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Research Paper

A probabilistic assessment of agricultural water scarcity in a semi-arid and snowmelt-dominated river basin under climate change

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ABSTRACT

Water resources planning and management is crucial and challenging in semi-arid regions to minimize water scarcity. Potential impacts due to climate change are a concern to water managers and stakeholders in semi-arid river basins with limited water availability. This study provides a probabilistic assessment of climate change impacts on water scarcity in the Sevier River Basin of Utah, which has a snowmelt-driven water supply and high agricultural water demands, using a decision-scaling framework. The methodology consists of a bottom-up approach that uses climate response functions, together with projections from 31 general circulation models (GCMs), to assess vulnerability to water scarcity for 2000–2099. Water scarcity is defined using an index comparing water availability to crop water demand predicted by the AquaCrop model from the Food and Agriculture Organization. Results showed that off-season precipitation is the most sensitive factor affecting water scarcity in the basin, followed by precipitation and temperature during the growing seasons. The GCM projections of temperature and precipitation suggest an increasing availability of water for agriculture in the basin. Still, a considerable risk probability of agricultural water shortage was found in years 2025 through 2049 with the emission scenario RCP4.5, suggesting the need for adaptation and mitigation strategies. The bottom-up decision scaling approach used here with a wide range of GCMs was practical to explore climate risk to agricultural water scarcity given the simplicity and minimal computational requirement.

1. Introduction

Limited water availability and increasing water demands make planning and management of water resources in semi-arid regions a challenging task. Approximately 20% of the world's population lives in arid or semi-arid regions (Sivakumar et al., 2005). These regions are prone to unprecedented water scarcity because of rapidly growing populations and nonstationary climate (Gourbesville, 2008). In particular, global warming driven by anthropogenic greenhouse gas emissions is a major concern that can significantly affect sustainability of water supply and food production. More than 70% of total global fresh water withdrawals are used for irrigation in rural semi-arid regions (Fischer et al., 2007). The impacts of anthropogenic climate change on agricultural and hydrologic systems, hence, are keen interests of water managers and policy-makers.

When assessing impacts of global warming on a climate-dependent system (e.g., atmosphere-plant-soil continuum), projections of the general circulation models (GCM) are commonly used as inputs to system models that simulate natural and human-made processes responsive to changing climate. Then, impacts of increasing greenhouse gas concentrations are evaluated by the model outputs. This type of framework fully dependent on GCM projections (referred to as the top-down framework hereafter) has been commonly employed, for instance, for irrigation requirements (e.g., Döll, 2002; Gondim et al., 2012; Mainuddin et al., 2014), crop productivity (e.g., Stöckle et al., 2010), reservoir operation for irrigated agriculture (e.g., Vano et al., 2010) among many examples. An important limitation of the top-down framework, however, is severe uncertainty stemming from climate projections. It is well known that long-term climate projections have showed sizeable incongruities between GCMs (e.g., Whateley et al., 2014; Orlowsky and Senevirantne, 2013; Brown et al., 2012), which are associated

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with inappropriate model formulations and insufficiently understood physical processes (Stainforth et al., 2005; Deser et al., 2012; Dufresne and Bony, 2008; New and Hulme, 2000). Given the deep uncertainty inherent in GCMs, the top-down framework can produce significant bias in the assessment and thus lead to unreliable mitigation and adaptation policies (Teng et al., 2012; Masutomi et al., 2009). Even when a number of GCMs are used (e.g., Lopez et al., 2009), the top-down framework cannot capture the true range of system responses to changing climate but scenario-based output variations only. Given the computational cost and efforts associated with the use of many GCMs in a classical top-down framework, most simulations include a handful of GCMs. Potential regrets from large uncertainty caused by the use of a limited number of GCMs together with less than ideal emission scenarios may become a decision nightmare in formulating adaptation policies (Brown et al., 2012).

A sensitivity-based assessment, on the other hand, is an alternative approach that enables to address the shortcomings of the top-down framework (hereafter referred to as the bottom-up framework). The bottom-up framework identifies system performance over a wide range of plausible climatic conditions. The future impacts are assessed based on sensitivity of the system performance to changing climate. Prominent examples include robust decision-making on water management (Lempert and Grove, 2010), scenario-neutral flood risk assessment (Prudhomme et al., 2010), and decision-scaling on reservoir reliability (Steinschneider et al., 2015; Brown et al., 2012). The bottom-up framework provides convenience to visualize possible ranges of system performance under a wide variation of climatic conditions. Importantly, it enables to simply translate GCM projections into decision metrics in which policymakers are interested. Brown et al. (2012) defined a multi-dimensional function that converts key climatic variables to system performance (or decision metrics) as the climate response function (CRF), highlighting its usefulness to evaluate a large number of GCMs in a probabilistic domain. Although uncertainty sources of the system models are still embedded in the CRF (Steinschneider et al., 2015), the bottom-up framework can avoid the high dependency on GCMs and the inability to draw a true range of climatic risk in the top-down framework.

Particularly when assessing multi-dimensional systems (e.g., a system with agriculture, hydrological, and socioeconomic processes together), the bottom-up framework is practical to integrate multiple facets of the system into the performance metrics. Turner et al. (2014) developed a yield-based assessment of a municipal water supply system, emphasizing that the decision-scaling could accommodate large and complex systems. Shortridge et al. (2017) showed that combined sensitivity of streamflow and evapotranspiration (ET) to climate change strongly determines whether existing infrastructure can achieve performance goals. Therefore, in problems with irrigated agriculture within which hydrologic and agricultural systems respond to changing climate together, assessments under the bottom-up framework may be essential to prepare robust and reliable adaptation strategies.

In this study, we explored future water scarcity in a large semi-arid snow-fed river basin in which rural livelihoods are rely on irrigated agriculture. Here, we provided a probabilistic climate change impact assessment using a bottom-up decision-scaling framework, considering nonstationarity of natural water supply and irrigation water demand together. A conceptual hydrologic model and a crop growth model were used to simulate natural water supply and irrigation demand, respectively. Climate change impacts were assessed at a basin scale using a CRF between a predefined water scarcity index and a set of key climatic variables. Numerous GCMs with multiple greenhouse gas emission scenarios were used to consider the severe uncertainty in GCM projections.

2. Description of study area and data

2.1. The sevier river basin

The study area is the Sevier River Basin located in south-central Utah (Fig. 1). It encompasses an area of approximately 27,389 km^2 that account for 12.5% of Utah's area. The basin has high ET and low precipitation, and is characterized by snowmelt-driven streamflow due to its high elevation and winter precipitation. Mean annual precipitation varies between 250 and 1000 mm along the elevation profile. Water from the Sevier River is highly regulated to supply irrigation for the farm lands that have been developed along the main channel and its tributaries, served mostly by three reservoirs: Piute, Otter Creek, and Sevier Bridge.

Most of the water supply from the reservoirs supports agriculture for rural livelihood. Major irrigated crops are pasture and grass hay (45%), alfalfa (44%), maize (6%), barley (4%), and wheat (1%). Crop productivity is significantly dependent on water availability from the three reservoirs during the growing season (April to September). Thus, a decreasing snowfall and early spring runoff may become challenges to efficient water management. Municipal and industrial water demands also exist, but these are relatively small in comparison to the dominant agricultural water demand.

In the Sevier River Basin, streamflows mostly originate from the upper watersheds in higher elevations but are consumed mostly by farm lands in the lower elevations according to the prior appropriation doctrine of the western U.S., which is the water right of “first in time, first in right” (Gopalakrishnan, 1973). Hence, farm lands near Delta have adequate supplies of water from the reservoirs. The farm lands near Fillmore which are outside the Sevier River Basin are irrigated with surface water from the Sevier River transported via the Central Utah Canal and local groundwater sources.

For climate change impact assessment, the upper basin above the Sevier Bridge Reservoir was divided into 23 watersheds to simulate streamflow that accounts for most of the natural water supply to the reservoirs. Runoff from the watersheds below the Sevier Bridge Reservoir was not considered due to high ET losses. To estimate agricultural water demands, the farm lands along the main channel and tributaries were divided into eight regions: Delta, Oak, Ephraim, Fillmore, Richfield, Angle, Circleville and Panguitch as shown in Fig. 1.

2.2. Climate and soil data

Daily precipitation and maximum and minimum temperatures from 1994 to 2015 were collected from 25 Snow Telemetry (SNOTEL) stations operated by the U.S. Department of Agriculture (USDA) (available at http://www.wcc.nrcs.usda.gov/snow/). The same datasets were also collected from six stations from the Global Historical Climate Network of the National Climatic Data Center (NCDC; available at http://www.ncdc.noaa.gov/) at the National Oceanic and Atmospheric Administration (NOAA). Locations of the climatic stations are shown in Fig. 1. Note that only 18 of the 31 stations located inside the basin were used for runoff and crop growth simulations. The other stations located outside the Sevier River Basin were used only for spatial coherence between the stations when generating stochastic weather conditions. Due to the absence of wind speed and relative humidity data similar to precipitation and temperatures, we used constant wind speed from the nearby USDA Soil Climate Analysis Network (SCAN) stations and minimum temperatures to estimate reference ET in the eight farming regions.

Soil physical properties required for estimating the irrigation water requirement with AquaCrop software are saturated