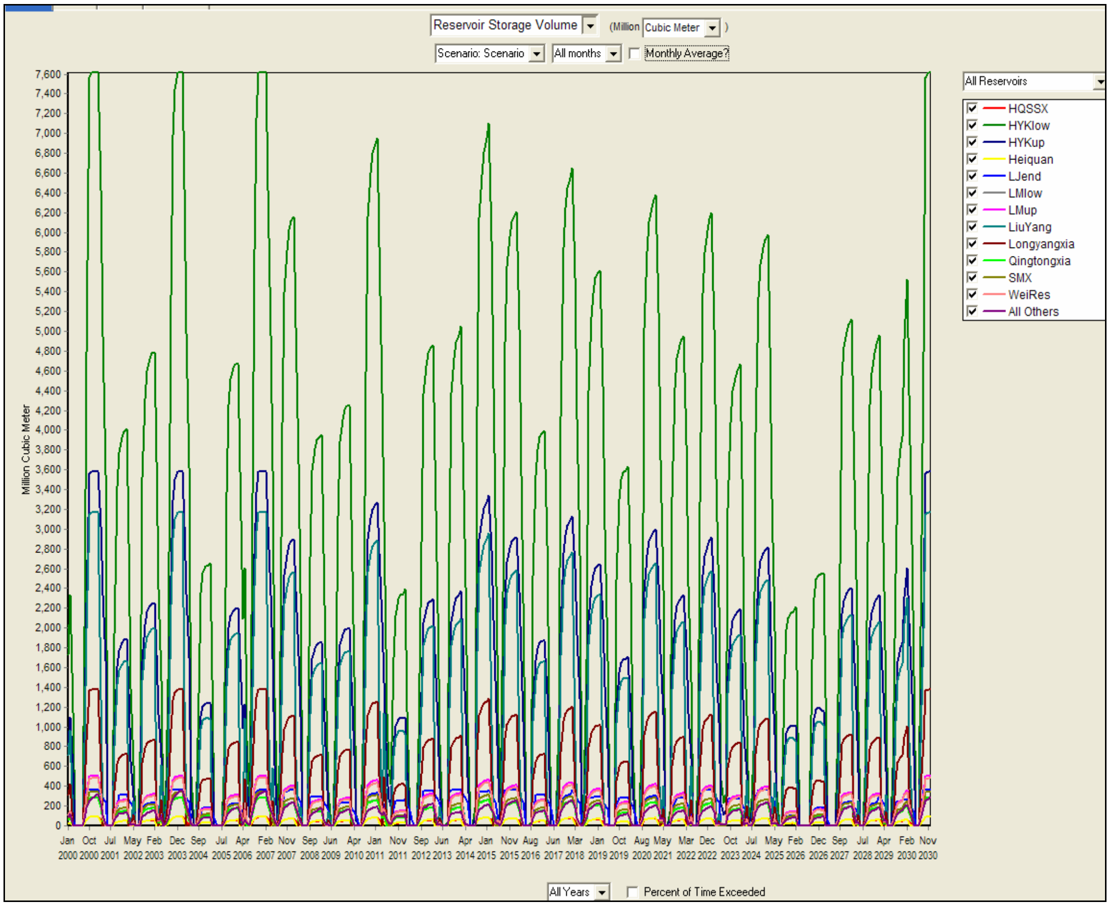


Figure 122 Average Monthly Reservoir Storage Volume in Yellow River 4-Region Representation with Management

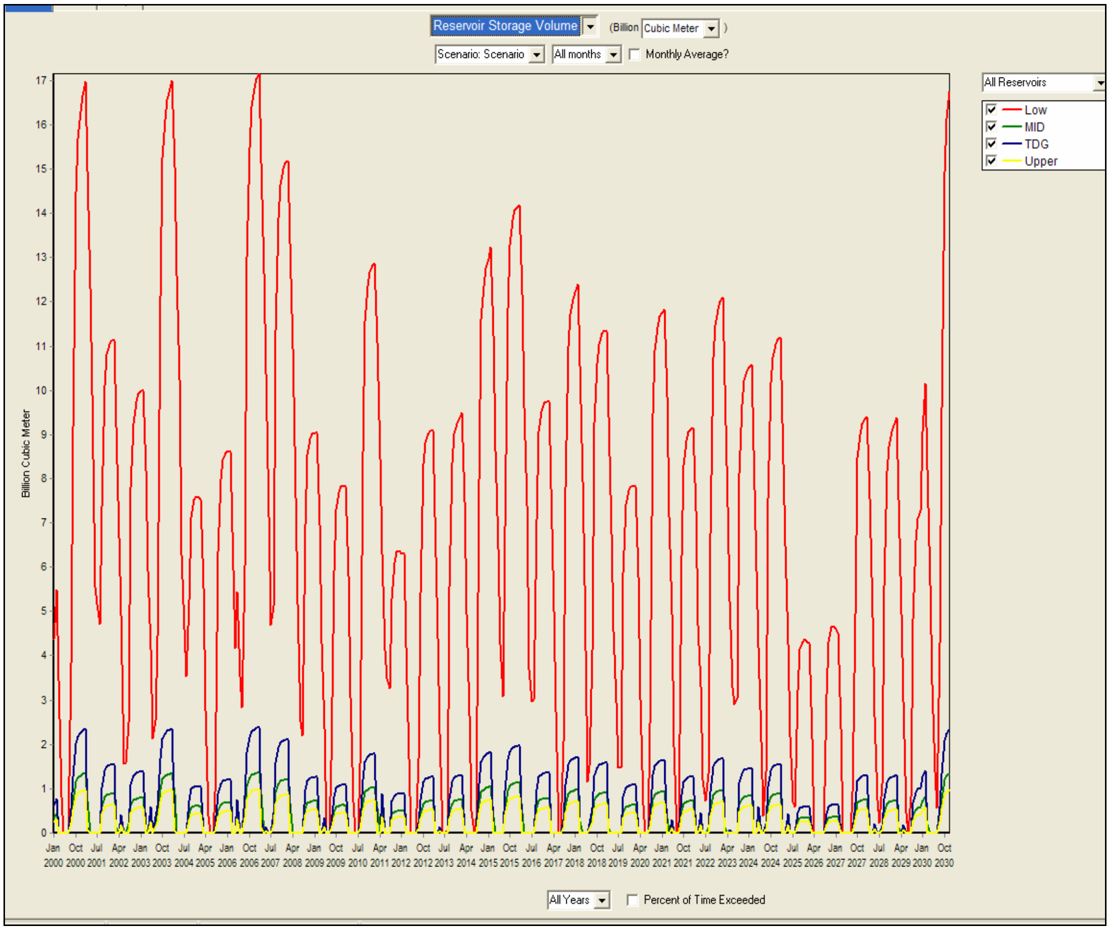


Figure 123 Average Monthly Reservoir Storage Volume in Yellow River 3A-Region Representation with Management

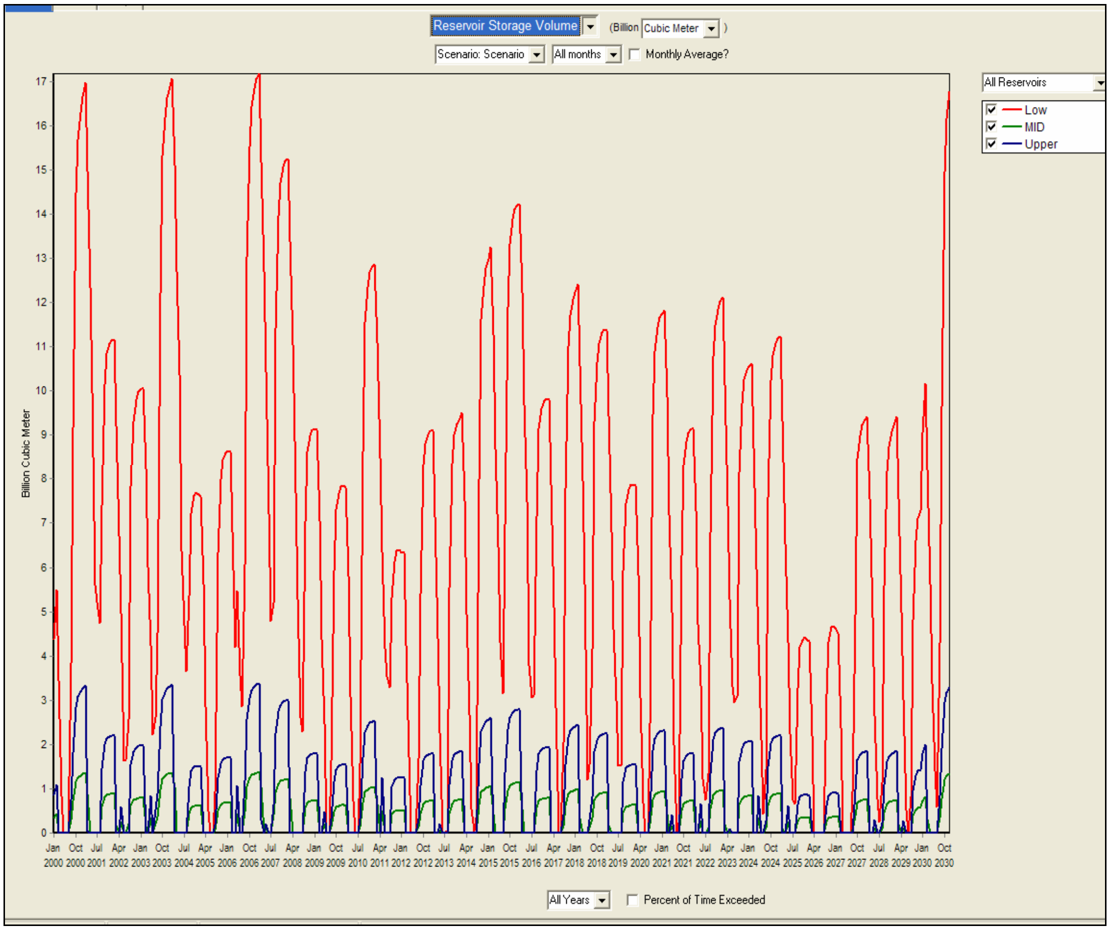


Figure 124 Average Monthly Reservoir Storage Volume in Yellow River 3B-Region Representation with Management

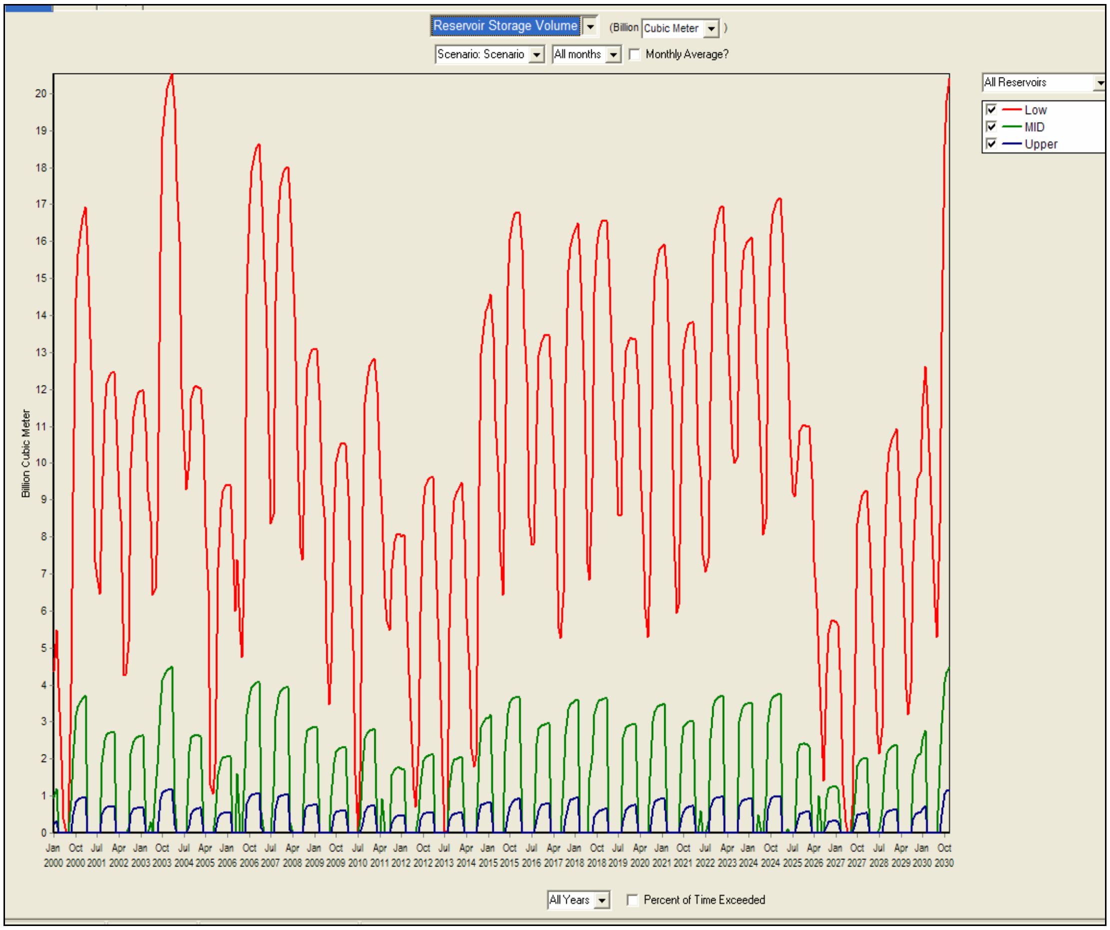


Figure 125 Average Monthly Reservoir Storage Volume in Yellow River 1-Region Representation with Management

Yellow River Basin without Management

Figure 126 Average Monthly Reservoir Storage Volume in Yellow River Detailed Representation without Management

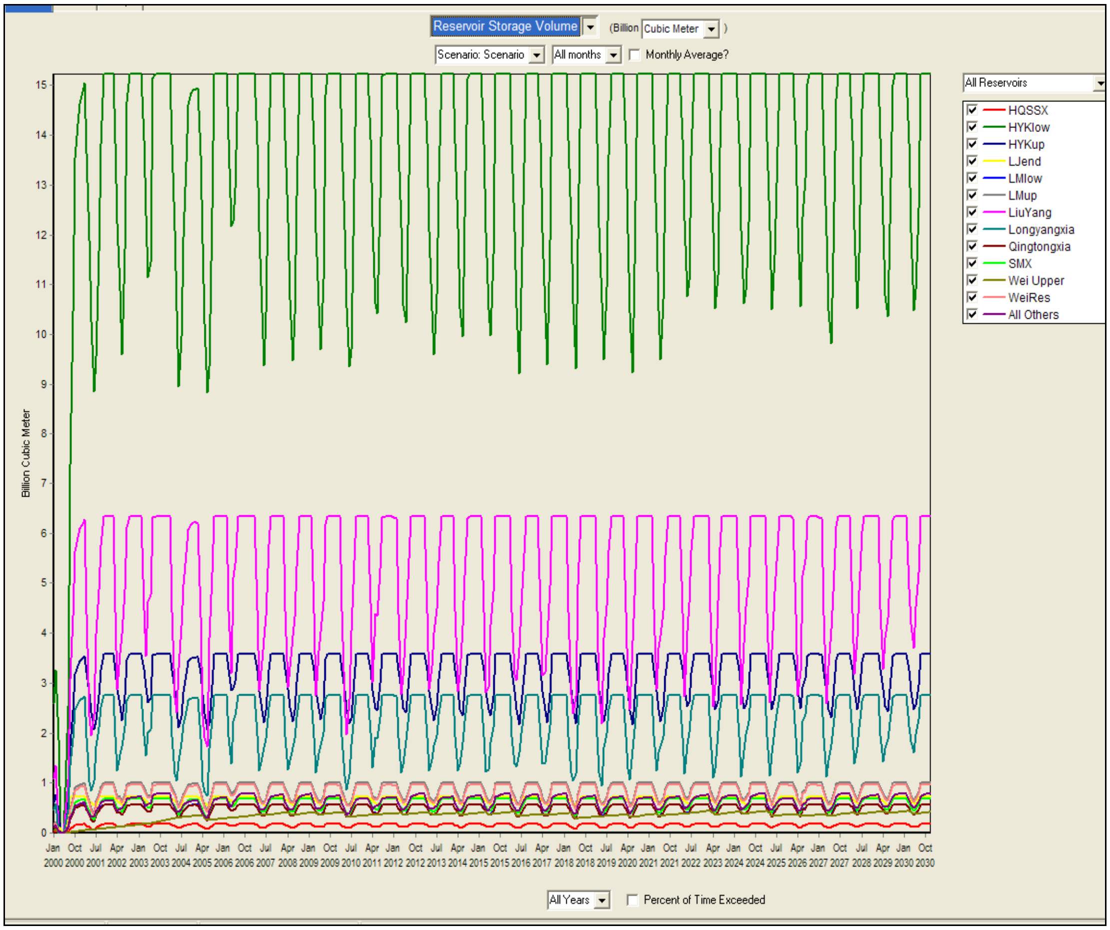
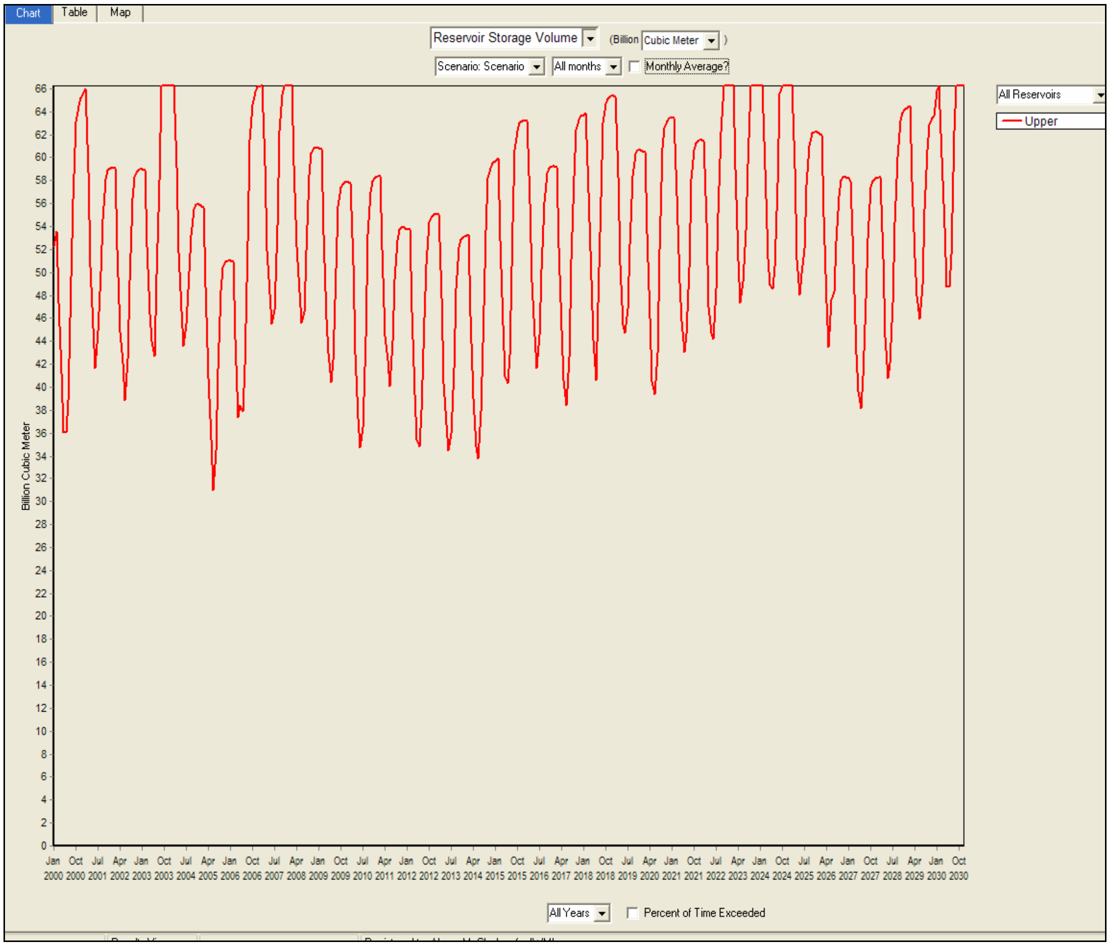


Figure 127 Average Monthly Reservoir Storage Volume in Yellow River 4-Region Representation without Management

Figure 128 Average Monthly Reservoir Storage Volume in Yellow River 3A-Region Representation without Management

Figure 129 Average Monthly Reservoir Storage Volume in Yellow River 3-B Region Representation without Management

Figure 130 Average Monthly Reservoir Storage Volume in Yellow River 1-Region Representation without Management



Volta River Basin

Figure 131 Average Monthly Reservoir Storage Volume in the Full, Country Level 1, and 2 Representations of the Volta River Basin

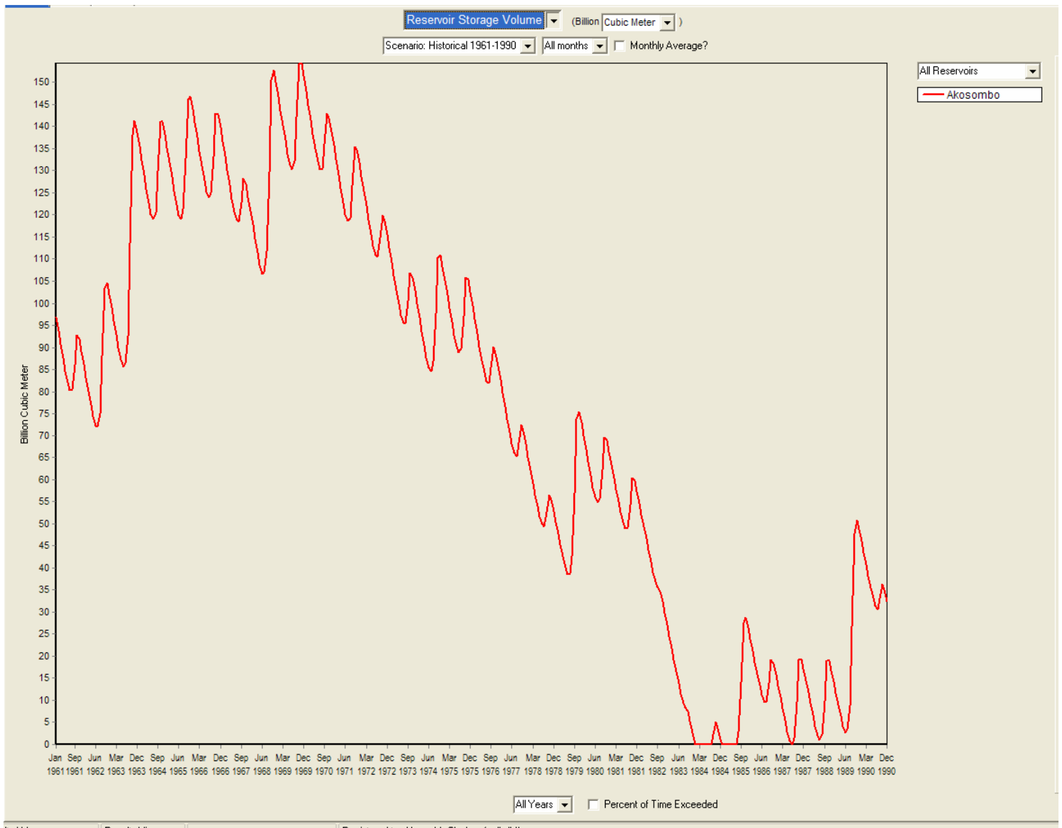
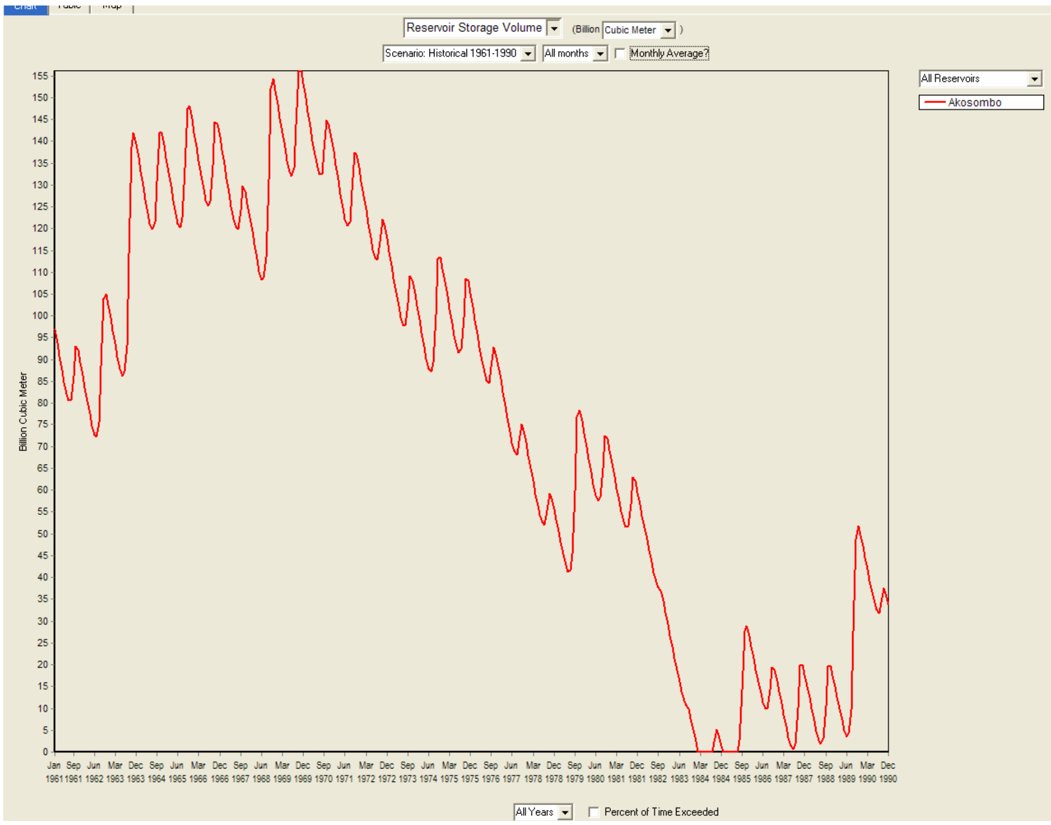


Figure 132 Average Monthly Reservoir Storage Volume in the Single Representation of the Volta River Basin



APPENDIX D

AVERAGE MONTHLY HYDROPOWER GENERATION FOR EACH BASIN'S SPATIAL REPRESENTATION

Missouri River Basin

Figure 133 Average Monthly Hydropower Generation in Full Representation of the Missouri

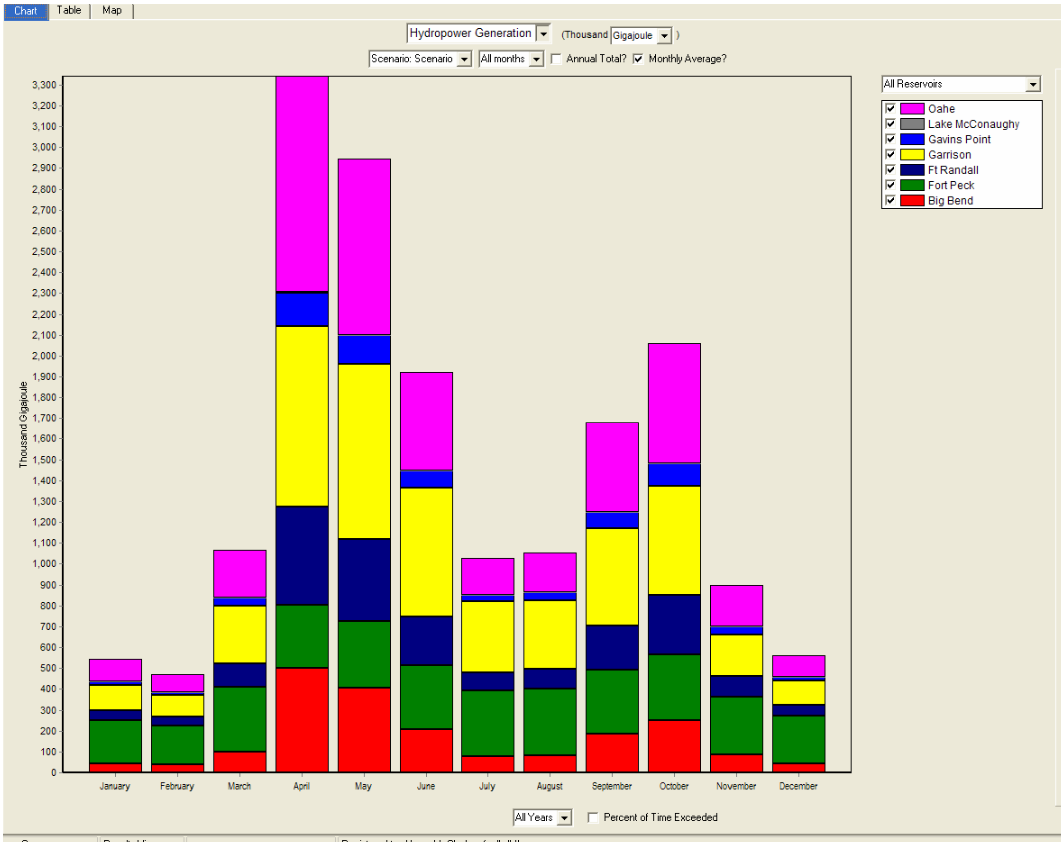


Figure 134 Average Hydropower Generation in the 8-Region Representation of the Missouri

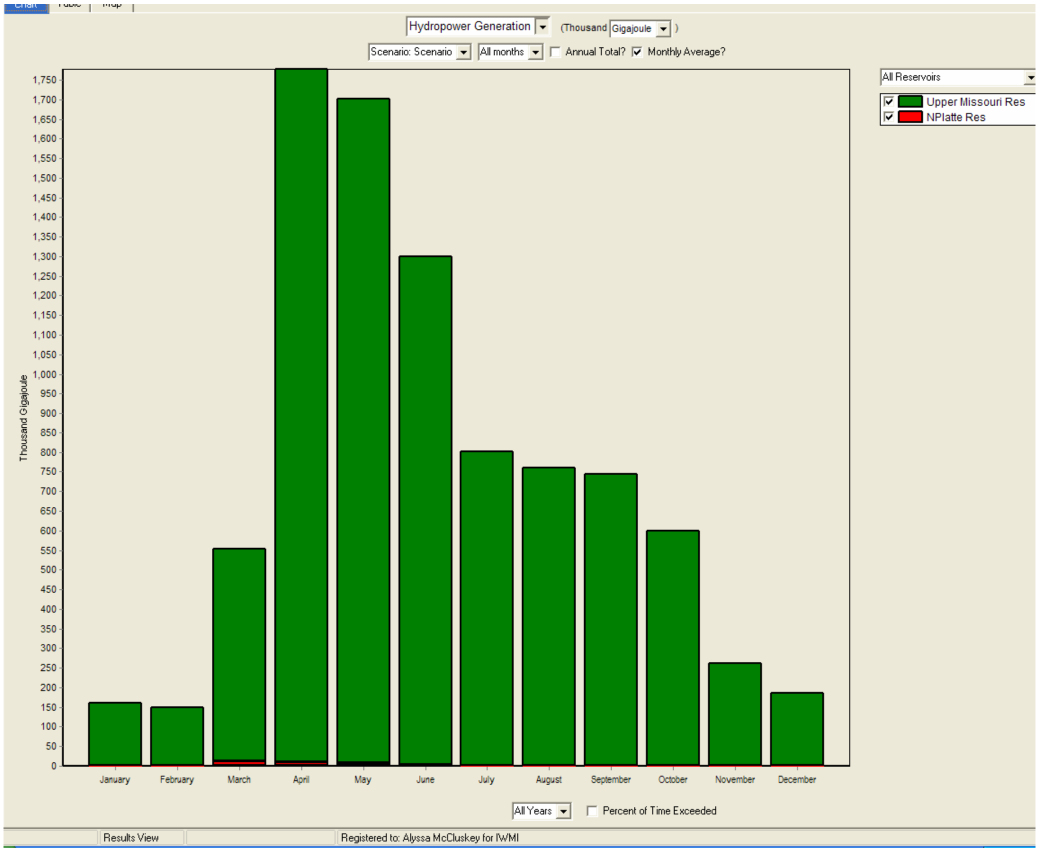


Figure 135 Average Hydropower Generation in the 3-Region Representation of the Missouri

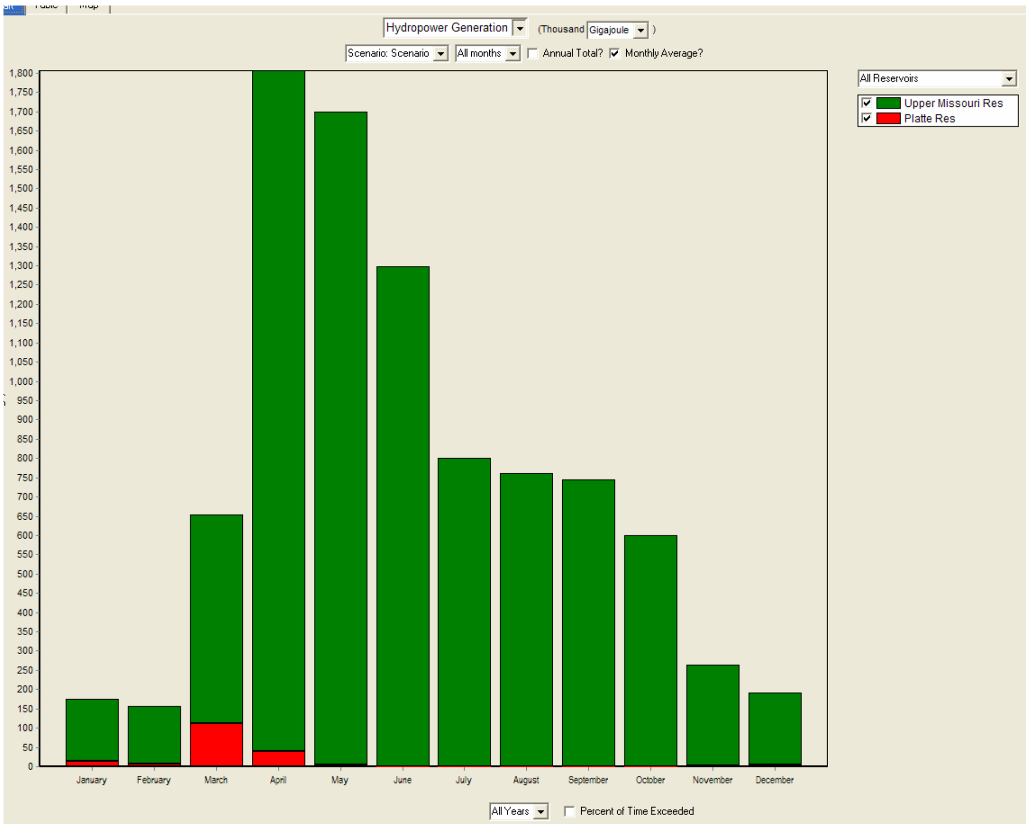
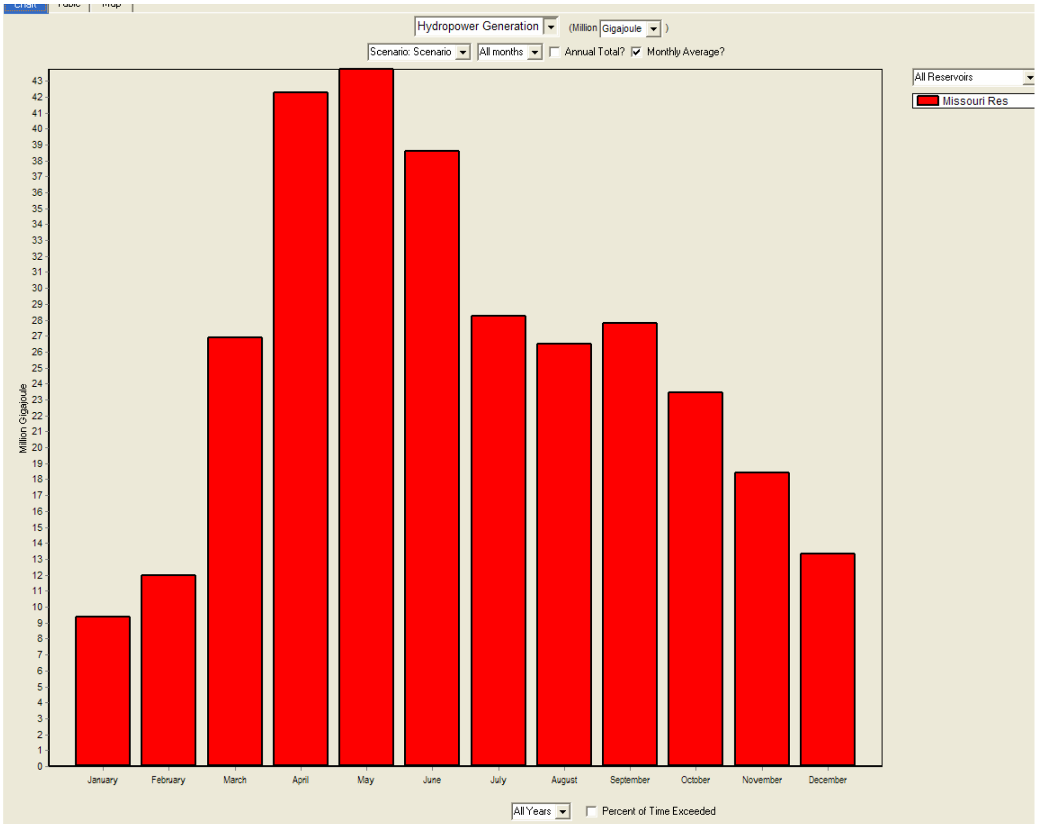


Figure 136 Average Hydropower Generation in the 1-Region Representation of the Missouri



Senegal River Basin

Figure 137 Average Monthly Hydropower Generation in the Full Representation of the Senegal

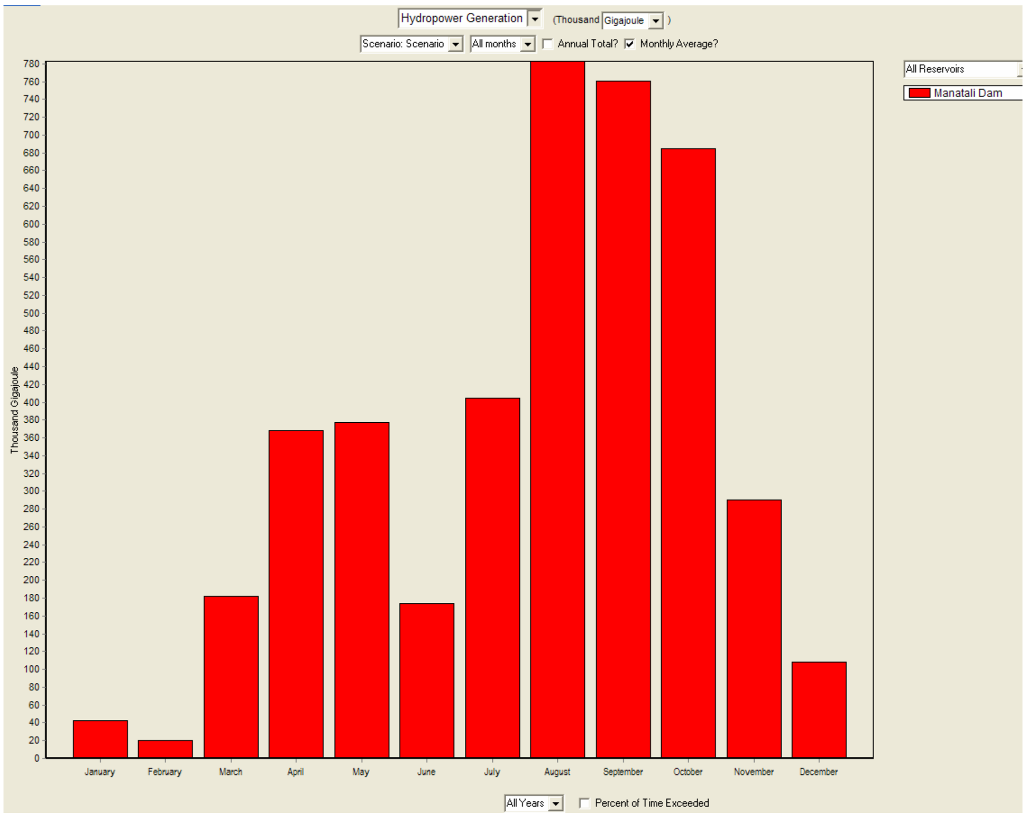
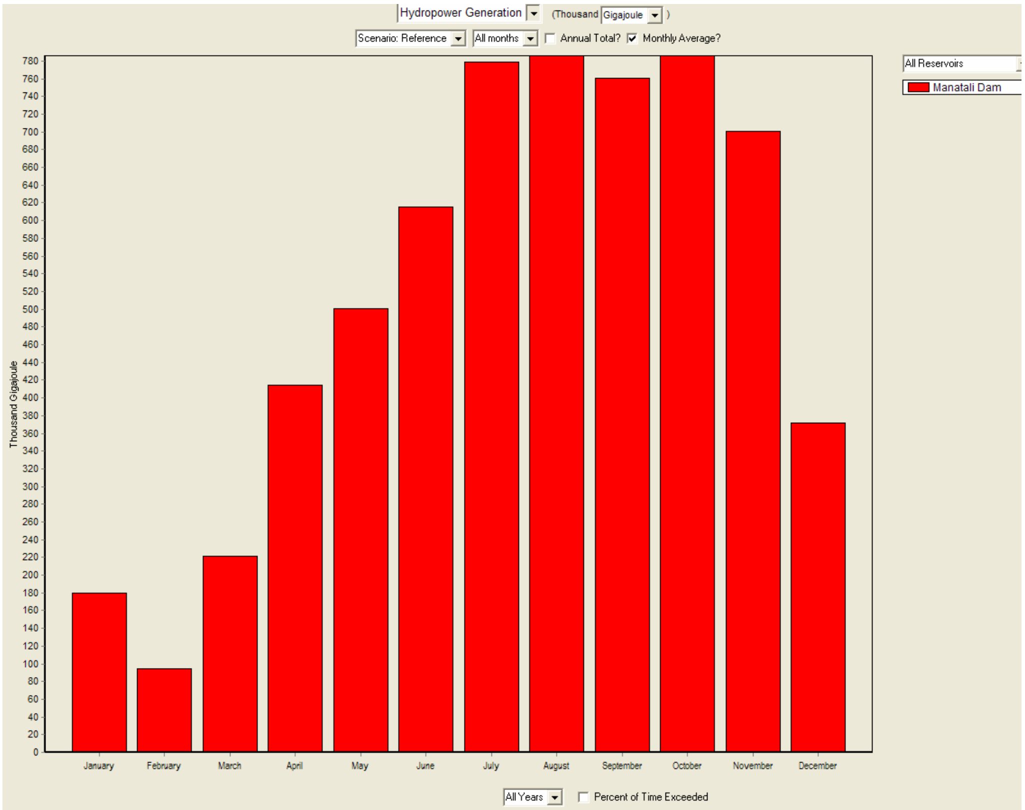


Figure 138 Average Hydropower Generation in the 1-Region Representation of the Senegal



Yellow River Basin with Management

Figure 139 Average Monthly Hydropower Generation in Yellow River Detailed Representation with Management

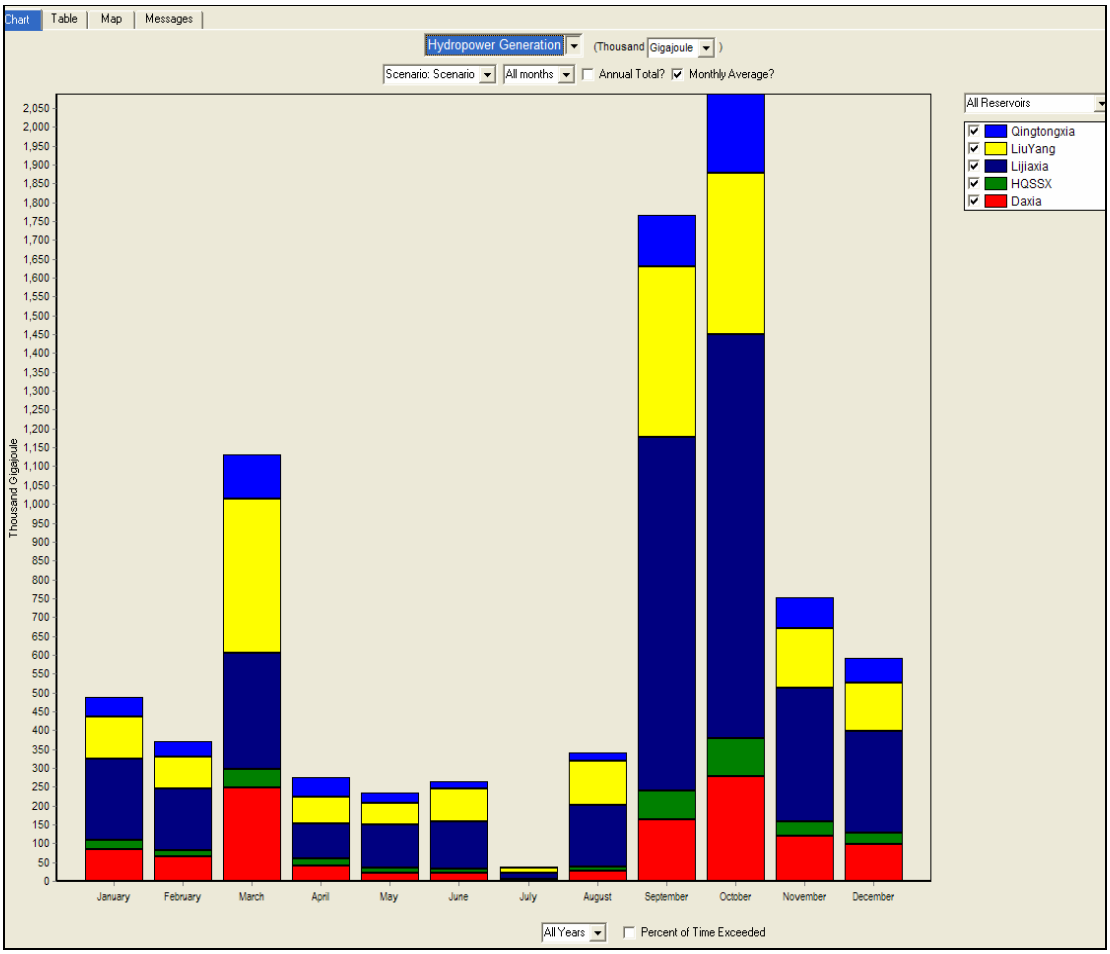


Figure 140 Average Monthly Hydropower Generation in Yellow River 4-Region Representation with Management

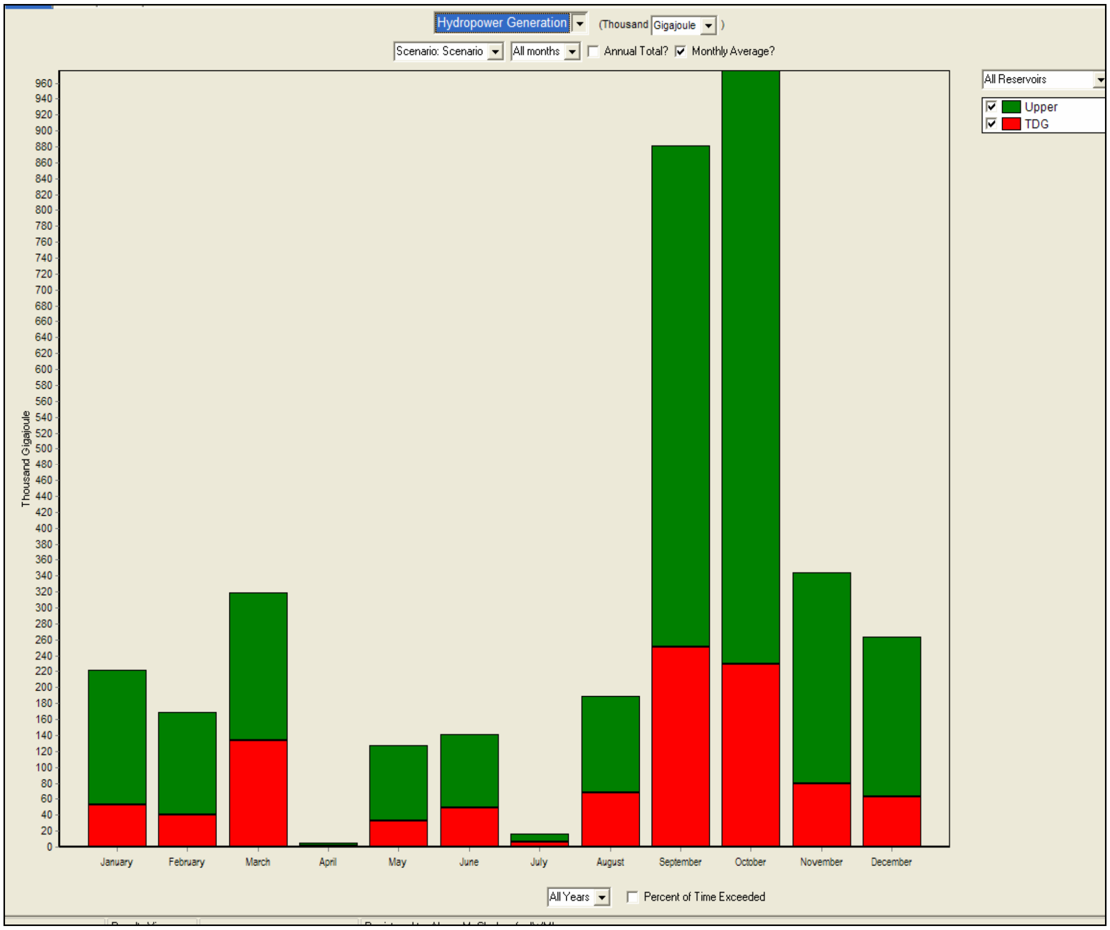


Figure 141 Average Monthly Hydropower Generation in Yellow River 3A-Region Representation with Management

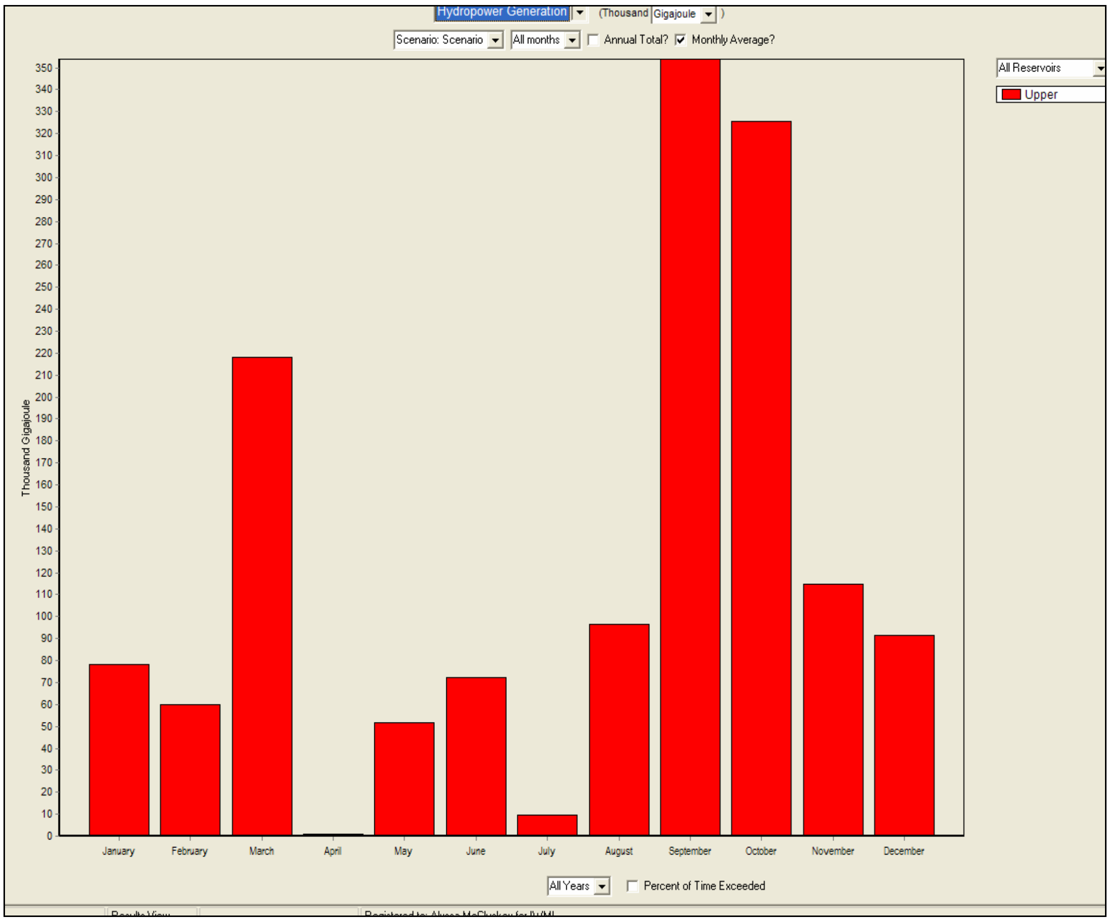


Figure 142 Average Monthly Hydropower Generation in Yellow River 3B-Region Representation with Management

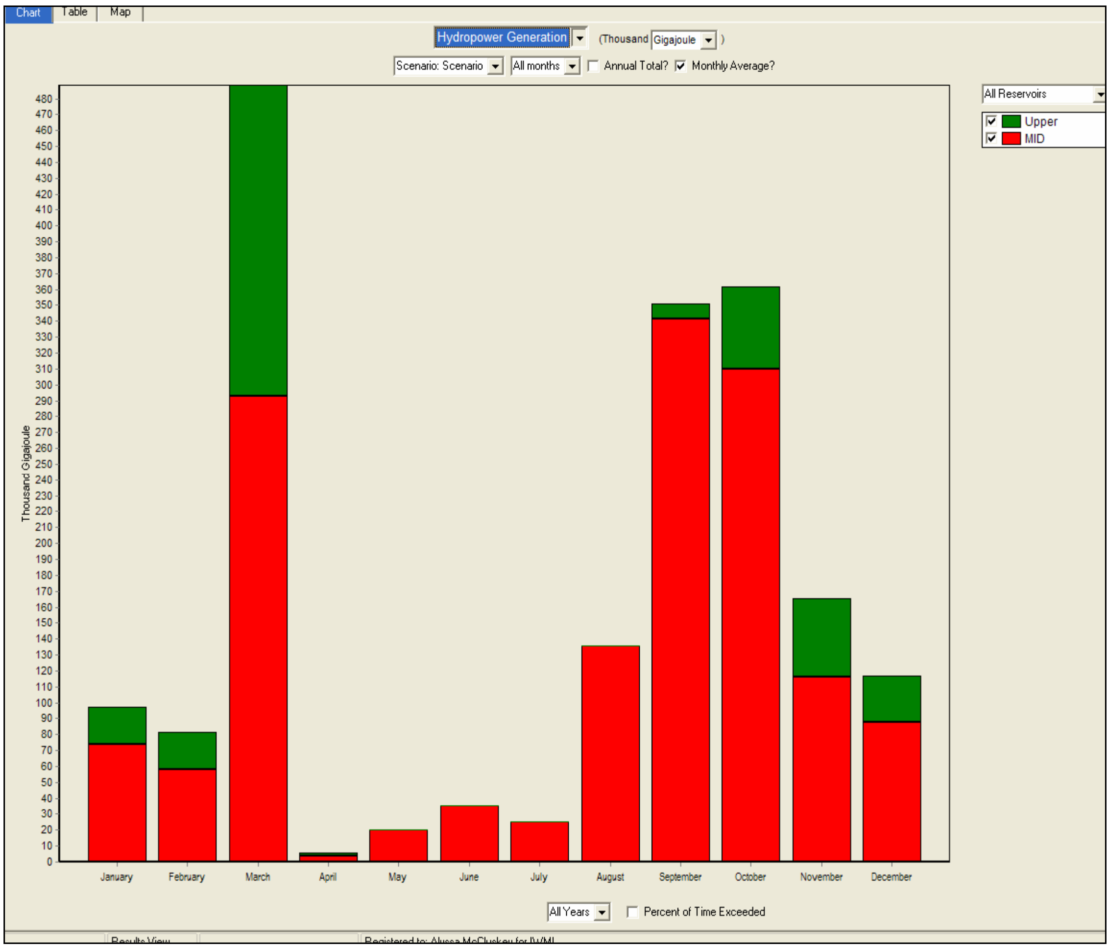
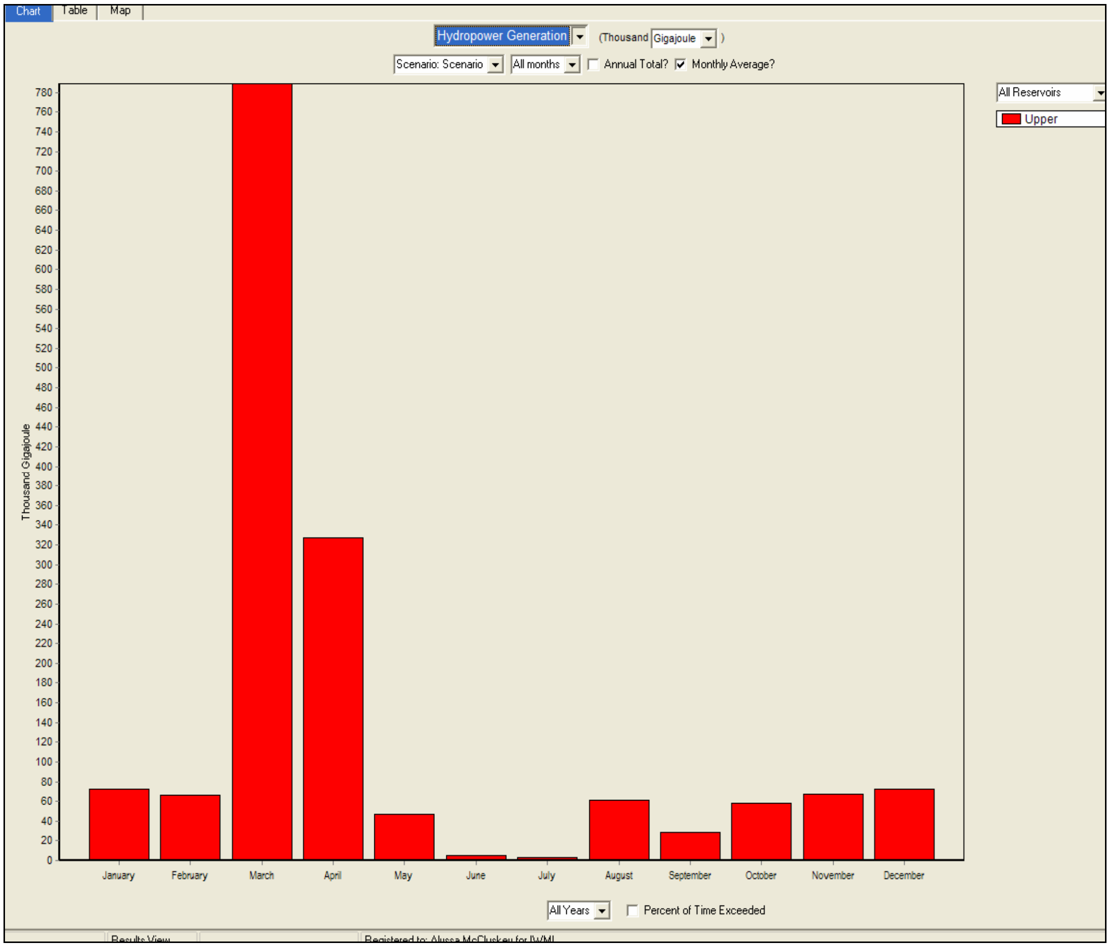


Figure 143 Average Monthly Hydropower Generation in Yellow River 1-Region Representation with Management



Yellow River Basin without Management

Figure 144 Average Monthly Hydropower Generation in Yellow River Detailed Representation without Management

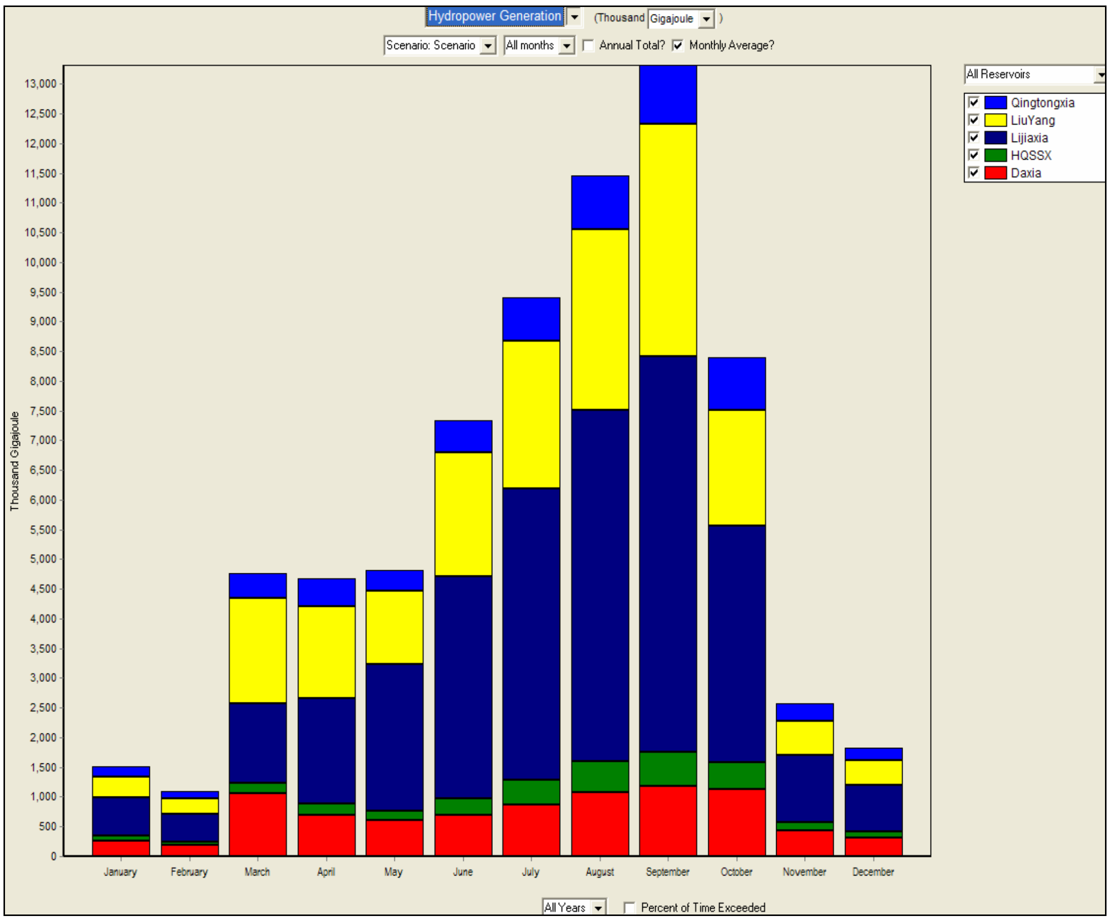


Figure 145 Average Monthly Hydropower Generation in Yellow River 4-Region Representation without Management

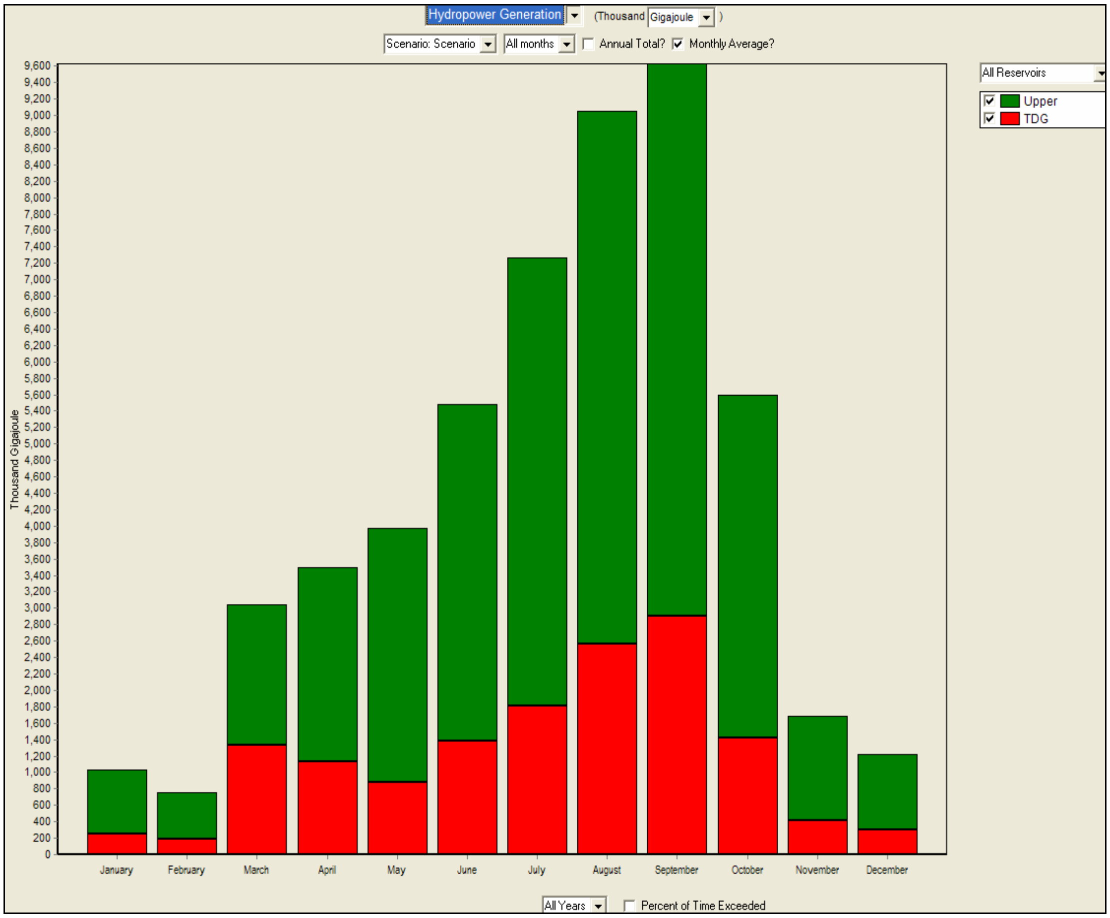


Figure 146 Average Monthly Hydropower Generation in Yellow River 3A-Region Representation without Management

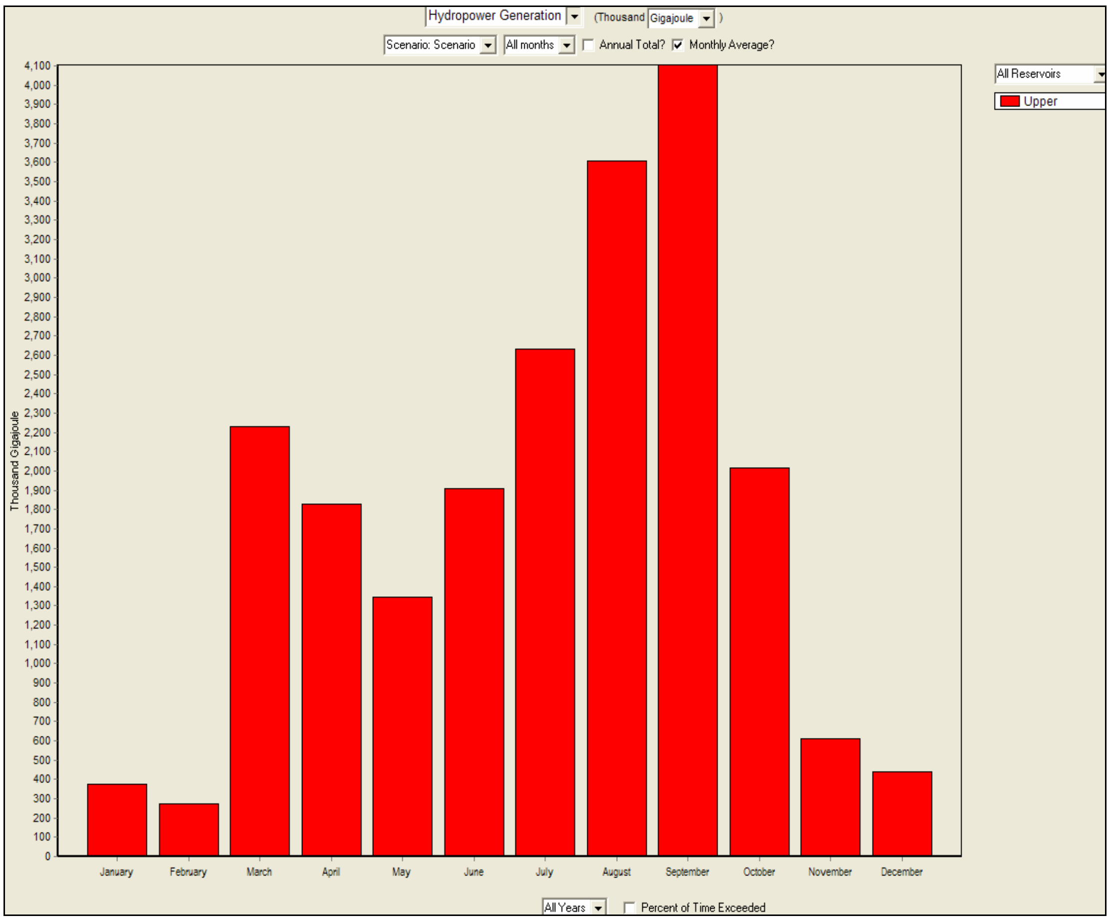


Figure 147 Average Monthly Hydropower Generation in Yellow River 3B-Region Representation without Management

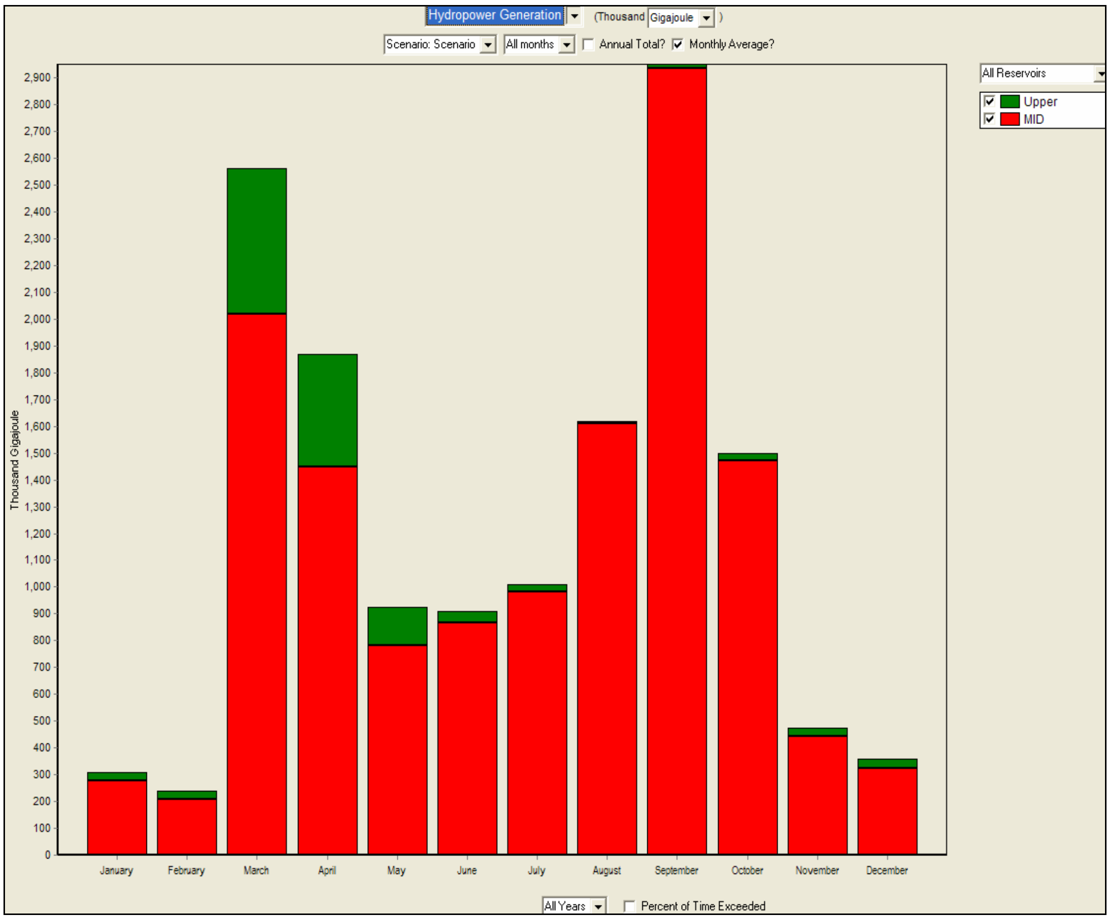
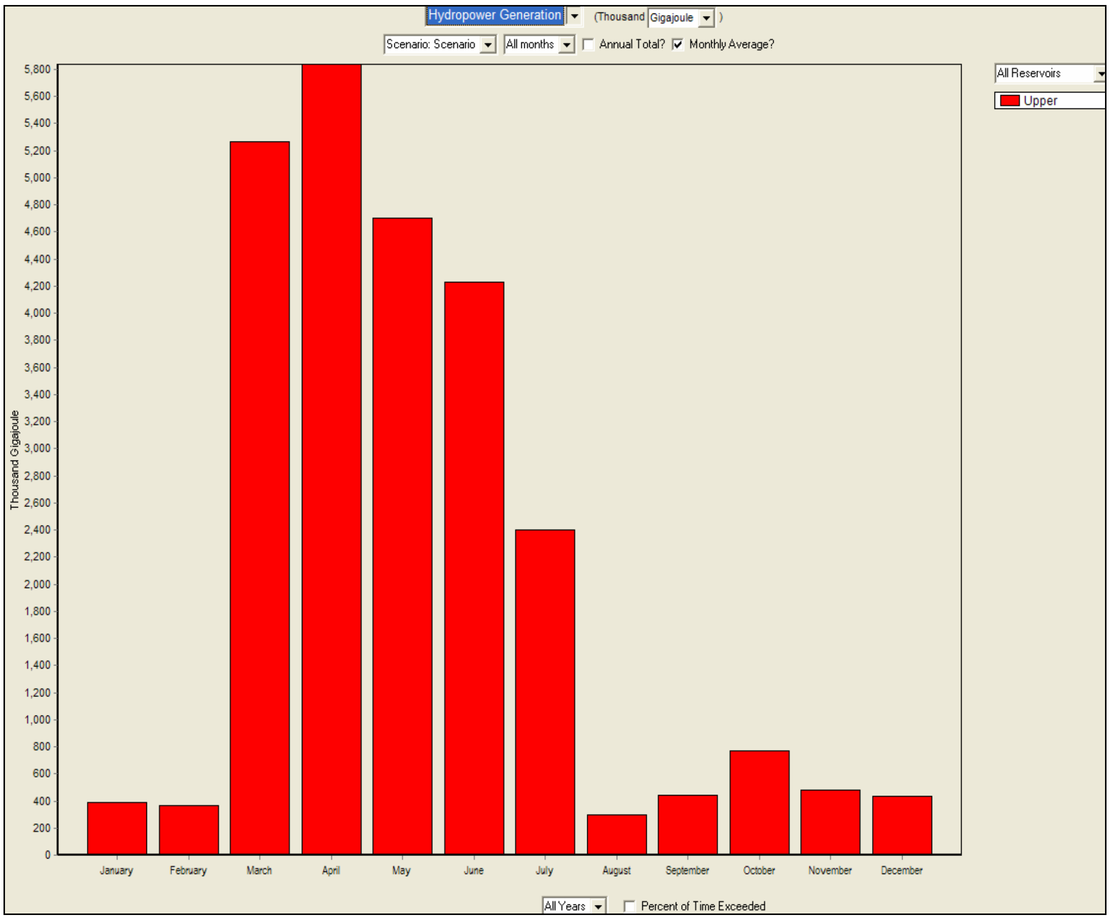


Figure 148 Average Monthly Hydropower Generation in Yellow River 1-Region Representation without Management



Volta River Basin

Figure 149 Average Monthly Hydropower Generation in Volta River Basin – Simple Representation

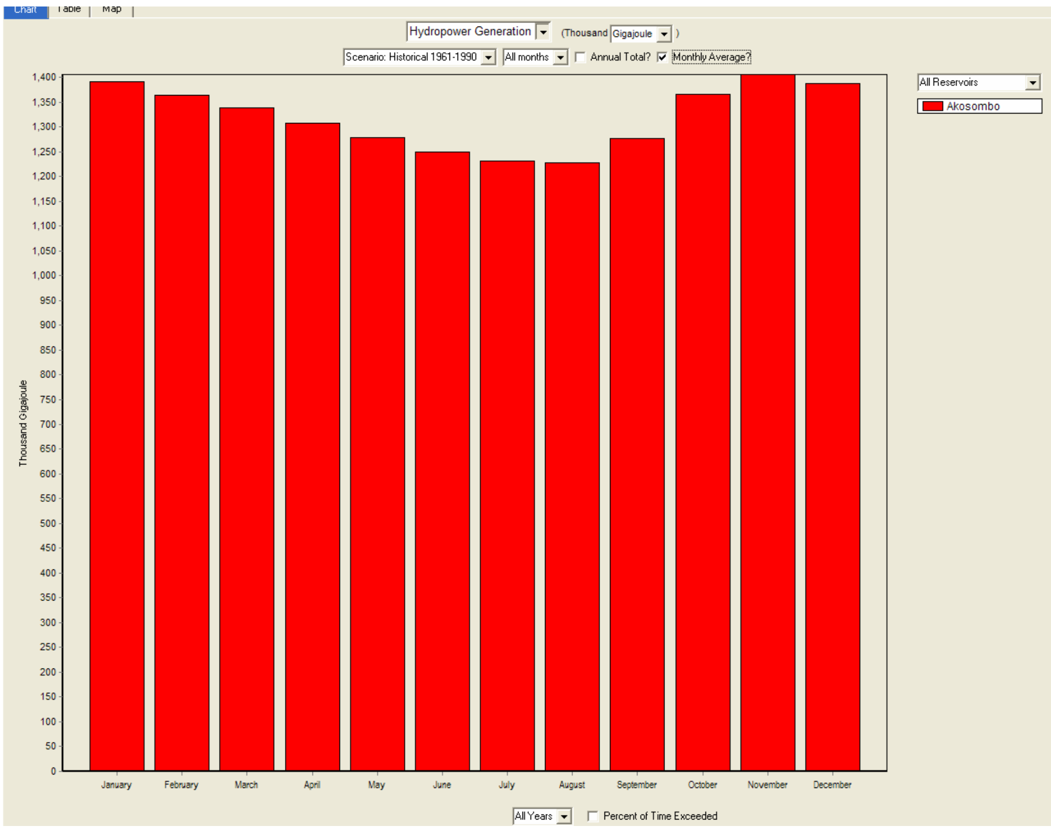


Figure 150 Average Monthly Hydropower Generation in Volta Basin Country Level 1 Representation

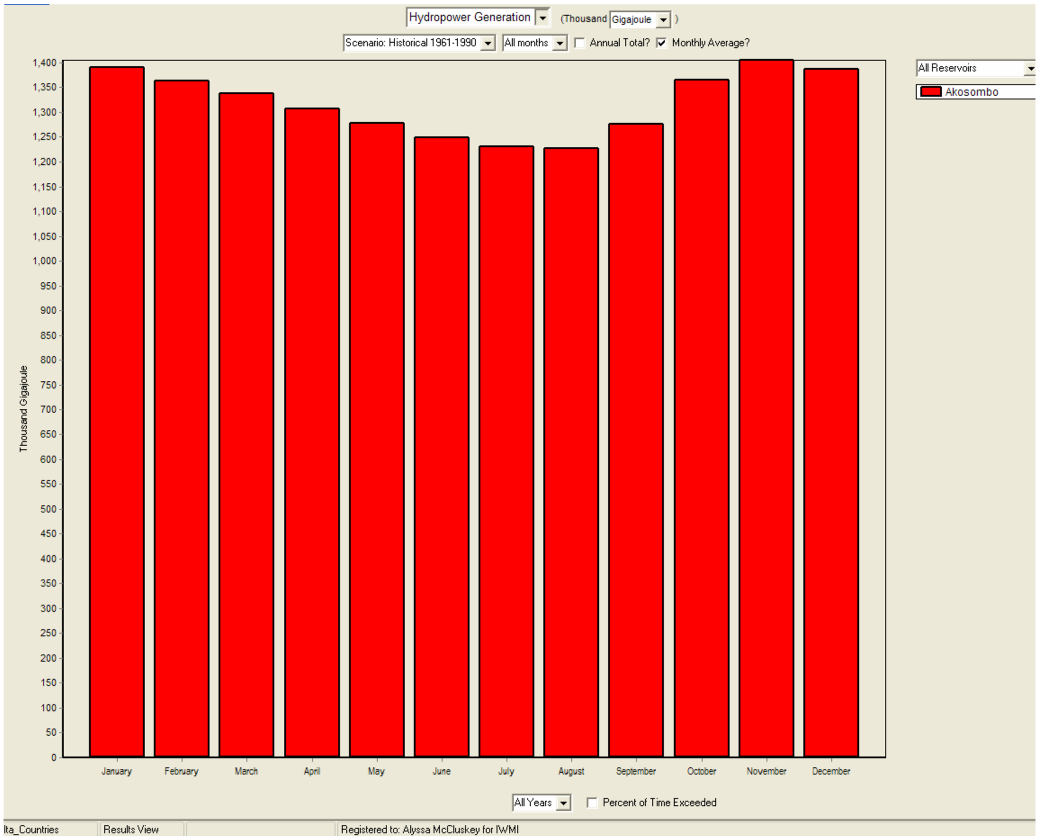
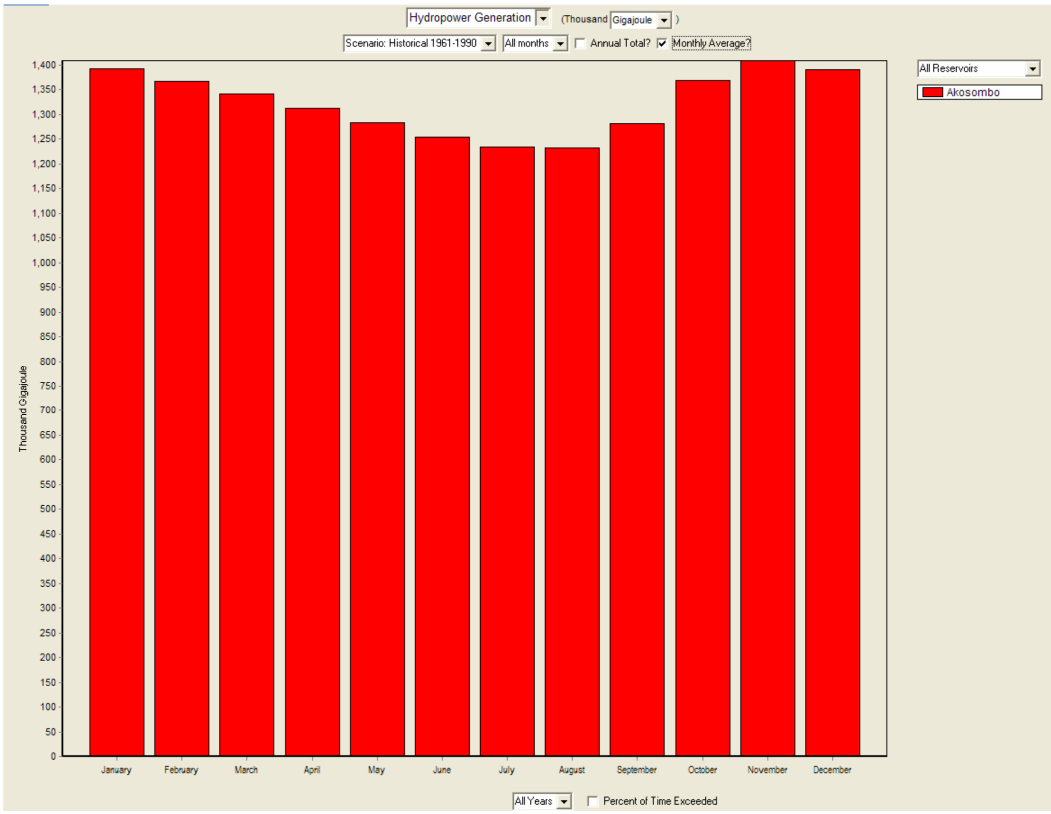


Figure 151 Average Monthly Hydropower Generation in Volta Basin Country Level 2 Representation



APPENDIX E

WEAP21 (Water Evaluation and Planning Model)

Water Evaluation and Planning System (WEAP)

Description

This is a PC based surface and groundwater resource simulation tool, based on water balance accounting principles, which can test alternative sets of conditions of both supply and demand. The user can project changes in water demand, supply, and pollution over a long-term planning horizon to develop adaptive management strategies. WEAP is designed as a comparative analysis tool. A base case is developed, and then alternative scenarios are created and compared to this base case. Incremental costs of water sector investments, changes in operating policies, and implications of changing supplies and demands can be economically evaluated.

Appropriate Use

What-if analysis of various policy scenarios and long-range planning studies. Adaptive agriculture practices such as changes in crop mix, crop water requirements, canal linings; changes in reservoir operations; water conservation strategies water use efficiency programs, water pricing policies; changes in instream flow requirements; implications of new infrastructure development. Strengths include detailed demand modeling.

Scope

All locations, surface and groundwater systems; national, international or site-specific.

Key Output

Mass balances, water diversions, sectoral water use; benefit/cost scenario comparisons; pollution generation and pollution loads.

Key Input

Configuration of system (can use GIS layers for background) and component capacities and operating policies. Water demand: Spatially explicit demographic, economic, crop water requirements; current and future water demands and pollution generation. Economic data: Water use rates, capital costs, discount rate estimates. Water supply: Historical inflows at a monthly timestep; groundwater sources. Scenarios: Reservoir operating rule modifications, pollution changes and reduction goals, socio-economic projections, water supply projections.

Ease of Use

Relatively easy to use. Requires significant data for detailed analysis.

Training Required

Moderate training/experience in resource modeling required for effective use.

Training Offered

On-line tutorial available at http://www.weap21.org/. Contact SEI for details regarding available training (see below).

Computer Requirements

200 MHz or faster Pentium class PC with Microsoft Windows 95 or later (a 400 MHz PC with Windows 98 or later is recommended). A minimum of 32 MB of RAM and 50 MB of free hard disk space is also required (64 MB of RAM recommended). In addition Microsoft Internet Explorer version 4.0 is required for viewing WEAP's HTML Help. Monitor should be set to a minimum resolution of 800x600, but preferably even higher (e.g., 1024x768 or 1280x1024), to maximize the presentation of data and results.

Documentation

WEAP21 User Guide; available online at http://www.weap21.org as pdf file.

Applications

Has been used for projects in the Aral Sea; Beijing, China; Rio San Juan, Mexico; Rajasthan, India; South Africa; West Africa; California, Texas, and Southeast, USA; Central Asia; India; Nepal; Korea; and Cairo, Egypt.

Contacts for Tools, Documentation, and Technical Assistance

Jack Sieber, Senior Software Scientist, Stockholm Environment Institute (SEI), Boston; SEI-Tellus Institute, 11 Arlington St., Boston, MA 02116-3411 USA; Tel: +1.617.266.5400; e-mail: weap@tellus.com; website: http://www.weap21.org/.

Cost

US$2000 for commercial users includes free upgrades and technical support; Discounts available for government, universities, and not-for-profit organizations; Free to developing countries

Model References

Huber-Lee, A., D. Yates, D. Purkey, W. Yu, B. Runkle. 2003. “Water, Climate, Food, and Envrironment in the Sacramento Basin – Contribution to ADAPT: Adaptation strategies to changing environment.” Stockholm Environment Institute.

Raskin, P., E. Hansen, Z. Zhu, and D. Stavisky. 1992. “Simulation of water supply and demand in the Aral Sea region.” Water International, 17(2)55-67.

Evan Hansen. 1994. “WEAP- A system for tackling water resource problems.” In Water Management Europe 1993/94: An annual review of the European water and wastewater industry. Stockholm Environment Institute: Stockholm.

U.S. Water News, Oct. 1992. “Aral Sea is classic example of ecological suicide.” No. V4. pg. 12.