Technological Forecasting & Social Change 81 (2014) 205–226

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

Long-term global water projections using six socioeconomic scenarios in an integrated assessment modeling framework

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ARTICLE INFO

Article history:
Received 31 January 2013
Received in revised form 16 May 2013
Accepted 18 May 2013
Available online 28 June 2013

Keywords:
Integrated assessment
GCAM
Socioeconomic scenarios
Water scarcity
Water withdrawals
Water consumption

ABSTRACT

In this paper, we assess future water demands for the agricultural (irrigation and livestock), energy (electricity generation, primary energy production and processing), industrial (manufacturing and mining), and municipal sectors, by incorporating water demands into a technologically-detailed global integrated assessment model of energy, agriculture, and climate change — the Global Change Assessment Model (GCAM). Base-year water demands – both gross withdrawals and net consumptive use – are assigned to specific modeled activities in a way that maximizes consistency between bottom-up estimates of water demand intensities of specific technologies and practices, and top-down regional and sectoral estimates of water use. The energy, industrial, and municipal sectors are represented in fourteen geopolitical regions, with the agricultural sector further disaggregated into as many as eighteen agro-ecological zones (AEZs) within each region. We assess future water demands representing six socioeconomic scenarios, with no constraints imposed by future water supplies. The scenarios observe increases in global water withdrawals from 3710 km^3 $year^{-1}$ in 2005 to 6195–8690 km^3 $year^{-1}$ in 2050, and to 4869–12,693 km^3 $year^{-1}$ in 2095. Comparing the projected total regional water withdrawals to the historical supply of renewable freshwater, the Middle East exhibits the highest levels of water scarcity throughout the century, followed by India; water scarcity increases over time in both of these regions. In contrast, water scarcity improves in some regions with large base-year electric sector withdrawals, such as the USA and Canada, due to capital stock turnover and the almost complete phase-out of once-through flow cooling systems. The scenarios indicate that: 1) water is likely a limiting factor in meeting future water demands, 2) many regions can be expected to increase reliance on non-renewable groundwater, water reuse, and desalinated water, but they also highlight an important role for development and deployment of water conservation technologies and practices.

1. Introduction

Global freshwater use has grown over the past century from an estimated annual 580 km^3 in 1900 to 3829 km^3 in 2000, and continued growth is expected in the coming century [1,2]. Humans currently withdraw 8% of the total annual renewable freshwater and 54% of accessible runoff [3] and modify the timing of global runoff sufficiently to make us significant players in the hydrological cycle [4–6]. Further, more than two billion people currently live in highly water-stressed areas [7] (similar estimates given by Vörösmarty et al. [8], Arnell [9], Hanasaki et al. [10], and Arnell et al. [11]) because of the uneven distribution of runoff in time and space,

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http://dx.doi.org/10.1016/j.techfore.2013.05.006

and the situation is likely to worsen in the future as regions are subjected to more extreme climate conditions and rapidly growing demands in water-use sectors: agriculture (crop production, livestock), domestic (municipal), and industry (energy, manufacturing) [8–10]. Irrigated agriculture accounts at present for approximately 70% of the global water withdrawal and 85% of the consumptive use [2,12], and the global area of irrigated land is expected to continue to expand (albeit at slower rate than historically) in the next few decades [13,14]. Industrial and municipal water demands are closely linked to GDP and population, so these demands may increase even as water resources become increasingly scarce [2,8,15–17].

Estimation of growth in total water demands relies on our understanding of the underlying social, economic, and environmental drivers to changes in sectoral water demands. A sufficient, secure water supply is essential for meeting basic human needs and for the functioning of many sectors of the economy, making an understanding of future water demands crucial for policy makers to address the water scarcity challenge for the generations to come [18,19]. Indeed, the consequences of imbalances between water supply and demand are already well known, and are occurring in many basins around the globe [14,20]. Ecological damages include the depletion of rivers (e.g., Yellow River in China [21]), lakes (e.g., Aral Sea [22,23]), and aquifers (e.g., in India due to excessive groundwater irrigation [24]); human and economic impacts include reduced crop production, reduced power production [25], and restrictions on industrial and domestic activities that use water [26].

Rather than extrapolating trends, water demand assessments should be based on an understanding of the main drivers of the various sectoral demands of water, and should consider relevant technological and structural changes. In recent years in many basins, whole-system water use efficiency has increased due to developments such as demand-side management – switching from flat-rate pricing to increasing block rate structure, or deployment of water-conserving practices and technologies [27–30] – improvements to water supply and distribution infrastructure, and other technology changes. For example, changes to power plant cooling systems, required by law in many nations for improvement of water quality, have steadily decreased the electric-sector water withdrawal intensity in the USA and Europe, a trend that can be expected to continue in the coming decades due to capital stock turnover [31,32].

Integrated assessment models (IAMs) present a consistent, technologically-detailed, process-based modeling framework to system interactions in the context of climate change and mitigation policies. Several prominent IAMs combine sub-models of energy, land, agriculture, and climate, and have been developed over the past several decades to 1) examine dynamic, large-scale interactions between various human and Earth systems over long periods of time, typically decades to centuries [33], and 2) support assessments of climate change and climate policy, both in the United States (e.g., the National Climate Assessment) and internationally (e.g., the Intergovernmental Panel on Climate Change (IPCC) Assessment Reports). In support of these aims, the models already contain technologically-detailed, structural representations of many of the sectors relevant for future water demands, particularly in the agricultural and energy systems.

The present study incorporates sector- and technology-specific representations of water demands into the Global Change Assessment Model (GCAM), an IAM that has been employed for US and international climate assessments for decades [34–37]. GCAM is a dynamic-recursive model combining representations of the global economy, the energy system, agriculture and land use, and climate. Exogenous inputs include (among other variables) present and future population, labor productivity, energy and agricultural technology characteristics, and resource availabilities. In its current implementation, GCAM has fourteen geopolitical regions: the United States, Canada, Western Europe, Japan, Australia & New Zealand, Former Soviet Union, Eastern Europe, Latin America, Africa, Middle East, China [& Asian reforming economies], India, South Korea, and the rest of South & East Asia. The model is calibrated to historical energy, agricultural, land, and climate data through the 2005 time period, and runs in five-year time steps to 2095, establishing market-clearing prices for energy and agricultural commodities for each modeling period.

This work represents the first incorporation of sectoral water demands into a prominent, technologically-detailed integrated assessment model that already includes energy, agriculture, land use, and climate in a single modeling framework. As compared to existing water use assessments [12,15,16,38], the present study endogenously incorporates a suite of sectoral water demand models with detailed representations of subsectors (e.g., energy, fuel, and crop types) and technology (e.g., cooling system) in the GCAM framework in a consistent fashion. Despite the coarse spatial representation of regions, this integration platform facilitates the focus on interactions and feedbacks between human choices in the context of energy and land use decisions, and water demands under a set of six socioeconomic scenarios.

While previous efforts have used the SRES scenarios [11,39] in order to span the range of potential future outcomes, the present study takes advantage of six scenarios of future sectoral water demands based on the six different socioeconomic scenarios of Eom et al. [40]. IPCC SRES scenarios and RCP scenarios were designed essentially to span uncertainty in greenhouse gas emissions and year-2100 radiative forcing as common points of reference in the assessment process. Although the six scenarios presented in this paper serve the same purpose, they also provide a consistent framework that could be used to explore variety in the challenges to societies and ecosystems to adapt to and mitigate for climate challenge (for the concept, see [41,42]). Differently from the SRES and RCP approaches, we have proposed six different storylines, around which a consistent set of quantitative descriptions of economic, demographic, and technological improvement possibilities have been built to generate the scenarios. This would allow us, for example, to explore a variety of socioeconomic pathways that could underpin scenarios leading to specific year-2100 radiative forcing levels.

This approach permits analysis of the implications of different socioeconomic futures for global and regional water demands, and potentially the sufficiency of water availability. As our focus in this paper is on water demands as influenced by all other modeled systems, both human and natural, we do not incorporate a dynamic water supply module, and