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Climate and human development impacts on municipal water demand: A spatially-explicit global modeling framework

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ABSTRACT

Municipal water systems provide crucial services for human well-being, and will undergo a major transformation this century following global technological, socioeconomic and environmental changes. Future demand scenarios integrating these drivers over multi-decadal planning horizons are needed to develop effective adaptation strategies. This paper presents a new long-term scenario modeling framework that projects future daily municipal water demand at a 1/8° global spatial resolution. The methodology incorporates improved representations of important demand drivers such as urbanization and climate change. The framework is applied across multiple future socioeconomic and climate scenarios to explore municipal water demand uncertainties over the 21st century. The scenario analysis reveals that achieving a low-carbon development pathway can potentially reduce global municipal water demands in 2060 by 2–4%, although the timing and scale of impacts vary significantly with geographic location.

1. Introduction

Global hydrological models (GHM) provide a virtual environment to explore the impacts of long-term development pathways on water resources and the effectiveness of policy (Vörösmarty et al., 2000; Alcamo et al., 2003; Arnell et al., 2011; Wada et al., 2011; Haddeland et al., 2014; Hejazi et al., 2014a). As the quality and magnitude of water resources vary with geography, GHMs incorporating spatially-resolved water demand projections have been crucial in the assessment of future water challenges, such as resource scarcity and ecosystem quality (van Drecht et al., 2009; McDonald et al., 2014). Municipal water systems extract and distribute water for direct use by the population and play an important role in the global hydrological cycle, representing 12–14% of total water withdrawn globally for human purposes in 2010 (Flörke et al., 2013a; Hejazi et al., 2014b). Most GHMs incorporating municipal water demand estimate average per capita trends at the national-level, and then downscale to a finer resolution by assuming national trends hold within countries (Wada et al., 2011; Hejazi et al., 2014a; Flörke et al., 2013a; Hanasaki et al., 2013). Yet, historical observations suggest that per capita municipal water demand within countries varies spatially, mostly due to a combination of local climate conditions, economic status and urban form (Howe and Linaweaver, 1967; Mayer et al., 1999; Thompson, 2001; House-Peters and Chang, 2011). Furthermore, global models applied for future projections assume a static population distribution and are therefore unable to represent the sub-national spatial demand variability that will accompany projected urbanization.

Also less explored at the global-scale are the potential impacts of future climate change on municipal water demand. The direct climate sensitivity arises in the municipal sector from the

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freshwater used for municipal irrigation (Howe and Linaweaver, 1967; Cohen, 1987; Dandy et al., 1997; Downing et al., Weatherhead; Gutzler and Nims, 2005; Brown et al., 2013; Thebo et al., 2014). Municipal irrigation includes water to support household and municipal landscaping (e.g., turf grass and gardens), and outdoor water features (e.g., swimming pools and fountains). Municipal irrigation represents more than 50% of total municipal water demand in many regions of the United States (Mayer et al., 1999), and could play a key role in meeting future urban food requirements (Badami and Ramankutty, 2015) and mitigating urban heat island effects (Gober et al., 2009). Future variations in urban climate will affect water requirements of vegetation as well as the rate of evaporation from outdoor water features. Understanding the scale of climate change impacts on municipal water demand will provide insight into suitable adaptation strategy and the potential water co-benefits of global climate change mitigation policy.

The objective of this paper is to provide a new approach to developing and analyzing long-term global municipal water demand scenarios. A spatially-explicit modeling framework is proposed that incorporates enhanced representations of human migration, economic development and climate sensitivity. The framework is applied across multiple future human development and climate scenarios to explore the impact of coupled climate-development trajectories on municipal water demand uncertainties over the 21st century. The results provide important insight into model formulation and the potential water co-benefits in the municipal sector of policy targeting climate change mitigation.

2. Methods

2.1. Overview

Combined impacts of climate change and human development on municipal water demand are assessed at the global-level with the computational framework depicted in Fig. 1. The approach involves mapping per capita demand on a gridded representation of the earth's surface (i.e., a raster). The per capita water demand in each grid-cell is modeled as a function of a number of spatially-explicit indicators including projected income, population density, climate and historical observations. Per capita demand is then multiplied by spatial projections of population to estimate aggregate municipal water requirements in each grid-cell. The methodology utilizes spatially-explicit, quantitative interpretations of the most recent global change scenarios as a basis for the projections: the Shared Socioeconomic Pathways (SSP) (O'Neill et al., 2014), and the Representative Concentration Pathways (RCP) (van Vuuren et al., 2011a).

A key output of the analysis is therefore a new harmonized dataset well-suited for further application in global integrated assessment models (IAMs). Increasingly, global IAMs are being adapted with GHMs to examine the interplay between long-term economic development, water constraints and climate change mitigation (Hejazi et al., 2014a; Kim et al., 2016). Global IAMs incorporating future water constraints must project the scale of demand from different end-use sectors in order to devise economic responses at scales relevant to water system transformations. The simulated water demands from the municipal sector will aid in the quantification of constraints on water availability for land-use and energy, which are the historical focus of global IAMs used to study climate change mitigation (Krey, 2014).

Demand scenarios are computed at a $1/8^\circ$ spatial resolution (grid cells approximately 14 km × 14 km near the equator) and out to the year 2100 to align with the downscaled SSP and RCP datasets. The spatial resolution also ensures that parameterized demand sensitivities to population density are captured. Urban and rural populations are modeled separately in the framework to feature diversity in per capita demand stemming from differences in economic status, urban form and local climate conditions. A temporal downscaling approach enables generation of the demand scenarios at a daily time-scale. The daily time-scale is investigated to capture anticipated effects of changing socioeconomic and climatic conditions on extreme (peak) demand events important to water supply reliability (Laucelli et al., 2012). Spatially-explicit validation of the modeling framework is currently limited due to the absence of suitable historical data. We alternatively calibrate the model to observed national data and use demand projections from other global models to evaluate the reliability of model results.

We use the term *municipal water demand* in this paper to refer to the volume of water that is needed in a particular location to fulfill useful end-use services in the municipal sector. We emphasize the definition here to differentiate the modeled water volumes from withdrawals, which often occur at locations other than end-use due to the reach of urban water infrastructure (McDonald et al., 2014). A separate analysis is required to parameterize corresponding scenarios for water supply e.g., with a hydro-economic model including investment decisions for alternative water supply options (reservoirs, wastewater recycling, desalination, etc.) (Beh et al., 2014; Parkinson et al., 2016). Hydro-economic models are able to quantify economic tradeoffs between upstream and downstream users, as well as economic impacts of conjunctive management of different sources. Future water prices can be simulated with a hydro-economic model and used to parameterize an expected response from municipal consumers (Jenkins et al., 2003). In this context, the demand scenarios presented in this paper provide a useful reference point for analysis of additional responses to future water availability.

2.2. Income effects

Previous studies highlight that as household income increases, demand for water from the municipal sector increases because part of this new income is spent on increasingly water-intensive end-uses (Howe and Linaweaver, 1967; House-Peters and Chang, 2011; Cole, 2004). However, as income continues to rise, per capita demand for water increases less proportionally, due to eventual saturation of useful services (Alcamo et al., 2003). This suggests a non-linear relationship between household income and municipal sector water demand, and we propose an empirical model capturing these characteristics.

The lack of comprehensive consumer income and water use data makes identifying household-level models on a global-scale impractical. At the national-level, the Food & Agriculture Organization of the United Nations (FAO) provides estimates of aggregate municipal sector water demand (FAO, 2014). Concurrent observations of GDP are further available from organizations such as the World Bank (World Bank, 2014). Consequently, per capita GDP has been widely applied as a surrogate for average income in national-level municipal sector water demand models (Alcamo et al., 2003; Flörke et al., 2013a; Hanasaki et al., 2013; Trieb and Müller-Steinhagen, 2008; Shen et al., 2008; Hejazi et al., 2013; Guo et al., 2013). Yet, the non-linear demand response to income changes expected at the household-level means consumers respond differently depending on their current income-level. Therefore, aggregating the response of households following non-linear demand curves to average income changes should involve treatment of the income distribution (Cirera and Masset, 2010).

The effects of income inequality are included in the demand model applied in this paper following the formulation proposed in (Cirera and Masset, 2010). The approach takes advantage of the