Modeling U.S. water resources under climate change*

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Key Points:
- Integrated assessment modeling of water
- Largest water stress projected in the Southwest of the U.S.
- Emission abatement policy help reduce water stress intensity and variability

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Modeling U.S. water resources under climate change

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Abstract Water is at the center of a complex and dynamic system involving climatic, biological, hydrological, physical, and human interactions. We demonstrate a new modeling system that integrates climatic and hydrological determinants of water supply with economic and biological drivers of sectoral and regional water requirement while taking into account constraints of engineered water storage and transport systems. This modeling system is an extension of the Massachusetts Institute of Technology (MIT) Integrated Global System Model framework and is unique in its consistent treatment of factors affecting water resources and water requirements. Irrigation demand, for example, is driven by the same climatic conditions that drive evapotranspiration in natural systems and runoff, and future scenarios of water demand for power plant cooling are consistent with energy scenarios driving climate change. To illustrate the modeling system we select "wet" and "dry" patterns of precipitation for the United States from general circulation models used in the Climate Model Intercomparison Project (CMIP3). Results suggest that population and economic growth alone would increase water stress in the United States through mid-century. Climate change generally increases water stress with the largest increases in the Southwest. By identifying areas of potential stress in the absence of specific adaptation responses, the modeling system can help direct attention to water planning that might then limit use or add storage in potentially stressed regions, while illustrating how avoiding climate change through mitigation could change likely outcomes.

1. Introduction

Water availability is a growing global concern [*UN*, 2012], and many rivers are affected by water scarcity and quality issues. Troubling examples include the Ganges and Indus in India; the Amu Dar'ya and Syr Dar'ya in Central Asia; the Murray and Darling in Australia; and the Yellow and Yangtze in China [*Postel*, 2000]. The United States is no exception, with the Colorado and the Rio Grande rivers so severely exploited that they often do not reach the oceans [*Benke and Cushing*, 2005]. A significant area of the Southwest of the United States is prone to water scarcity with more than 75% of the river flow used for agriculture, industries, and domestic purposes [*IWMI*, 2007]. *Pritchett et al.*'s [2009] survey of more than 6000 people in the 17 westernmost states of the continental United States shows that respondents are aware of the water scarcity issue, but believe that it is less important in their own state than in other states.

Heavy exploitation of many U.S. water resources is the consequence of growing population and economic activity, and lack of conservation measures. Under the threat of climate change, and the likely effects on surface hydrology, the water issue is even more pressing. These issues have been extensively studied, more recently taking account of climatic effects [e.g., *Vörösmarty et al*., 2000; *Oki et al*., 2001; *Arnell*, 2004; *Alcamo et al*., 2007; *Shen et al*., 2008; *Brown et al*., 2013]. *Barnett and Pierce* [2008] estimate that there is a 50% chance that Lake Mead, the largest man-made reservoir in the United States, will be dry by 2021.

Water modeling efforts vary greatly in terms of scope (hydrologic detail, handling of vegetation, and integration of economic drivers), spatial scale (river basin to global), and time scale (daily to yearly). Water resources are often estimated using macroscale hydrological models, such as Water Balance Model (WBM) [*Vörösmarty et al*., 1998, 2000], WaterGAP [*Alcamo et al*., 2007], or H08 [*Hanasaki et al*., 2008]. However, most hydrological models represent hydrological processes in a stylized fashion and do not consider important surface energy balance issues. Additionally, they are often only loosely coupled with climate models used to analyze the effects of climate on surface hydrology. Land surface models, such as the Community Land Model (CLM) [*Oleson et al*., 2008], address both these issues. To represent water demand, some studies consider only a single sector of the economy. For instance, *Vassolo and Döll* [2005] and *Davies et al*. [2013] focus on thermoelectric and industrial water uses. Other studies detail water use only for irrigation [e.g., *Vörösmarty et al*., 1998, 2000]. Such efforts may fail to consider how changes in water demand from other sectors may affect water availability to the sector of interest.

There are other issues regarding the integration of the many drivers of water stress. While many studies consider the impact of anthropogenic climate change on water supply using climate model outputs or account for the effects of economic activity using a national or global economic model, few models, if any, are set up to consider the interdependence of these influences. Coupling of natural and social science components, and the assessment of the resulting complex effects on water, has been attempted in only a small number of integrated frameworks, such as TARGETS [*Rotmans and de Vries*, 1997], WorldWater [*Simonovic*, 2002], IMPACT-WATER [*Cai and Rosegrant*, 2002], WATERSIM [*de Fraiture*, 2007], and ANEMI [*Davies and Simonovic*, 2011].

However, the spatial and temporal scales of models are also important. Small river basin scale models provide very precise and useful management tools at the watershed level. For instance, the California Value Integrated Network (CALVIN) model [*Draper et al*., 2003], a hydro-economic optimization model, provides a very detailed representation of California's water system. But small-scale models do not easily connect to studies of global influences. Global-scale models, on the other hand, such as IMPACT-WATER [*Cai and Rosegrant*, 2002] and WATERSIM [*de Fraiture*, 2007], provide larger-scale analysis capacities, but they provide results of limited use in understanding local problems. The annual time scale of some models [e.g., *Vörösmarty et al*., 2000; *Oki et al*., 2001; *Alcamo and Henrichs*, 2002; *Arnell*, 2004; *Islam et al*., 2007; *Viviroli et al*., 2007] is often inadequate to assess water stress as it does not account for intra-annual variability.

High-quality water resource assessments meeting the desired scope, scale, and time step for climate-effect studies are rare because of data and modeling limitations. For the continental United States, for example, the challenge of such water models can be explained by the diversity of factors to consider: the United States comprises more than 3000 stream catchments, 18 Koppen-Geiger climate zones (half of the global range), and three major water rights paradigms over 50 states. A useful modeling framework at this scale requires a collection of tools that reflect the reality of water management while remaining computationally efficient.

In this article, we apply a framework that combines treatment of climatic, biological, and physical interactions that determine runoff, engineered systems of storage and transport, and multiple sources of water demand to meet residential, industrial, energy, and agricultural activity needs. The system is an extension of the Massachusetts Institute of Technology (MIT) Integrated Global System Model (IGSM) framework and is unique in its consistent treatment of factors affecting water resources and water demand. Irrigation demand, for example, is driven by the same climatic conditions that drive evapotranspiration in natural systems and runoff, and future scenarios of water demand for power plant cooling are consistent with energy scenarios driving climate change. This analysis builds on the MIT IGSM-Water Resource System (IGSM-WRS) [*Strzepek et al*., 2012b], which was developed to address the many shortcomings of existing modeling frameworks and, most importantly, to facilitate integration of water resource, land surface, and climate and economic processes. To analyze water issues specific to the United States, we develop a U.S. version of this approach, termed the IGSM-WRS-US, with greater sectoral and water basin detail. Specifically:

(i) U.S. waters are modeled at a 99-basin level compared to 14 U.S. basins in the global model.
(ii) The economy is modeled for 11 U.S. regions, replacing the single-nation representation in the global application, with water demand for power plant cooling modeled for 134 regions.
(iii) Interbasin transfers (IBTs), which are not considered in the global application, are included.
(iv) The systems supplying irrigation water and management practices at the crop level are based on county-level data, and calibrated to observed water application, which is often less than the water necessary to obtain maximum yield.
(v) An improved estimation of energy demand is incorporated, allowing a better estimation of water requirements for mining (MI) and thermoelectric power generation.
(vi) Detailed estimation of water requirements for public supply (PS) and self-supply (SS) sectors is added.

The IGSM-WRS-US was developed to identify areas of potential water stress, considering the multiple factors affecting available resources and competing demands from all sectors, including requirement for in-stream flows that are needed to maintain freshwater ecosystems. As such, it can point in the direction for further, more detailed, analysis and for longer-term water resource planning that could identify effective adaptation responses. For this reason, adaptation—other than reallocation or IBTs—is not evaluated endogenously. As an illustration, we provide an evaluation of two greenhouse gas (GHG) emission scenarios combined with two climate change scenarios to provide insights on the spatial and temporal patterns of climate impacts on water resources in the United States.

The description of the model and its application is organized as follows. First, in section 2, we summarize the various model components and how they are integrated into the modeling framework. Section 3 presents the core of the water allocation system. Section 4 describes the treatment of the hydrologic inputs: runoff, groundwater, IBTs, and basin storage. Section 5 describes the modeling components that project water requirements for SS, PS, MI, irrigation, and thermoelectric cooling and the treatment of environmental flow requirements (EFRs). Results are presented in section 6. Section 7 concludes with a review of the effort undertaken and a discussion of the advantages and limitations of the approach in analyzing water management in a changing world.

2. Integrated Assessment Structure

In the IGSM-WRS-US framework, the interaction of water resources and anthropogenic water requirements are analyzed using an integrated set of economic and earth system models. A schematic of the framework is provided in Figure 1 with the economic, climatic, and hydrologic drivers on the left-hand side and the water system on the right-hand side.

Within the integrated assessment framework, IGSM [*Sokolov et al*., 2005], the global economy is represented by the Emissions Prediction and Policy Analysis (EPPA) model [*Paltsev et al*., 2005]. This general equilibrium model simulates GHG emissions associated with the economic activity at the global level every 5 years. Interpolated hourly, global GHG concentrations are inputs into the MIT Earth System Model (MESM) [*Sokolov et al*., 2009], which encompasses both climate and land surface models. Latitudinally resolved climate variables are distributed longitudinally using precipitation patterns from archived global circulation models (GCMs) using a hybridized frequency distribution (HFD) approach [*Schlosser et al*., 2012] to provide hourly climate variables needed to simulate hydroclimatic conditions. Runoff is simulated as an output of CLM (version 3.5).

Daily accumulated precipitation and average temperature are used to drive the biophysical crop model, CliCrop [*Fant et al*., 2012], are also simulated using the HFD approach, and are thus consistent with the climatic conditions used to simulate runoff. With these climate inputs, CliCrop simulates daily crop water requirements to maximize crop yields.

The EPPA model, in addition to simulating global GHG emissions contributing to simulated changes in climate, provides projections of U.S. economic activity resulting from different global policies. To obtain region-specific economic activity, EPPA provides boundary conditions to the U.S. Regional Economic and Environmental Policy (USREP) model coupled with the Regional Energy Deployment System (ReEDS) model [*Rausch and Mowers*, 2012]. The USREP model [*Rausch et al*., 2010] provides economic projections driving water requirements. The ReEDS model [*Short et al*., 2009] integrated with USREP provides highly resolved (region and technology) projections of electricity production. Thermal power generation by region from USREP-ReEDS is used by the Withdrawal and Consumption for Thermo-electric Systems (WiCTS) model [*Strzepek et al*., 2012a] to compute monthly water withdrawal and consumption (see section 5.1.1). Also, gross domestic product (GDP) and population outputs from USREP are inputs to the calculation of water requirements for the other sectors, which are based on econometric estimated relationships.

The right-hand side of Figure 1 describes the water system components of the framework, WRS-US. Water requirements are composed of anthropogenic water needs for five sectors and environmental requirements. More details on these model components are provided in section 5. Water resources simulation is provided in section 4. The estimated resources and requirements are inputs to a Water System Management (WSM) module. As detailed in section 3, WSM computes water balance and water stress for each

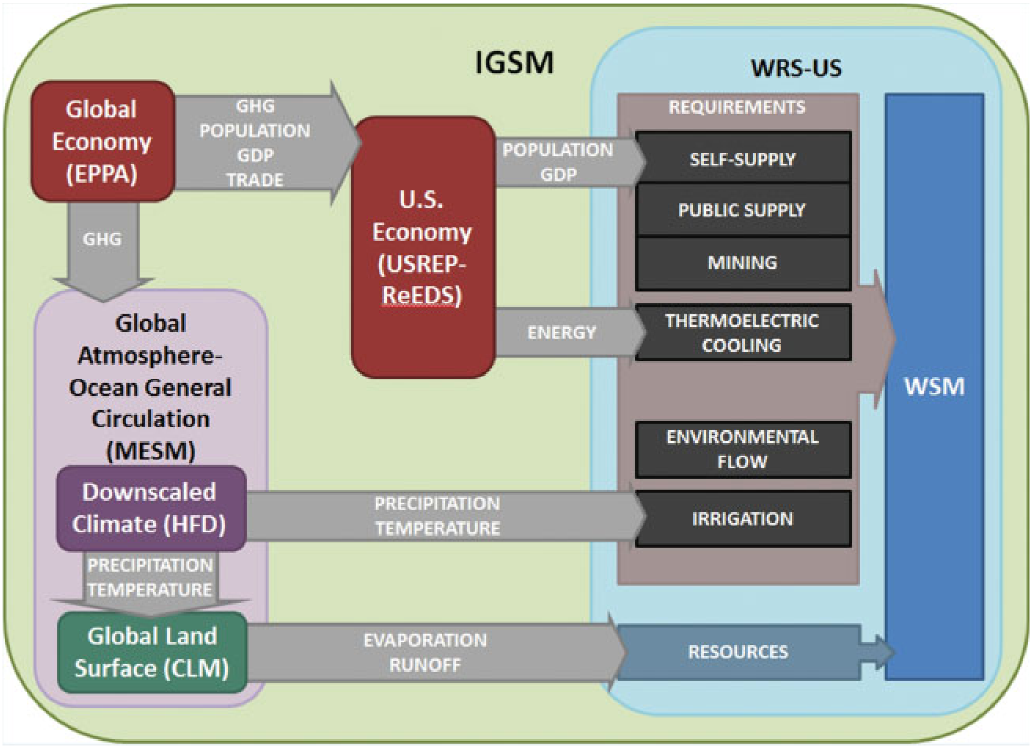

Figure 1. Schematic of the IGSM-WRS-US framework illustrating the connections between the different components of the IGSM framework and the WRS-US components. Notes: The description, spatial and temporal scales of the models are summarized in Table B1. HFD, hybridized frequency distribution; EPPA, Emissions Prediction and Policy Analysis; USREP, U.S. Regional Economic and Environmental Policy; ReEDS, Regional Energy Deployment System; CLM, Community Land Model; WSM, Water System Management.

basin. In this application, there is no feedback effect between sectoral water stress and national economic activity or agricultural production. There is also no measure of adaptation taken to prevent water stress and no land-use change from areas where water is scarce to locations with greater water availability. International trade is also not taken into account as a response to water stressed activities in the United States.

In summary, projections of economic activity under a given policy determine global GHG emissions, which in turn drive GHG concentrations and changes in climate. Weather, associated with this climate, determines runoff and evaporation (which affects water resources) and changes in crop growth (which influences water requirements). Economic activity, associated with the global policy, also drives changes in the economic activity at the regional level, which results in changes in sectoral water requirements. Given resources and requirements, the water is allocated across sectors in each basin and water stress occurs if water resources are less than water requirements within the basin.

The set of models used in this analysis and their characteristics are summarized in Table 1. This table provides information on the spatial and temporal scales of the models. Details regarding the downscaling or aggregation techniques used to integrate the models together are provided in section 4 for water resources and in section 5 for water requirements.

3. Basin-Level WSM Structure

The WSM model is based on the Water System Module developed by the International Food Policy Research Institute [*Rosegrant et al*., 2008]. In this framework, however, the WSM module follows the 99 Assessment Sub-Region (ASR) delineation set out by the U.S. Water Resources Council [*USWRC*, 1978] shown in Figure 2. The color scale represents the distance of the basin from the outlet. Dark green basins are located the furthest upstream and dark orange basins are the closest to the sea or border. Purple basins are closed and have no outlet.

Table 1. Summary of Model Characteristics Considered in the WRS-US Framework

Model	Reference	Spatial Scale	Temporal Scale
EPPA	[*Paltsev et al.*, 2005]	16 regions globally (1 U.S. region)	5 years
USREP	[*Rausch et al.*, 2010]	11 U.S. regions	2 years
ReEDS	[*Short et al.*, 2009]	134 U.S. regions	2 years
MESM	[*Sokolov et al.*, 2009]	2° × 2.5° grid	hour
HFD	[*Schlosser et al.*, 2012]	2° × 2.5° grid	hour
CliCrop	[*Fant et al.*, 2012]	2° × 2.5° grid	day
CLM	[*Oleson et al.*, 2008]	2° × 2.5° grid	hour
WSM	This issue	99 ASRs	month

Note: See acronym description in Notes of Figure 1.

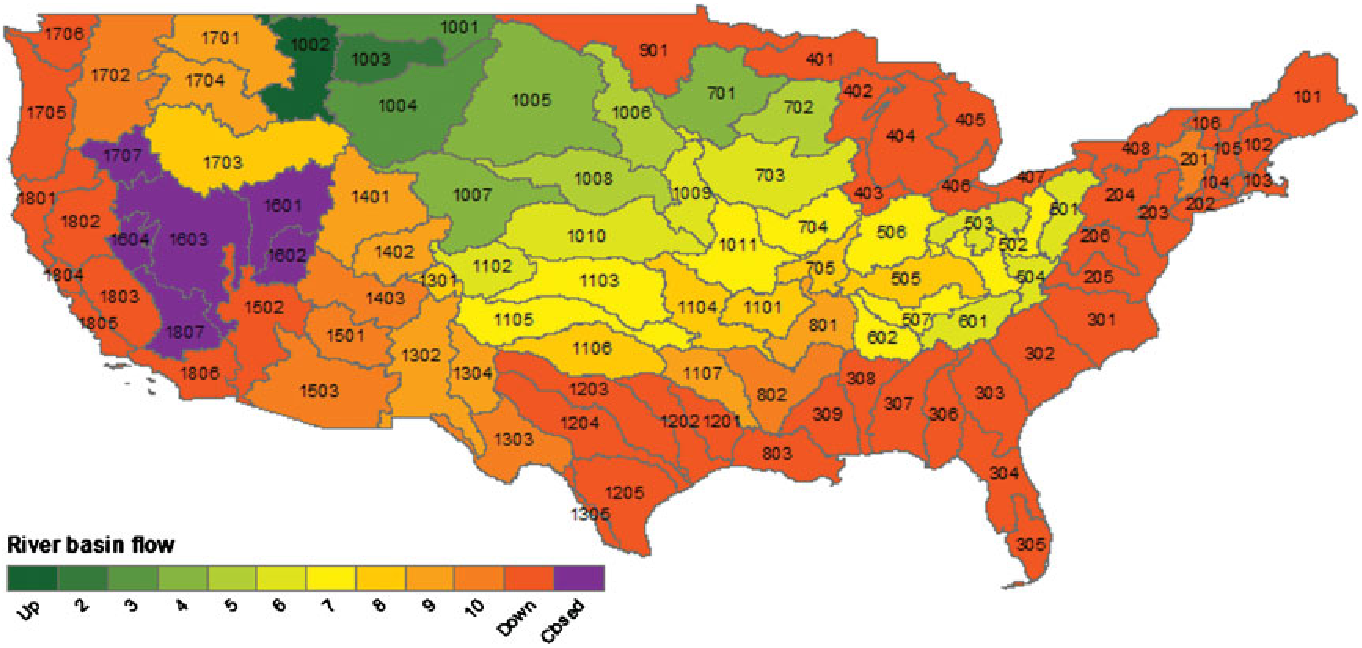

Figure 2. River basins in the continental U.S. and river flow structure.

For each ASR, the model allocates available water among users each month while minimizing annual water deficits (i.e., water requirements that are not met) and smooths deficit across months. The allocation of water for each ASR is solved simultaneously for the months of each year. Upstream basins are solved first, and the calculation proceeds downstream following the structure of river flows. Water spilled from upstream basins becomes the inflow for downstream basins. Closed basins are solved last.

A schematic of reservoir operation is presented in Figure 3. All water storage in the ASR is aggregated into a single virtual reservoir (STO). Total water supply (TWS) is composed of this surface water storage plus groundwater supply (GWS). In this application, we do not consider water from desalination or groundwater recharge. STO receives the river basin runoff (RUN) and inflows from upstream basins (INF). This version of WRS also accounts for IBT. Part of the STO is lost through evaporation (EVP).

Releases from surface storage (REL) and GWS constitute the TWS, which is used to fulfill the water requirements of the different sectors (SWR). (We use the term “requirements” instead of “demand” as the model does not yet consider the potential effect of changes in water price on its use. Water requirements for each sector are estimated based on recent experience and therefore implicitly assume current or recent prices.) We identify five sectors: thermoelectric plant cooling (TH), irrigation (IR), PS, SS, and MI. For all sectors, except irrigation, water requirements are represented by consumptive use on the assumption that any return flow (withdrawal in excess of consumption) is likely returned to the ASR storage within the month. This assumption is not appropriate for irrigation, because return flow, which may be substantial, may not be returned to the ASR storage immediately. Instead, the water lost in conveyance and field inefficiency is accounted as a return flow (RTF_{IR}), which will contribute to the outflow of the basin (OUT) in the next month. For thermoelectric cooling, the temperature of the return flow can influence reuse. However, given the spatial and temporal scales of the model, we assumed that water requirements for this sector are better represented by consumptive use.

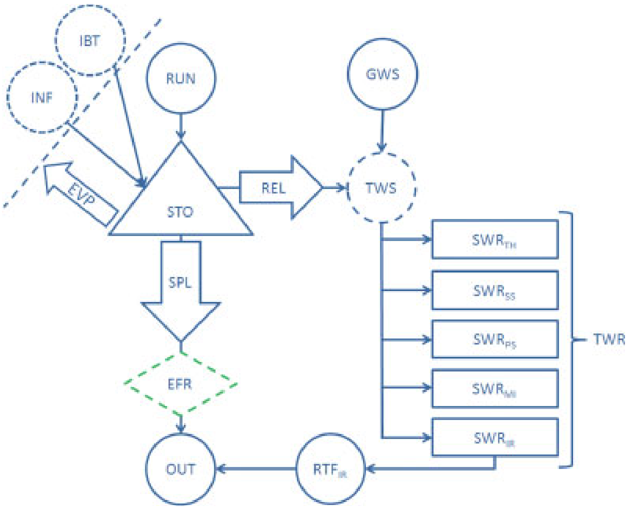

Figure 3. Schematic of the Water System Management (WSM) module at ASR scale in the WRS-US. Notes: Total water requirement (TWR) is calculated by summing self-supply (SWR_{SS}), public supply (SWR_{PS}), mining (SWR_{MI}), and irrigation (SWR_{IR}) requirements. Surface water supply comes from inflow from upstream basins (INF) and local basin natural runoff (RUN) and goes into the virtual reservoir storage (STO) where evaporation (EVP) is deducted. The reservoir operating rules attempt to balance the water requirements (TWR) with the total available water (TAW). Water requirements are met by groundwater supply (GWS) and releases from the virtual reservoir (REL). Water is released to the downstream basin (SPL) accounting for environmental flow requirements (EFR).

The degree to which total water requirements (TWRs) are met is determined by the total water supplied (TWS). This water is allocated proportionally among all sectors, except irrigation. Water is available for irrigation only if there is sufficient water to meet the requirements of all other sectors. This assumption is based on the relative economic value of water in these different uses. If TWS is insufficient to meet the nonirrigation requirements, those sectors take an equal proportional cut.

After accounting for water supply to the different sectors and evaporation from surface storage, excess water in each ASR is spilled onto its downstream basin (SPL) while respecting a minimum EFR to constitute the outflow, which is the inflow of the downstream ASR.

4. Water Resources Simulation

Surface water resources are largely a function of local climate, which in turn is influenced by GHG concentrations in the atmosphere. To provide meteorological variables (precipitation, temperature, and reference evapotranspiration) at the relevant scales of the WRS, we use the HFD approach [*Schlosser et al*., 2012]. Projected regional temperature and precipitation data, at $2° \times 2.5°$ resolution on an hourly scale, are used as inputs into the land surface model to determine runoff. The estimated total basin runoff, accounting for upstream basin inflows and IBTs, constitutes the surface water resources, which are then combined with GWS. Each of these components is estimated at the ASR level following the methodology outlined below.

4.1. Runoff

Runoff represents the water flowing over the surface and immediately below the surface of the ground and is caused by rainfall or snow melt. In this study, runoff is estimated using CLM. CLM models soil-plant-canopy processes of the surface and subsurface, which include key fluxes to the hydroclimate system. The hydrologic component of CLM estimates runoff taking explicit account of infiltration, canopy interception, root-active and deep-layer soil hydrothermal processes, soil evaporation, evapotranspiration, snowpack, and melt. CLM provides gridded runoff data to the ASRs and the management of the runoff routing is endogenously determined by WRS-US—inflows from upstream basins are sequentially estimated starting by the further upstream basins.

Recent studies show that CLM simulates mean annual cycles of runoff over continental-scale basins rather well [e.g., *Lawrence et al*., 2011]. Yet at the scale of the 99 U.S. ASRs employed herein, runoff estimates of CLM require further refinement. Following *Strzepek et al*. [2012b], monthly runoff of CLM at each basin is adjusted using the maintenance of variance extension (MOVE) procedure [*Hirsch*, 1982]. This technique is commonly used to transfer streamflow information from gauged to ungauged basins. To standardize streamflow, MOVE requires estimates of the first two moments (mean and standard deviation) of runoff for every ASR. However, observed data on natural flow at the ASR basins (which most closely represents runoff generated by CLM) are not available due to human interference via river management (e.g., dams). We therefore use the U.S. Water Resources Council [*USWRC*, 1978] data set, which provides statistics (mean and standard deviation of a log-normal distribution) representative of monthly natural flow for the 99 ASRs for the 1954–1977 period.

To apply MOVE to CLM runoff at the ASR level, we first calculate the CLM monthly runoff, $Q_{\mathrm{CLM}}(m,y)$, and its mean, $\mu(m)_{\mathrm{CLM}}$, and standard deviation, $\sigma(m)_{\mathrm{CLM}}$, over the period 1954–1977. Using the mean and standard deviation for the USWRC flows over the same period, $\mu(m)_{\mathrm{USWRC}}$ and $\sigma(m)_{\mathrm{USWRC}}$, we then transform the CLM runoff to estimate WRS-US basin runoff, RUN:

$$\mathrm{RUN}\,(m,y) = \mu_{\mathrm{USWRC}}\,(m) + \frac{\sigma_{\mathrm{USWRC}}\,(m)}{\sigma_{\mathrm{CLM}}\,(m)} * \left(Q_{\mathrm{CLM}}\,(m,y) - \mu_{\mathrm{CLM}}\,(m)\right),$$

where $\frac{\sigma(m)_{\mathrm{USWRC}}}{\sigma(m)_{\mathrm{CLM}}}$ is the bias correction factor.

The procedure assumes that monthly streamflows over the period 1954–1977 are stationary. However, under climate change, this assumption is unlikely to hold. To address this issue, we apply a nonstationary extension to the MOVE technique. We use a 10 year moving average of CLM monthly runoff, $\mu_{\mathrm{CLM\_MA10}}(m,y)$, and estimate a trend relative to the 1954–1977 baseline:

$$\mathrm{TR}_{\mathrm{CLM}}\,(m,y) = \frac{\mu_{\mathrm{CLM\_MA10}}\,(m,y)}{\mu_{\mathrm{CLM}}\,(m)}.$$

RUN is then transformed following the formula:

$$\mathrm{RUN}\,(m,y) = \mu_{\mathrm{USWRC}}\,(m) + \mathrm{TR}_{\mathrm{CLM}}\,(m,y) + \frac{\sigma_{\mathrm{USWRC}}\,(m)}{\sigma_{\mathrm{CLM}}\,(m)} * \left(Q_{\mathrm{CLM}}\,(m,y) - \mu_{\mathrm{CLM\_MA10}}\,(m)\right).$$

As demonstrated in Figure 4, the MOVE procedure successfully adjusts CLM runoff to match that of the USWRC estimates. Accordingly, these adjusted runoff values (at a monthly time scale) are then provided as runoff (RUN) within the WSM module presented in Figure 3.

4.2. Surface Storage

Surface storage is composed of constructed and natural reservoirs. The constructed reservoir storage for the base year is assumed to be equal to the maximum storage capacity, which is sourced from the National Inventory of Dams database [*USACE*, 2013]. The storage capacity of natural reservoirs is provided by the land surface model, CLM.

4.3. Interbasin Water Transfers

Water is transferred from water-abundant basins to water-limited ones via conveyance systems such as canals and aqueducts. These transfers are most common in the Western United States. We model them by assuming that a fixed amount of water is transferred annually based on past observations. In this application, we account for transfers (i) from the Colorado River to the Metropolitan Water District (1193 MCM), the Imperial Irrigation District (3305 MCM), and the Coachella Valley (398 MCM) in California through the All American Canal [*U.S. Bureau of Reclamation*, 2009]; (ii) from the Colorado River to Southern California (1604 MCM) via the Colorado River aqueduct [*Zetland*, 2011]; and (iii) from the Sacramento Valley to the San Joaquin Valley (7078 MCM) and from the Tulare region to Southern California (684 MCM) via the California State Water Project [*Connell-Buck et al*., 2011].

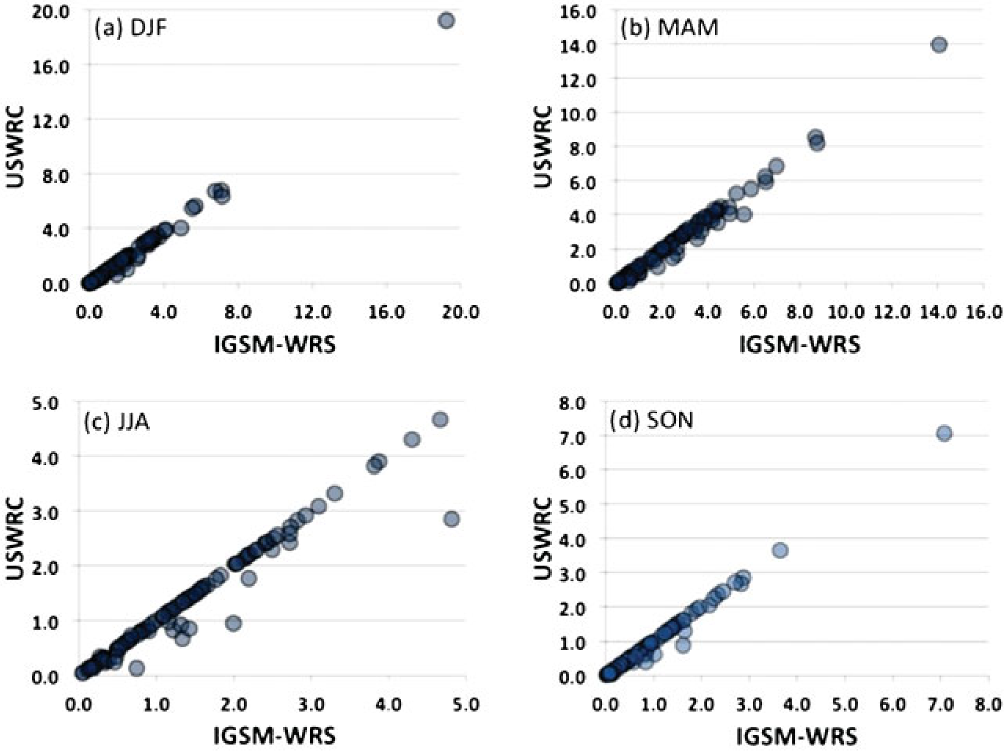

Figure 4. Seasonal-mean natural flow of the CLM values adjusted via the MOVE procedure (abscissa values) compared against the empirical estimate of the USWRC (1978) study (ordinate values) for the period 1954–1977. Scatterplots present the comparisons of the 99 ASRs seasonal mean for (a) December to February (DJF), (b) March to May (MAM), (c) June to August (JJA), and (d) September to November (SON). All flow values are given in units of billion cubic meters (BCMs) per month.

4.4. Groundwater

Groundwater reservoirs (aquifers) represent an important source of freshwater as they store 25% of global freshwater [*USGS*, 2012]. The depletion and recharge of these reserves is a controversial issue globally [*van der Gun*, 2012]. Numerous methods have been devised to estimate groundwater recharge, but they are prone to uncertainties and errors [*Scanlon et al*., 2002]. In this study, GWS is assumed to be limited to the 2005 groundwater uses estimated by *USGS* [2011] at the county level. This estimation is based on the assumption that the amount of groundwater used in 2005 is representative of annual water availability. To obtain groundwater data at the basin level, we aggregate the county-level data within each basin. When a county intersects with different ASRs, we assume that the county belongs to the ASR where the majority of its area is located. Groundwater recharge modeling is a topic of future research.

5. Water Requirements Simulation

5.1. Sectoral Water Requirements

As presented in Figure 5a, freshwater in the United States is mainly withdrawn for thermoelectric cooling and irrigation, which represented 42% and 36% of total freshwater, respectively, in 2005 [*USGS*, 2011]. In terms of consumption (Figure 5b), however, thermoelectric cooling is a small sector. Irrigation, on the other hand, consumes 60% of the water withdrawn. As explained in section 3, we consider withdrawal for the irrigation requirement and consumption for the other sectors. This combination of estimates leads to Figure 5c, which shows that the largest user in the United States is irrigation, with 87% of TWRs measured at the ASR level.

These water requirements are projected using population and GDP growth estimated by the USREP model, a recursive-dynamic multiregion, multicommodity general equilibrium model of the U.S. economy. Population growth is exogenous in USREP, and projections by state are taken from the *U.S. Census Bureau* [2000]. USREP has a 2 year time step and divides the continental United States into 11 regions. The

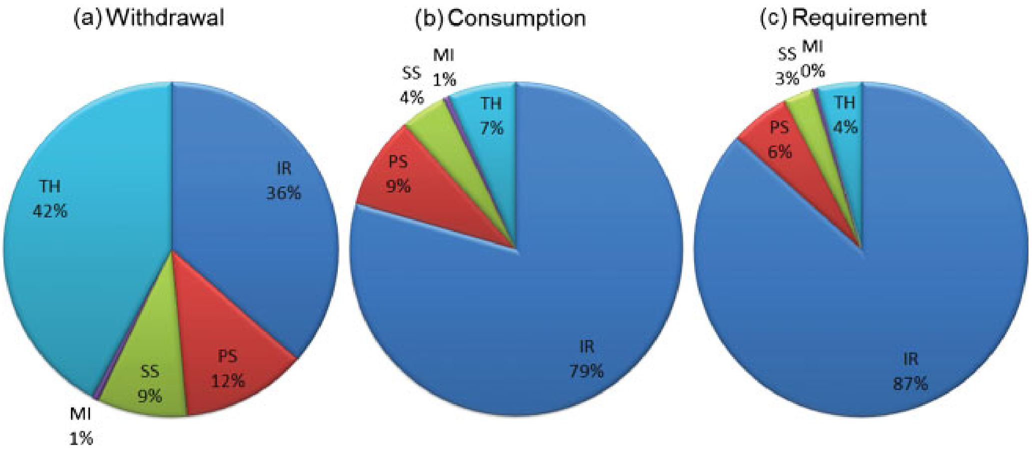

Figure 5. U.S. water withdrawal, consumption, and requirement by sector in 2005. Notes: Pie charts constructed using withdrawal and consumption data estimated by *USGS* [2011]. Water requirements for irrigation correspond to irrigation withdrawal. Requirements for the other sectors correspond to consumption. TH, thermoelectric cooling; IR, irrigation; SS, self-supply; PS, public supply; MI, mining.

regional population and GDP growth rates estimated by USREP are interpolated to obtain annual figures for the corresponding ASRs. We assume that GDP and population remain constant across the year. USREP is run with external conditions (prices and trade) set to be consistent with the global simulations of the EPPA model, which provides GHG concentration associated with the level of economic activity. These GHG emissions are input to the climate simulations. These climate projections will impact future water requirements for irrigation. The remainder of this section presents the methods used to estimate water requirements at the ASR level for each sector.

5.1.1. Thermoelectric Cooling

Water withdrawn for power plant cooling either goes through cooling towers or ponds before being reused (recirculating or recycle systems) or is returned to the stream (once-through systems) — dry cooling is used only in 1% of U.S. thermal electric generation [*DOE*, 2006]. The share of withdrawn water that is consumed depends on the cooling system employed [*Templin et al*., 1997]. In recirculating/recycling systems, water goes through cooling towers or ponds and is then reused so that a large share of the water withdrawn from the stream is consumed. In once-through systems, the water is used once and returned to the stream so that a relatively small share of the withdrawn water is consumed. U.S. power systems requiring thermoelectric cooling are represented using the ReEDS model, a recursive-dynamic linear programming model that simulates the least-cost expansion of electricity generation capacity and transmission, with detailed treatment of renewable electric options. ReEDS is composed of 134 power control areas and models electricity generation by fuel type (fossil fuel, nuclear) and cooling system (once-through, recycle). The ReEDS model is fully integrated in USREP. This allows us to include general equilibrium economy-wide effects while capturing important electricity-sector details with respect to technology innovation and investments in transmission capacity. The integrated USREP-ReEDS model and the methodology used to link the two models are presented in *Rausch and Mowers* [2012].

Based on the electricity system demand provided by the ReEDS model, monthly withdrawal and consumption in thermoelectric cooling is estimated using the WiCTS model [*Strzepek et al*., 2012a]. In this version of the model, we estimate water requirements for thermoelectric cooling (SWR_{TH}) considering consumption only, assuming that nonconsumed withdrawals are returned to the ASR within the same period. The temperature of the water returned to the stream is often a concern both for the environment and for immediate reuse. In this regard, water can be thought as thermal consumption. We are currently not capable of modeling this type of water consumption. We, therefore, only account for evaporative consumption occurring during the cooling process.

To validate the accuracy of the thermoelectric cooling water requirement estimates, we compared WiCTS total thermoelectric cooling withdrawal estimates for the year 2006 with USGS withdrawal for the year

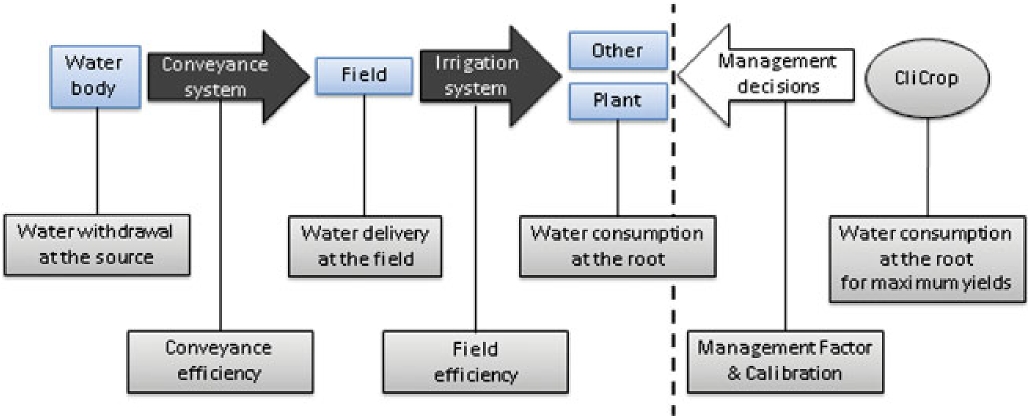

Figure 6. Schematic of Irrigation System Model in WRS-US. Notes: Irrigation requirements at the root are estimated by the biophysical model CliCrop and adjusted by management practices. Ultimate withdrawals to meet the requirements take account of losses in the field and in conveyance from the source to the field.

2005 (which is the latest available data). Over the United States, the WiCTS estimate of 206 billion gal/d is very close to the USGS estimate of 201 billion gal/d in 2005.

5.1.2. Irrigation

To estimate water use for irrigation, we need to consider several aspects of the delivery system. As represented in Figure 6, water withdrawn from the stream or reservoir is delivered to the cropping field via a conveyance system (e.g., canal and pipes). Depending on the type of system installed, part of the water withdrawn is lost through seepage and/or evaporation. This fraction of water reaching the field (i.e., delivery at the field) is represented by conveyance efficiency (CEF). The water delivered at the field is either applied to crops directly or used for irrigation-related activities (e.g., frost prevention and leaching) or lost in the field distribution system. The fraction of water reaching the plant is called field efficiency (FEF) and depends on the irrigation system used (e.g., sprinkler and drip).

To estimate the water requirement at the crop level, we use the CliCrop model, which estimates crop water required at the root to eliminate all water stress. As actual irrigation practices may not correspond to optimal amounts of water estimated by CliCrop, we develop a crop-specific management factor and a region-specific calibration that allows us to adjust modeled irrigation water use to observed use. As a benchmark for estimating this factor, we use water consumption data extracted from the Farm and Ranch Irrigation Survey (FRIS), which provides detailed information on farm irrigation practices in 2003 [*USDA*, 2003]. FRIS reports, for each crop and each state, the amount of irrigation water consumption at the field and the irrigated area. Each of these steps is explained in greater detail in the supporting information (Appendix A).

To validate the accuracy of our irrigation estimation procedure, we present a comparison of predicted irrigation withdrawal with observed irrigation withdrawal in Figure 7. To obtain the predicted values, we use climate input data from the National Climatic Center (NCC) [*Ngo-Duc et al*., 2005] for the period 1980–2000 (NCC is available only until 2000) as input into CliCrop. The observed values are sourced from *USGS* [2011]. We provide the withdrawal data per unit of land irrigated as is common in the literature. Figure 7 shows that predicted data are close, although somewhat overestimate irrigation compared to the observed data, which is supported by a correlation coefficient of 0.74.

5.1.3. Other Sectors

Other water requirements are classified into three groups: PS, SS, and MI as defined by *USGS* [2011]. PS withdrawal refers to water use for residential purposes, commercial activities, and industrial activities provided by public and private water suppliers. SS water withdrawal includes water use for residential purposes, commercial, industrial, livestock, and aquaculture activities sourced directly by the user. MI water withdrawal is defined as “water use during quarrying rocks and extracting minerals from the land” [*USGS*, 2011]. Water use for shale gas fracking is embedded in the MI category.

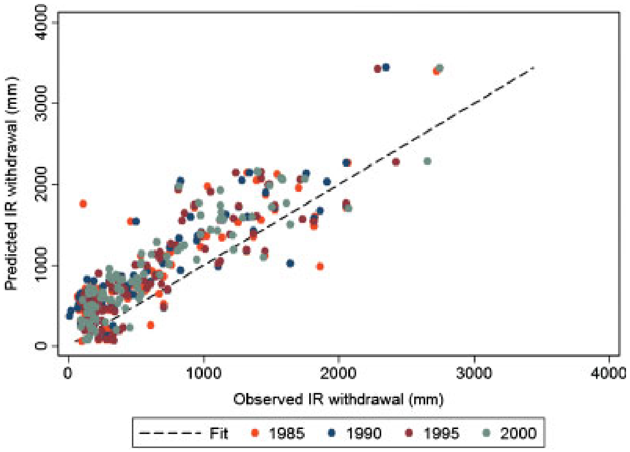

Figure 7. Comparison of predicted values of irrigation annual water withdrawals per unit of land irrigated with observed withdrawal per unit of land irrigated values at the ASR level. Note: We have removed one outlier for the Sabine-Neches in the Texas Gulf region (ASR 1201) for 1995 for which the observed IR withdrawal corresponds to 8727 mm/yr and predicted IR withdrawal corresponds to 1094 mm/yr.

Water withdrawal for each of these sectors is estimated econometrically using water data collected at the county level by *USGS* [2011]. Details of the econometric analysis are provided in Appendix B. Future water requirements for these sectors are projected by estimating consumption. Sectoral consumption is assumed to be a constant share of sectoral withdrawals, which is obtained by applying the population and GDP growth estimates from the USREP model to the corresponding variables in the regression for each sector presented in Appendix B.

To demonstrate the ability of the model to predict future water requirements for the PS, SS, and MI sectors, we compare the model estimates to historical data. We project sectoral withdrawal for past years using the econometric estimates described in Appendix B and compare these to observed withdrawal for each sector collected by USGS every 5 years from 1985 to 2005. A graphical comparison provided in Figure 8 shows that the econometric model performs reasonably well. Fitted values for each year are distinguished by color to highlight eventual annual outliers. Except for the SS in 1995, no other year appears to stand out. The best predictions are obtained with the PS model. The total water withdrawal predicted over the United States matches the observations very closely. Water requirements for the MI sector show the highest dispersion around the econometric fit.

5.2. Environmental Water Requirements

In the United States, water is regulated by national legislations such as the 1969 National Environmental Policy Act and the 1972 Clean Water Act. In addition, water resource management is decentralized by state and region, which has led to a variety of additional regional water policies [*Hirji and Davis*, 2009]. These policies usually protect water ecosystems through the regulation of water levels and flows.

To model these environmental requirements, we apply two constraints on surface water in the model. First, releases from surface storage are limited to a proportion of the storage capacity in order to respect an environmental minimum storage threshold. Minimum lake levels are usually determined as an elevation below which the water body should not fall, and they vary by district. We assume a minimum surface water storage of 10% of the surface water storage capacity. Second, the spill from each basin must meet a minimum EFR. The determination of the volume and timing of these flows should also be determined locally. According to L. Anantha and P. Dandekar (Towards restoring flows into the earth's arteries: A primer on environmental flows, 2012, http://www.internationalrivers.org/files/attached-files/eflows_primer_062012.pdf), more than 200 methodologies have been considered to asses global environmental flows. The first environmental flow protection rule considered a minimum flow of 10% of mean annual runoff [*WCD*, 2000]. More recently, *Smakhtin et al*. [2004] consider that flows that are exceeded 90% of the time (Q90 flows) are sufficient to maintain riparian zones in "fair" condition. In a comprehensive review of EFR definitions, *Acreman and Dunbar* [2004] note that "no method is necessarily better than another" and depend on the application. In this application, we set an EFR equivalent to 10% of mean monthly flow for each ASR.

Other environmental concerns relate to water temperature and water quality (often measured by the biochemical oxygen demand). However, we are currently not able to represent these issues.

6. Application: Projection Through 2050

Water uses and resources are modeled to 2050, considering both alternative emission scenarios and potential regional shifts in climate patterns. Starting in 2010, two emission scenarios are considered: (i) an unconstrained emissions (UCE) scenario assumes that no specific effort is made to abate GHG emissions, and (ii) a "level 1 stabilization" (L1S) scenario assumes that GHG emissions are restricted to limit the atmospheric concentration of CO_2 equivalent GHGs to 450 ppm [*Clarke et al*., 2007]. These scenarios serve as inputs into the IGSM 2D model using median parameter values of climate sensitivity, rate of ocean heat uptake, and aerosol forcing [e.g., *Forest et al*., 2008]. To provide meteorological variables at the relevant scale for WRS, we then downscale the results using the HFD approach. We use two representative shifts in the regional climate patterns, or "climate-change kernels"—as determined from climate model projections from the Coupled Model Intercomparison Project Phase 3 (CMIP3) [*Meehl et al*., 2007]—to explore a plausible range of relatively dry and wet trending conditions over the majority of U.S. ASRs. The Geophysical Fluid Dynamics Laboratory (GFDL) version 2.1 [*Delworth et al.*, 2006] and the NCAR Community Climate System Model (CCSM) version 3 [*Collins et al*., 2006] provide representative "dry" and "wet" projections, respectively. Hereafter, we refer to these climate model outcomes as U.S.-DRY and U.S.-WET.

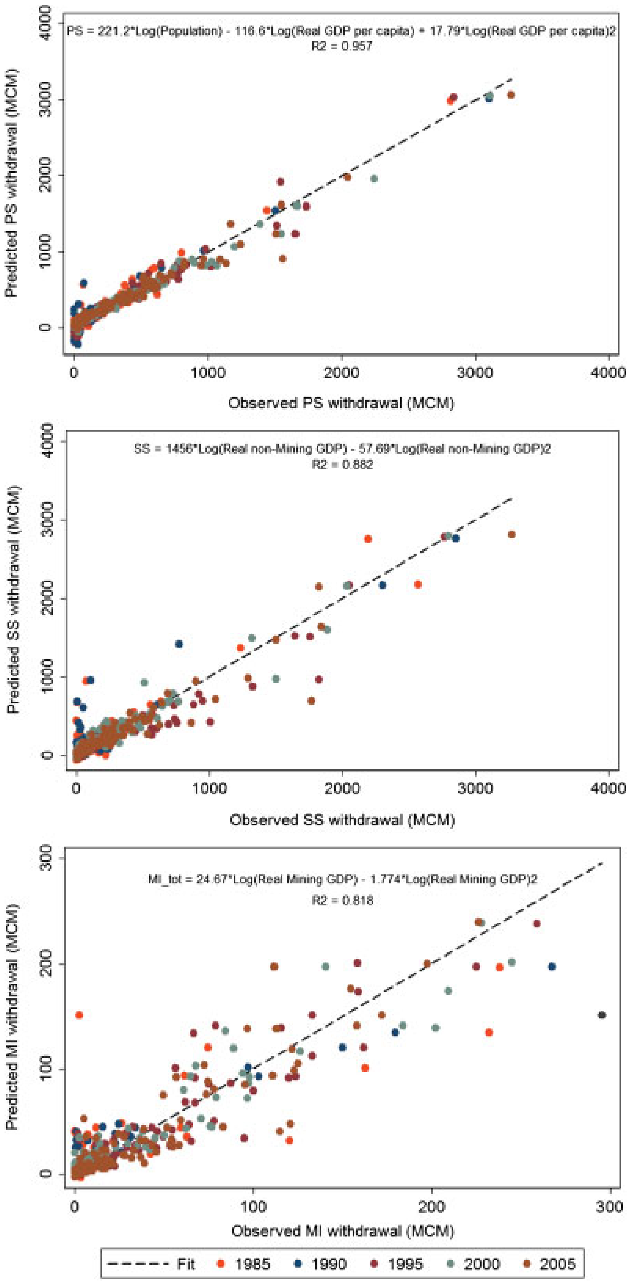

Figure 8. Comparison of predicted values of public supply (PS), self-supply (SS), and mining (MI) annual water withdrawals with observed withdrawal values at the ASR level.

The two climate change scenarios considered in this study are assumed to be representative of the patterns from the CMIP3 climate model projections of hydroclimate change through the 21st century [as described by *Schlosser et al*., 2012]. In this particular study, we determine the "wet" and "dry" characterizations from the CMIP3 climate models' projections of climate-moisture index change over the contiguous United States. Due to the spatially heterogeneous nature of the hydrologic cycle, for every basin within the United States, the U.S.-WET and U.S.-DRY cases would not necessarily be reflective of an "extreme" condition. Rather, on average a majority of basins would see "dry" or "wet" outcomes. Generally speaking, the U.S.-DRY pattern is characterized by substantially drier conditions (particularly in the summer) throughout most of the United States. The widespread relative decreases in precipitation will coincide with strong relative warming as global temperature increases. The U.S.-WET case replaces the drying conditions in many regions with relatively wetter conditions and less warming (relatively to their U.S.-DRY conditions). Results from the WRS-US model forced by these two climate-change kernels aim at providing insight into the impact of climate change on water-management risks under two differing climate responses.

To explore the relative influence of the economic effect of policy (L1S and UCE) versus the climatic effect, we also consider a scenario of no climate change. For this case, labeled “NoCC,” we assume that the climate is similar to the twentieth century. We use data from a run of the IGSM driven by historical GHG concentrations.

6.1. Water Requirements Projections

Water requirements for each sector are projected following the methodology described in section 5.1. To calculate requirements for the thermoelectric cooling, PS, SS, and MI sectors, WRS-US requires predictions of population, total GDP, and value added of the MI sector (where value added measures income generated by each sector). These inputs are predicted by the USREP model under the two emission scenarios described above. Population is projected to increase steadily over the period 2005–2050 with no difference between the UCE and L1S scenarios. Differences between scenarios are predicted for total GDP, with larger increases under the UCE scenario than under L1S, especially in Texas. Predictions for value added in the MI sector differ, especially under the L1S scenario, where it is expected to decrease by 2050. Reduced MI activities (especially coal MI) under the constrained GHG emissions scenario explain this trend. Irrigation water requirements are projected using the CliCrop model. In this study, we assume that there will be no change in the location and amount of irrigated cropland. This condition can be relaxed in subsequent model development as production, area under production, and the location of production may change in the future, with or without climate change. Our goal is to identify currently irrigated areas that may be subject to water limits.

As shown in Figure 9, U.S. water requirements are projected to increase for all sectors under the UCE scenario. Under the L1S scenario, however, water requirements decrease overall for thermal cooling and MI, which reflects a change in energy production due to a slower pace of economic growth and a transition to cleaner energy. Beyond 2030, significant shares of electricity are generated from nonthermal renewables, and as a result, electricity from coal—the largest source of thermal power generation—is gradually reduced. Hence, the water required for cooling of thermal power plants greatly decreases (in our case, requirements for this sector are represented by water consumption). Water requirements for irrigation are driven indirectly through the effect of the different policy scenarios on climate. Figure 9 shows some increases in irrigation water requirements over time, especially under the UCE scenario. Under the scenario of no climate change, irrigation requirements are expected to decrease. Water requirements for self-service are expected to grow steadily. For PS, however, we observe a nonlinear trend reflecting the fact that the effect of a higher requirement is offset by greater water use efficiency as GDP per capita increases. In total, water requirements are projected to increase with the largest increases in water requirements being projected under the UCE scenario.

As shown in Figure 10, the share of TWRs for each sector (averaged over the projection period) reflects the evolution of water requirements for the different scenarios and climate patterns. The pie chart shows that the share of irrigation requirements is larger under the U.S.-DRY climate pattern. Thermoelectric cooling is lower under the L1S scenario than under the UCE scenario.

Water requirements at the ASR level are provided in Figures 11 and 12. In these figures, we first present water requirements in quantitative terms for the base period (2005–2009). We next show for the projection period (2041–2050) the changes relative to the base period (in %) under the two scenarios and three climate patterns. Figure 11 shows that the largest water requirements in the base period originate from the Upper/Central Snake (ASR 1703) and San Joaquin-Tulare (ASR 1803) basins. The graph shows no difference between requirements across the three scenarios in the base period. Total requirements are indeed very similar by the end of 2009.

In the period 2041–2050 TWRs are projected to increase by more than 300% in the Little Colorado (ASR 1501), Lower Rio Grande (ASR 1305), and Richelieu (ASR 106) basins. Increases are generally slightly lower

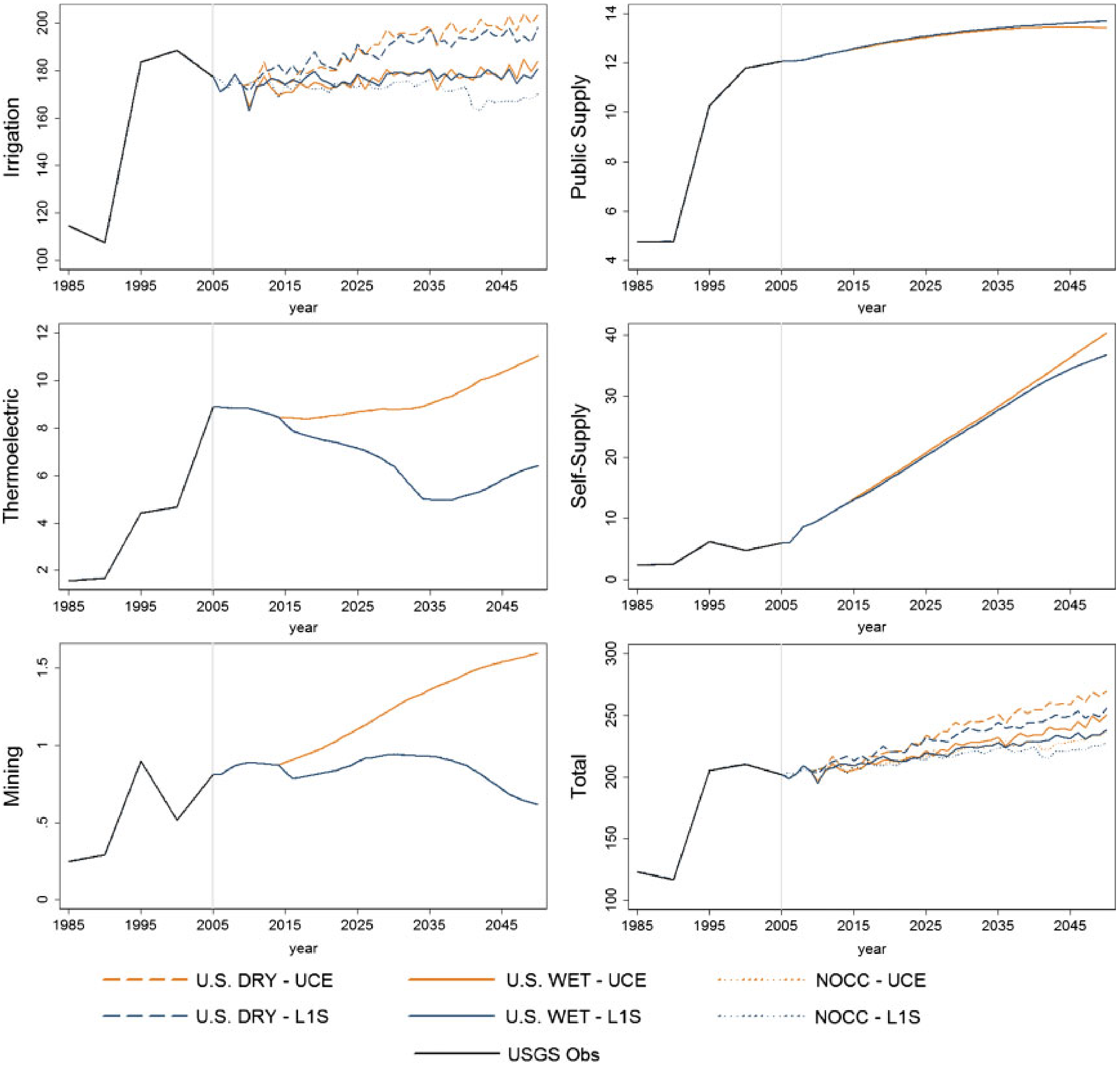

Figure 9. U.S. water requirements (in 1000 MCM) from 1985 to 2050.

under the L1S scenario than under the UCE scenario. Small regional divergences across scenarios are projected in the Indiana/West Virginia region with decreases in water requirements projected under the L1S scenario. Similar to what is observed in Figure 9, TWR increases are projected to be the largest under the U.S.-DRY climate change pattern.

We also provide a geographical representation for irrigation, which is the largest user in the United States. As shown in Figure 12, the Upper/Central Snake (ASR 1703) and San Joaquin-Tulare (ASR 1803) basins have the largest irrigation requirements. Very little water is used for irrigation in the East due to high precipitation and relatively low evaporative demand. Water requirements for irrigation purposes are expected to increase in the West under both climate change patterns. Depending on the climate pattern

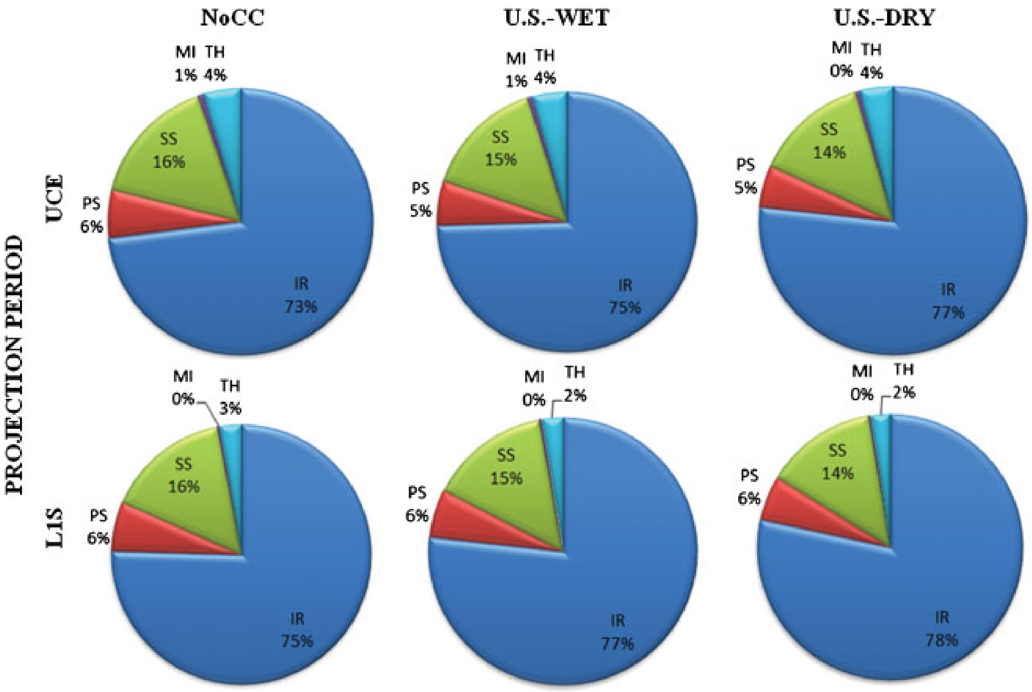

Figure 10. Average total water requirements for the projection period (2041–2050). Notes: Pie charts constructed using the sum of total water requirements over all ASRs. TH, thermoelectric cooling; IR, irrigation; SS, self-supply; PS, public supply; MI, mining.

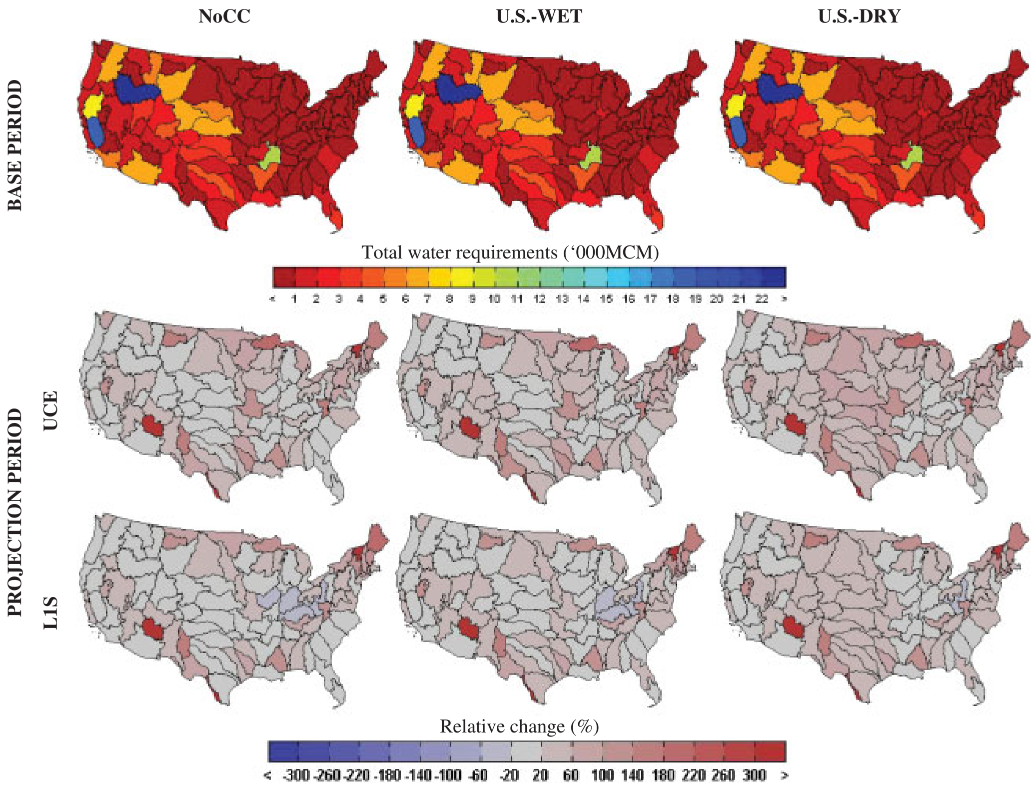

Figure 11. Total water requirement (in '000 MCM) for the base period (2005–2009) and relative change (in %) for the projection period (2041–2050). Note: For presentation purposes, estimates for the base period displayed in the first part of the graph are averaged over the L1S and UCE scenarios. However, relative change figures are calculated based on the scenario-specific estimates.

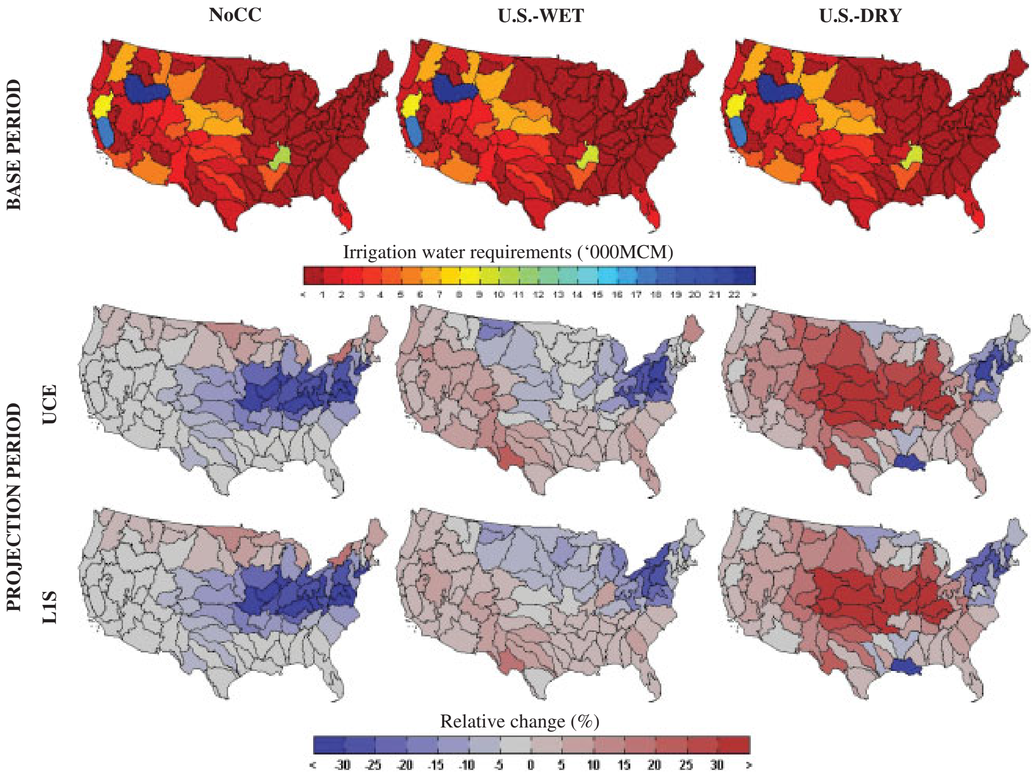

Figure 12. Irrigation water requirement (in '000 MCM) for the base period (2005–2009) and relative change (in %) for the projection period (2041–2050). Note: See Note of Figure 11.

considered, however, irrigation water requirements differ in the North-Central part of the United States, with decreases projected under the U.S.-WET climate pattern and increases under the U.S.-DRY climate pattern. The NoCC climate pattern projects water requirement increases along the Canadian border. All climate patterns show a decrease in irrigation water requirements in the Northeast.

6.2. Water Resource Projections

As described in section 4, runoff is projected using bias-corrected estimates from CLM under the two policy scenarios and three climate patterns. Total basin natural runoff (not including inflows from upstream basins) is projected to slightly increase toward the mid-century in all cases but to be generally lower under the L1S than under the UCE scenario. For each policy, the projected runoff is very similar for the two climate change patterns (wet vs. dry). Runoff under the NoCC climate pattern has slightly different interannual variations.

A geographical representation of natural runoff, provided in Figure 13, shows absolute values for the base period (2005–2009) and percentage changes for the projection period (2041–2050). The figure shows large spatial discrepancies at the regional level. In the Southwest, where runoff is relatively small in the base period, runoff is projected to slightly decrease under all climate patterns. In the U.S.-WET case, however, some increases are projected in some of these Southwest basins as well as in most other basins of the country. In the U.S.-DRY case, large decreases in runoff are predicted over most of the West.

6.3. Water Stress Projections

Using the sectoral water requirements and water resource estimates presented above, we evaluate water stress using two indicators: the water supply-requirement ratio (SRR) and the water stress index (WSI).

6.3.1. Supply-Requirement Ratio

SRR is calculated monthly as the ratio of TWS over total water required for each sector. This water stress indicator is used to represent physical constraints on anthropogenic water use. Projections of SRR from

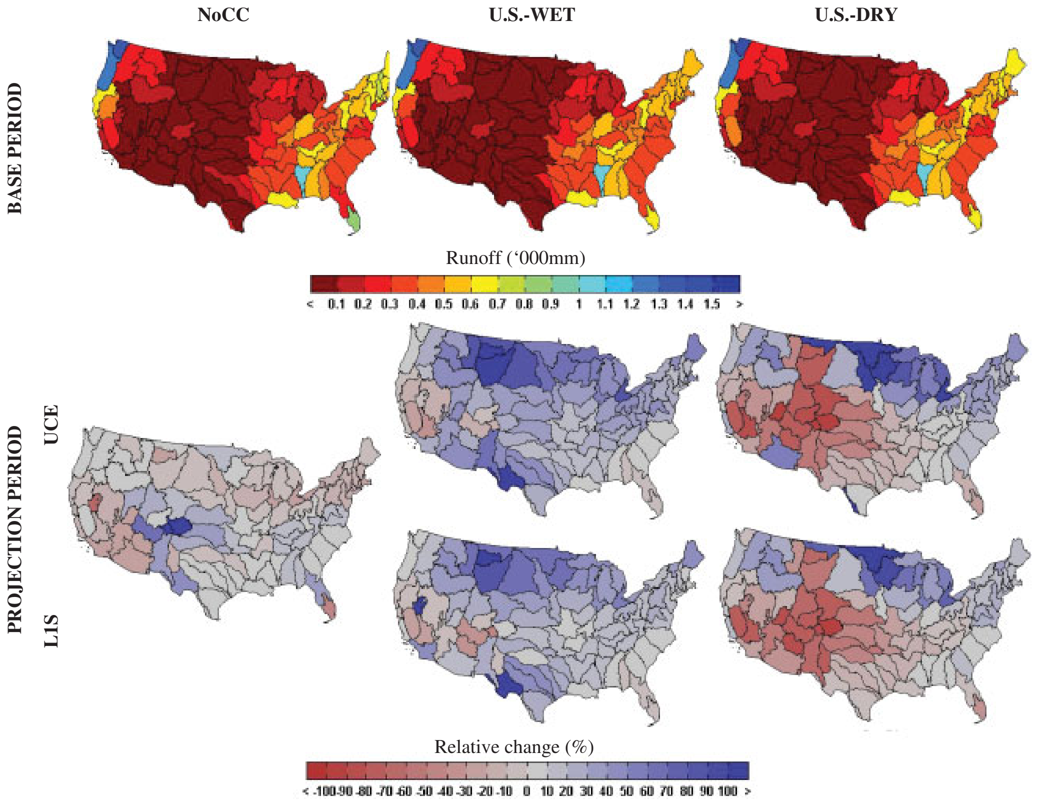

Figure 13. Average annual natural runoff (in '000 mm) for the base period (2005–2009) and relative change (in %) for the projection period (2041–2050). Note: See Note of Figure 11.

2005 to 2050 are presented in Figure 14 as an annual average for all ASRs weighted by their sectoral water requirements. The figure shows that water stress is generally increasing (as the average SRR decreases) under all climate patterns, and especially under the U.S.-DRY climate pattern. The water stress is slightly smaller under stringent GHG controls.

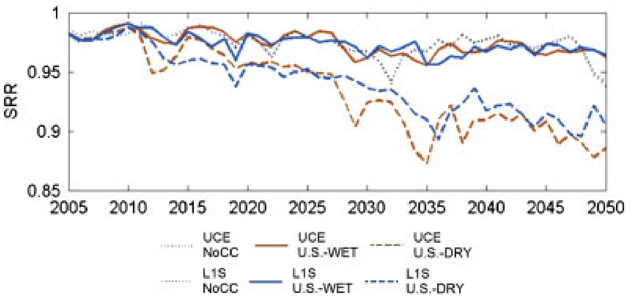

Figure 14. Weighted average over all ASR of the mean annual depletion-requirements ratio (SRR) from 2005 to 2050.

The representation of SRR by ASR provided in Figure 15 indicates that most water requirements are met in the base period. Water stress is observed in only four basins: Gila (ASR 1503), Sevier Lake (ASR 1602), Rio Grande Headwaters (ASR 1301), and Upper Arkansas (ASR 1102). The SRR is projected to decrease (or remain constant) in all cases, except in the Rio Grande Headwaters (ASR 1301) basin under the NoCC climate pattern. The largest decreases in SRR (i.e., increases in water scarcity) are projected in the Little Colorado (ASR 1501) basin where water requirements are mainly self-supplied. In the U.S.-DRY case, the decrease in SRR spreads further to the North and shows larger reductions overall.

To isolate the effect of GHG emission mitigation policies on water stress, we calculate the difference between the average annual SRRs (SRR_{L1S} minus SRR_{UCE}) in 2050 for each climate pattern. The blue-colored basins presented in Figure 16 correspond to basins where the SRR under the L1S scenario is higher than under the UCE scenario. For most basins affected by water stress, the climate mitigation

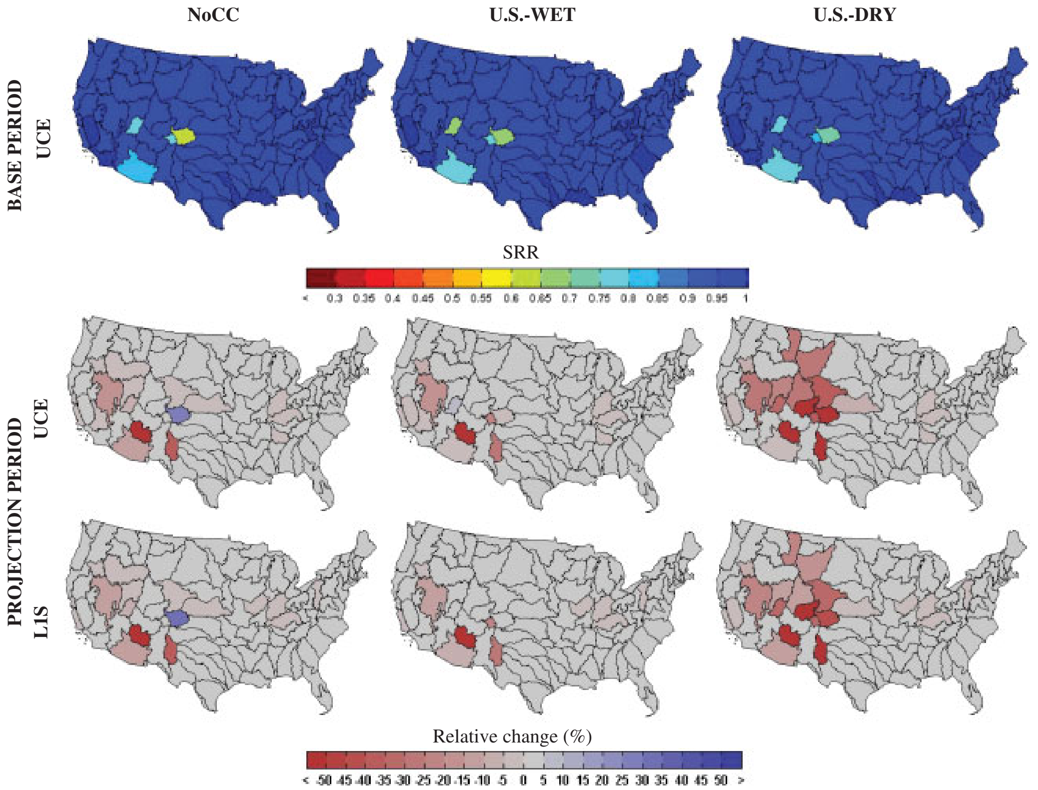

Figure 15. Average supply-requirements ratio (SRR) for the base period (2005–2009) and the projection period (2041–2050). Note: See Note of Figure 11.

policy will be effective at reducing water stress under both climate patterns, but the beneficial effect of a policy is small. However, for the Gila (ASR 1503), Little Colorado (ASR 1501), and Upper Pecos (ASR 1304) basins, climate policies worsen water stress in both the U.S.-Dry and U.S.-WET cases. This counterintuitive result is explained by a smaller runoff in the L1S scenario than under the UCE scenario in both climate patterns. This result is explained by a lower runoff rates in the L1S scenario than under the UCE scenario in both climate patterns, and indicates that the acceleration of that basin's hydroclimate toward a wetter cycle has been buffered under the L1S scenario. This result simply underscores that unconstrained climate change, in some cases, can lead to greater water supply resulting from stronger precipitation trends. The presence of this result for some basins in both the U.S.-WET and the U.S.-DRY cases indicates two conditions at play: (i) the characterization of U.S.-WET and U.S.-DRY was made in the context of averaged conditions over the United States and may not be reflective of every basin's result, and (ii) the zonal-scale trends of the IGSM's water-cycle response dominate over the U.S.-WET and U.S.-DRY patterns we have applied over the United States. For the Sevier Lake (ASR 1602) and the Rio Grande Headwaters (ASR 1301) basins, however, the impact of a climate policy on water stress depends on the climate pattern used. In the NoCC case, where policy scenarios affect water requirements but not water resources, the graph shows a unanimous beneficial effect of a reduction in water requirements driven by the L1S scenario.

The average number of ASRs affected by monthly water stress (i.e., ASRs where monthly SRR < 1) rises from around 5 (with on average 6 months of water stress per year) in the base period to around 7–15 (with on average 7 months of water stress per year) in the projection period. To focus on the effect of water stress within the year, we provide in Figure 17 a series of box plots of monthly SRRs for the basins significantly affected by water stress in the prediction period. The figure shows that the spread of the SRRs (i.e., water stress variability) is larger under the U.S.-DRY case for all basins except the Upper Pecos (ASR 1304) basin. For this basin, the plot shows that the water stress is consistently more important under the U.S.-DRY case than under the U.S.-WET case. The boxes for the L1S scenario are generally smaller and

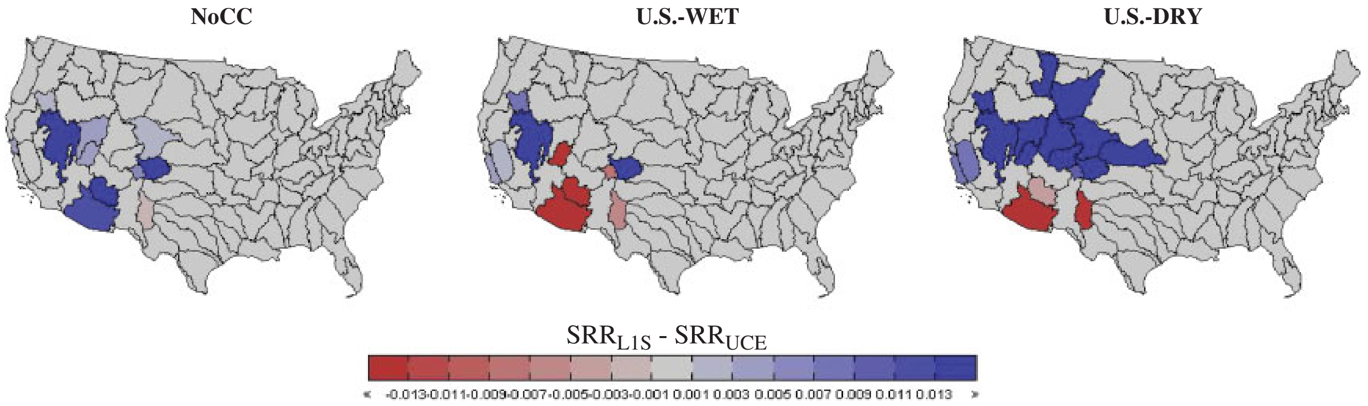

Figure 16. Difference between the average depletion-requirements ratio (SRR) under the L1S and UCE scenarios for each climate pattern in the projection period (2041–2050).

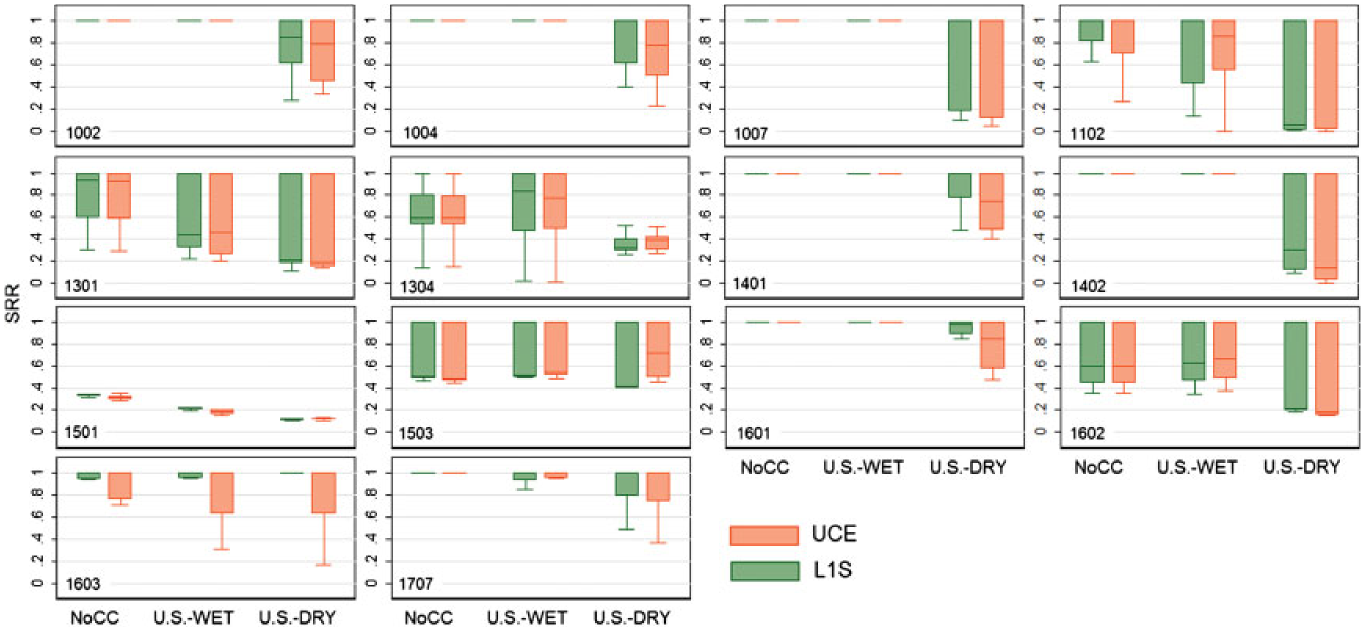

Figure 17. Box plot of the monthly deficit SRRs over all ASRs for the projection period (2041–2050). Notes: Each box represents, for each climate pattern and scenario, the range of monthly SRRs between the 25th and 75th percentile. The line inside each box represents the median. The whiskers represent adjacent values (=1.5*(upper quartile − lower quartile)).

closer to one than those for the UCE scenario, which shows that the climate policy is effective at reducing water stress severity and variability.

6.3.2. Water Stress Index

Water scarcity can also be estimated using the WSI developed by *Smakhtin et al*. [2005]. This index is used to estimate the pressure that human water use exerts on renewable surface freshwater. In this regard, this index is closer to a measure of water reliability. This index is calculated as a ratio of mean annual withdrawals for all sectors over mean annual runoff minus environmental requirements. Due to the spatial disaggregation of this study, we account for inflow from upstream basins to estimate total annual runoff. The environmental water requirements are implicitly accounted in the inflows, which are constrained to minimum environmental flows. The severity of water stress is classified as "heavily exploited" when $0.6 \leq WSI \leq 1$ and "overexploited" when $WSI > 1$. In the literature, similar WSIs are computed and generally consider a threshold of 0.4 to indicate sever water limitation [*Vörösmarty et al*., 2000; *Wada et al*., 2011].

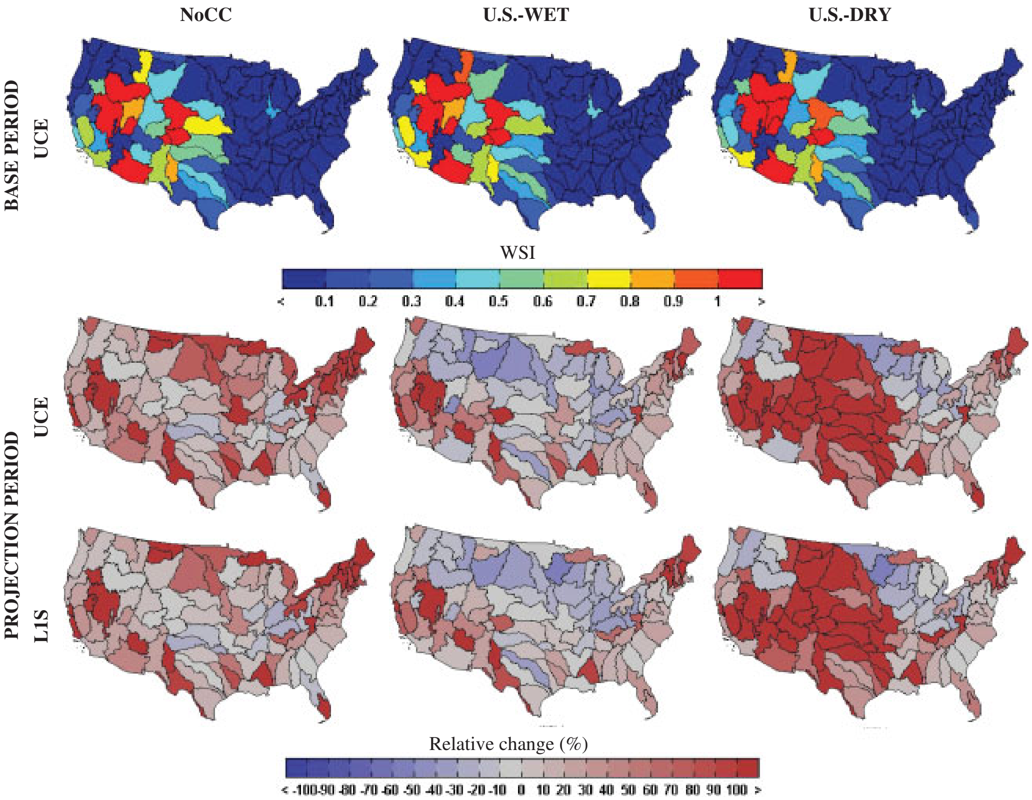

Figure 18. Average water stress index (WSI) for the base period (2005–2009) and the projection period (2041–2050). Note: See Note of Figure 11.

Figure 18 shows that in the base period, surface freshwater is generally heavily exploited in the Western United States and is overexploited in seven basins. Considering a threshold of 0.4 commonly used in the literature, 30 basins are affected by water scarcity. We find historical water stress geographical patterns over the United States similar to *Wada et al*. [2011] and *Vörösmarty et al*. [2000] (with the exception of Florida).

In the prediction period, WSI is generally increasing in the Central and Western United States under the U.S.-DRY climate pattern and decreasing in the Northeast. In the U.S.-WET case, the WSI is projected to decrease generally, except on the coasts. The WSI is projected to increase more uniformly under the NoCC climate pattern.

This index shows that although most basins will not be affected by unmet water requirements as shown by the SRR ratio, a large number of basins in the West will experience increasing pressure on water resources. This will be especially the case under the U.S.-DRY climate pattern, where overexploited basins are more prone to water shortages.

7. Conclusions

This article presents IGSM-WRS-US, a model of U.S. water resource systems. It is unique in its consistent treatment of the complex interactions of climatic, biological, physical, and economic elements. By identifying areas of potential stress in the absence of specific adaptation responses, the modeling system can help direct attention to water planning, while illustrating how avoiding climate change through mitigation policy could change likely outcomes. For this exercise, we downscale the IGSM-WRS model to the 99 ASR level for the continental United States. We also produce new estimates of water resources and water requirements for five sectors. The extended framework is used to allocate these water resources among the different sectors to minimize water stress, which measures the degree to which water requirements cannot be met. As an illustration, the model is used to project water stress through 2050 under two climate policies.

We estimate that, with or without climate change, average annual water stress is predicted to increase in the Southwest. This increase is mostly attributable to increases in water requirements. The study reveals that the choice of climate pattern considered for projections greatly influences the outcome of the model. On average, larger water stresses are projected under the U.S.-DRY climate pattern than under the U.S.-WET pattern. The impact of a constrained GHG emission policy (L1S scenario) will generally lessen the increase of mean annual water stress, especially in the U.S.-DRY case. However, water stress will be lower under an unconstrained emission policy (UCE scenario) than under a climate policy (L1S scenario) in some basins, i.e., 38% of the water-stressed basins in the U.S.-WET case and 14% in the U.S.-DRY case. A more detailed analysis of water stress at the monthly level reveals that the extent and intensity of monthly water stress is less under the L1S scenario than under the UCE scenario in most basins. The WSI measure, representing the reliability of water resources, shows that, although most basins will not be affected by unmet water requirements in the future (as shown by the SRR measure), a large number of basins in the West will see increased pressure on water resources, especially under the U.S.-DRY climate pattern.

In developing an integrated model of changes in water supply, climate change, and water use, some simplifications are necessary. The most important of these simulations is the assumption that irrigated areas remain unchanged in the future. In principle, we may see adjustments in areas affected by more frequent water shortages where maintenance of irrigation infrastructures may become uneconomic. On the other hand, irrigation may expand in areas with ample water supplies (e.g., groundwater) but subject to more droughts. Alternatively, losses of food production in some regions could be addressed via a spatial shift of cropland elsewhere in the United States or abroad. In this regard, international trade would have important implications on food availability given the role it currently plays in the U.S. economy. The expansion of biofuel production would also need to be considered, as it may become an important user of irrigation. We also assume that current rates of groundwater withdrawal are sustainable. If they are not, either because withdrawal exceeds recharge or climate reduces recharge, then irrigation dependent on groundwater may cease and possibly increase pressure on surface water flows. Another simplification, inherent to this modeling framework, is the lack of adaptation strategy. In this framework, no measure is taken to avoid water stress. For SS, PS, and MI, the econometric estimates take into account energy efficiency measures as represented by the nonlinear relationship between GDP and water withdrawal. However, even these conservation measures are prescribed and do not respond to water shortage relevant to the basin considered. These simplifications represent opportunities for further research.

Notwithstanding these simplifications, IGSM-WRS-US is an important tool for climate change impact assessments, policy evaluations, and advances in earth system modeling. It has the substantial advantages over other water models to be part of a larger framework, which allows integrated assessments of water resources and uses in the context of global climate and economic changes. The endogenous estimation of climate change also allows the consideration of climate change uncertainty in assessments of water resources and water stress. The framework will also support the development of feedbacks to assess the implications of water stress on the economy.

This model framework also represents a significant improvement compared to global water models. By focusing on the United States, we take advantage of water-use data detailed at the county level to estimate and project water requirements. The spatial disaggregation allows the detection of local water issues, such as the water deficit in the West. Future applications could focus on the impact of such water stress on economic activities, such as food production or naval transportation. It would also allow investigating uncertainty in future climate impacts deriving from uncertainty in climate response [*Monier and Gao*, 2014], multiple levels of mitigation policy, and uncertainty in the economic drivers of water use. This downscaled model also lays the foundations for further investigation of water allocation strategies, which are not possible at wide river basin delineations.

Appendix A: Irrigation Water Requirements Estimation

A1. Water Consumption at the Root Level

CliCrop is a biophysical model developed for use in integrated assessment frameworks [*Fant et al.*, 2012]. It is global, fast, and requires a minimal set of inputs. It is based on the Food and Agriculture Organization (FAO)'s CropWat model [*Allen et al.*, 1998] for crop phenology and irrigation requirements and

Table A1. Correspondence Between Crops Modeled by CliCrop and Actual Crops

CliCrop Crop Type	Actual Crop Type
Forage/Alfalfa	Forage/alfalfa
	Pastureland
	Orchards
Cotton	Cotton
Grains or barley	Grains or barley
Groundnuts	Groundnuts
Maize	Maize (grain and silage)
	Berries
Potatoes	Vegetables
	Other
Pulses	Pulses
Rice	Rice
Sorghum	Sorghum
Soybeans	Soybeans
Sugar beets	Sugar beets
Sugar cane	Sugar cane
Wheat (average spring/winter wheat)	Wheat, spring and winter

on the Soil and Water Assessment Tool (SWAT) [*Neitsch et al*., 2005] for soil hydrology. CliCrop runs on a daily time scale, has a 2° × 2.5° grid resolution for the globe, and estimates crop water requirements (in mm/crop/month) to obtain maximum yields under given weather conditions for 13 of the most commonly grown crops. The irrigation requirement at the roots of the plant is defined as the difference between the evapotranspiration requirement [as defined by *Allen et al*., 1998] and the actual evapotranspiration as computed by CliCrop. For water requirements of crops not modeled by CliCrop, we use crops with similar irrigation needs as proxies (the generic crops used in CliCrop as proxies for crop water requirements in the United States are presented in Table A1). For each crop, the planting date has been specified according to data from the Centre for Sustainability and the Global Environment (SAGE), University of Wisconsin [*Sacks et al*., 2010].

Annual water consumption $\mathrm{CON_{IR}}$ is estimated at the county level for each crop using monthly crop water consumption estimated by CliCrop and irrigated area, $\mathrm{ARE_{IR}}$, sourced from FRIS:

$$\mathrm{CON_{IR}} = \sum_{\text{month}} \sum_{\text{crops}} \mathrm{CON_{IR}}\,(\text{crop, month}) \times \mathrm{ARE_{IR}}\,(\text{crop}) \tag{A1}$$

As the delineations of states and ASRs do not match perfectly, we estimate water consumption data at the county level. FRIS [*USDA*, 2003] provides irrigated area detailed by crop. However, these data are provided at the state level only. *USGS* [2011] provides irrigated area every 5 years at the county level but does not detail irrigated area by crop. To obtain irrigated area for each crop at the county level, we use county-level total irrigated area estimated by USGS for the year 2005 and state-level crop-specific irrigated areas estimated by FRIS for the year 2003. We allocate state-level irrigated areas from FRIS using the ratio of total irrigated area at the county level within each state from USGS following the formula:

$$\mathrm{ARE_{IR}}\,(\text{crop, county}) = \mathrm{ARE\_FRIS_{IR}}\,(\text{crop, state}) \cdot \frac{\mathrm{ARE\_USGS_{IR}}\,(\text{county})}{\sum_{\text{state}} \mathrm{ARE\_USGS_{IR}}\,(\text{county})} \tag{A2}$$

To obtain water consumption at the ASR level, we aggregate county-level consumptions for all counties lying within the ASR. For counties overlapping several ASRs, the matching is based on the share of the county area lying within the ASR.

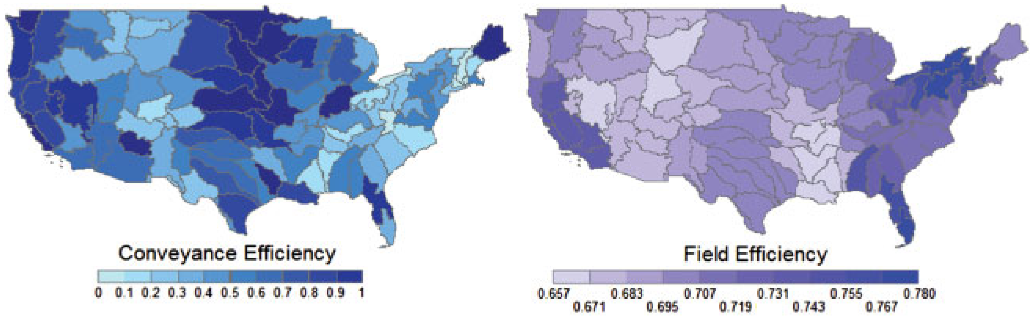

Figure A1. Conveyance and field efficiencies.

A2. Crop-Specific Management Factor

The CliCrop estimate of water requirements corresponds to the level of water necessary to eliminate water stress in the crop and, assuming that other factors are not limiting, achieve maximum yield. In practice, however, farmers may not aim to maximize yields. For instance, lower-valued crops such as forage may not justify irrigation expenses associated with maximum yields. For other crops, water is used for irrigation-related activities (e.g., field flooding to harvest cranberries). Alternatively, CliCrop's representation may be imperfect as it uses a proxy for some crops. To account for varying irrigation practices and modeling errors, we estimate for each crop an average management factor over the United States enabling us to adjust the water consumption estimated by CliCrop to the water actually consumed. Actual water consumption data (i.e., water used to obtain actual yields) are obtained using FRIS survey data on water delivery at the field, to which we apply a FEF (shown in Figure A1 and presented in the next subsection).

To estimate the U.S.-wide crop-specific management factors, *M*, we employ a univariate regression for each crop at the county level:

$$\mathrm{CON}_{\mathrm{IR,FRIS}}\,(\mathrm{crop},\mathrm{county}) = M\,(\mathrm{crop}) \times \mathrm{CON}_{\mathrm{IR,CLICROP}}\,(\mathrm{crop},\mathrm{county}) + \epsilon, \qquad \text{(A3)}$$

where $\mathrm{CON}_{\mathrm{IR,FRIS}}$ is the irrigation water consumption at the root calculated from FRIS data for 2003 (see paragraph on water consumption at the field for details regarding the calculation of water consumption at the root using the system efficiency). We consider $\mathrm{CON}_{\mathrm{IR,CLICROP}}$ as an annual average of CliCrop water consumption over the period 1998–2003, as survey responses from farmers might not be strictly representative of 2003 (most water withdrawals are not metered) but rather a short-term average of water uses. The results of these regressions are reported in Table A2.

Management factors lower than 1.0 indicate that farmers irrigate less than is necessary to obtain maximal yields. As expected, small *M* factors are obtained for low-value crops such as pasture. For other crops, management factors higher than 1.0 capture irrigation-related uses (e.g., berries) or imperfect crop representation by CliCrop. For wheat, the low coefficient can be explained by the fact that this crop is irrigated differently in winter and summer. The allocation of irrigation across the year is not known, so we assume that CliCrop takes an average of irrigation need between the two seasons. For vegetables, the high management factor is due to the fact that vegetables are proxied by potatoes in CliCrop. We estimate future water consumption for each crop by multiplying CliCrop crop water consumption by the corresponding management factor.

A3. Region-Specific Irrigation-Related Uses

A portion of irrigation water is also used for preirrigation, frost protection, chemical application, weed control, field preparation, crop cooling, harvesting, dust suppression, and leaching of salts from the root zone [*Kenny*, 2004]. Most of these irrigation-related uses are region specific (e.g., soil leaching in dry regions and frost protection in cool regions). However, CliCrop is not designed to capture these uses. FRIS data, on the other hand, include all irrigation-related water uses but do not distinguish the amount of water used specifically for irrigation from the water used for other purposes. To estimate these other irrigation uses, we calculate irrigation consumption for other purposes at the ASR level, $\mathrm{CON}_{\mathrm{IRO}}$, as the difference between

Table A2. Univariate Regression Results for the Estimation of the Management Factors

Crops	M	Standard Errors	Observations	R^2
Forage	0.695***	0.00704	1570	0.861
Pasture	0.579***	0.00692	2564	0.732
Cotton	0.695***	0.0237	284	0.753
Grains	0.902***	0.0369	154	0.796
Groundnuts	0.466***	0.00818	134	0.961
Maize	1.304***	0.0152	1036	0.876
Pulses	1.390***	0.0492	151	0.842
Rice	0.664***	0.0209	108	0.904
Sorghum	0.570***	0.0114	200	0.926
Soybeans	1.311***	0.0216	569	0.866
Sugarbeets	1.335***	0.0724	60	0.852
Wheat	0.562***	0.0125	458	0.815
Vegetables	1.669***	0.0249	1210	0.788
Potatoes	1.837***	0.0333	3082	0.497
Berries	1.334***	0.0425	239	0.805
Orchard	1.837***	0.0657	668	0.540
Other	0.824***	0.00644	925	0.947

***$p < 0.01$.

FRIS and CliCrop water consumption at the county level:

$$\mathrm{CON}_{\mathrm{IRO}} = \sum_{\mathrm{cnt}} \mathrm{CON}_{\mathrm{IR,FRIS}}\left(\mathrm{crop},\mathrm{county}\right) - \sum_{\mathrm{cnt}} M\left(\mathrm{crop}\right) \times \mathrm{CON}_{\mathrm{IR,CLICROP}}\left(\mathrm{crop},\mathrm{county}\right) \tag{A4}$$

$\mathrm{CON}_{\mathrm{IRO}}$ is assumed to remain constant at the 2005 level (this assumption merits further study as water resource changes might influence irrigation-related water consumption). To obtain monthly calibration, we spread the calibration constant across the year proportionally to irrigation water consumption estimated by CliCrop.

A4. Field Efficiency

As explained above, some water losses occur at the irrigation apparatus level: furrows are, for example, less efficient than sprinklers or drip irrigation. These losses are represented by irrigation FEFs also called application efficiencies. To account for these water losses, we calculate the average efficiency for each technique [*Kenny*, 2004] weighted by the area over which such system is in use in each state. We assume that the FEF is the same for each county within a state. FEFs at the ASR level are represented in Figure A1.

A5. Water Delivery at the Field

Water delivery at the field represents the amount of water delivered to the farm for irrigation purposes. It is estimated by applying the FEFs discussed above, to water consumption at the root for crop and other irrigation-related purposes:

$$\mathrm{DEL}_{\mathrm{IR}} = \frac{\sum_{\mathrm{cnt,crop}} \mathrm{CON}_{\mathrm{IRO}}\left(\mathrm{crop},\mathrm{county}\right) + M\left(\mathrm{crop}\right) \times \mathrm{CON}_{\mathrm{IR,CLICROP}}\left(\mathrm{crop},\mathrm{county}\right)}{\mathrm{FEF}} \tag{A5}$$

We then aggregate all the county-level water consumption at the ASR level.

A6. Conveyance Efficiency

A major portion of agricultural water loss occurs in transport between the source and the field. This loss is usually represented by a CEF, which is calculated as the ratio of water reaching the field over the water withdrawn at the source [*Howell*, 2003]. We determine CEF for each ASR using county irrigation data of withdrawal sourced from *USGS* [2011] for 2005 and delivery at the field data from FRIS for 2003 (water delivery data and water withdrawal data are not available for the same year). CEFs calculated for each ASR are shown in Figure A1.

A7. Water Withdrawal at the Stream

Irrigation water withdrawal at the stream is the total amount of water diverted from the natural hydrologic system for irrigation purposes. To calculate water withdrawal, WTH, we apply the CEF to the field delivery, DEL:

$$\mathrm{WTH}_{\mathrm{IR}} = \mathrm{DEL}_{\mathrm{IR}}/\mathrm{CEF} \tag{A6}$$

Appendix B: Public Supply, Self-Supply, and Mining Estimation

Water withdrawals for the PS, SS, and MI sectors are estimated using panel data econometric techniques. We use county-level data on water withdrawals from *USGS* [2011]. USGS provides water withdrawal data every 5 years from 1985 until 2005. Water withdrawals are given in millions of gallons per day (Mgal/d). *USGS* [2011] also provides population estimates by county. These county-level estimates are aggregated at the ASR level. Sectoral- and state-level GDP is sourced from the Bureau of Economic Analysis [*BEA*, 2011]. To obtain GDP at the ASR level, we assign the GDP for the state where the ASR lies in. When the ASR is spread across different states, we apply the weighted average based on the area of the ASR contained within the state.

County-level water withdrawal data are aggregated at the ASR level. However, there are no water-use data available for two river basins (ASR 1602 and 1807). As indicated in Figure 2, these basins are closed and are sparsely populated. We assume that there is no water requirement in these regions.

Water withdrawal for PS is specified as:

$$\mathrm{PS} = f\left(\log(\mathrm{pop}), \log(\mathrm{GDP}/\mathrm{pop}), \log(\mathrm{GDP}/\mathrm{pop})^2\right), \tag{B1}$$

where PS is a function of total population (pop), real gross domestic product per capita (GDP/pop), and a square term of GDP/pop to represent nonlinear effects. The regression results provided in Table B1 indicate that as population increase, PS water requirement increases, and that as GDP per capita grows, households become more environmentally conscious and reduce water use per capita. The square term, however, represents a concave relationship and indicates that the marginal decrease in water requirement due to an increase in GDP per capita diminishes as the economy develops. This structural change represents the temporal continuation of the income growth effect on domestic water use reported by *Alcamo et al.* [2003], where household water consumption increases rapidly as larger incomes enable access to plumbing and appliances, then stabilizes once these needs are satisfied.

SS water requirement is specified as a function of GDP for all sectors except MI and its square term:

$$\mathrm{SS} = f\left(\log\left(\mathrm{GDP}_{\mathrm{noMI}}\right), \log\left(\mathrm{GDP}_{\mathrm{noMI}}\right)^2\right) \tag{B2}$$

The estimated relationship, also presented in Table B1, shows that as GDP grows, water requirement increases, but the marginal increase becomes smaller as the agents become more efficient in their water use and shift toward less industrial, i.e., water intensive, activities.

Water withdrawals for MI purposes are estimated as a function of MI GDP and its square term:

$$\mathrm{MI} = f\left(\log\left(\mathrm{GDP}_{\mathrm{MI}}\right), \log\left(\mathrm{GDP}_{\mathrm{MI}}\right)^2\right) \tag{B3}$$

GDP has a nonlinear effect on MI water withdrawal similar to that estimated for SS.

We have not modeled explicitly the effect that environmental regulation would have on water conservation. However, the implementation of regulation can be indirectly taken into account by the effect of GDP as countries' preference for cleaner environment increase with income [*Lucas et al*., 1992].

Table B1. Water Withdrawals Regression Results

Variables	PS	SS	MI
Log(Population)	221.2*** (5.103)		
Log(Real GDP per capita)	−116.6*** (6.755)		
Log(Real GDP per capita)^2	17.79*** (0.463)		
Log(Real nonmining GDP)		1456*** (136.1)	
Log(Real nonmining GDP)^2		−57.69*** (5.721)	
Log(Real mining GDP)			24.67** (10.35)
Log(Real mining GDP)^2			−1.774* (0.913)
Observations	422	422	370
R^2	0.957	0.882	0.818
Number of groups	99	99	98

Notes: Dependent variable is annual water withdrawal in Mgal/d for each sector. Standard errors in parentheses. Significance levels: ***$p < 0.01$; **$p < 0.05$; *$p < 0.1$.

Water withdrawals for these sectors are estimated using a panel estimator providing Driscoll-Kraay standard errors, which are robust to very wide forms of temporal and cross-sectional correlation. River basin fixed effects are included to account for unobserved characteristics that vary across basins but not over time.

Due to data limitations, we make several assumptions in order to comply with the model definition (see section 3), which treats the water requirements for these sectors (SWR) not as withdrawal but as consumption. First, consumptive-use data, which represent the amount of water not returned to the source for immediate reuse, are available only until 1995. To calculate water consumption for other years, we assume that the proportion of water consumption in water withdrawal remains the same as in 1995. Second, water withdrawals for the PS, SS, and MI sectors are estimated only annually. To obtain monthly water values, we assume that withdrawals are spread evenly across the year (this assumption can be modified in future development of the model). Third, the data set does not provide details regarding water demanded that was not met. This might be the case for some sectors, such as PS, for example, when a city applies water restrictions during dry periods. We assume that estimated water requirements were always met by water supplied.

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